Decoupled Sectors and Wolf-Rayet Galaxies

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Abstract. The universe may contain several decoupled matter sectors which primarily couple through gravity to the Standard Model degrees of freedom. We focus here on the description of astrophysical environments that allow for comparable densities and spatial distributions of visible matter and decoupled dark matter. We discuss four Wolf-Rayet galaxies (NGC 1614, NGC 3367, NGC 4216 and NGC 5430) which should contain comparable amounts of decoupled dark and visible matter in the star forming regions. This could lead to the observation of Gamma Ray Burst events with physics modified by jets of dark matter radiation.
1 Introduction

Decoupled sectors interact only very weakly with the Standard Model and may play an important role in our universe accounting for some of the energy density present in the dark matter and/or dark energy sector (see for example [1–29]). Decoupled sectors are not greatly constrained from collider searches [30] since they couple only very weakly to the Standard Model. However, cosmological and astrophysical constraints provide a powerful probe into decoupled sectors since gravitational interactions are crucial in those cases. Furthermore, it has been suggested that the study of astrophysical jets such as Gamma Ray Burst events may provide a direct probe into the type of interactions present in the decoupled sector [22, 24].

Decoupled sectors need not be composed entirely of a single particle species. For instance, our universe is only \(\sim 5\%\) visible matter [31, 32] but we observe all of the complexity that the Standard Model entails. The dark matter sector and dark energy sector comprise \(\sim 27\%\) and \(\sim 68\%\) of our universe respectively [31, 32]. Therefore to
Figure 1. The energy budget of the universe today could include a decoupled sector as a sub-component of the dark matter and/or dark energy sector. Only 18% of the dark matter sector or 7% of the dark energy sector must consist of decoupled sector content in order to be comparable with the visible matter density globally. Except for section 2.2, the remainder of this study we will focus on the case that the decoupled sector is a component of the dark matter sector.

In order to apply astrophysical bounds, an assumption must be made about how the global density of decoupled sector particle content is related to the local (galactic scale) density. To be precise let us define two parameters \( \epsilon_{\text{Global}} \) and \( \epsilon_{\text{Galactic}} \) that represent relative amount of decoupled sector density to the total dark matter density [16, 17],

\[
\epsilon_{\text{Global}} = \frac{\Omega_{\text{Decoupled}}}{\Omega_{\text{DM}}} \quad \text{and} \quad \epsilon_{\text{Galactic}} = \frac{\Omega_{\text{Gal} \text{Decoupled}}}{\Omega_{\text{Gal} \text{DM}}}.
\]

The exact relationship between these ratios will in principle depend on the exact theory of the decoupled sector content and the formation history of the galaxy of interest. For
our current purposes it is sufficient to note that the decoupled sector matter will follow gravitational potential wells throughout the evolution of the universe just as does usual cold dark matter and visible matter. Since the decoupled sector is not very sensitive to feedback from the visible sector, the decoupled sector matter should spatially evolve in a manner that is closely related to the evolution of the usual cold dark matter. Therefore we expect that $\epsilon_{\text{Global}} \approx \epsilon_{\text{Galactic}}$.

In addition to the relative density of decoupled sector matter to the total dark matter density on galactic scales, one must also know about the spatial distribution of decoupled sector matter within galactic scales. This question is very difficult to answer since the ways in which galaxies form and interact is so diverse with multiple relevant timescales. Naively, the microphysics of the decoupled sector gas determines its spatial distribution within a galaxy. However, we will be able make a statement about how decoupled sector matter is distributed throughout galactic scales for at least one class of galaxies by focusing on a particular class of mergers known as minor mergers.

A Major merger event occurs between galaxies of comparable masses, the most conservative definition being a mass ratio of 1:1 or 1:2 [33]. Minor merger events, which will be the focus of this paper, occur when a merger takes place between two galaxies which are of significantly different mass. A defining characteristic of these events is that the properties of the larger galaxy largely dictate the dynamics of the merger. As we will see, this will result in the spatial distribution of decoupled sector matter being comparable to the spatial distribution of visible sector matter. This result allows us to discuss other possible probes of decoupled sector matter (see section 6).

