Dark matter-induced collapse of neutron stars: a possible link between fast radio bursts and the missing pulsar problem

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ABSTRACT

Fast radio bursts (FRBs) are an emerging class of short and bright radio transients whose sources remain enigmatic. Within the Galactic Centre, the non-detection of pulsars within the inner ~ 10 pc has created a missing pulsar problem that has intensified with time. With all reserve, we advance the notion that the two problems could be linked by a common solution: the collapse of neutron stars (NS) due to capture and sedimentation of dark matter (DM) within their cores. Bramante & Linden showed that certain DM properties allow for rapid NS collapse within the high DM density environments near galactic centres while permitting NS survival elsewhere. Each DM-induced collapse could generate an FRB as the NS magnetosphere is suddenly expelled. This scenario could explain several features of FRBs: their short time scales, large energies, locally produced scattering tails, and high event rates. We predict that FRBs are localized to galactic centres, and that our own galactic centre harbours a large population of NS-mass ($M \sim 1.4 \, M_{\odot}$) black holes. The DM-induced collapse scenario is intrinsically unlikely because it can only occur in a small region of allowable DM parameter space. However, if observed to occur, it would place tight constraints on DM properties.

Key words: relativistic processes – stars: neutron – Galaxy: centre – dark matter – radio continuum: general.

1 INTRODUCTION

1.1 Fast radio bursts

Fast radio bursts (FRBs) are a recently discovered class of radio transients (Lorimer et al. 2007; Keane et al. 2012; Thornton et al. 2013; Burke-Spolaor & Bannister 2014; Spitler et al. 2014b) shrouded in both mystery and controversy. They are characterized by short ($t \sim$ ms) isolated radio bursts detected at $\sim$GHz frequencies with large dispersion measures ($D_M \sim$ several $\times \, 100 \, \mathrm{cm}^{-3}$ pc). The estimated event rate of detectable FRBs is large, up to 10^4 per sky per day (Thornton et al. 2013).

Unless FRBs are a form of local radio interference, they likely originate at cosmological distances (Dennison 2014; Katz 2014a,b; Luan & Goldreich 2014; Tuntsov 2014). If their observed D_M originates from the IGM, typical FRB distances are large, $D \sim 2$ Gpc) and emitted radio energies are high (10^{38} to 4×10^{40} erg) (Thornton et al. 2013; Dolag et al. 2014; Kulkarni et al. 2014). Conversely, the scattering tails observed in some FRBs cannot be explained by scattering by the intergalactic medium (IGM), and likely originates within the host galaxy of the source (Katz 2014b; Luan &

Goldreich 2014). This may indicate that at least some FRBs originate near galactic centres (GC). Typical comoving distances of $D \sim 2$ Gpc and an event rate of $10^4 \, \mathrm{day}^{-1}$ imply a volumetric rate of $R \sim 10^{-4} \, \mathrm{yr}^{-1} \, \mathrm{Mpc}^{-3}$, comparable to the volumetric core-collapse supernova rate (Li et al. 2011). Many progenitors have been suggested to be the sources of FRBs, although most seem unlikely (see the discussion in Kulkarni et al. 2014). Here, we simply re-iterate that the short durations, large luminosities, and high brightness temperatures naturally suggest a neutron star (NS) origin.

1.2 Missing GC pulsar problem

Within our own galaxy, the missing pulsar problem at the GC has recently become more puzzling. Despite several deep searches (Johnston et al. 2006; Deneva, Cordes & Lazio 2009; Macquart et al. 2010; Bates et al. 2011), no ordinary pulsars have been discovered within a projected distance of 10 pc of the GC despite predictions that there should be more than 10^3 active radio pulsars in this region (Pfahl & Loeb 2004). The problem recently intensified with the radio detection of a magnetar within the central parsec (Eatough et al. 2013). Subsequent studies (Bower et al. 2014; Spitler et al. 2014a) indicated that the magnetar indeed lies very close to Sgr A* and that the temporal scattering was not severe enough to have prevented the detection of ordinary pulsars in previous surveys.

