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Introduction

1.1 Evidence for Dark Matter

Today, the amount of evidence in support of dark matter's existence is overwhelming. This evidence comes from astrophysical and cosmological observations that are inconsistent with a universe composed entirely of visible matter. This section reviews this evidence.

1.1.1 Astrophysical Observations

Galaxy Clusters

Some of the first hints for the existence of dark matter came from observations of galaxy clusters. Perhaps the most famous analysis was performed by Fritz Zwicky [1], who was puzzled by the high rotational velocities of galaxies within the Coma Cluster. By applying the virial theorem, equating the cluster's kinetic and gravitational potential energies, he found that the cluster would need to contain a much more significant amount of *dunkle materie* (dark matter) than visible matter to accommodate these high velocities.

Rotation Curves of Spiral Galaxies

The anomalous rotational velocities observed in galaxy clusters can also be observed at the galactic scale. The rotation curves of spiral galaxies, which relate

the rotational velocities of stars to their distance from the galactic centre, were observed to be flat at large distances. From the observed distribution of visible matter, Newtonian mechanics predicts that the orbital velocity of a star a distance r from the galactic centre, $v_*(r)$, is related to the mass contained within a radius r , $M(r)$, through

$$v_*(r) = \sqrt{\frac{GM(r)}{r}}, \quad (1.1)$$

indicating that the velocity should fall off as $1/\sqrt{r}$ at the outer regions of the galaxy where $M(r)$ is constant. Instead, observations of many spiral galaxies indicate that this velocity remains constant out to the galaxy's edge.

A simple way to produce such a rotation curve is to introduce a spherically symmetric distribution of dark matter surrounding the galaxy,

$$\rho_{\text{DM}}(r) = \frac{v_0^2}{4\pi G r^2}, \quad (1.2)$$

which results in a constant rotational velocity of v_0 out to the galaxy edge. Detailed simulations of structure formation in a Cold Dark Matter (CDM) Universe indicate that the true distribution is better represented by distribution functions such as the Navaro-Frenk-White (NFW) profile [2, 3] or Einasto [4] profiles, which are commonly used in the literature.

An example rotation curve for galaxy NGC 6503 is presented in Fig. 1.1, with the contributions from each of the matter components to the rotational velocity shown [5, 6]. As can be seen, the visible matter constituting disk and gas components does not explain the observed rotational velocity.

Gravitational Lensing

As described by General Relativity, the curvature of space-time around massive entities causes light to travel along curved paths. As such, the mass of astrophysical structures can be deduced from the extent to which they distort the images of objects in the background. The extent of the distortions depends on how massive the foreground object is, ranging from the shearing of the background image (weak lensing), to multiple copies of the background object appearing (strong lensing) [7]. The disparity between the mass obtained from gravitational lensing and the mass of visible matter in the system is further evidence of dark matter's existence [8, 9].

The Bullet Cluster

Galaxy cluster 1E 0657-56, commonly referred to as the “bullet cluster”, was formed by the collision of two separate galaxy clusters. The baryonic matter in these

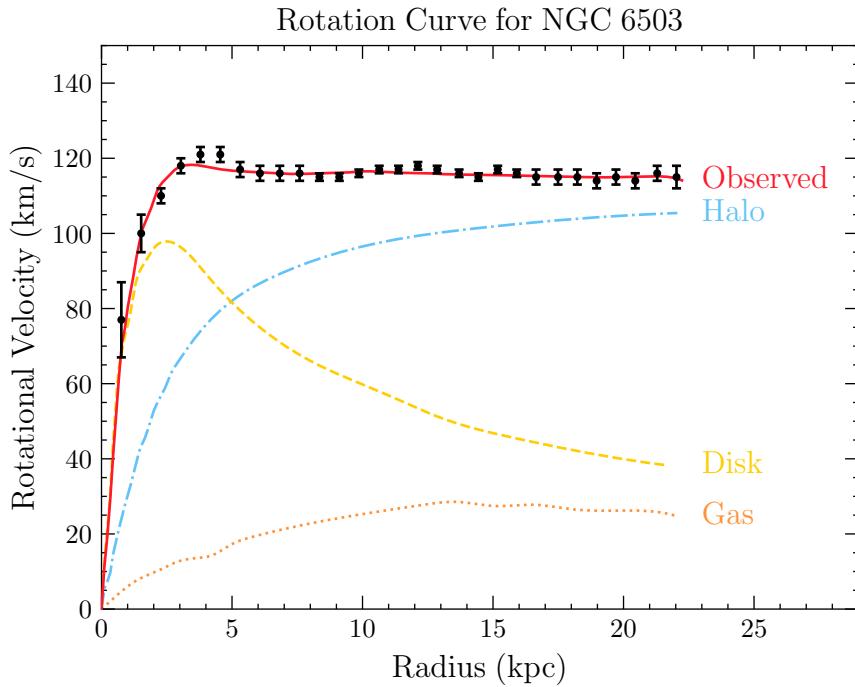


Figure 1.1: Galaxy rotation curve for NGC 6503, showing the contributions to the total velocity (red) from the DM halo (blue), disk (yellow), and gas components. Data used in making this plot was obtained from [5, 6].

clusters is mostly composed of a strongly interacting gas and, as expected, produced a significant amount of X-rays during the collision. These X-rays were imaged by the Chandra X-Ray telescope [10], providing information on the resulting distribution of the visible matter. This is shown by the red regions of Fig. 1.2, where it can be seen how the visible matter has been smeared due to the collision. However, when the gravitational potential was mapped using gravitational lensing, it was clear that the majority of the mass was displaced relative to the visible matter. This mass is attributed to the dark matter components of the original clusters. As indicated by the purple regions in Fig. 1.2, the dark matter halos seem to have passed through each other mostly unperturbed. This tells us that not only is the majority of the mass comprised of dark matter, but that the dark matter has extremely weak interactions with both the visible matter and itself.

1.1.2 Cosmological Evidence

The current best cosmological model is the Λ -Cold Dark Matter model (Λ CDM), in which Λ refers to the cosmological constant associated with dark energy, and