In section 2 we will review current constraints on decoupled sector matter from cosmology and astrophysics. In section 3 we review some properties and phenomenology of Wolf-Rayet stars and galaxies. In section 4 we discuss four example Wolf-Rayet galaxies\(^1\) that are good candidates for further investigations of the properties of decoupled sector physics. In section 5 we discuss some properties of decoupled sector matter and its spatial distribution within galaxies relative to visible sector matter. In section 6 we discuss new possible phenomenology associated with the presence of a decoupled sector gas. In section 7 we conclude.

2 Present Constraints on Decoupled Sectors

2.1 Component of Dark Matter Sector

Cosmological constraints on the decoupled dark matter sector arise from measurements of primordial element abundance, the cosmic microwave background, the matter power spectrum and supernovae. Astrophysical probes arise from considerations of dark matter distribution within a halo, observations of galactic cluster collisions, local dark matter density bounds and potentially from astrophysical jets such as Gamma Ray Burst events.

\(^1\)For a catalog of Wolf-Rayet galaxies see [34].
2.1.1 Number of Relativistic Species

Big Bang Nucleosynthesis (BBN) and the Cosmic Microwave Background (CMB) provide strong constraints on the number of relativistic degrees of freedom during the evolution of the early universe. BBN constraints arise from observations of primordial abundances [35]. The neutron has a mean lifetime of $881.5 \pm 1.5$ seconds and therefore if the expansion is too fast the neutrons will decay before they have an opportunity for form elements. Observations of the CMB allow us to determine the total radiation density to a high level of accuracy [32]. An increase in radiation energy density results in a dampening and phase shift of peaks in the CMB power spectrum [36].

The usual way of parameterizing the number of relativistic degrees of freedom is the effective number of neutrino species, $N_{\text{eff}}$, which is defined by the relationship

$$\rho_{\text{radiation}} = \rho_\gamma \left[ 1 + \frac{7}{8} \left( \frac{4}{11} \right)^{4/3} N_{\text{eff}} \right].$$

(2.1)

We have used that $(T_{\text{neutrino}}/T_\gamma) = (4/11)^{1/3}$ and that the effective degeneracy factor for relativistic fermions contains an additional factor of 7/8. Electrons and positrons can annihilate into photons and contribute to the overall radiation density yielding a Standard Model value of $N_{\text{eff}}$ which is slightly larger than three [37, 38], $N_{\text{eff,SM}} = 3.046$.

Temperature anisotropies alone do not strongly constrain $N_{\text{eff}}$, therefore the constraint from the CMB is usually combined with distance measurements from baryon acoustic oscillations (BAO) and measurements of the Hubble constant $H_0$ from supernovae observations. The observed values at 95% confidence level are given by [32, 35]

$$N_{\text{BBN}}^{\text{eff}} = 3.71^{+0.94}_{-0.90} \quad \text{and} \quad N_{\text{CMB+H}_0+\text{BAO}}^{\text{eff}} = 3.52^{+0.48}_{-0.45}.$$  

(2.2)

The close agreement of the observed values with the Standard Model prediction greatly constrain the amount of allowed relativistic decoupled sector matter.$^3$

As an example, consider the addition of a decoupled sector radiation source. In this case we find $N_{\text{eff}}$ is given by

$$N_{\text{eff}} = 3.046 + \frac{8}{7} \left( \frac{11}{4} \right)^{4/3} \frac{\rho_{\text{dec}}}{\rho_\gamma}. $$

(2.3)

If we take the decoupled sector radiation source to be dark sector photons with a temperature $T_{\text{dec}} = \xi T_\gamma$, we find the following constraint to 95% confidence

$$\xi \leq 0.78 \, (\text{BBN}) \quad \text{and} \quad \xi \leq 0.69 \, (\text{CMB+H}_0+\text{BAO}).$$

(2.4)

This would correspond to a dark sector photon temperature today of $T_{\text{dec}} \leq 2.13$ K and $T_{\text{dec}} \leq 1.88$ K respectively.$^4$

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$^2$Recall the usual $\rho_{\text{boson}} = \frac{\pi^2}{30} g T^4$ and $\rho_{\text{fermion}} = \frac{7 \pi^2}{8} \frac{g}{30} T^4$, where g is the degeneracy factor. Explicitly, $\rho_\gamma = \frac{\pi^2}{15} T_{\text{CMB}}^4 (1 + z)^4$.

