

Dark gamma-ray burstsVedran Brdar,^{*} Joachim Kopp,[†] and Jia Liu[‡]*PRISMA Cluster of Excellence and Mainz Institute for Theoretical Physics,
Johannes Gutenberg-Universität Mainz, 55099 Mainz, Germany*

(Received 26 July 2016; published 31 March 2017)

Many theories of dark matter (DM) predict that DM particles can be captured by stars via scattering on ordinary matter. They subsequently condense into a DM core close to the center of the star and eventually annihilate. In this work, we trace DM capture and annihilation rates throughout the life of a massive star and show that this evolution culminates in an intense annihilation burst coincident with the death of the star in a core collapse supernova. The reason is that, along with the stellar interior, also its DM core heats up and contracts, so that the DM density increases rapidly during the final stages of stellar evolution. We argue that, counterintuitively, the annihilation burst is more intense if DM annihilation is a p -wave process than for s -wave annihilation because in the former case, more DM particles survive until the supernova. If among the DM annihilation products are particles like dark photons that can escape the exploding star and decay to standard model particles later, the annihilation burst results in a flash of gamma rays accompanying the supernova. For a galactic supernova, this “dark gamma-ray burst” may be observable in the Čerenkov Telescope Array.

DOI: 10.1103/PhysRevD.95.055031

I. INTRODUCTION

A series of pioneering papers from the 1980s has established that stars are likely to capture large amounts of dark matter (DM) particles from the galactic halo [1–6]. This happens because DM particles scattering on atomic nuclei or on previously captured DM particles inside the star may lose enough energy to become gravitationally bound to it. Subsequently, as they orbit its center, they experience additional scatterings and eventually settle down into a thermalized DM core extending over the inner regions of the star. There, they can self-annihilate, and if some of their annihilation products, in particular neutrinos, are able to leave the star, observable signals are expected from the Sun [1,3–37]. Indeed, some of the strongest limits on DM scattering on nuclei are obtained this way [38–41]. The potential impact of light DM particles on supernova cooling rates has been studied in [42].

The aim of this work is to follow the evolution of the DM core of a massive ($\gtrsim 8 M_{\odot}$) star from the formation epoch all the way through its death in a core collapse supernova. As the star burns first hydrogen and then heavier and heavier elements at its center [43], the density and temperature of the baryonic matter increase, and as long as DM scattering rates are sufficiently large, the DM core heats up and contracts in the same way. As we show in this paper, this leads to strongly enhanced DM annihilation rates at the end of the stellar life cycle, and, in some DM models, to

observable signals. We dub these signals dark gamma-ray bursts (not to be confused with the scenario from Ref. [44]).

II. DARK MATTER CAPTURE

Assuming spherical symmetry, the rate at which DM particles are captured by the star can be written as [5,26,27,45]

$$C_{\text{cap}} = \sum_i \int_0^{R_{\text{star}}} dr 4\pi r^2 \frac{dC_i(r)}{dV}. \quad (1)$$

Here, the sum runs over the different isotopes in the star, R_{star} is its total radius, and $dC_i(r)/dV$ is the capture rate per volume element [5]. The latter is proportional to the number density $n_i(r)$ of nuclei of type i , to the galactic DM density $\rho_{\text{DM}}^{\text{gal}}$, and to the DM-nucleon scattering cross section σ_n .

We take the radial density profile of the star and its chemical composition from a simulation of a $12 M_{\odot}$ star by Heger *et al.* [46–49]. $\rho_{\text{DM}}^{\text{gal}}$ depends on the distance from the Galactic center (GC), and we model this dependence with an Einasto profile [50–52]. For the velocity distribution of galactic DM particles, we assume a Maxwell–Boltzmann form with velocity dispersion $\bar{v} = 270 \text{ km sec}^{-1}$. This number is almost independent of the location of the star, except for stars very close ($\ll 1 \text{ kpc}$) to the Galactic center [53]. The DM-nucleon scattering cross section can include both spin-independent (SI) contributions (for instance from scalar or vector interactions) and spin-dependent (SD) contributions (for instance from axial vector interactions): $\sigma_n = \sigma_n^{\text{SI}} + \sigma_n^{\text{SD}}$. We allow for both types of interactions