It remains possible that (for some unknown reason) ordinary pulsars near the GC have a steep spectral index and are not bright enough at high frequencies to be detected with current instrumentation (Bates et al. 2011). Alternatively, Dexter & O'Leary (2014) have suggested that the missing pulsar problem is created by a very high magnetar formation efficiency near the GC, such that GC pulsars spin-down so rapidly that they are unlikely to be observed before crossing the death line. Given our current (incomplete) understanding of magnetar formation (e.g. Thompson & Duncan 1993; Keane & Kramer 2008), there is no known physical process or condition that could favour magnetar formation near the GC.

1.3 Dark Matter-induced NS collapse

We propose that the seemingly separate problems posed by FRBs and missing pulsars may have the same solution: the DM-induced collapse of NS. In this scenario (recently described by Bramante & Linden 2014, see also Kouvaris & Tinyakov 2011; Kouvaris 2012; McDermott, Yu & Zurek 2012; Bramante, Fukushima & Kumar 2013 and references therein), ambient DM particles scatter-off of nucleons within an NS and become gravitationally bound. The DM particles continue to scatter until they thermalize at the NS temperature and sink to the centre of the NS where they accumulate within a small volume. When the DM agglomeration exceeds a critical mass, the DM forms a black hole (BH) at the NS centre that may consume the NS. The NS collapses into the BH on a dynamical time-scale ($t_{dyn} \sim 1$ ms), and a $\sim 1.4\,M_\odot$ BH remnant is left behind.

During the collapse, the magnetosphere must suddenly detach from the BH horizon, and the rapid reconfiguration of the field lines generates a burst of electromagnetic energy. If a small fraction of this energy is radiated in radio wavelengths, an FRB is generated. The process occurs most rapidly near the GC where DM densities are highest, causing NSs near the GC to quickly collapse (but permitting long-term NS survival in the solar neighbourhood and in globular clusters), thereby accounting for the lack of pulsar detections near the GC.

There is only a limited range in DM properties that allow for the process described above to occur. These have been explored in the works listed above, here we simply restate their basic results. First, there is only a narrow (2–3 orders of magnitude) range of DM scattering cross-sections σ that allows for rapid DM accumulation within GC NSs while allowing more local NSs to survive for several Gyr. Secondly, the DM must be weakly annihilating, otherwise it will annihilate upon accumulation at the centre of the NS and will not be able to form a BH. Thirdly, the DM mass, particle type (boson versus fermion), self-interaction, and NS temperature must allow for DM sedimentation and BH formation at the centre of the NS.

The DM-collapse scenario also hinges on the DM density profiles of NS host galaxies. The DM capture rate is proportional to the ambient DM density, ρ_{DM}, and so the NS lifetime scales as $t_c \propto \rho_{DM}^{-1}$. To collapse a GC pulsar located at a galactocentric radius $r = 1$ pc within 10^6 yr, while allowing for the 10^{10} yr survival of a solar neighbourhood NS ($r \sim 10^4$ pc), requires the DM density within the inner parsec to be enhanced by at least a factor of 10^4.

2 GENERATION OF A FAST RADIO BURST

The detailed electromagnetic signature of a collapsing NS is well beyond the scope of this paper, but here we make some rough estimates. The FRB emission energy cannot greatly exceed the energy contained in the magnetosphere,

$$E_M \sim 10^{42}\,\text{erg}\,B_{12}^2, \tag{1}$$

where B_{12} is the dipole field strength in units of 10^{12} G. The radio emission from our collapsing NS scenario is similar to that described in Falcke & Rezzolla (2014, hereafter FR14), who examined rapidly rotating supramassive NS collapse.

