Constraints on primordial black holes from observation of stars in dwarf galaxies

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(Dated: June 1, 2023)

We propose a way to constrain the primordial black hole (PBH) abundance in the range of PBH masses \(m\) around 10\(^{20}\)g based on their capture by Sun-like stars in dwarf galaxies, with subsequent star destruction. We calculate numerically the probability of a PBH capture by a star at the time of its formation in an environment typical of dwarf galaxies. Requiring that no more than a fraction \(\xi\) of stars in a dwarf galaxy is destroyed by PBHs translates into an upper limit on the PBH abundance. For the parameters of Triangulum II and \(\xi = 0.5\), we find that no more than \(\sim 35\%\) of dark matter can consist of PBHs in the mass range 10\(^{18}\) – (a few) \(\times 10^{21}\)g. The constraints depend strongly on the parameter \(\xi\) and may significantly improve if smaller values of \(\xi\) are established from observations. An accurate determination of \(\xi\) from dwarf galaxy modeling is thus of major importance.

I. INTRODUCTION

As the parameter space of particle dark matter (DM) models becomes more and more constrained by the direct and indirect detection experiments \cite{1} \cite{2}, other nonparticle candidates start attracting considerable attention. Among these candidates, an interesting possibility is that DM is composed of primordial black holes (PBHs), which could have been created in the early Universe and survived until today \cite{3} \cite{4}. A variety of mechanisms to create such black holes has been proposed in the literature (see Ref. \cite{5} for a review). Their masses \(m\) may range from \(\sim 10^{17}\) g, below which they would evaporate too fast by Hawking radiation, to tens of solar masses where they could contribute to, or potentially explain, the black hole merger events observed by gravitational wave detectors \cite{6} \cite{7}. Their relative abundance \(f = \Omega_{\text{PBH}}/\Omega_{\text{DM}}\) can typically be adjusted to match the whole or a fraction of the observable DM.

For PBH masses roughly above \(\sim 10^{20}\)g, their contribution to the total DM density has been constrained from various observations \cite{8}. However, a large — several orders of magnitude — range of masses around 10\(^{20}\)g remains virtually unconstrained. These asteroid-mass PBHs are particularly difficult to constrain as they have atomic size, and are too few to hope for a direct detection. A proposal has been made to use the capture of these PBHs by neutron stars (NS) and white dwarfs in DM-rich environments like dwarf galaxies \cite{9} \cite{10}; however, no observations of NS in dwarf galaxies exist at present.

In this paper we propose a way to constrain the abundance of asteroid-mass PBHs in the mass range around 10\(^{20}\)g based on their capture by main sequence, sun-like stars. While main sequence stars offer less favorable conditions for capture as compared to NS and white dwarfs, the advantage is that they are routinely observed in dwarf galaxies. The direct PBH capture during the star lifetime is not efficient in the case of main sequence stars \cite{11}; we will concentrate instead on their capture at the stage of star formation, which is the dominant mechanism for main sequence stars, as will be explained below.

If a Sun-like star captures a PBH of mass around \(m \sim 10^{20}\)g, the latter starts accreting the star matter. Assuming the Bondi accretion, which is justified by the fact that the Bondi radius \(r_B = 2Gm/c^2_s \sim 5 \times 10^{-3}\)cm is much larger than the interatomic distance, the accretion time is estimated as

\[
t_{\text{acc}} = \frac{c^2_s}{4\pi \rho_c G^2 m} = 5.2 \times 10^6 \text{yr} \left(\frac{10^{20} \text{g}}{m}\right),
\]

where we have used the value of the sound speed in the Sun core \(c_s = 511 \text{ km/s}\) and the core density \(\rho_c = 146 \text{ g/cm}^3\). This is much smaller than the star lifetime \(t_* \sim 10^{10}\) yr, so that a star that has captured a PBH gets rapidly destroyed. Mere observations of stars then constrain the probability of capture, which translates into constraints on the PBH abundance \(f\).

The rest of this paper is organized as follows. In Sec. \textbf{II} we calculate the probability of the PBH capture by a star in a DM halo with reference values of parameters. In Sec. \textbf{III} we show how this result can be used to constrain the PBH abundance in concrete dwarf galaxies. Section \textbf{IV} contains concluding remarks.