^{*}vbrdar@uni-mainz.de[†]jkopp@uni-mainz.de[‡]liuj@uni-mainz.de

and, unless otherwise noted, choose $\sigma_n^{\text{SI}} = 10^{-46} \text{ cm}^2$ and $\sigma_n^{\text{SD}} = 10^{-40} \text{ cm}^2$, in accordance with constraints [54–56]. For these values, DM scattering on hydrogen is entirely dominated by σ_n^{SD} , while for heavier nuclei, σ_n^{SI} is usually more relevant. The reason is that most of the nuclei abundant in stars do not carry spin. The exception is ^{14}N , which has an unpaired proton and an unpaired neutron. Lacking numerical values for the corresponding spin matrix elements $\langle \mathbf{S}_p \rangle$ and $\langle \mathbf{S}_n \rangle$, we approximate $\langle \mathbf{S}_p \rangle$ ($\langle \mathbf{S}_n \rangle$) by its value for ^{15}N (^{13}C) [57]. For spin-independent scattering, nuclear form factors are modeled following Ref. [5,58]. We verified that the nonzero temperature of the nuclei in the star is negligible as long as we consider only DM masses $m_{\text{DM}} \gtrsim 10 \text{ GeV}$ [26].

In addition to scattering on nuclei, DM particles may also scatter on previously captured DM particles if the underlying particle physics model admits DM self-interactions [59]. Self-interacting DM is motivated for instance by discrepancies between observed and predicted DM distributions on small scales [60]. Though they are not crucial for our conclusions, we allow for self-interactions mediated by a scalar or vector mediator of mass M and with coupling $\alpha' \equiv g^2/(4\pi)$. The DM self-capture rate is computed in analogy to the capture rate on ordinary matter [5]. We compute the DM-DM scattering cross section σ_{DM} in the classical limit, where $m_{\text{DM}}v/M \gg 1$ (with v being the DM velocity) [61,62], and in the perturbative regime, where $\alpha'm_{\text{DM}}/M \ll 1$ [35,63]. Between the two limiting regimes, we use linear interpolation. Numerically, we find that the self-capture rate can be comparable to the capture rate on nuclei, especially when DM annihilation is a p -wave process. As we see below, the number of DM particles in the stellar core is larger in this case.

After the initial DM-nucleon or DM-DM scattering that captures a DM particle by reducing its velocity below the escape velocity, the particle scatters multiple more times, eventually thermalizing with the baryonic matter. The DM core of the star can therefore be assigned a temperature T_{DM} , which we take equal to the baryon temperature at its average radius [26],

$$\bar{r} = \frac{\int_0^{R_{\text{star}}} d^3r r n_{\text{DM}}(r)}{\int_0^{R_{\text{star}}} d^3r n_{\text{DM}}(r)}. \quad (2)$$

The DM number density is parametrized as [26]

$$n_{\text{DM}}(r) = n_0 \exp[-m_{\text{DM}}\phi(r)/T_{\text{DM}}], \quad (3)$$

with $\phi(r)$ being the gravitational potential at radius r .

Scattering of a previously captured DM particle on nuclei or other DM particles can also increase its energy and lead to evaporation [4,6,26,64], but we have confirmed numerically that for the DM masses of interest to us ($m_{\text{DM}} \gtrsim 10 \text{ GeV}$), this effect is negligible.