$^3$It has been suggested that a disagreement between the value obtained from BBN and the CMB could be evidence of phenomenology in a decoupled sector [10, 20].
2.1.2 Matter Power Spectrum

An additional cosmological constraint is testing for the existence of dark acoustic oscillations from measurements of the matter power spectrum [14, 19, 23]. If there exists dark matter and dark radiation that form a plasma such as in atomic dark matter models there will be a restoring force that opposes gravitational infall. The details of how this affects the physics depends on the hierarchy of the dark matter sound horizon and the Silk damping scale. A strong bound on the amount of dark matter capable of forming plasma has been obtained [19, 24].

2.1.3 Dark Matter Distribution within a Halo

The decoupled sector is subject to astrophysical constraints as well. Self-interactions in the dark matter sector drive galactic halos to become more spherical. Furthermore, the galactic center of dark matter profiles will become less cuspy if dark matter is self-interacting [39–45]. Therefore measuring halo eccentricity or galactic center distributions provides a bound on either the dark matter self-interaction rate or the amount of dark matter which can interact frequently.

Measurements of halo eccentricity can place bounds on dark matter self-interactions. Measurements of elliptic galaxy NGC 720 find that the best fit is either an oblate spheroid with eccentricity of 0.37 ± 0.03 or a prolate spheroid with eccentricity of 0.36 ± 0.02 [46]. Simulations have been performed for a self-interacting dark matter with a velocity independent cross section and a bound of \( \sigma/m \lesssim 1 \text{ cm}^2/\text{g} \) has been obtained [44]. If the self-interacting dark matter is only a fraction of the total dark matter sector, this observation must be reinterpreted as a bound on the number of interactions within the decoupled sector. These bounds are usually easy to satisfy [16, 17].

Simulations with non-interacting cold dark matter find halo profiles that have cusps (diverge) at the center. One example is the Navarro-Frenk-White profile with \( \rho \sim r^{-1.5} \), where \( r \) is the radial distance from the center of the galaxy [39]. This is in conflict with observations which find low density cores at the center of dwarf satellite galaxies [40, 41]. However, if self-interacting dark matter has a velocity independent cross section of \( \sigma/m \sim 0.5–6 \text{ g/cm}^2 \) this conflict may be alleviated [40–42]. Simulations have constrained this region further to \( \sigma/m \lesssim 1 \text{ cm}^2/\text{g} \) [43], consistent with observations of NGC 720.

It is worth noting that recent studies have investigated the impact of visible sector feedback on the central dark matter density profile of dwarf satellite galaxies [47]. They have found that star formation alone is sufficient to alleviate the central cusp and bring theory into agreement with observation, hence there is no need for self-interacting dark matter. As the visible matter is ejected from the galactic central region, the gravitational coupling between dark matter and visible matter allow the dark matter to be carried away as well. Further numerical studies may confirm that it is indeed not necessary to incorporate dark matter self-interactions in order to obtain central region cores.
2.1.4 Galactic Cluster Collisions

Recent observations of galactic cluster collisions, such as the Bullet Cluster 1E0657-56, also provide strong bounds on interactions in the dark matter sector. The bullet cluster constrains the self-interaction of dark matter since a significant amount of dark matter mass is present outside of the central region [9, 48–50]. Therefore we conclude that if a significant portion of dark matter is self-interacting, the interaction strength must be very weak. If a portion of dark matter interacts strongly, it must be a small fraction of the total amount of dark matter.

To be concrete, we note that the high velocity subcluster would be expected to lose more dark matter particles during the collision if dark matter interacted strongly. If we assume that initially the main cluster and the subcluster had comparable mass-to-light ratios, we may define the particle loss fraction as

\[ f = \frac{|(M/L)_{I,\text{main cluster}} - (M/L)_{\text{subcluster}}|}{(M/L)_{I,\text{main cluster}}}. \]  

Here I refers to the infrared frequency band which was chosen to measure \((M/L)\). Infrared observations for local universe galaxies are typically better tracers of stellar mass than blue filters which preferentially detect only the biggest and brightest stars. Analysis of lensing maps [49, 50] has found that \((M/L)_{\text{main cluster}} = 214 \pm 13\) and \((M/L)_{\text{subcluster}} = 179 \pm 11\), resulting in a particle loss fraction of \(f \leq 0.30\) [50] to 95% confidence level. This corresponds to a velocity independent cross section bound of \(\sigma/m \lesssim 1 \text{ cm}^2/\text{g} \) [9, 48, 50].