II. CAPTURE OF PBHS BY MAIN SEQUENCE STARS

For a successful capture a PBH must first get on a bound orbit that crosses the star, and then gradually loses energy during periodic collisions with the star until it finally sinks completely inside the latter. The second, “cooling” stage is common to both capture mechanisms (the direct capture during the star lifetime and the capture at the time of star formation), so let us first look at this stage in more quantitative terms.

A PBH crossing the star loses energy to the dynamical friction \cite{12} described by the force

\[
F = -4\pi G^2 m^2 \rho_c \frac{\ln \Lambda}{v^2}
\]  

(2)
where \( m \) is the PBH mass, \( \rho_* \) the mean star density, \( v \) the PBH velocity, and \( \ln \Lambda \approx 30 \) the Coulomb logarithm. This mechanism is very inefficient. In addition, most of the PBHs that eventually get captured start on extremely elongated orbits and spend most of their time in a loss-free Keplerian motion. Everywhere except in the vicinity of the star, such orbits are well approximated as radial and are characterized by their apastron \( r_\text{max} \gg R_* \), \( R_* \) being the star radius. The initial value of \( r_\text{max} \) together with Eq. (2) determine the duration of the cooling stage. Following the method of Ref. [13], the cooling time can be estimated as

\[
t_{\text{cool}} \sim \frac{\pi M_* R_*}{m \ln \Lambda} \sqrt{\frac{r_\text{max}}{R_g}} \sim 10^{10} \text{yr} \left( \frac{r_\text{max}}{100 \text{AU}} \right)^{1/2} \left( \frac{10^{20} \text{g}}{m} \right)^{1/2}
\]

where \( M_* \) is the star mass and \( R_g = 2GM_* \) its gravitational radius. The PBHs that have cooling times exceeding \( \sim 10^{10} \text{yr} \) do not get captured.

Apart from the insufficient time, the cooling may be unsuccessful if interrupted by the deviation of the PBH from the star-crossing orbit due to perturbations produced by, e.g., nearby stars. Such PBHs stop losing energy and do not get captured. To quantify the effect of perturbers we first note that for very extended, nearly radial orbits the periastron \( r_\text{min} \) is determined by the PBH angular momentum \( J \) with respect to the star,

\[
r_\text{min} = J^2/(m^2 R_g).
\]

The condition under which the orbit crosses the star \( r_\text{min} < R_* \) translates into the maximum angular momentum \( J/m \), in the presence of perturbations the angular momentum may change; successful cooling requires that these changes are smaller than \( J_{\text{max}} \). For the estimate, assume the original radial trajectory \( x(t) \) is perturbed in the plane \((x, y)\) by a small potential \( U(\vec{r}) \). The change of the angular momentum over the time of one free fall from \( r_\text{max} \gg R_* \) to \( r \sim R_* \) is

\[
\Delta J/m = \int_0^{T/4} x^2(t) U_{xy} dt,
\]

where \( T \) is the period of the Keplerian orbit and \( U_{xy} = \partial_x \partial_y U \). Substituting the unperturbed motion and neglecting the variations of \( U_{xy} \) along the trajectory we get

\[
\Delta J/m = \frac{5\pi}{16} \frac{r_{\text{max}}^{7/2}}{R_g^3} U_{xy}.
\]

In the case when the perturbation is caused by another star, considered static, at a distance \( d \gg r_{\text{max}} \), we obtain from Eqs. (4) and (5) the condition on the periastron of the perturbed orbit

\[
r_\text{min} = \alpha r_{\text{max}} \left( \frac{r_{\text{max}}}{d} \right)^6 < R_*,
\]

where \( \alpha \) is a calculable numerical coefficient of order 1 depending on the direction to the perturber. This imposes a second constraint on \( r_{\text{max}} \). While the first condition resulting from Eq. (3) becomes less important as the PBH mass increases, the second one, Eq. (6), is independent of the mass. We will use these constraints later when calculating the capture probability.