III. DARK MATTER ANNIHILATION

The DM annihilation rate is given by [26,27]

$$\Gamma_{\text{ann}} = \frac{1}{2} \int d^3r \langle \sigma v_{\text{rel}} \rangle n_{\text{DM}}^2(r) \equiv \frac{1}{2} C_{\text{ann}} N_{\text{DM}}^2. \quad (4)$$

Here, $\langle \sigma v_{\text{rel}} \rangle$ is the annihilation cross section, multiplied by the relative velocity v_{rel} of the annihilating DM particles and averaged over their thermal velocity distribution. We have here defined the annihilation coefficient C_{ann} in terms of the total number of DM particles in the stellar core, $N_{\text{DM}} = \int d^3r n_{\text{DM}}(r)$.

Below, we distinguish between models in which $\langle \sigma v_{\text{rel}} \rangle$ is approximately independent of v_{rel} (s -wave annihilation) and models where $\langle \sigma v_{\text{rel}} \rangle \propto \langle v_{\text{rel}}^2 \rangle$ (p -wave annihilation) [63,65]. As a benchmark model for s -wave (p -wave) annihilation, we consider DM annihilation into dark photons A' (dark sector scalars ϕ) through t -channel and u -channel diagrams. We choose the annihilation cross section such that $\langle \sigma v_{\text{rel}} \rangle = 4.4 \times 10^{-26} \text{ cm}^3/\text{sec}$ at $\langle v_{\text{rel}}^2 \rangle \approx 0.24$ [66], characteristic for thermally produced Dirac DM particles [67,68]. In the star, at temperatures much lower than in the early Universe, the annihilation cross section is then much smaller for p -wave annihilation than for s -wave annihilation. Therefore, more DM can accumulate inside the star in the p -wave case. If A' or ϕ is much lighter than m_{DM} , also Sommerfeld enhancement needs to be taken into account [63,69,70].

IV. EVOLUTION OF THE DM POPULATION INSIDE THE STAR

The number of DM particles gravitationally bound to the star obeys the differential equation

$$\dot{N}_{\text{DM}}(t) = C_{\text{cap}}(t) - C_{\text{ann}}(t)N_{\text{DM}}(t)^2 + C_{\text{self}}(t)N_{\text{DM}}(t), \quad (5)$$

with C_{cap} and C_{ann} from Eqs. (1) and (4), respectively, and with C_{self} being the self-capture coefficient [59]. The time dependence of C_{cap} , C_{ann} , and C_{self} arises from the time-dependent density, temperature, and chemical composition of the baryonic matter. Our input data for these quantities from Ref. [46] consist of 52 nonlinearly spaced snapshots between the beginning of hydrogen burning in the stellar core and the presupernova stage, 250 ms before core bounce. Between snapshots, we interpolate linearly. We assume quasi-instantaneous thermalization of captured DM particles because during most of the star's life, the time between DM-nucleus collisions is much shorter than the time scales over which the properties of the baryonic matter change significantly. Note that DM particles captured during the last ~ 1000 yrs do not thermalize, but their number is negligibly small. Particles that were captured earlier and are already thermalized follow the evolution of

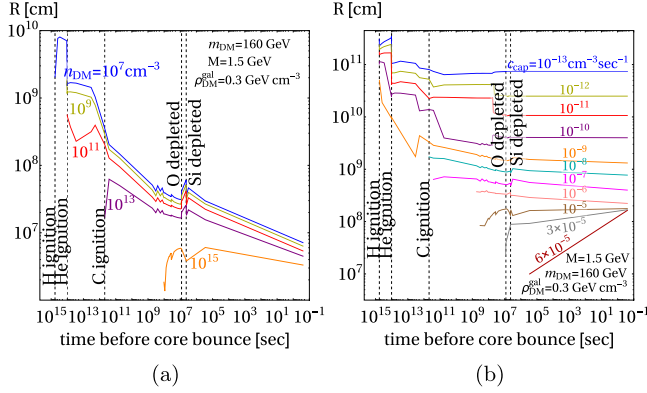


FIG. 1. Contours of constant DM number density n_{DM} (left) and constant DM capture rate c_{cap} (right) in the t - R (time-radius) plane. c_{cap} is defined as $\sum_i dC_i(r)/dV$ where the sum runs over different nuclei. Note that the time axis is reversed to better reflect the fast evolution in the late stages. We have assumed s -wave annihilation of 160 GeV DM particles into dark photons of mass $M = 1.5$ GeV.

the baryonic matter even shortly before the supernova. For instance, in the hot iron core just before collapse (temperature ~ 3 MeV, density 10^{14} grams/cm 3), the collision time of a 100 GeV DM particle via σ_n^{SI} is of order 0.001 sec.