During the collapse, electrons/positrons bound to field lines generate coherent radiation as the field reconfigures. If $\sim 10^{-3}$ of the field energy is emitted as radiation near GHz frequencies, an FRB can be generated. However, the coherent curvature radiation will initially have frequency near $\nu \sim 1/t_{dyn} \sim$ kHz. To emerge at GHz frequencies, the radiation must be up-converted to higher frequencies. FR14 argue that this will occur until the coherent radiation is near the plasma frequency

$$\nu_p \sim 2\,\text{GHz}\,B_{12}^{1/2}P_1^{-1/2}, \tag{2}$$

where B_{12} is the field strength in units of 10^{12} G, and P_1 is the spin period in seconds. Following their analysis, we calculate that electrons are boosted to Lorentz factors of $\gamma \sim 60\,B_{12}^{1/6}P_1^{-1/2}$, and radiate a power near GHz frequencies of

$$P_R \sim 2 \times 10^{41}\,\text{erg s}^{-1}\,B_{12}^{13/6}P_1^{-13/6}. \tag{3}$$

We expect the emission to be generated over roughly one magnetosphere light crossing time, $t \sim 1$ ms. The corresponding radio energy emission is then $E_R \sim 2 \times 10^{38}$ erg, but can be substantially larger for higher field strengths or smaller rotation periods. While the frequency of equation (2) and the power estimate of equation (3) are encouraging, the details of the emission process may be quite complex, and these estimates may not be robust.

The radiative power of equation (3) can be compared to simulations of the non-rotating collapse of an NS by Lehner et al. (2012, see also Dionysopoulou et al. 2013; Palenzuela 2013), who find $P_{rad} \sim 10^{42}$–$10^{43}\,B_{12}^2$ erg s^{-1} over a duration of roughly a millisecond, implying $E_{rad} \sim 10^{39}$–$10^{40}\,B_{12}^2$ erg. Unfortunately, these authors do not compute a radiation spectrum, so it is unclear how much energy is emitted in the radio band. If a significant fraction of it is emitted near GHz frequencies, as argued by FR14, then an FRB could be generated. It is possible that some of the radiation is emitted at optical/UV/X-ray/γ-ray wavelengths, however, any transient produced is unlikely to be detected. Its maximum luminosity is $L \lesssim 10^{45}$ erg s^{-1}, and its duration is expected to last $t \lesssim 1$ ms, preventing even very rapid follow-up observations.

The energy estimates above are similar to the isotropic radio energies estimated by Thornton et al. (2013) and Spitler et al. (2014b), but smaller than those estimated by Kulkarni et al. (2014) and Dolag et al. (2014). The total energy emitted depends on the slope of the spectral emission, and we do not attempt to quantify those details here. We simply note that our rudimentary estimates yield a radio luminosity similar to that inferred for FRBs. Slightly beamed emission (as seen in Lehner et al. 2012) would entail smaller total radiative luminosities, but larger collapse rates.

The observed scattering tails in some FRBs are also consistent with the DM-induced collapse scenario, as Luan & Goldreich (2014) and Katz (2014a) have shown that the scattering is most likely generated near the source deep within a host galaxy. Similarly, our scenario entails that FRBs occur near GCs where the scattering could be produced, e.g. by the ionized surfaces of nearby molecular clouds (Lazio & Cordes 1998). Moreover, at least some of the observed D_M may be contributed by the host galaxy. The NE2001 model for the electron density distribution (Cordes & Lazio 2002)

implies an average number density of $n_e \sim 0.2 \, \mathrm{cm}^{-3}$ within the inner 500 pc (Ferrière, Gillard & Jean 2007). A typical FRB occurring within the inner 500 pc (see Section 3) would then incur a dispersion measure of $D_M \sim 100 \, \mathrm{cm}^{-3}$ pc, depending on the viewing angle. An additional $\sim 50 \, \mathrm{cm}^{-3}$ pc will likely be contributed by its host's galactic halo (Dolag et al. 2014), entailing a net contribution of $D_M \approx 150 \, \mathrm{cm}^{-3}$ pc from the host galaxy. If the FRB occurs within the inner ~ 100 pc, the local D_M could be much larger, of the order of $D_M \sim 10^3 \, \mathrm{cm}^{-3}$ pc (Cordes & Lazio 2002). This implies FRBs could be somewhat closer (by ~ 25 per cent or more) than estimated by assuming the observed D_M is generated in the IGM.