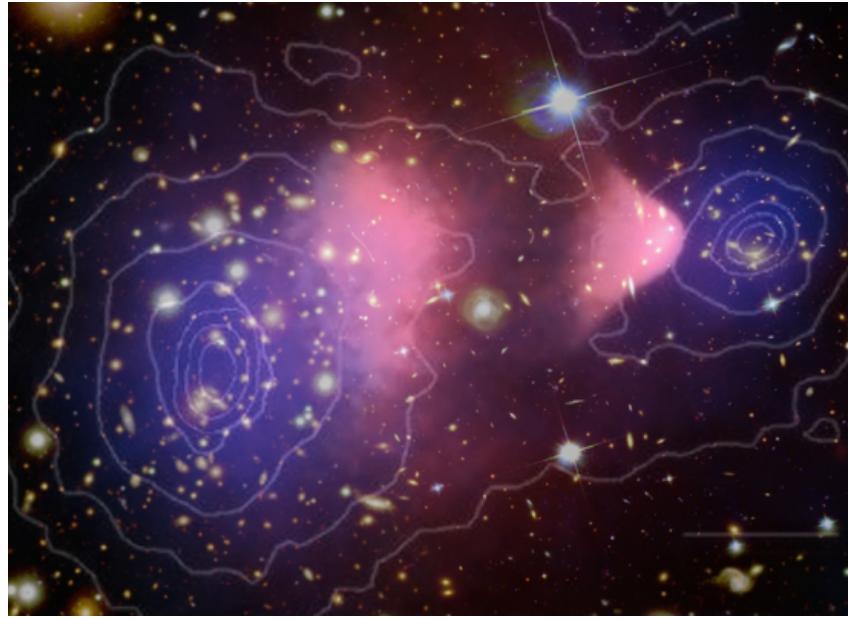


Figure 1.2: Image of the Bullet Cluster with contours of the gravitational potential superposed. The red regions indicate the baryonic matter after the collision, while the purple regions are the expected DM components deduced from gravitational lensing. [10, 11]

as the name suggests, cold (i.e. non-relativistic) dark matter plays a prominent role. The key components of this model are the aforementioned dark energy and dark matter, along with baryonic matter, and it assumes that gravity is described by Einstein's General Relativity. The total energy density of the universe, $\rho_{\text{Univ.}}$, can be broken down into three components based on how their density redshifts with the expansion of the Universe. In the Λ CDM model, these components are matter, radiation, and the vacuum energy Λ . The cosmological abundances of each component, (Ω_m , Ω_r , Ω_Λ respectively), are expressed as a fraction of the critical density, ρ_{crit} ,

$$\rho_{\text{crit}} = \frac{H^2}{8\pi G_N}, \quad (1.3)$$

$$\Omega_i = \frac{\rho_i}{\rho_{\text{crit}}}, \quad (1.4)$$

where H is the Hubble parameter, such that the total energy density of the Universe satisfies

$$\Omega_m + \Omega_r + \Omega_\Lambda = \frac{\rho_{\text{Univ.}}}{\rho_{\text{crit}}}. \quad (1.5)$$

The ratio $\rho_{\text{Univ.}}/\rho_{\text{crit}}$ determines the curvature of the universe, with values greater than 1 corresponding to a closed universe, less than 1 to an open universe, and equal to 1 to a spatially flat universe. Current observations are consistent with a spatially flat universe, and so we have $\sum_i \Omega_i = 1$.

The Λ CDM model has seen huge success as it provides explanations for observed the power spectrum of the Cosmic Microwave Background (CMB), the large-scale structure of the Universe, the abundances of light elements (hydrogen, deuterium, helium, and lithium), and the accelerated expansion rate of the Universe. These observations constrain the parameters of the model and hence provide a complementary probe of the properties of dark matter to the astronomical observations discussed above.

The Cosmic Microwave Background

One of the strongest probes of cosmological models is the Cosmic Microwave Background (CMB), relic photons from the time epoch of last scattering. This occurred after recombination, at a temperature of around ~ 3000 K, once the photons had decoupled from the baryonic matter and could freely propagate through the universe. The photons observed today have been redshifted by the expansion of the Universe and are well described by a blackbody spectrum with a temperature of $T_{\text{CMB}} = 2.73 \pm 0.0006$ K. Observations of the CMB temperature reveal that it is not exactly isotropic, with anisotropies at the level of $\delta T_{\text{CMB}}/T_{\text{CMB}} \sim 10^{-5} - 10^{-6}$ seen on a range of angular scales in the sky. These anisotropies were seeded by the primordial density perturbations that arise during inflation. These perturbations evolve due to the acoustic oscillations of the photon-baryon plasma driven by the interplay between the pressure from the photons and the gravitational attraction of the matter. The oscillations cease once the photons decouple, freezing in their temporal phases that are observed as peaks in the angular power spectrum of the temperature anisotropies.

Measurements of the CMB power spectrum provide information on many of the cosmological parameters. The locations of the acoustic peaks depend on the spatial geometry of the Universe and hence constrains Ω_{tot} . The total matter density, Ω_m , affects how the CMB spectrum is gravitationally lensed. The relative amplitudes of the peaks probe the baryon-to-photon ratio and hence the baryon density, Ω_b . Finally, the density of dark matter, Ω_{DM} , is obtained by fitting the cosmological parameters to the exact shape of the spectrum [5, 12].

The Planck collaboration most recently performed a precise measurement of the CMB power spectrum in 2018, obtaining best-fit parameters [12, 13]

$$\Omega_m = 0.311 \pm 0.006, \quad \Omega_\Lambda = 0.689 \pm 0.006, \quad (1.6)$$

for the matter and dark energy densities. They obtained a total energy density of $\Omega_{\text{tot}} = 1.011 \pm 0.006$ at 68% confidence level, providing strong evidence for a spatially flat Universe. The breakdown of the matter density into the dark and baryonic components is determined by combining the CMB results with constraints from Big Bang Nucleosynthesis (BBN)¹ giving

$$\Omega_{\text{DM}} h^2 = 0.1193 \pm 0.0009, \quad \Omega_b h^2 = 0.02242 \pm 0.00014, \quad (1.7)$$

where h is the dimensionless Hubble constant such that the Hubble parameter today is $H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}$.

Large Scale Structure

After recombination, the pressure on the baryonic matter from photons began to decrease, eventually allowing the small density perturbations to grow. This led to the growth of stars, galaxies, and the large-scale structure we observe today [14]. N-body simulations of the Universe's evolution require a cold dark matter component for this structure to form. While a small component of the dark matter can be warm, hot dark matter would wash out small-scale structures [15].

1.2 Potential Models of Dark Matter

Given that baryonic matter is composed of particles described by the Standard Model (SM) of particle physics, it is a fair assumption that dark matter will also have a particle nature. Therefore, models of particle dark matter are built by extending the SM in a way consistent with its symmetries. Such models may be as simple as introducing a single new field into the SM, or there may be a more extensive hidden sector with a complicated symmetry structure. Additionally, there are compelling theories in which dark matter is not a fundamental particle, such as primordial black holes (PBHs) formed in the early universe. Given the few details we know about dark matter, there exists an enormous library of viable dark matter candidates. However, there are generic properties a good dark matter candidate must satisfy, namely:

- **Stable on Cosmological Timescales:** Dark matter must either be stable or have a lifetime significantly longer than the age of the Universe to be present in its current abundance.

¹BBN is the process that produced the light elements (D , ^3He , ^4He , and ^7Li) were produced in the early universe. This process is highly sensitive to the physical condition of the universe at that time, allowing for strong constraints to be placed on physics beyond the Standard Model.