The evolution of the stellar DM core is illustrated in Fig. 1. We see that the DM core grows during hydrogen burning and then contracts along with the baryonic matter. The reason is that capture is very efficient at early times [see Fig. 1(b)], thanks to the large spin-dependent scattering rate on hydrogen. Later, when hydrogen is depleted, the capture rate drops.

The time evolution of several radius-integrated parameters of the DM core is shown in Fig. 2. Panel (a) illustrates again that the capture rate rapidly decreases after core hydrogen burning ceases. This decrease is accompanied by

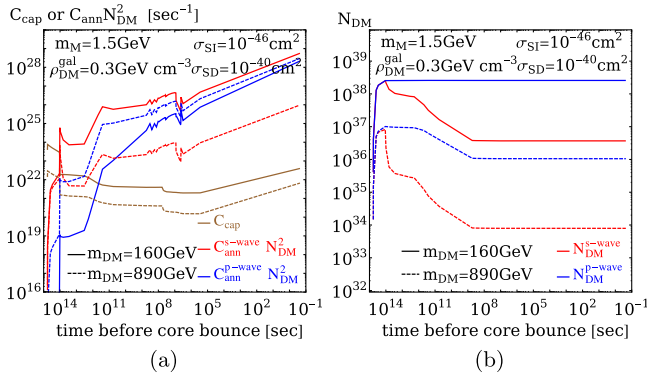


FIG. 2. (a) Time evolution of the radius-integrated capture and annihilation rates [see Eqs. (1) and (4)] for two different models (s -channel annihilation to dark photons and p -channel annihilation to dark scalars) and for two different DM masses. (b) Time evolution of the total number of captured DM particles N_{DM} for the same benchmark models.

an increase in the DM annihilation rate, caused by contraction of the DM core. (The slight increase of C_{cap} shortly before the supernova is due to contraction of residual hydrogen.) For s -wave annihilation (red curves), the number N_{DM} of DM particles in the star decreases by several orders of magnitude once core hydrogen burning is over; see Fig. 2(b). For velocity-suppressed p -wave annihilation (blue curves), the qualitative behavior of the annihilation rate is similar, but since its magnitude is much smaller, N_{DM} remains larger.

Increasing m_{DM} leads to a moderate decrease in C_{cap} . For s -channel annihilation it also leads to a significant decrease of the annihilation rate because of the smaller N_{DM} . For p -wave annihilation, the annihilation rate *increases* with m_{DM} because of more efficient Sommerfeld enhancement.

It is interesting to observe from Fig. 2(a) that, in contrast to the more widely studied DM core of the Sun, the DM core of a massive star evolves so fast that capture and annihilation never reach a stable equilibrium. C_{cap} is larger during hydrogen burning, while the annihilation rate becomes dominant later. The crossover between the two occurs much later for p -wave annihilation than for s -wave models.