3 RATES AND GC NS DEPLETION

The NS collapse time is determined by the DM accumulation rate and the amount of DM required to form a BH at the NS centre. We calculate both using the method outlined in Bramante & Linden (2014). In general, only a very small amount of DM ($M_{\mathrm{acc}} \lesssim 10^{-10} \, \mathrm{M}_\odot$) is accreted before collapse. The most salient detail of the process is that the collapse time-scales as $t_c \propto \rho_{\mathrm{DM}}^{-1}$, allowing for short collapse times in high DM density environments.

To estimate the FRB rate in a Milky Way-like galaxy, we construct a simple galactic model similar to the exponential spheroid model of Sofue (2013). The model contains components from the central star cluster at $r < 1$ pc, inner bulge at $r < 20$ pc, bulge at $r < 1$ kpc, and exponential disc at $r < 20$ kpc. We also include a DM component with a generalized NFW profile (Navarro, Frenk & White 1997),

$$\rho(r) = \frac{\rho_0}{(r/R_{\mathrm{s}})^\alpha (1 + r/R_{\mathrm{s}})^{(3-\alpha)}} \qquad (4)$$

with scale radius $R_{\mathrm{s}} = 12$ kpc and density normalization $\rho_0 = 1.1 \times 10^{-2} \, \mathrm{M}_\odot \, \mathrm{pc}^{-3}$. These models have $\rho \propto r^{-\alpha}$ near GCs, with $\alpha = 1$ for a standard NFW profile. For simplicity, we assume a constant DM velocity dispersion of $v_{\mathrm{DM}} = 200 \, \mathrm{km \, s}^{-1}$ at all radii. Fig. 1 shows the density profile and enclosed mass of our model.

We caution that the DM profiles near the centres of galaxies are somewhat poorly constrained, especially within the inner ~ 100 pc, which is typically not probed by observations nor simulations. The current understanding is that in galaxies less massive than the Milky Way, the DM profiles are cored due to star formation feedback, i.e. their central density profiles are shallower than the cuspy $\rho_{\mathrm{DM}} \propto r^{-1}$ profiles of an NFW profile (Del Popolo & Kroupa 2009; Inoue & Saitoh 2011; Macciò et al. 2012). However, simulations of more massive galaxies indicate DM profiles with $\rho_{\mathrm{DM}} \propto r^{-1}$ (Di Cintio et al. 2014), or in many cases even steeper density profiles due to adiabatic contraction (Blumenthal et al. 1986; Gnedin et al. 2004; Gustafsson, Fairbairn & Sommer-Larsen 2006). Lensing studies have also revealed steep central DM density profiles in massive early-type galaxies (Tortora et al. 2010; Grillo 2012; Sonnenfeld et al. 2012), and high DM densities within central cluster galaxies (Newman et al. 2013). Hence, we expect long (greater than a Hubble time) NS collapse times in low-mass galaxies, although short collapse times are achievable in massive spirals, early-type galaxies, and central cluster galaxies, where central DM densities may greatly exceed $1 \, \mathrm{M}_\odot \, \mathrm{pc}^{-3}$. Below, we shall consider a range of DM profiles, with slopes $0.5 < \alpha < 1.5$.