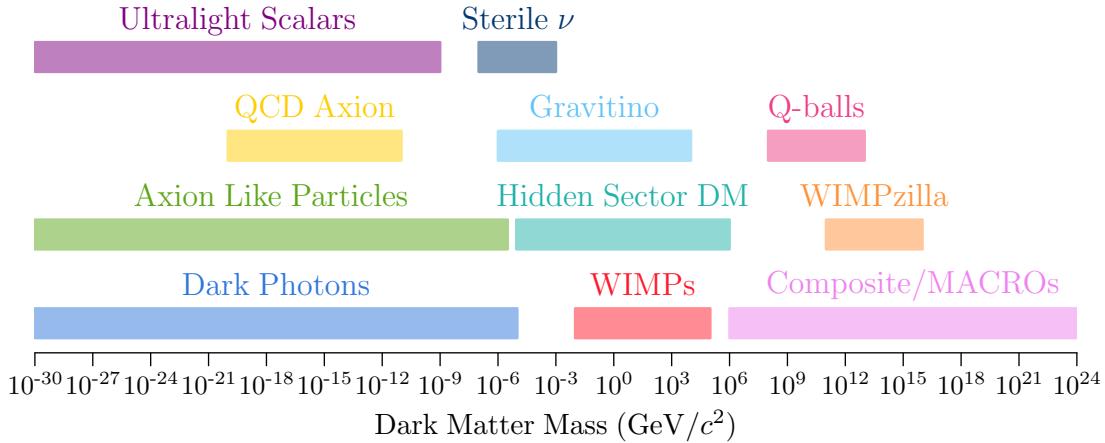


Figure 1.3: Illustrative landscape of dark matter models and the mass range for which they predict a valid candidate. Details can be found in the Dark Matter chapter of the PDG [20].

- **Neutral or milli-charged under Electromagnetism:** Dark matter, as its name suggests, does not significantly interact with light. Requiring that dark matter be completely decoupled from the Standard Model plasma by the time of recombination yields an upper bound on the electric charge of dark matter [16]

$$q_{\text{DM}}/e < \begin{cases} 3.5 \times 10^{-7} \left(\frac{m_{\text{DM}}}{1 \text{ GeV}}\right)^{0.58}, & m_{\text{DM}} > 1 \text{ GeV} \\ 4.0 \times 10^{-7} \left(\frac{m_{\text{DM}}}{1 \text{ GeV}}\right)^{0.35}, & m_{\text{DM}} < 1 \text{ GeV} \end{cases} \quad (1.8)$$

- **Small Self-Interactions:** The standard Λ CDM cosmology assumes that the dark matter is collisionless. However, small dark matter self-interactions can help resolve existing small-scale structure issues [17, 18]. Current limits on the self-interaction cross-section are $\sigma_{\text{DM-DM}}/m_{\text{DM}} < 0.48 \text{ cm}^2/\text{g}$ come from merging galaxy clusters [11] and the ellipticity of galaxies obtained from X-ray observations [19].
- **Cold:** Dark matter is required to be non-relativistic at the time of structure formation. At most, a small component of the dark matter can be warm (semi-relativistic).

A selection of the more prominent dark matter candidates is shown in Fig. 1.3. The key features of a few of these models are discussed below.

WIMPs

Weakly Interacting Massive Particles (WIMPs) are a class of dark matter candidates that generically have masses and interaction strengths around the weak scale. Many extensions of the SM naturally predict the existence of such a particle, with famous examples being the lightest supersymmetric particle in supersymmetric theories [21], or the lightest stable Kaluza-Klein mode in theories with extra dimensions [22].

Nowadays, WIMP dark matter is used almost synonymously to mean thermal relic, referring to a species whose relic abundance is produced thermally in the early universe through the freeze-out mechanism [23]. In this paradigm, the WIMP is initially in thermal equilibrium with the Standard Model bath. This equilibrium is maintained as long as the interaction rates of the WIMP with the bath, denoted Γ , remain faster than the Hubble expansion of the universe, H . As the universe continues to expand, the temperature of the bath drops, slowing down the interaction rates. Eventually, the expansion rate overtakes the interaction rates, $\Gamma/H \lesssim 1$, and the interactions “freeze out” causing the WIMP to fall out of equilibrium with the bath. At this point, the WIMPs can no longer efficiently annihilate, and their abundance gets “frozen-in” to the value it had at freeze-out, leading to the abundance observed today.

A cold thermal relic, such as dark matter, will freeze out after it has become non-relativistic. In this scenario, the interaction rates become Boltzmann suppressed², and the species rapidly freezes out. The relic density is therefore sensitive to the annihilation cross-section of the species, $\langle\sigma_{\text{ann}}v\rangle$. More efficient annihilations correspond to larger cross-sections, resulting in the species remaining in equilibrium for longer times. This allows the number density to continue following the exponentially decreasing Boltzmann distribution and yield a smaller relic abundance. The evolution of the abundance of a Majorana fermion WIMP of mass $m_{\text{WIMP}} = 100 \text{ GeV}$ is shown in Fig. 1.4 for three values of the annihilation cross-section. A simple expression relating the annihilation cross-section and the abundance that is correct to $\sim 5\%$ can be obtained [24]

$$\Omega_{\text{DM}} h^2 = \frac{10^{-27} \text{ cm}^3 \text{ s}^{-1}}{\langle\sigma_{\text{ann}}v_\chi\rangle} \frac{x_*}{g_*^{1/2}} \quad (1.9)$$

$$\sim 0.12 \left(\frac{2.2 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1}}{\langle\sigma v\rangle} \right), \quad m_\chi \gtrsim 10 \text{ GeV}, \quad (1.10)$$

where $x_* = m_{\text{WIMP}}/T_*$ is evaluated at an intermediate temperature between equilib-

²The number density of a non-relativistic species in thermal equilibrium with the bath will follow $n \propto (m T_{\text{bath}})^{3/2} \exp(-m/T_{\text{bath}})$. Once the temperature falls below the mass of the species, the number density becomes exponentially suppressed. This is what is known as “Boltzmann suppression”.