2.1.5 Local Dark Matter Density

The Oort limit is a bound on the amount of matter within the vicinity of our Sun [51]. The Oort limit constrains certain types of phenomenology such as the creation of galactic disks of dark matter [16, 17]. If some matter in the dark matter sector is capable of forming atoms and radiatively cooling it is possible for such matter to form dense astrophysical objects such as galactic disks. Therefore, if some matter in the dark matter sector collapses to a dense astrophysical object that exceeds the Oort limit, one must explain why the spatial location does not coincide with our Sun.

The surface density at the position of our Sun within an envelope of \(|z| < 1.1 \text{ kpc}\) above and below our galactic disk has contributions from both visible sector matter and the dark matter sector. The surface density of visible matter obtains contributions from visible stars, stellar remnants and interstellar gas which add up to \(\Sigma_{\text{visible}} \sim 46 \pm 16 \text{ M}_\odot/\text{pc}^2\). The total density is measured to be \(\Sigma_{\text{total}} \sim 71 \pm 6 \text{ M}_\odot/\text{pc}^2\) [51], which provides an upper bound on dark matter density of \(\Sigma_{\text{DM}} \lesssim 46 \text{ M}_\odot/\text{pc}^2\) to 95% confidence [16, 17].

2.1.6 Gamma Ray Burst Events

An additional probe of decoupled sector properties may be long Gamma Ray Burst events [22, 24]. This phenomenology differs from the previously discussed probes since one may not bound properties of the decoupled sector physics, but may test for certain
types of self-interactions. The discussion of gas infall dynamics in section 5 furthers this idea by stating some conditions that will lead to a comparable density of decoupled sector and visible sector gas in the vicinity of progenitor stars. We will discuss the case of Gamma Ray Burst phenomenology in greater detail in section 6.2. For now, we will review some theory of long Gamma Ray Bursts [52] and how decoupled sector physics may influence the Gamma Ray Burst event [22, 24].

Gamma Ray Burst events that have a duration longer than two seconds are referred to as long Gamma Ray Bursts, while those with a duration of less than two seconds are referred to as short Gamma Ray Bursts. Stellar merger events are believed to be the origin of short Gamma Rays Bursts while the collapse of a massive star is believed to be the origin of long Gamma Ray Bursts. In this study we will only focus on long Gamma Ray Bursts.

The massive star which undergoes collapse is called the progenitor star of the Gamma Ray Burst. The theory for how such a collapse proceeds is termed the “collapsar model”. The iron core of the progenitor star collapses to form a black hole. Sufficient angular momentum exists to form an accretion disk which then feeds into the production of relativistic jets. Typically stars termed “Wolf-Rayet” stars are considered good progenitor star candidates because of their large mass.

The mechanism we will consider for launching jets is the Blandford-Znajek mechanism. The Blandford-Znajek mechanism is a force free magnetohydrodynamics solution for a Kerr black hole with a monopole magnetic field. The solution contains a Poynting flux dominated jet which may be the origin of the relativistic outflow for astrophysical objects. The energy for the jet comes from magnetic braking slowing the rotation of the black hole.

There are two phases during which we may observe light from Gamma Ray Burst events. The initial phase is termed the “prompt emission phase”. The high energy photons that we observe from this phase seem to be the result of synchrotron radiation produced from collisions between shells of relativistic debris and an external medium. Such collisions are termed “external forward shocks”. It is the gamma rays emitted during the prompt emission phase that trigger detectors on satellite experiments. However, we mention that it may also be that the prompt emission is the result of collisions between different relativistic debris, which are termed “internal forward shocks” if instead of Poynting flux jets there is a relativistic fireball.