Let us now turn to the first stage of capture which sets initial conditions for the cooling. Two mechanisms have been considered in the literature: capture during the star lifetime, and at the star formation. In the first case, during the star lifetime some PBHs from the ambient DM halo may collide with the star, lose energy due to dynamical friction, Eq. (2), and become gravitationally bound. In the context of capture by neutron stars this process has been considered in Ref. [2]. Only very slow PBHs can become bound after a single collision. Their energies then become of order \( -E_{\text{loss}}, \) which determines the initial size of their orbits. In the case of main sequence stars the energy loss is very small and is estimated from Eq. (2) as

\[
E_{\text{loss}} \sim \frac{2GM^2}{R_*} \ln \Lambda.
\]

Converting this to the orbit size we find

\[
r_{\text{max}} = \frac{M_* R_*}{2m \ln \Lambda} = 7.5 \text{kpc} \left( \frac{10^{20} \text{g}}{m} \right).
\]

This is by many orders of magnitude larger than needed to satisfy any of the two cooling constraints, cf. Eqs. (3) and (6). We conclude, in agreement with Ref. [11], that the direct capture does not work in the case of main sequence stars.

Consider finally the capture at the star formation [9,10]. When the star is formed from a gas cloud, the contracting baryons create a time-dependent gravitational potential that drags along the DM particles (PBHs in this case) which lose energy and develop a cuspy density profile centered on the star. Only a fraction of PBHs that are gravitationally bound to the cloud and eventually cross it during the contraction are significantly affected. By the end of the contraction some of them settle on orbits crossing the newly formed star, and thus enter the cooling stage.

We now proceed to the calculation of the number of PBHs captured by a star in this way. The capture is a random process; the number of PBHs captured by a single star follows the Poisson distribution characterized by the mean captured PBH mass. The latter can be written as \( f \bar{M} \), where \( f \) is the PBH abundance and \( \bar{M} \) is the captured mass assuming all of the DM consists of PBHs. For an ensemble of stars in identical conditions the mean captured mass \( f M \) determines the fraction \( \xi \) of stars that have been infected (and eventually destroyed) by PBHs of mass \( m \), \( \xi = 1 - \exp(-f M/m) \). The fraction of destroyed stars \( \xi \) is assumed to be constrained from observations. Inverting the above relation we thus obtain the constraint on the PBH abundance \( f \),

\[
f < \frac{m}{M} \ln \frac{1}{1 - \xi}.
\]
Note that no constraints arise when the rhs of Eq. 8 is larger than one as \( f \leq 1 \) by definition.

Following the logic of Refs. 9, 10, we calculate the mean captured mass \( M \) by numerically evolving randomly generated PBH trajectories, one at a time, in the time-dependent gravitational field of a contracting baryon cloud, counting those that correspond to star-crossing orbits at the end of the contraction and satisfy the cooling conditions. Knowing the DM abundance and distribution, and the fraction of “successful” trajectories, we can determine \( M \). The detailed steps of the simulation are as follows.

We assume that the initial distribution of baryons is a uniform sphere of radius \( R_C = 4300 \) AU and density \( 1.78 \times 10^{-18} \) g/cm\(^3\) as corresponds to the parameters of a pre-stellar core of a star of \( 1 M_\odot \) [14]. The baryonic sphere is slowly contracted in size, while its profile is gradually changed from a uniform one to the actual star density profile rescaled to the current sphere size, with the total mass being constant. At the end of the contraction the result is a star of Sun radius \( R_* = R_C \) and with the Sun density profile [15]. In the adiabatic approximation the precise way of contraction does not matter; we use the linear decrease in radius as well as a linear evolution of the profile. We have checked that the results are stable with respect to changes of the contraction law provided it is much slower than the free fall (in practice, several times slower is sufficient [9]).

The initial conditions for the PBH trajectories sample the DM distribution. We assume that the DM is uniformly distributed in space with density \( \rho_{DM} \) and follows the Maxwell velocity distribution with the dispersion \( \bar{v} \). The reference values \( \rho_{DM} = 100 \) GeV/cm\(^3\) and \( \bar{v} = 7 \) km/s are adopted at this stage and will be rescaled in Sec. 11 according to conditions in concrete dwarf galaxies.

In position space, we sampled the region \( r < 20R_C \). We have checked that increasing further the size of this region does not change the results as those trajectories that start further away do not satisfy the cooling conditions and will in any case be rejected.