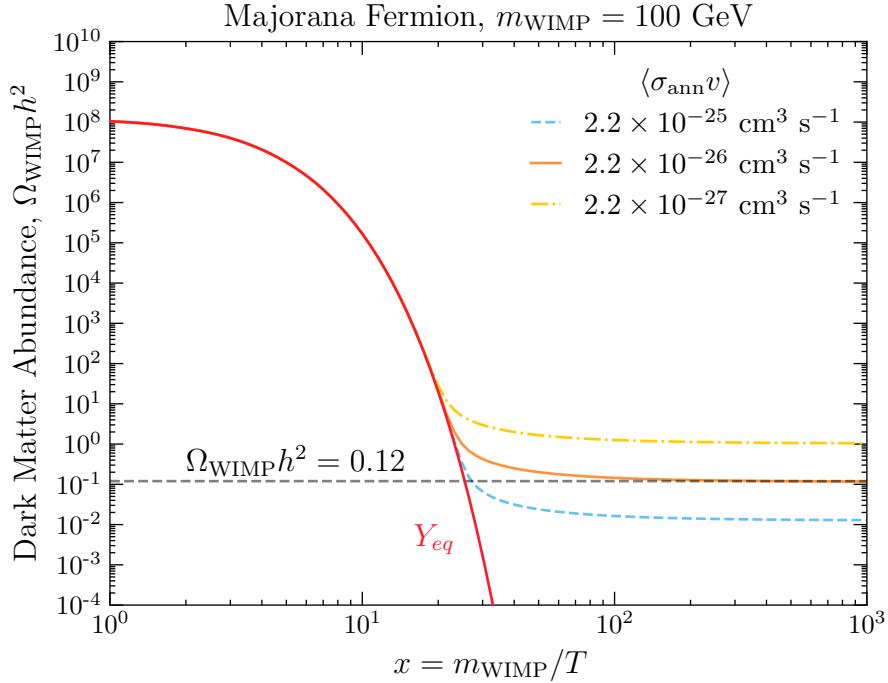


Figure 1.4: Evolution of the DM abundance as a function of $x = m_{\text{DM}}/T$. The red line tracks the abundance of the WIMP if it remains in equilibrium with the bath. The relic abundance for three different annihilation cross-sections is shown in blue, orange, and yellow for $\langle \sigma_{\text{ann}} v \rangle = 2.2 \times 10^{-25}, 2.2 \times 10^{-26}, \text{ and } 2.2 \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}$ respectively.

rium and freeze-out, with g_* the effective number of relativistic degrees of freedom present at this time.

The allowed mass range for a thermal WIMP is between $10 \text{ MeV} \lesssim m_{\text{WIMP}} \lesssim 100 \text{ TeV}$. Lighter WIMPs will make non-negligible contributions to the effective number of neutrinos at the time of Big Bang Nucleosynthesis, measured to be $N_{\text{eff}}^{\text{BBN}} = 3.044$ [25], altering the observed abundances of the light elements. The CMB offers an additional probe of N_{eff} at the later time of recombination and can be combined with the BBN result leading to the value $N_{\text{eff}} = 2.99 \pm 0.17$ [12]. Given the Standard Model predicts a value of $N_{\text{eff}} = 3.044$, contributions from additional relativistic degrees of freedom must be less than $\Delta N_{\text{eff}} < 0.28$ [25]. At the high end of this range, masses larger than $\sim 100 \text{ TeV}$ are excluded from partial wave unitarity [26].

Axions

The axion originally arose from the Pecci-Quinn solution to the Strong CP problem. This refers to the lack of observed CP-violation in the QCD sector of the Standard Model that arises from the topological term in the Lagrangian

$$\mathcal{L}_{\theta_{\text{QCD}}} = \frac{g_s^2}{32\pi} \theta_{\text{QCD}} G_{\mu\nu} \tilde{G}^{\mu\nu}, \quad (1.11)$$

where g_s is the QCD coupling constant, $G_{\mu\nu}$ is the gluon field strength tensor and $\tilde{G}^{\mu\nu}$ is its dual. This term generates an electric dipole moment for the neutron (nEDM) that has yet to be observed experimentally. The current upper bound on the nEDM is $|d_n| < 0.18 \times 10^{-26} e\text{ cm}$ [27] and can be translated to an upper bound on the CP-violating QCD θ -parameter such that $|\theta_{QCD}| \lesssim 10^{-10}$, raising questions as to why this value seems to be fine-tuned to such a small value.

The Peccei-Quinn solution to this problem introduces a new, anomalous, global $U(1)_{\text{PQ}}$ symmetry and promotes θ_{QCD} to be a dynamical field. Wilczek [28] and Weinberg [29] showed that the axion emerges as the pseudo-Goldstone boson associated with the breaking of $U(1)_{\text{PQ}}$. Though the original axion was quickly out, many modern extensions of the SM predict the existence of a QCD axion. Two of the most prominent UV completions of the axion are the KSVZ [30, 31] and DFSZ [32, 33] models. In these models, the axion produced in the early Universe can serve the role of cold dark matter today. This makes it a very compelling dark matter candidate, as it solves two of the biggest mysteries of physics in one neat package.

However, solving the Strong CP problem can be rather restrictive on the model parameters. For example, the QCD axion's coupling to the photon, $g_{a\gamma\gamma}$, is not a free parameter and depends on the scale at which the PQ symmetry is broken. Many models introduce a light pseudoscalar particle, say a , that couples to the photon in the same way as the QCD axion,

$$\mathcal{L}_{a\gamma\gamma} = -\frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu}, \quad (1.12)$$

but is not associated with a solution to the Strong CP problem. Such pseudoscalars are known as “Axion Like Particles” (ALPs) and can make a good dark matter candidate.

Primordial Black Holes

Primordial black holes (PBHs) are formed during the early Universe through various mechanisms. The simplest mechanism predicts that PBHs are produced from

the gravitational collapse of superhorizon density fluctuations seeded during inflation [34–36]. Unlike black holes that originate from stellar collapse, which have masses $\gtrsim 3M_\odot$, the mass of a PBH can be arbitrary. PBHs can also make a good dark matter candidate, satisfying all the criteria points outlined above. In fact, PBHs with a mass between $\sim (10^{-17} - 10^{-12}) M_\odot$, dubbed “asteroid mass PBHs”, can account for 100% of the dark matter content in the Universe [37]. Outside this range, PBHs can still make up a small fraction of dark matter [38].

1.2.1 Dark Matter in an Effective Field Theory Framework

For a dark matter candidate to be truly compelling, it should be able to be embedded into an ultraviolet (UV) complete theory. Such theories are renormalisable³ and gauge invariant under the SM gauge group $SU(3)_{\text{colour}} \otimes SU(2)_L \otimes U(1)_Y$. This allows them to be predictive up to arbitrarily high energies. These theories are typically quite complex, requiring the introduction of multiple new fields and many more free parameters. As an example, consider the phenomenological Minimal Supersymmetric Standard Model (pMSSM) [38] in which the lightest neutralino⁴ can be a thermal WIMP dark matter candidate. In this theory, 19 free parameters are introduced on top of the free parameters in the SM, requiring 38 independent experimental observations to fully constrain the model. Given that at this time, all good dark matter candidates are equally likely to be the correct one, a model-independent approach to interpreting experimental results is desirable. This is achieved by describing the interactions of dark matter with the SM through an effective field theory (EFT).

1.2.2 Overview of Effective Field Theory

Modern physics can be thought of as a ladder of theories that are designed to describe the physics present at a given energy (or length) scale. For example, Newtonian mechanics is a sufficient description of the physics experienced in our everyday lives. However, in situations where the energy is comparable to the mass of the system, Newtonian mechanics breaks down, and Special Relativity must be used to describe the physics. In particle physics, the Standard Model provides an excellent description of particle interactions up to the energies reached at LHC, 13.6 TeV, and perhaps even further beyond. However, even it is expected to break

³In a renormalisable theory, the infinities that arise from UV divergences can be absorbed by fixing a finite number of parameters to experimentally observed values.

⁴The neutralinos are the mass eigenstates of the supersymmetric partners of the neutral gauge bosons and the higgsino.

down at higher energy scales, in particular at the Planck scale, where a quantum theory of gravity is required. Hence, both Newtonian mechanics and the SM are low-energy, effective descriptions of a more complete theory.