We briefly comment on the dependence of our results on the DM scattering and annihilation cross sections. If σ_n (or $\rho_{\text{DM}}^{\text{gal}}$) is lowered by a factor 10–100, the number of captured DM particles $N_{\text{DM}}(t)$ decreases correspondingly if DM annihilation is a p -wave process, but only slightly for s -wave annihilation. The reason is that already a slight decrease in $N_{\text{DM}}(t)$ leads to an appreciable decrease in the annihilation rate, which counteracts the smaller capture rate. This feedback effect is relevant mostly in the s -wave case, while for p -wave annihilation, it becomes appreciable only for heavy m_{DM} , where Sommerfeld enhancement is strong. For the same reason, increasing (decreasing) the DM annihilation rate by a factor of 10 in s -wave models leads to a decrease (increase) of $N_{\text{DM}}(t)$ by a similar factor, while doing the same in p -wave scenarios has only a small impact on $N_{\text{DM}}(t)$. Annihilation cross sections larger than the canonical value 4.4×10^{-26} cm 3 /sec are possible for example in models of multicomponent DM [71–73], while annihilation cross sections smaller than the canonical value are required in scenarios with late time entropy production [74–76].

V. THE ANNIHILATION BURST

We see from Fig. 2(a) that the DM annihilation rate increases sharply just prior to the supernova. This trend continues when the iron core of the star collapses and eventually reaches nuclear density $\rho_{\text{SN}} \sim 10^{14}$ g/cm 3 . The result is a sudden burst of DM annihilations. To compute the annihilation rate during this burst, we assume that DM particles located within the newly forming neutron star ($R_{\text{core}} \approx 30$ km) [77] thermalize instantaneously with the

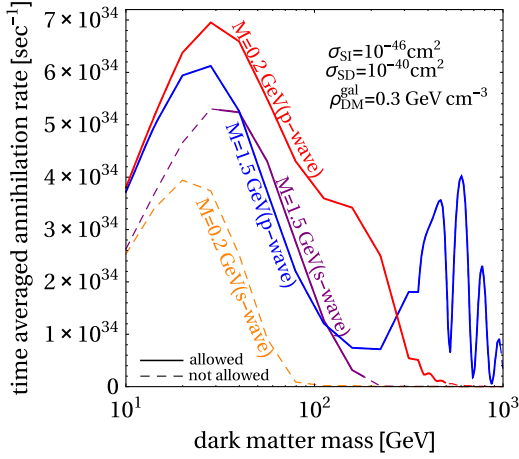


FIG. 3. Average DM annihilation rate during the annihilation burst accompanying a supernova (duration Δt_{burst}). Dashed lines indicate parameter regions that are in tension with cosmic microwave background (CMB) constraints [78,79].

baryonic matter. This is justified because in the protoneutron star, collisions via σ_n^{SD} occur every $\sim 10^{-7}$ sec. To be conservative, DM particles at larger radii are discarded at this stage. We assume for simplicity that throughout the supernova and the early cooling stage of the newborn neutron star (first $\sim 10^3$ seconds), its temperature is constant at $T_{\text{SN}} \sim 3$ MeV. Since according to Eq. (3), cooling leads to further contraction of the DM distribution and thus to more efficient annihilation, this assumption is conservative. The annihilation rate during the burst is given by Eq. (4), where now [27]

$$C_{\text{ann}}^{\text{SN}} = \langle \sigma v_{\text{rel}} \rangle \left(\frac{G_N m_{\text{DM}} \rho_{\text{SN}}}{3T_{\text{SN}}} \right)^{3/2} \quad (6)$$

and $N_{\text{DM}}(t)$ evolves as

$$N_{\text{DM}}(t) = \frac{N_0}{1 + t C_{\text{ann}}^{\text{SN}} N_0} \quad (7)$$

[see Eq. (5), neglecting the capture terms]. Here, N_0 is the number of DM particles in the star just prior to the supernova. Equation (7) also determines the duration of the DM annihilation burst $\Delta t_{\text{burst}} \sim (C_{\text{ann}}^{\text{SN}} N_0)^{-1}$. For s -wave annihilation, Δt_{burst} varies between 10^2 and 10^3 sec for the DM masses and cross sections considered in this paper, while for p -wave annihilation, Δt_{dur} can be as small as 10 sec or as large as 10^4 sec. The reason is the weaker dependence of N_0 on the model parameters for s -wave annihilation, caused by the stronger feedback of annihilation on $N_{\text{DM}}(t)$ throughout the star's life.