As a matter of demonstration, we choose a non-self-interacting and non-annihilating bosonic DM particle with mass of $m = 10 \, \mathrm{MeV}/c^2$ and nucleon scattering cross-section $\sigma = 3 \times 10^{-49} \, \mathrm{cm}^2$. For these choices, BH formation will occur upon formation of a super-Chandrasekhar mass Bose–Einstein condensate at the centre of the NS, and the BS will be massive
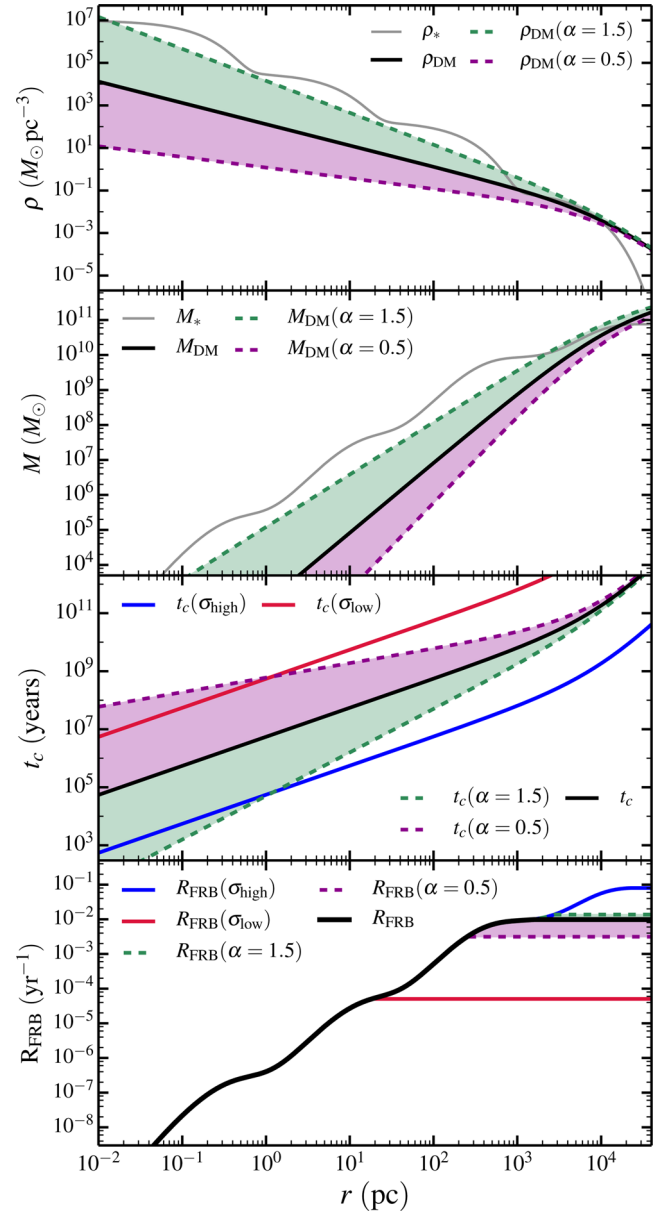

Figure 1. Top: spherically averaged density profile of a simple galactic model, including the stellar mass density ρ_* and the DM density ρ_{DM}. Green shaded regions have steep DM density profiles ($1 < \alpha < 1.5$), while purple shaded regions have shallow DM density profiles ($0.5 < \alpha < 1$). Second Row: corresponding enclosed mass for our galactic models. Third Row: NS collapse time (black line) as a function of radius, for bosonic DM with a nucleon scattering cross-section of $\sigma = 3 \times 10^{-49} \, \mathrm{cm}^2$ and mass $m = 10 \, \mathrm{MeV}/c^2$. Shaded regions correspond to the DM density profiles above. We have also plotted t_c for $\alpha = 1$ but with a DM cross-section that is larger (blue) and smaller (red) by a factor of 10^2. Bottom: enclosed FRB rates, assuming each NS collapse generates an FRB.

enough to consume the NS on a short time-scale. For more massive DM particles, the number of DM particles required for BH formation will depend on the NS core temperature.[1] Additional

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[1] An NS core temperature $T_c = 10^4$ K is reasonable for old NSs in the photon-cooling phase (see, e.g. Yakovlev & Pethick 2004, and cooling tracks obtained with the NSCOOL code; http://www.astroscu.unam.mx/neutrones/NSCool). Young NSs (with ages less than

issues (e.g. self-interacting bosonic DM, fermionic DM, the DM thermalization time-scale, and BH evaporation) can affect the DM accumulation, sedimentation, and BH formation process. A full exploration of these issues is beyond the scope of this work, and we refer the reader to previous studies (e.g. Kouvaris & Tinyakov 2011; Kouvaris 2012; McDermott et al. 2012; Bramante et al. 2013; Bramante & Linden 2014). For our chosen parameters, the collapse time is dependent primarily on the DM cross-section σ and ambient DM density ρ_{DM}, with the collapse time scaling as $t_c \propto (\rho_{DM}\sigma)^{-1}$.