This philosophy based on only describing the physics relevant below some energy scale, Λ , is the core principle of EFTs. The Lagrangian for the effective theory only contains the degrees of freedom that can be produced below the scale Λ , i.e. fields that have masses less than this scale. This low-energy regime described by the EFT is often called the infrared (IR) regime.

In general, the EFT Lagrangian will contain renormalizable terms, $\mathcal{L}_{\text{renorm.}}$, built out of operators that have mass dimension ≤ 4 , as well as operators with mass dimension $n > 4$, $\mathcal{O}_i^{(n)}$, that encapsulate the contributions from the UV physics. Each of these higher dimensional operators will be suppressed by the scale of new physics, Λ^{4-n} . The effective Lagrangian can then be written as

$$\mathcal{L}_{\text{EFT}} = \mathcal{L}_{\text{renorm.}} + \sum_{n>4} \sum_{i=1}^{j_n} \frac{C_i^{(n)}(\tilde{\mu})}{\Lambda^{n-4}} \mathcal{O}_i^{(n)}, \quad (1.13)$$

where we sum over all j_n operators present at mass dimension n . The expansion coefficients, $C_i^{(n)}$, are the Wilson coefficients that contain the effects of the UV physics. In general, the Wilson coefficients run with the energy scale they are evaluated at, $\tilde{\mu}$, described by the renormalisation group equations (RGEs). The sum over the mass dimension of the operators is typically terminated at some sensible value, as higher dimensional operators get increasingly suppressed by the cutoff scale Λ .

The series of operators in Eq. 1.13 can be constructed in two different ways. First, we assume some prior knowledge of the underlying UV theory. Then, for a given energy scale Λ , the heavy degrees of freedom are known, and can be explicitly integrated out. There are various methods for performing this process, the simplest being expanding the propagator of the heavy fields in powers of the momenta over the heavy mass, $(p/M)^2$. For the simple case of a heavy scalar, this corresponds to

$$\frac{i}{p^2 - M^2} = \frac{-i}{M^2} \left(\frac{1}{1 - (p/M)^2} \right) \approx \frac{-i}{M^2} \left(1 + \left(\frac{p}{M} \right)^2 + \mathcal{O} \left(\left(\frac{p}{M} \right)^4 \right) \right). \quad (1.14)$$

An alternate method is to replace the heavy fields in the Lagrangian with their classical equations of motion. The resulting effective Lagrangian will contain all the operators generated by the UV theory at tree level. Constructing an EFT in this way is called the *top-down* method.

The second method of constructing an EFT is to be agnostic to the UV physics and write down all possible operators that can be constructed from the IR degrees of freedom. These operators must obey the symmetries of the IR theory, as well as

any other constraints one wishes to impose⁵. This is the *bottom-up* approach, offering a more model-independent approach than the top-down method. The Wilson coefficients, in this case, will be arbitrary functions of the energy scale determined by solving the RGEs.

In general, the parameter space of the EFT will be lower dimensional than those of the corresponding UV models. This allows for an easier comparison with experimental results, as fewer parameters need to be fit to the data. Once the Wilson coefficients have been constrained at the low energy scale of the experiments, they can be matched to the coefficients generated by some UV theory at another scale, thereby constraining the UV parameters.

1.2.3 Dimension 6 EFT Operators for Dirac Fermion Dark Matter

This work will focus on dimension 6 EFT operators that describe the interactions of Dirac fermion dark matter with standard model fermions. These operators will have a structure

$$\mathcal{L}_{\text{EFT}}^{(6)} \sim \frac{1}{\Lambda^2} (\bar{\chi} \Gamma_{\text{DM}} \chi) (\bar{f} \Gamma_{\text{SM}} f), \quad (1.15)$$

where the Γ_i determines the Lorentz structure of the interaction by taking appropriate combinations from the set

$$\Gamma_i \in \{1, i\gamma_5, \gamma^\mu, i\gamma^\mu\gamma^5, \sigma^{\mu\nu}, i\sigma^{\mu\nu}\gamma^5\}. \quad (1.16)$$

For example, the case of $\Gamma_\chi = \Gamma_{\text{SM}} = 1$ yields scalar currents for both the DM and SM fermions and would correspond to integrating out a heavy scalar mediator in the UV theory. Under the assumption of minimal flavour violation (MFV)⁶ are ten such operators at dimension six that form a linearly independent basis. These are given in Table 1.1, along with spin-averaged squared matrix element for dark matter scattering with a fermion. The operators are classified based on the Lorentz nature of the SM fermion bilinear; D1-2: Scalar (S), D3-4: Pseudoscalar (P), D5-6: Vector (V), D7-8: Axial-vector (A), and D9-10: tensor (T). The coupling constant, g_f , for operators that involve the S and P fermion bilinears (operators D1-4) are normalised by the corresponding Yukawa couplings. This is because, in a UV complete theory, these bilinears would couple to the new scalar/pseudoscalar field that mediates the interactions with the dark matter. In many models, this new

⁵For example, one might require that no flavour changing processes are present at dimension 5, despite such operator being allowed by the symmetries.

⁶MFV is the assumption that the only source of flavour violation in the quark sector comes from the SM Yukawa matrices and not from any new physics introduced at a higher scale.

Name	Operator	g_f	$ \overline{M}(s, t, m_i) ^2$
D1	$\bar{\chi}\chi \bar{f}f$	$\frac{y_f}{\Lambda_f^2}$	$g_f^2 \frac{(4m_\chi^2 - t)(4m_\chi^2 - \mu^2 t)}{\mu^2}$
D2	$\bar{\chi}\gamma^5\chi \bar{f}f$	$i \frac{y_f}{\Lambda_f^2}$	$g_f^2 \frac{t(\mu^2 t - 4m_\chi^2)}{\mu^2}$
D3	$\bar{\chi}\chi \bar{f}\gamma^5 f$	$i \frac{y_f}{\Lambda_f^2}$	$g_f^2 t (t - 4m_\chi^2)$
D4	$\bar{\chi}\gamma^5\chi \bar{f}\gamma^5 f$	$\frac{y_f}{\Lambda_f^2}$	$g_f^2 t^2$
D5	$\bar{\chi}\gamma_\mu\chi \bar{f}\gamma^\mu f$	$\frac{1}{\Lambda_f^2}$	$2g_f^2 \frac{2(\mu^2 + 1)^2 m_\chi^4 - 4(\mu^2 + 1)\mu^2 s m_\chi^2 + \mu^4(2s^2 + 2st + t^2)}{\mu^4}$
D6	$\bar{\chi}\gamma_\mu\gamma^5\chi \bar{f}\gamma^\mu f$	$\frac{1}{\Lambda_f^2}$	$2g_f^2 \frac{2(\mu^2 - 1)^2 m_\chi^4 - 4\mu^2 m_\chi^2 (\mu^2 s + s + \mu^2 t) + \mu^4(2s^2 + 2st + t^2)}{\mu^4}$
D7	$\bar{\chi}\gamma_\mu\chi \bar{f}\gamma^\mu\gamma^5 f$	$\frac{1}{\Lambda_f^2}$	$2g_f^2 \frac{2(\mu^2 - 1)^2 m_\chi^4 - 4\mu^2 m_\chi^2 (\mu^2 s + s + t) + \mu^4(2s^2 + 2st + t^2)}{\mu^4}$
D8	$\bar{\chi}\gamma_\mu\gamma^5\chi \bar{f}\gamma^\mu\gamma^5 f$	$\frac{1}{\Lambda_f^2}$	$2g_f^2 \frac{2(\mu^4 + 10\mu^2 + 1)m_\chi^4 - 4(\mu^2 + 1)\mu^2 m_\chi^2 (s + t) + \mu^4(2s^2 + 2st + t^2)}{\mu^4}$
D9	$\bar{\chi}\sigma_{\mu\nu}\chi \bar{f}\sigma^{\mu\nu} f$	$\frac{1}{\Lambda_f^2}$	$8g_f^2 \frac{4(\mu^4 + 4\mu^2 + 1)m_\chi^4 - 2(\mu^2 + 1)\mu^2 m_\chi^2 (4s + t) + \mu^4(2s + t)^2}{\mu^4}$
D10	$\bar{\chi}\sigma_{\mu\nu}\gamma^5\chi \bar{f}\sigma^{\mu\nu} f$	$\frac{i}{\Lambda_f^2}$	$8g_f^2 \frac{4(\mu^2 - 1)^2 m_\chi^4 - 2(\mu^2 + 1)\mu^2 m_\chi^2 (4s + t) + \mu^4(2s + t)^2}{\mu^4}$