The later phase is termed the “afterglow” phase and consists of much lower energy photons. This light also seems to be produced by an external forward shock, but the timescale of the shock is different by an order of magnitude or more in seconds. The prompt emission may last $\sim 100$ seconds, while the afterglow may last $\sim 10^4 - 10^5$ seconds.

One proposed method for detecting the existence of a model of partially interacting dark matter (PIDM)\footnote{We will discuss the model of PIDM in greater detail in section 5. For now we simply know that it is a model in which a subcomponent of the dark matter sector has an electromagnetic self-interaction.} is the way in which it affects the Blandford-Znajek mechanism for Gamma Ray Burst production within the framework of the collapsar model [22, 24]. The collapsar model [53–55] states that the iron core of a progenitor star...
(perhaps a Wolf-Rayet star) will collapse to form a black hole and that a jet will be launched. We will assume the jet engine is the Blandford-Znajek process \cite{56–69}. In particular, the rotating black hole will lose angular momentum to both the emission of dark radiation jets and visible radiation jets. The change in dimensionless spin parameter\(^5\), \(\frac{-1}{1 - a^2} \equiv \frac{J}{G N M^2_B} < 1\), is given by \cite{22, 24}

\[
\dot{a} \approx \frac{\lambda \gamma}{M_B} \left( \dot{M}_{\text{in,v}} + \dot{M}_{\text{in,D}} - L_{\text{jet,v}} - L_{\text{jet,D}} \right), \quad \lambda \gamma = 2 \left( \frac{(1 - a^2) (1 + \sqrt{1 - a^2})}{1 - \sqrt{1 - a^2}} \right)^{1/2}.
\] (2.6)

Here \(M_{\text{in,v,D}}\) corresponds to the infall rate for the visible/dark matter respectively and \(L_{\text{jet,v,D}}\) corresponds to the jet luminosity for the visible/dark radiation respectively. We will compare the dark sector and visible sector more explicitly in section 6.2.

### 2.2 Component of Dark Energy Sector

We note for completion that if the decoupled sector is part of the dark energy sector, the constraints are placed on the evolution of the equation of state parameter. In order to see how this arises theoretically, consider that some of the energy density in the dark energy sector is due to a slowly rolling scalar field so that the kinetic energy of the field is much less than the potential energy of the field \(\frac{1}{2} \dot{\phi}^2 \ll V\) \cite{70}. If the scalar field is homogeneous, its evolution is described by the following Klein-Gordon equation

\[
\ddot{\phi} + 3H \dot{\phi} + V_{,\phi} = 0.
\] (2.7)

The equation of state parameter for such a scalar field is given by the ratio of the pressure, \(P\), to the energy density, \(\rho\),

\[
w = \frac{P}{\rho} = \frac{\frac{1}{2} \dot{\phi}^2 - V}{\frac{1}{2} \dot{\phi}^2 + V} \approx -1 + \frac{\dot{\phi}^2}{V} + \mathcal{O} \left( \frac{\dot{\phi}^2 V}{V^2} \right).\] (2.8)

Existing studies of such models have assumed that the scalar field comprises the entire dark energy sector density. It may be that the scalar field is only a fraction of the entire dark energy sector. In that case there is some component that satisfies \(P_{\text{other}} = -\rho_{\text{other}}\). The equation of state parameter becomes

\[
w = \frac{P_{\text{other}} + P_{\phi}}{\rho_{\text{other}} + \rho_{\phi}} \approx -1 + \frac{\dot{\phi}^2}{\rho_{\text{other}}} + \mathcal{O} \left( \frac{\dot{\phi}^2 V}{\rho_{\text{other}}^2} \right).
\] (2.9)

We have required that \(\rho_{\phi} \ll \rho_{\text{other}}\), though one could explore the allowed parameter space in more generality.

Observationally the constraints on the equation of state parameter come from CMB, BAO and supernovae observations. From measurements of the CMB and BAO the equation of state parameter is constrained to be \(w = -1.04^{+0.24}_{-0.25}\) to 95% confidence \cite{32}. If the equation of state parameter is found to deviate from \(w = -1\) it would indicate that the energy source for dark energy is not constant. Additionally, one may test features such as spatial inhomogeneity with observations of supernovae \cite{72}.