In velocity space, we limited the sampled region to \( v < v_{\text{esc}} \), where \( v_{\text{esc}} = \sqrt{(3GM_\odot/R_C)} = 0.79 \) km/s is the escape velocity from the center of the uncontracted cloud. Note that, since \( v_{\text{esc}} \ll \bar{v} \), the volume of this region is proportional to \( \bar{v}^3 v_{\text{esc}}^3 \). To increase the computational efficiency we further limited the sampled region to small tangential velocities \( v_L < \sqrt{2GM_\odot R_C}/r \); this condition eliminates trajectories with large angular momenta since they do not cross the star after the contraction of the cloud. The volume of the resulting phase space, as well as the total DM mass it contains, was calculated analytically.

Not all the initial conditions from the above region of phase space correspond to bound particles. We sampled the whole region randomly and discarded the unbound (positive energy) trajectories keeping track of their fraction. The remaining ones were evolved in the gravitational field of the contracting cloud; those that did not have periastrons within the star radius at the end of the contraction (a very small fraction) were again discarded. Combining all the fractions, the total amount of the DM sampled by the accepted trajectories is \( 8.34 \times 10^{21} \) g. We have simulated in this way a total of \( 4 \times 10^6 \) trajectories, recording for each of them the periastron and the apastron after the contraction.

To compute the mass of PBHs that actually get captured, the cooling conditions have to be checked for each trajectory. The fraction of trajectories respecting both these conditions, multiplied by the total mass previously obtained, gives the mean mass \( \bar{M} \) of PBHs captured by the star. The estimate [3] cannot be used to check individual trajectories as it was based on an average energy loss. Instead, we use Eq. (2) directly to calculate the cooling time for each trajectory, taking into account its parameters and making use of the actual star density profile [15]. The problem is, in general, complicated since the energy and angular momentum losses have to be calculated every time the PBH crosses the star, all the way until it sinks inside. However, several approximations may be used to simplify the task.

Clearly, the cooling time is dominated by the first stages when the orbits are nearly radial. One may check that for such orbits the star crossing episodes have negligible effect on the periastron \( r_{\text{min}} \) and mainly affect the apastron \( r_{\text{max}} \). Moreover, the energy loss at one crossing is practically independent of \( r_{\text{max}} \) and only depends on \( r_{\text{min}} \). Since the motion between the crossings is Keplerian, one can calculate the cooling time analytically in terms of \( E_{\text{loss}}(r_{\text{min}}) \). Requiring that the cooling time does not exceed the star lifetime \( t_* = 10^{10} \) yr, one obtains the constraint on \( r_{\text{max}} \),

\[
E_{\text{loss}}^2(r_{\text{min}}) \ll 2\pi^2 GM_\odot m^2 t_*^2.
\]

Note that if we use here the estimate [7] for \( E_{\text{loss}} \) instead of \( E_{\text{loss}}(r_{\text{min}}) \), we recover Eq. 3. The function \( E_{\text{loss}}(r_{\text{min}}) \) was calculated numerically for the PBH mass \( m = 10^{20} \) g. For other PBH masses it can be obtained by a simple rescaling \( E_{\text{loss}} \propto m^2 \), cf. Eq. [7]. We have checked that the analytically calculated cooling time is well reproduced by a direct numerical integration for several trajectories.

The second cooling constraint arises from the requirement that the PBH trajectory is not deviated from the star-crossing regime by gravitational perturbations. We model these perturbations by static randomly placed stars with the density \( n_* \). Making use of the three-dimensional version of Eq. 5, we determine the maximum size of the trajectory such that the deviations remain small in at least 50% of random realizations of the perturbers. We discard the trajectories that have larger apastrons. Note that this second condition is independent of the PBH mass.

The net result of the capture process is summarized in Fig. 1, which shows the mean captured mass \( \bar{M} \) as a
function of the PBH mass $m$. The star density of $n_\ast = 9.2 \times 10^{-3} \text{pc}^{-3}$ was used in producing this figure, which is about the highest among the dwarf galaxies considered in the next section. The behavior is approximately linear below $m = (a \text{ few}) \times 10^{20} \text{g}$; the cooling time constraint is dominant in this region. At higher masses the constraint due to perturbers starts to dominate and the behavior flattens out.