Table 1.1: Dimension 6 EFT operators [39] for the coupling of Dirac DM to fermions (column 2), together with the squared matrix elements DM-fermion scattering (column 5), where s and t are Mandelstam variables, $\mu = m_\chi/m_T$, and m_T is the target mass.

field will mix with the SM Higgs field, leading to couplings that depend on the fermion masses. The remaining bilinears have coupling constants that depend only on the cutoff scale, Λ_f .

1.2.4 From DM-Quark to DM-Nucleon Interactions

The operators in Table 1.1 describe dark matter interactions at the quark level, as these are the degrees of freedom most models are formulated with. However, we will primarily be interested in dark matter scattering with baryons, which requires taking the matrix element of the quark operators between baryon states, i.e. $\langle \mathcal{B} | \bar{q} \Gamma_q q | \mathcal{B} \rangle$. These matrix elements can be calculated through the application of Chiral Perturbation Theory (ChPT), giving a baryon level EFT. The operators of this EFT will have the same form as those in Table 1.1, with the obvious replacement of $f \rightarrow \mathcal{B}$, as well as additional form factors that take into account the structure of the baryons.

The required form factors for each operator have been calculated at zero mo-

momentum transfer in Ref. [40] and are given by

$$c_{\mathcal{B}}^S(0) = \frac{2m_{\mathcal{B}}^2}{v^2} \left[\sum_{q=u,d,s} f_{T_q}^{(\mathcal{B})} + \frac{2}{9} f_{T_G}^{(\mathcal{B})} \right]^2, \quad (1.17)$$

$$c_{\mathcal{B}}^P(0) = \frac{2m_{\mathcal{B}}^2}{v^2} \left[\sum_{q=u,d,s} \left(1 - 3 \frac{\bar{m}}{m_q} \right) \Delta_q^{(\mathcal{B})} \right]^2, \quad (1.18)$$

$$c_{\mathcal{B}}^V(0) = 9, \quad (1.19)$$

$$c_{\mathcal{B}}^A(0) = \left[\sum_{q=u,d,s} \Delta_q^{(\mathcal{B})} \right]^2, \quad (1.20)$$

$$c_{\mathcal{B}}^T(0) = \left[\sum_{q=u,d,s} \delta_q^{(\mathcal{B})} \right]^2, \quad (1.21)$$

where $v = 246$ GeV is the vacuum expectation value of the SM Higgs field, \mathcal{B} is the baryonic species, $\bar{m} \equiv (1/m_u + 1/m_d + 1/m_s)^{-1}$ and $f_{T_q}^{(\mathcal{B})}$, $f_{T_G}^{(\mathcal{B})} = 1 - \sum_{q=u,d,s} f_{T_q}^{(\mathcal{B})}$, $\Delta_q^{(\mathcal{B})}$ and $\delta_q^{(\mathcal{B})}$ are the hadronic matrix elements, determined either experimentally or by lattice QCD simulations. The specific values of these matrix elements for various baryons are provided in Appendix A.

The assumption of zero-momentum transfer is valid when considering interactions with momentum transfers $\lesssim 1$ GeV, such as in direct detection experiments. Once the momentum transfer exceeds this, the internal structure of the baryon begins to be resolved, and an additional momentum-dependent form factor is required to account for this [41],

$$F_{\mathcal{B}}(t) = \frac{1}{(1 - t/Q_0)^2}, \quad (1.22)$$

where t is the Mandelstam variable, and Q_0 is an energy scale that depends on the hadronic form factor. For simplicity, we will conservatively take $Q_0 = 1$ GeV for all operators. Putting everything together, the squared coupling constants for dark matter-baryon interactions are obtained by making the replacement

$$g_f^2 \rightarrow \frac{c_{\mathcal{B}}^I(t)}{\Lambda_q^4} \equiv \frac{1}{\Lambda_q^4} c_{\mathcal{B}}^I(0) F_{\mathcal{B}}^2(t), \quad I \in S, P, V, A, T, \quad (1.23)$$

in the matrix elements in the final column of Table 1.1.

1.3 Current Status of Dark Matter Constraints

In broad terms, there are three main ways that we can search for evidence of dark matter, often termed “make it, shake it, or break it”. “Make it” refers to the production of dark matter at colliders; “break it” to dark matter annihilation signals; and “shake it” to dark matter scattering. This section discusses the current status of these detection methods.

1.3.1 Collider Bounds

If dark matter is produced in a collider, it will simply leave the detector without depositing any energy. To determine if such an invisible particle was produced, conservation of energy-momentum is used to determine if any events are missing energy. In practice, what is searched for is missing momentum that is transverse to the beamline.

Currently, dark matter has not been observed to be produced in particle colliders. This non-observation has instead been used to constrain the dark matter mass and production cross-sections or couplings of various models. These limits are typically interpreted in a model-dependent manner, as different dark matter - Standard model couplings can significantly alter the production rates.

The ATLAS and CMS experiments at the LHC have performed analyses on various dark matter production mechanisms, including the exchange of a Z/Z' or Higgs, EFTs and heavy mediators, and mono-jet searches [42]⁷. Collider searches also offer complimentary probes of the dark matter-nucleon scattering cross-section [43] as they probe the same underlying coupling of dark matter to quarks.

It is important to note that an observation of an invisible massive particle at a collider is not enough to infer that it is dark matter. Such an observation will only tell us that such a particle exists. On its own, it does not determine the abundance of the species or if it is stable in cosmological times. As such, it could be just a sub-component of a larger dark sector. To measure enough of the model parameters and determine these important properties, complimentary observations from direct or indirect detectors are often required.