\footnote{Here \(M_B\) is the mass of the black hole, \(J\) is the angular momentum and \(G_N\) is Newton’s gravitational constant.}
3 Wolf-Rayet Stars and Galaxies

In section 4, we present four Wolf-Rayet galaxies that provide an excellent testing grounds for theories involving a decoupled sector of matter. These galaxies have the following advantages:

1. They are rotationally supported discy galaxies which means their kinematics are well understood and their dark matter profiles could reasonably be measured.
2. They have recently undergone minor mergers with a dwarf galaxy. We will discuss in section 5 that this means the decoupled sector gas and visible sector gas accreted into the larger galaxy and are comparably distributed within the larger galaxy.
3. The satellite dwarf galaxy that merges with the massive spiral galaxy is dark matter rich. For example, observational studies of Blue Compact Dwarf galaxies have shown their ratios of dark matter to be within the range of 80-95% [73–76].
4. They contain Wolf-Rayet stars. Wolf-Rayet stars may play a critical role in Gamma Ray Burst physics (see section 6.2).

We will first review the general properties of Wolf-Rayet stars and Wolf-Rayet galaxies before proceeding to discuss the four candidate galaxies.

A typical Wolf-Rayet star is in the mass range 10-25 M$_{\text{Sun}}$ or greater [77]. They begin their life as an O-type star with a mass of at least 25 M$_{\text{Sun}}$ and have short lifetimes of $\sim 5$ Myr. This mass limit assumes a solar metalicity. As the metalicity decreases, the lower limit on stellar mass increases. Only $\sim 10\%$ of the star’s lifetime is spent in the Wolf-Rayet phase [78] making them remarkably short-lived astronomically. These massive stars produce heavy elements at a high rate as well as dense and powerful stellar winds [77]. As a result, they contribute significantly to the chemical enrichment and feedback of their host galaxy. They are also the primary progenitor candidates for some long Gamma Ray Bursts [52].

The Wolf-Rayet galaxy classification comprises several very different galaxy populations. They do not describe a particular morphology. They are classified as Wolf-Rayet by their Wolf-Rayet nebular emission, such as the broad HeII 4686 Å feature observed as a result of the high-energy intense stellar winds of Wolf-Rayet stars [77]. As such, it is difficult to draw any conclusions about Wolf-Rayet galaxies as a population.

The baryonic gas within a galaxy is mostly hydrogen which is typically classified in two groups, HI and HII. HI gas is comprised of neutral atomic hydrogen, which is cold ($\sim 100$ K [79]) and does not emit in the visible spectrum. It is detected via radio observations at 21 cm. HII gas is hot and partially ionized atomic hydrogen gas. It is detected through emission in the visible spectrum and is largely associated with star formation as young bright stars are required to produce the high levels of ionization of the surrounding gas. Simulations show that HII regions are short lived (less than ten million years [80]) in mini-halos similar to the mass of dwarf galaxies because the intense stellar winds and supernova required to produce them also remove the gas from the galaxy. Although large amounts of HI gas would be required to form the massive progenitors of Wolf-Rayet stars in the larger galaxies, the type Ib and type Ic
supernova that are expected to result from Wolf-Rayet stars are conspicuously lacking in hydrogen spectral features. This is likely due to the strong stellar winds removing the neutral HI gas from the immediate vicinity of the star as observed in Circinus [81].

4 Example Wolf-Rayet Galaxies

Wolf-Rayet galaxies are galaxies which contain Wolf-Rayet stars. We are ultimately interested in how the decoupled sector gas relevant for this study is distributed with respect to the visible sector gas within a Wolf-Rayet galaxy. To that effect we searched through the literature to identify galaxies from the Wolf-Rayet catalog [34] that are late-type spiral galaxies currently undergoing a minor merger: NGC 1614 [82], NGC 3367 [83], NGC 4216 [84] and NGC 5430 [85]. Dark Matter mass estimates can vary widely from galaxy to galaxy, even within populations such as late-type spirals, however the generally accepted typical value for a spiral galaxy is 10% visible matter and 90% dark matter based on observations of stellar rotation curves [86].