III. APPLICATION TO OBSERVED DWARF GALAXIES

The mean captured mass $\bar{M}$ together with Eq. (8) allow one to constrain the PBH abundance $f$ given the value of $\xi$. Since the captured mass is directly proportional to the factor $\rho_{DM}/\bar{v}^3$, the strongest constraints come from the environments with the largest DM density and smallest velocity dispersion, the conditions realized in the ultra-faint dwarf galaxies. Several tens of dwarf galaxies have been observed around the Milky Way; for a review see Ref. [16]. Table II lists the essential properties of five of the most promising ones.

| Galaxy       | $R_{1/2}$ [pc] | $\sigma$ [km/s] | $\rho_{DM}$ [GeV/cm$^3$] | $n_\ast$ [10$^{-3}$ pc$^{-3}$] | $\eta$ |
|--------------|----------------|------------------|---------------------------|-------------------------------|-------|
| Triangulum II| 16             | < 5.9            | 161                       | 9.2                          | 0.95  |
| Tucana       | 37             | < 10.2           | 343                       | 2.6                          | 0.39  |
| Draco II     | 19             | < 10.2           | 343                       | 2.6                          | 0.39  |
| Segue I      | 24             | 6.4              | 85                        | 2.1                          | 0.39  |
| Grus I       | 28             | 5.0              | 38                        | 9.6                          | 0.37  |

TABLE I. The parameters of dwarf galaxies.

For each galaxy, the directly measured parameters are the line-of-sight velocity dispersion of stars that determines the 3D dispersion $\sigma$, and the projected half-light radius $R_{1/2}$ related to the 3D one by $R_{3D} = 4/3 R_{1/2}$.

We assume that the velocity dispersions of stars and of DM are the same, and that both follow the Maxwell distribution. We then obtain the DM dispersion in the star rest frame $\bar{v} = \sqrt{2}\sigma$. Knowing $R_{1/2}$ and $\sigma$ we can calculate the mass $M_{1/2}$ within the half-light radius by means of Eq. (1) of Ref. [16]. Assuming baryons are subdominant, from $M_{1/2}$ and $R_{1/2}$ one obtains the DM density $\rho_{DM}$. Knowing the luminosity one can then calculate the number density of stars $n_\ast$ within $R_{3D}$ and check that their mass density is indeed subdominant to that of the DM. We have therefore all the parameters needed to determine the mean captured mass $\bar{M}$ as a function of $m$ in the conditions of a concrete dwarf galaxy.

The constraining power of a given dwarf galaxy is proportional to the “merit factor”

$$\eta = \frac{\rho_{DM}}{100 \text{ GeV/cm}^3} \left(\frac{7 \text{ km/s}}{\sqrt{2}\sigma}\right)^3.$$ 

The merit factors of observed dwarf galaxies are listed in Table II. Where only the upper limit on $\sigma$ exists, this limit was used in calculations, which is conservative since, including the factor $\sigma^2$ coming from the DM density $\rho_{DM}$, the merit factor is proportional to $1/\sigma$. The highest merit factor corresponding to the strongest constraints is found for Triangulum II. It is important to note, however, that this galaxy is not an exception; several other galaxies have similar constraining power.

Once the mean captured mass per star $\bar{M}$, is determined for a given galaxy, one may use Eq. (8) to constrain the PBH abundance provided that the maximum allowed fraction of destroyed stars $\xi$ is known. While there exist quantitative models of dwarf galaxies, see Ref. [16] for a review, no estimates of $\xi$ have yet been performed. Such estimates require a dedicated analysis of galaxy evolution models and lie beyond the scope of this paper. Nonetheless, including the new mechanism of star destruction by PBHs in galaxy evolution codes and requiring that the present-time properties (such as the stellar mass, stellar-to-halo mass ratio, mean metallicity, and metallicity dispersion) correspond to the ones observed in UFDs should allow one to determine the value of $\xi$. For now, we treat $\xi$ as a free parameter and choose $\xi = 0.5$ as a benchmark value, which corresponds to half of the stars in a galaxy, typically several hundred, having been destroyed by PBHs. Since this would imply order 1 changes in the galaxy modeling, we expect that this choice is reasonable. For illustration, we also present the constraints for $\xi = 0.2$. Note that the scaling of the constraints with $\xi$ trivially follows from Eq. (8).