⁷These searches refer to a single jet being produced alongside a pair of dark matter particles. This jet could be of Standard Model or dark sector origin, with the latter commonly referred to as “mono-X” searches.

1.3.2 Direct Detection Searches

In colliders, dark matter with mass below the collision energy can be produced as long as it couples to the electroweak or colour sectors of the SM. Direct detection experiments, on the other hand, must employ different experimental techniques to probe different mass ranges. For ALP dark matter that is wavelike, haloscope experiments such as ADMX [44] and MADMAX [45] attempt to convert ALPs to photons via the Primakoff effect. Searches for WIMP-like dark matter look for the dark matter scattering with some detector material, causing it to recoil and deposit energy into the detector. Given that our focus is on WIMP-like dark matter, this section will review the status of these experiments.

The differential rate at which the incoming flux of dark matter will scatter within a detector with N_T targets, as a function of the recoil energy, E_R , is given by

$$\frac{dR(E_R, t)}{dE_R} = N_T \frac{\rho_{\text{DM}}}{m_{\text{DM}}} \int_{v > v_{\min}}^{v_{\text{esc}}} v f(\vec{v} + \vec{v}_E) \frac{d\sigma}{dE_R} d^3v, \quad (1.24)$$

and depends on the quantities:

- v_{\min} is the minimum dark matter velocity required by kinematics for a scattering event to occur;
- $v_{\text{esc}} = 528 \text{ km s}^{-1}$ is the Milky Way escape velocity;
- \vec{v}_E is the velocity of the Earth through the dark matter halo⁸;
- $f(\vec{v} - \vec{v}_E)$ is the dark matter velocity distribution in the Earth's frame;
- $d\sigma/dE_R$ is the differential scattering cross-section.

Given the low interaction rate of dark matter, the expected event rate in detectors is very low, around one event per day, per kilogram of target material, per kiloelectronvolt deposited. To contend with such a low event rate, as much of the background noise needs to be reduced as possible. This is achieved by placing the detectors deep underground in laboratories that are naturally shielded from the majority of the cosmic rays incident on the surface.

The particle physics input into the scattering rate is encapsulated within the differential cross-section, $d\sigma/dE_R$. It is common to separate the cross-section into contributions from spin-dependent (SD) and spin-independent (SI) interactions such

⁸This accounts for the orbit of the Earth around the Sun, which induces an annual modulation in the flux of DM.

that

$$\frac{d\sigma}{dE_R} = \frac{(m_{\text{DM}} + m_T)^2}{m_T m_{\text{DM}}^2 v^2} (\sigma^{\text{SI}} |F_{\text{SI}}(E_R)|^2 + \sigma^{\text{SD}} |F_{\text{SD}}(E_R)|^2), \quad (1.25)$$

$$\sigma^{\text{SI}} \approx \sigma_0^{\text{SI}} A_T^2 \left(\frac{m_T}{m_p} \right)^2 \left(\frac{m_{\text{DM}} + m_p}{m_{\text{DM}} + m_T} \right)^2, \quad (1.26)$$

$$\sigma^{\text{SD}} \approx \sigma_0^{\text{SD}} \left(\frac{4(J_T + 1)}{3J_T} |\langle S_p \rangle + \langle S_n \rangle|^2 \right) \left(\frac{m_T}{m_p} \right)^2 \left(\frac{m_{\text{DM}} + m_p}{m_{\text{DM}} + m_T} \right)^2, \quad (1.27)$$

where m_T , A_T , J_T are the target mass, atomic mass number, and atomic spin, m_p is the mass of the proton, $\langle S_{p,n} \rangle$ are the expectation values of the protons and neutrons in the nucleus. The $\sigma_{p,0}^{\text{SI/SD}}$ are reference DM-proton scattering cross-sections evaluated in the zero-momentum transfer limit, with the form factors $F_{\text{SI/SD}}(E_R)$ depending on the recoil energy accounting for the finite size of the nucleus being probed at high momentum transfer. We have assumed that dark matter interacts the same with neutrons and protons for simplicity.

The SI interactions do not couple to the spin of the target and as such the nuclear cross-section is a coherent sum over all the nucleons. This results in an A_T^2 enhancement compared to the dark matter-nucleon cross-section. Experiments searching for SI interactions take advantage of this by using heavy noble gases as the target material, such as Xenon and Argon. On the other hand, the SD interactions do couple to the spin of the target. As the total cross-section is the sum of all the nucleon contributions, the result is expected to average out to zero unless there is an unpaired nucleon present. Chemicals that contain ^{19}F are the favourable targets as it contains an unpaired proton.

The current leading constraints on the dark matter-nucleon scattering cross-section are shown in Fig. 1.5, with SI in the top panel and SD in the bottom. The SI limits are set by liquid noble gas experiments (LZ [46], XENON-1T [47], PandaX-II [48], and DarkSide-50 [49]), solid-state cryogenic detectors (CRESST-III [50], CDMSlite [51], with projected DARWIN sensitivities [52]), and room temperature crystals (DAMA/LIBRA [53], and COSINE-100 [54]).

The constraints on the SD dark matter-proton scattering cross-section are shown in the bottom panel of Fig 1.5. Superheated liquid experiments such as the PICO-60 [55] as well as PICASSO [56] provide the leading constraints. These interactions are also constrained by many of the same experiments that focus on SI interactions, as they will inevitably contain isotopes with non-zero spin, such as ^{129}Xe and ^{131}Xe in XENONnT.

The orange dashed line represents the neutrino floor⁹, providing a lower limit on the cross-section that can be probed by conventional direct detection experiments. Below this line, detectors will become sensitive to the irreducible background from

⁹Calling this the “neutrino fog” rather than floor has been gaining traction in recent years [57]