These four galaxies satisfy the four criteria listed in section 3. This means that, as we will argue in section 5, we know the spatial distribution of decoupled sector gas is comparable to the visible sector gas. This will allow us to discuss how the presence of the decoupled sector gas may alter the galaxy phenomenology in section 6.

4.1 Other Possible Candidates

Throughout our search of the literature, we found the following galaxies which were close to our criteria of being late-type Wolf-Rayet galaxies undergoing a minor merger, but were unable to include for the reasons described below.

1. NGC 3003: Although there is reasonable evidence for a merger, the inclusion of this galaxy in the original Wolf-Rayet catalog may have been a mistake [87].
2. NGC 6764: The evidence for a merger within this galaxy is inconclusive [88].
3. NGC 7714: Although it is quite clearly undergoing a very visually stunning merger, by assuming a constant M/L ratio between the two progenitors, it would appear that the mass ratio is on the order of 1:3 so the dynamics are likely to be close to that of a major merger [89].

4.2 Observational Considerations

Despite the fact that our selection criteria is not incredibly stringent, we find the small number of galaxies (4-7) found to be quite reasonable. By the Galaxy Mass Function [90] we would expect dwarf galaxies to be more common than larger galaxies, and therefore we would expect a large number of minor mergers. However, several factors conspire to make ideal galaxies for our analysis difficult to find. Firstly, the evidence for a minor merger is difficult to detect due to the small mass influence on the larger galaxy, also evidence for a minor merger disappears faster than evidence for a major merger. Similarly, the short lifetime of Wolf-Rayet stars in the Wolf-Rayet phase means that they are only detectable for a very short timescales (∼0.5 Myrs [78]).
5 Visible and Decoupled Gas Inflow

The gas inflow strength during a minor merger between a rotationally supported massive galaxy and a satellite dwarf galaxy is mainly determined by the structure of the more massive galaxy (in particular, the parameterization of the compact bulge) and is relatively insensitive to the microphysics describing the gas \[91, 92\]. This means that despite the microphysical difference between the gas in the dark matter sector and the gas in the visible sector, their infall obeys a similar description since the gravitational environmental for the dark matter sector gas and the visible sector gas is the same. In particular, it was shown that gas inflow is robust against changes in gas viscosity and temperature [92]. The visible sector gas that inflows with the dark matter sector gas will go on to inhabit a star forming region which is surrounded by the dark matter sector gas. A full numerical analysis of both gases and the influence of their mutual gravitation on one another is beyond the scope of this study. Though we note that since self-gravity of the gas is not important in the absence of the dark matter sector gas [92, 93], it is unlikely to be important in the case that both gases are present. A numerical simulation which incorporates both star formation and the interstellar medium (such as that performed in [94]) would provide insight into possible phenomenological probes of a decoupled sector.

In principle the self-interaction in the dark matter sector could be mediated by any sort of force carrier familiar from quantum field theory. For definitiveness, we will discuss a model (first discussed by [16, 17]) in which there exists a component of dark matter sector which is self-interacting electromagnetically. This self-interacting dark matter is referred to as partially interacting dark matter (PIDM). The PIDM is essentially decoupled from the visible sector except for gravitationally. The case whereby the PIDM electron and proton analogs never decouple from the thermal bath of dark photons was studied in [24]. In that case, dark baryon acoustic oscillations limit the amount of PIDM to be at most 4% of the dark matter in the universe [14]. We have summarized the benchmark parameter values from [24] in Table 1. We emphasize that this is only one particular model of decoupled sector physics and that the benchmark parameter values may be very different than what is discussed here.

We will assume that the maximum global percentage of dark matter that may be PIDM is also the local percentage within any given dwarf galaxy \(\epsilon_{\text{Global}} \approx \epsilon_{\text{Galaxy}}\), similar as was done in [16, 17]. Since this statement depends on the details of galaxy formation, this needs to be verified with numerical simulation. We will discuss some possible phenomenological implications of such a dark matter component in the next section.