Using the DM properties and density profile described above, we compute the NS collapse time t_c as a function of radius, shown in Fig. 1. In the solar neighbourhood, the collapse time is $t_c \sim 10^{11}$ yr, while in the central parsec, $t_c \lesssim$ few $\times 10^6$ yr. DM-induced collapse could thus substantially reduce the number of detectable radio pulsars within the central ~ 10 pc assuming typical radio pulsar lifetimes are 10^7–10^8 yr (Faucher-Giguère & Kaspi 2006). Steeper DM density profiles (green shaded area in Fig. 1) will allow for shorter collapse times and more efficient pulsar destruction. Very steep profiles are problematic for the DM-induced collapse scenario because they predict very short collapse times that would preclude the observation of the GC magnetar, which is estimated to lie near $r \sim 0.1$ pc with an age of $\sim 10^4$ yr (Eatough et al. 2013; Bower et al. 2014; Dexter & O'Leary 2014; Spitler et al. 2014a). Shallower DM profiles (purple shaded area) would not allow for prompt NS collapse and could not resolve the missing pulsar problem, although they may still allow for relatively large FRB rates. A much smaller DM cross-section (red line in Fig. 1) would not allow for timely NS collapse and could not resolve the missing pulsar problem nor generate enough FRBs. A much larger DM cross-section (blue line) would cause NSs to quickly collapse even outside of GCs, and can be ruled out by existing observations of old NSs.

To compute an approximate FRB rate, we assume a constant star formation rate and galaxy age of $t_G = 10^{10}$ yr, such that the star formation rate within a radius r is simply $\dot{M}_* = M(r)/t_G$. Star formation rates peaking at early times will yield older populations of NSs and will increase the FRB rate. Given a current star formation rate of $\dot{M}_{*,0} \approx 1.6$ M$_\odot$ yr^{-1} (Licquia & Newman 2014) and a galactic core-collapse supernova rate of $R_{SN} \sim 2 \times 10^{-2}$ yr^{-1} (Li et al. 2011), we calculate an NS creation rate of $\dot{M}_{NS} \sim 1.5 \times 10^{-2} \dot{M}_*$, assuming each supernova generates an NS of mass $M_{NS} \simeq 1.4$ M$_\odot$. Finally, we set the FRB rate per unit volume equal to

$$\frac{dR_{FRB}}{dV} = \frac{1}{M_{NS}}\frac{d\dot{M}_{NS}}{dV} \quad \text{if } t_c < t_G \,,$$

$$\frac{dR_{FRB}}{dV} = 0 \quad \text{if } t_c > t_G \,. \tag{5}$$

The FRB rate within a radius r, R_{FRB}, is simply the volume integral over equation (5), and is shown in the bottom panel Fig. 1. This demonstrates that a Milky Way-like galaxy is capable of producing a total FRB rate of $R_{FRB} \sim 10^{-2}$ yr^{-1} gal^{-1}.

In comparison, the core-collapse supernova rate is $R_{SN} \sim 2 \times 10^{-2}$ yr^{-1} gal^{-1} for a Milky Way-like galaxy (Li et al. 2011). In our simple model, only about one-tenth of galactic

NSs (those born within roughly 1 kpc of the GC) can collapse within a Hubble time. However, the current FRB rate is comparable to the current supernova rate because the average galactic past star formation rate ($\dot{M} \sim 10$ M$_\odot$ yr^{-1}) is larger than the current star formation rate. Given a volumetric core-collapse supernova rate (at $z = 0$) of $R_{SN} \sim 10^{-4}$ Mpc^{-3} yr^{-1} (Li et al. 2011), a plausible FRB rate is then

$$R_{FRB} \sim 5 \times 10^{-5} \, \text{Mpc}^{-3} \, \text{yr}^{-1} \,. \tag{6}$$