In Fig. 2 we show the resulting constraints on the PBH abundance $f = \Omega_{PBH}/\Omega_{DM}$ as a function of the PBH mass for Triangulum II, the most constraining galaxy of those listed in Table II. The blue and orange regions are excluded assuming $\xi = 0.5$ and $\xi = 0.2$, respectively. We do not show the constraints for masses below $10^{18} \text{g}$ because in this range of masses the time of star destruction, Eq. (1), becomes comparable or exceeds the star lifetime.
The most important conclusion from our results is that in DM-rich environments such as dwarf galaxies the probability of capture of an asteroid-mass PBH by an ordinary star may be of order 1, provided these PBHs constitute a substantial fraction of the dark matter. This probability was thought to be negligible in the existing literature, the reason being that capture at the stage of star formation has not been included. While for neutron stars and white dwarfs this mechanism gives a contribution of the same order as the direct capture during the star lifetime, it is far more dominant in the case of ordinary stars. This opens a possibility to constrain the PBH abundance in the mass range $10^{18} - 10^{22}$ g where no other constraints exist at the moment. The advantage of the ordinary stars as compared to neutron stars and white dwarfs is that they are observed in dwarf galaxies.

We performed a detailed calculation of the PBH capture by a star at its formation. Similar calculations have been done previously in the context of compact stars. We have applied these calculations to ordinary stars, including, in addition, the effect of gravitational perturbations arising from nearby stars, and taking into account the actual star density profile. The results of our computation are summarized in Fig. 1 in terms of the mean captured mass per star $\bar{M}$ for the reference parameters of the ambient DM halo, $\rho_{DM} = 100$ GeV/cm$^3$ and $\bar{v} = 7$ km/s. This part of our calculations does not depend on astrophysical uncertainties.

We then converted the mean captured mass into constraints on the PBH abundance, assuming that no more than a fraction $\xi$ of all stars in a dwarf galaxy has been destroyed by PBHs. To derive the constraints for a concrete dwarf galaxy we rescaled the $\bar{M}$ of Fig. 1 according to the galaxy merit factor, Table I, and took into account the actual star density in the Galaxy, which determines precisely how the constraints are cut off at high masses. We present the result for Triangulum II in Fig. 2 using as a benchmark the value $\xi = 0.5$.

The resulting constraints depend crucially on the assumed value of $\xi$: they are marginal for the adopted value $\xi = 0.5$ and would disappear for $\xi \gtrsim 0.9$. Clearly, a quantitative determination of this parameter from dwarf galaxy modeling is of major importance. The example of $\xi = 0.2$ in Fig. 2 shows that limiting $\xi$ to lower values may significantly improve the constraints on the PBH abundance.

The conversion of $M$ into the constraints on $f$ involves a few additional astrophysical assumptions which may need to be better quantified together with a more precise determination of $\xi$. In the present calculation, we neglected the distribution of stars in masses assuming all stars in a dwarf galaxy have masses $\sim 1 M_\odot$. We also neglected the variations of the DM density within a dwarf galaxy. In view of higher DM density, a cuspy profile is likely to strengthen the constraints.

Finally, a more accurate data on dwarf galaxies, notably the measurements of velocity dispersions for galaxies where only the upper bounds exist at present, may further strengthen the results. New data are expected in the near future from the ongoing and upcoming surveys.

In this paper we have discussed only constraints resulting from a mere disappearance of stars in dwarf galaxies. There may exist other, independent signatures of star conversion to black holes by captured PBHs. First, it is likely that last stages of accretion are catastrophic events with supernova-type energy release. If so, these events may be important in the energy and/or gas balance of a dwarf galaxy and will have to be taken into account in its modeling. Furthermore, with total energy release of order of a supernova, these events will be easily observable even if they last for millions of years. Their nonobservation in this case may result in additional constraints on $\xi$ and, therefore, on PBH. Second, for sizeable values of $\xi$ the dwarf galaxy will have a large population of subsolar mass black holes — remnants of star destructions. These black holes may potentially be observed, e.g., through gravitational waves produced in their coalescence. We leave these questions for future study.

ACKNOWLEDGEMENTS

We are grateful to S. Clesse and M. Pshirkov for useful discussions and comments on the manuscript, and to J. Simon and E. Kirby for the discussion of dwarf galaxies. This work is supported in part by the Institut Interuniversitaire des Sciences Nucléaires Grant No. 4.4503.15. N. E. is a FRIA grantee of the Fonds de la Recherche Scientifique – FNRS.
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