6 Possible Phenomenology

6.1 Modified Spatial Distribution of Dark Matter

Decoupled sectors interact with the visible sector very weakly. Therefore the most obvious effect is that the mass to light ratio throughout the galaxy will be altered since now there is a decoupled sector gas additionally contributing mass but not emitting
The power emitted from the Blandford-Znajek mechanism depends on the black hole angular velocity, $\Omega_h$, and magnetic flux threading the black hole, $\Psi$, as \cite{56, 57}

$$\dot{E}_{BZ} \propto \Omega_h^2 \Psi^2. \quad (6.1)$$

The only difference between the visible sector and the dark matter sector will be the magnetic flux threading the black hole. For the case in which a well defined accretion disk forms and feeds the black hole the flux may be written as \cite{95}

$$\Psi^2 \sim (\text{Area})^2 B_z^2 \sim (\text{Area})^2 \left( \frac{\text{accretion disk height}}{\text{accretion disk radius}} \left( \frac{\text{plasma sound speed}}{\rho} \right) \right)^2 \rho. \quad (6.2)$$
We have argued that the density, $\rho$, of PIDM and visible sector matter may be comparable in the vicinity of the progenitor star. While the actual geometric distribution or the plasma sound speed of PIDM may be different from the visible sector matter, it is not unreasonable to expect that in general the magnetic flux threading the black hole can be comparable for the visible sector and the PIDM. Therefore the power emitted through the Blandford-Znajek mechanism may be comparable.

We note that the plasma sound speed is in general given by $\sim \sqrt{T_e/m_p}$. For the model parameters given in Table 1, the plasma sound speed is actually enhanced by a factor of $\sim 2$. However, this model does not ever decouple from the dark thermal bath and form atoms so it is unclear what the geometric distribution about the black hole is.

We are currently investigating methods that may be used to obtain a measurement for the evolution of spin of the black hole during a Gamma Ray Burst event. Currently, active galactic nuclei or binary black hole systems are the targets for black hole spin measurements [96–98]. In order to take advantage of the emission of decoupled sector jets, the change in spin of the black hole should be modeled or obtained during the prompt emission era.

Even if a means of measuring the change in black hole spin proves elusive for the near future, it would be interesting to numerically model a collapsar event with both a visible sector fluid and PIDM present. This would be the best way to explore whether the visible sector process is altered or not by the presence of PIDM. Furthermore, it would help clarify what are the requirements of the PIDM microscopic parameters in order to produce a jet luminosity comparable with the visible sector.

7 Conclusions

Astrophysics provides a laboratory to test theories of self-interacting dark matter even if it couples only very weakly to the Standard Model particles. As reviewed in section 2, many results already relevant for model building and constraining the dark matter sector have been obtained. In order to discover new opportunities for using astrophysics to study the nature of dark matter self-interactions, we have provided criteria for identifying galaxies which should contain a relatively large amount of self-interacting dark matter in the vicinity of star forming regions.

We reiterate here the criteria from section 3 for finding a good candidate galaxy with which dark matter sector physics may be probed:

1. They are rotationally supported discy galaxies.
2. They have recently undergone minor mergers with a dwarf galaxy.
3. The satellite galaxy that merges with the spiral galaxy is dark matter rich.
4. They contain Wolf-Rayet stars.

We have identified four candidate galaxies satisfying this criteria and three additional galaxies that may also satisfy these criteria but require further observations. The four candidate galaxies are NGC 1614, NGC 3367, NGC 4216 and NGC 5430. The three possible candidate galaxies are NGC 3003, NGC 6764 and NGC 7714.
In those candidate galaxies it may be that the particular model of self-interacting dark matter, PIDM, may be able to emit jets of dark matter sector radiation during a GRB event which is comparable to the emission of visible sector radiation. We have shown how this would affect the spin parameter of the central black hole during such an event. The possibility of studying an observable which uniquely probes the existence of electromagnetism in the dark matter sector is worth pursuing further even if present observational methods are not capable of testing this prediction.

We hope to have motivated the consideration of “two sector” models whereby both a visible sector gas and a decoupled sector gas are present with comparable densities in a galaxy. It is clear from the energy budget of the universe that we understand only a very small fraction of what matter exists. By using astrophysics to further inform our dark matter sector model building, we can refine our ideas about how dark matter is distributed within our own galaxy and interpret terrestrial experiments accordingly.

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