Note that the annihilation rate during the burst depends on the location of the star in the galaxy through $\rho_{\text{DM}}^{\text{gal}}$. For a star located about 1 kpc from Earth in the direction of the Galactic center, it is plotted in Fig. 3. We see that, with

increasing m_{DM} , the intensity of the burst increases at first thanks to the increase in $C_{\text{ann}}^{\text{SN}}$, cf., Eq. (6). At $m_{\text{DM}} >$ few $\times 10$ GeV, the intensity decreases again because of the lower galactic DM density, because capture of particles much heavier than the nuclei in the star is kinematically inefficient, and because of Sommerfeld-enhanced annihilation already at early times. The wiggles in the blue and red curves at $m_{\text{DM}} \gtrsim 300$ GeV are due to Sommerfeld enhancement.

VI. DARK GAMMA-RAY BURSTS

If the DM annihilation products are SM particles, they cannot escape the newly born neutron star and are therefore unobservable. This is true even for neutrinos. Phenomenological prospects are brighter in the benchmark models discussed above, with DM annihilating to dark photons A' or dark scalars ϕ [12,14–16,35]. Dark photons can decay to SM particles through a kinetic mixing interaction of the form $\mathcal{L}_{\text{mix}} = \epsilon F_{\mu\nu} F'^{\mu\nu}$, where $F_{\mu\nu}$ ($F'^{\mu\nu}$) is the QED ($U(1)'$) field strength tensor. Similarly, dark scalars ϕ could decay through a Higgs portal coupling of the form $\lambda \langle \phi \rangle \phi (H^\dagger H)$, where H is the SM Higgs doublet. We assume the coupling constant ϵ or $\lambda \langle \phi \rangle$ to be such that the decay length of A' or ϕ is much larger than the radius of the star, but much smaller than its distance from Earth. Among the secondary particles produced in the decays are photons from final state radiation or from meson decays. These provide an observable signal, which we dub a dark gamma-ray burst. The energy distribution dN_γ/dE_γ of burst photons is found along the lines of Ref. [65]

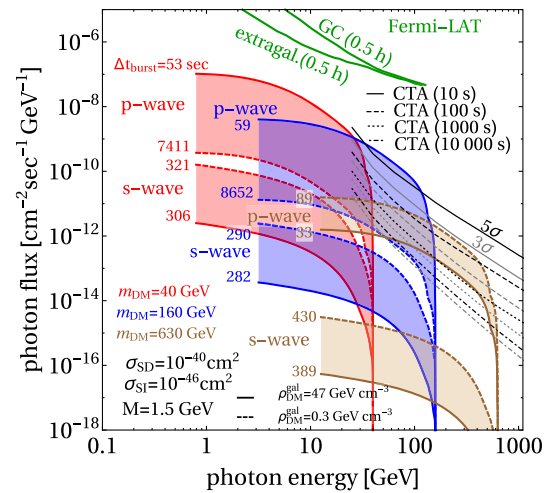


FIG. 4. Expected photon flux from a dark gamma-ray burst, assuming DM annihilates into dark photons (s -wave) or dark scalars (p -wave) of mass M , which decay to SM particles after leaving the supernova, but before reaching Earth. Results are shown for a star 0.1 (solid) or 7 kpc (dashed) from the Galactic center, and for various DM masses (different colors). We compare to the point source sensitivities of Fermi-LAT and CTA [80,81].