The observed FRB rate is somewhat debated, but may be as large as 10^4 d^{-1} (Thornton et al. 2013). This corresponds to a volumetric rate of

$$R_{obs} \sim 10^{-4} \, \text{Mpc}^{-3} \, \text{yr}^{-1} \left(\frac{D}{2\,\text{Gpc}}\right)^{-3} \,, \tag{7}$$

where D is the comoving distance out to which most FRBs are observed. The lack of FRB detections in lower galactic latitude surveys (Burke-Spolaor & Bannister 2014; Petroff et al. 2014b) indicates the FRB rate may be substantially lower than that quoted by Thornton et al. (2013). It is possible that the DM-induced collapse rate is dominated by other types of galaxies (e.g. early-type galaxies, galaxies in clusters) with larger DM densities. We therefore argue that the DM-induced collapse rate may be high enough to account for most FRBs.

4 DISCUSSION AND PREDICTIONS

There are several reasons why the DM-induced collapse scenario may not occur. The most likely is that DM properties are simply not compatible with this scenario, for the multitude of possibilities discussed in Bramante et al. (2013). On the contrary, if DM-induced collapse is observed to occur, it would provide constraints on DM properties. Below, we list several predictions of the DM-induced collapse scenario and its relation to the GC missing pulsar problem and FRB generation. If these predictions can be falsified, we can discount the scenario. However, if the predictions hold up, the scenario must be regarded seriously.

(1) Dark matter masses, scattering cross-sections, and self-interaction properties are in accordance with the limits discussed in Bramante & Linden (2014).[2]

(2) There is no GC X-ray or γ-ray excess due to DM annihilation.

(3) Large galaxies contain cusped DM density profiles, with central DM densities exceeding ~ 1 M$_\odot$ pc^{-3}.

(4) Long-lived NSs do not exist near most GCs, i.e. there should be no observed NSs with ages much larger than the collapse time shown in Fig. 1. The discovery of an old millisecond pulsar or low-mass NS X-ray binary within the inner ~ 50 pc of the GC would disfavour the NS-induced collapse scenario.

(5) There exists a large population of NS-mass ($M \approx 1.4$ M$_\odot$) BHs near GCs. The discovery of a low-mass X-ray binary containing a $M \lesssim 2$ M$_\odot$ BH near the GC would reinforce the DM-induced NS collapse scenario.

(6) FRBs are localized near (within ~ 1 kpc of) GCs of massive galaxies or central cluster galaxies where DM densities are large. A magnetar flare FRB scenario (Kulkarni et al. 2014; Lyubarsky

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$\sim 2 \times 10^6$ yr) may be substantially warmer, which may raise the DM mass required for BH formation and therefore increase collapse times. This could prevent prompt NS collapse near GCs for massive ($m \gtrsim$ GeV/c^2) DM particles. Additionally, DM particles with $m \sim 1$ GeV/c^2 may not be able to thermalize and settle within the NS fast enough to permit prompt collapse. We refer the reader to Bramante et al. (2013) and Bramante & Linden (2014) for discussion of how NS temperature affects the DM accumulation process.

[2] Note that the allowable parameter space depends on DM self-interactions, and in certain cases on NS interior temperature. Therefore, the allowable parameter space shown in Bramante & Linden (2014) should be viewed as a guideline rather than a strict limit.

2014; Pen & Connor 2015) may entail that many FRBs occur near GCs, but also allows FRBs to arise from young stellar populations in dwarf galaxies. In contrast, dwarf galaxy hosts (where DM densities are low) are unlikely in the DM-induced collapse scenario.

(7) FRBs exhibit little or no associated optical or X-ray transient, in agreement with the recent non-detection of any transient associated with FRB 140514 (Petroff et al. 2014a). FRBs will not ever repeat, although multiple FRBs could arise from the same galaxy as long as its GC is DM-rich.

We hope the exciting implications of these scenarios will reinvigorate searches for FRBs and GC pulsars, and we anticipate that future observations will elucidate the nature of these enigmas.

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