and plotted in Fig. 4. In the plot, we also compare to the point source sensitivities of the Fermi Large Area Telescope (Fermi-LAT) and of the future Čerenkov Telescope Array (CTA) [80,81]. For the latter, we show a conservative estimate (5σ excess and ≥ 10 signal events per bin) and a more optimistic one (3σ excess and ≥ 2 signal events per bin). Taking into account that the dark gamma-ray burst signal is spread over several energy bins, we find that the topmost curves for $m_{\text{DM}} = 40, 160,$ and 630 GeV are detectable at the $9.8, 41.6,$ and 15.6σ levels, respectively. For $m_{\text{DM}} = 160$ GeV and p -wave annihilation, a dark gamma-ray burst at 7 kpc from the Galactic center can be detectable at 6.4σ . We conclude that, for a sizeable range of DM masses, CTA may hope to observe dark gamma-ray bursts if annihilation is a p -wave process and if the supernova occurs during the 10% duty cycle of CTA. The fact that p -wave annihilation is easier to observe than s -wave annihilation sets dark gamma-ray bursts apart from other indirect DM signatures. It is also interesting to observe that, for p -wave annihilation of not too heavy DM particles, the expected signal from a star close to the GC is *larger* than for a nearby star because of the strong dependence of N_0 and Δt_{burst} on $\rho_{\text{DM}}^{\text{gal}}$ in p -wave models.

VII. CONSTRAINTS

Models with a light force mediator A' or ϕ are constrained by other indirect DM searches. Because of Sommerfeld enhancement, DM annihilation is particularly strong in environments with low DM velocities; therefore, the strongest constraints come from the CMB [78] and from gamma-ray observations of dwarf galaxies [82]. For s -wave annihilation, these constraints are shown in Fig. 5. If $M = 1.5$ GeV, only DM masses between ~ 30 and ~ 200 GeV are allowed, while for $M = 0.2$ GeV, no open parameter space remains. For p -wave annihilation (not shown in Fig. 5), Sommerfeld enhancement at low velocity is counteracted by smaller tree level cross sections. Therefore, in the p -wave case, all DM masses are allowed if the annihilation cross section at freeze-out is at the level required to explain the DM abundance today and if $M \gtrsim 1$ GeV. For lighter mediators, bound state formation may lead to stronger limits [79].

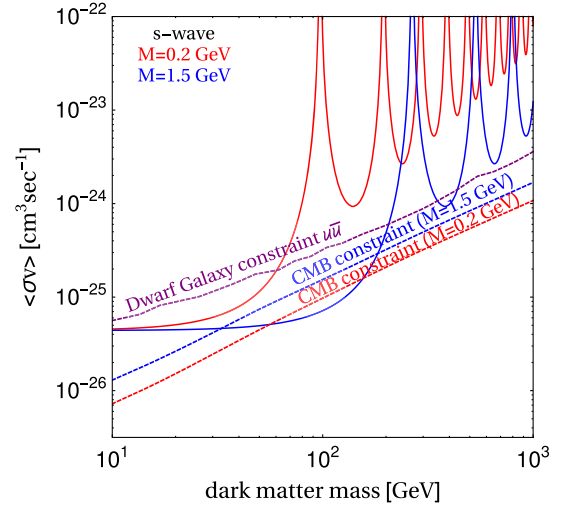


FIG. 5. Predicted DM annihilation cross section for models with s -wave annihilation into a light force mediators of mass M (solid curves), compared to constraints from CMB observations [78] and from gamma-ray observations of dwarf galaxies [82]. Note the strong impact of Sommerfeld enhancement on the model prediction (peaks and dips at $m_{\text{DM}} \gtrsim 100$ GeV).

VIII. SUMMARY

We computed the properties of the DM core of a massive star throughout its life, concluding that the death of the star in a supernova explosion is accompanied by an intense DM annihilation burst. If the DM annihilation products are able to leave the exploding star and decay to SM particles later, this may lead to a burst of secondary photons (dark gamma-ray burst), potentially observable in CTA.

ACKNOWLEDGMENTS

We are indebted to Alexander Heger for providing the data from [46–49] in machine-readable form and for discussing them with us. We are also grateful to Jatan Buch for useful discussions. The authors have received funding from the German Research Foundation (DFG) under Grants No. KO 4820/1–1, No. FOR 2239, and No. GRK 1581, and from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation program (Grant No. 637506, “ ν Directions”).

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