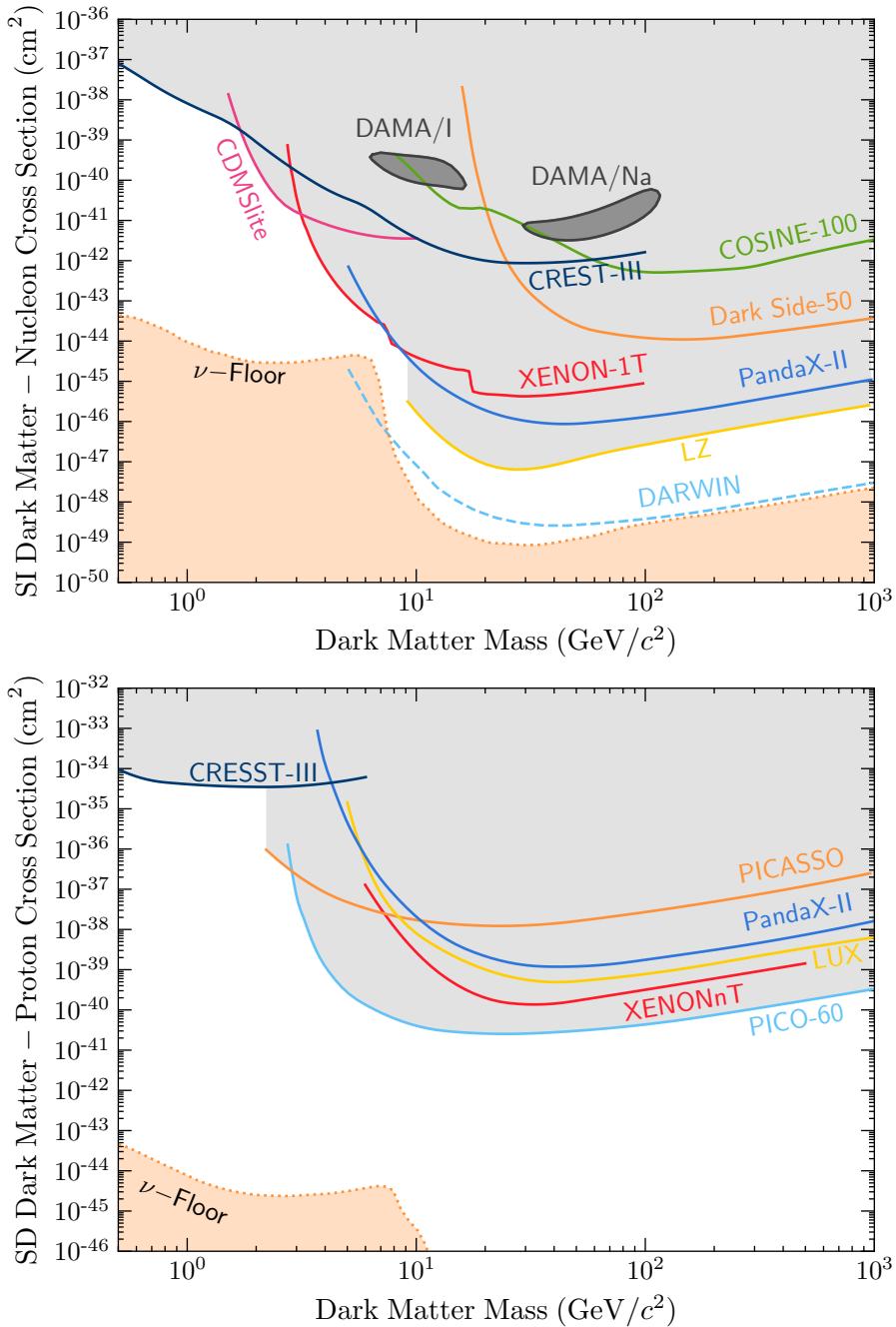


Figure 1.5: Current status of direct detection searches for dark matter. **Top:** Spin-independent dark matter-nucleon scattering. **Bottom:** Spin-dependent dark matter-proton scattering. Shaded regions above the coloured lines are excluded. Data was taken from the sources cited in the text.

Coherent Elastic Neutrino-Nucleus Scattering (CE ν NS). For dark matter masses $\lesssim 10\text{ GeV}$ the solar neutrino flux is the main background source, while the atmospheric neutrino flux becomes the dominant background for masses $\gtrsim 20\text{ GeV}$. A significant amount of effort is being put toward overcoming this limitation, with the main strategy being to take advantage of the directionality of dark matter flux [58]. Such experiments attempt to resolve the direction of the nuclear recoil event, giving information about the direction the incident particle came from. This could allow discrimination between dark matter events, that are expected to be from the direction of the Cygnus constellation, and the background solar and atmospheric neutrinos coming from the Sun and sky respectively.

Many experiments begin to lose sensitivity to low-mass dark matter ($m_{\text{DM}} \lesssim 10\text{ GeV}$) as the recoil energy of the targets falls below the threshold energy resolution of the detector. Current detectors can reach thresholds as low as $\sim \mathcal{O}(100\text{ eV})$, which is on the same order of magnitude as the recoil energy due to a 1 GeV dark matter collision.

On the other hand, above $\sim 10\text{ GeV}$ the sensitivities of the experiments all decrease at a rate inversely proportional to the dark matter mass. This is due to the interaction rate in Eq. 1.24 being proportional to the number of dark matter particles that pass through the detector, $N_{\text{DM}} = \rho_{\text{DM}}/m_{\text{DM}}$. As the local dark matter density is observed to be $\rho_{\text{DM}} = 0.4\text{ GeV cm}^{-3}$, N_{DM} decreases as the dark matter mass increases, and hence so do the detector sensitivities.

Direct detection limits also assume that the scattering cross-section is independent of the dark matter velocity and momentum transfer in the interaction. Given that the local dark matter dispersion velocity is predicted to be $v_d = 270\text{ km s}^{-1} \approx 10^{-3}c$, a back-of-the-envelope estimation for the momentum transfer gives $q_{\text{tr}} \lesssim 100\text{ MeV}$. Therefore, cross-sections proportional to v_{DM} or q_{tr} will result in significantly lower event rates and hence much weaker limits than the unsuppressed interactions.

1.3.3 Indirect Detection

This leads us to indirect detection methods, which can provide complementary probes to direct detection while also exploring interactions that are difficult, if not impossible, for terrestrial-based detectors to observe. Indirect detection experiments aim to infer the presence of dark matter through its annihilation or decay into Standard Model states. These searches look for dark matter annihilation products from astrophysical sources, including:

- Gamma-rays at terrestrial-based telescopes such as HESS [59–61], VERITAS [62–64], MAGIC [65, 66] and HAWC [67–70] as well as the Fermi-LAT [71–75] satellite;

- Neutrino signals at IceCube [76, 77], ANTARES [78–80], Super-K [81–83], and will be searched for at the upcoming Hyper-K [84–86], JUNO [87] experiments.
- Cosmic-Ray antimatter excess observed by the AMS-02 experiment [88, 89]

Signals from dark matter annihilation are best searched for by looking at regions where the dark matter density is expected to be high, boosting the annihilation rate. Natural places to look include the Galactic Centre [90, 91], dwarf-spheroidal galaxies [92], and celestial bodies where dark matter can accumulate over time. The latter scenario is central to this work and was pioneered by considering the effects of dark matter being captured within the Sun.

1.4 Dark Matter Signals from the Sun

Stars have a rich history of being used as astrophysical laboratories to help in the search for dark matter. Depending on the type of dark matter being searched for, there are various signals one can look for. Light bosonic dark matter, such as ALPs and dark photons, can be produced within the plasma of stars, altering the energy transport properties within them. This can ultimately lead to deviations in the evolution of the star, which can be used to place some of the strongest constraints on these models [93–95]. WIMP-like dark matter in the halo that couples to visible matter can scatter within the stars as they pass through. If the dark matter loses enough energy in these interactions, it can become gravitationally bound to the object and a population of dark matter will be accumulated within the star over time [23, 96–99].

This idea of WIMPs accumulating within the cores of stars has been applied extensively to the star closest to us, the Sun. The formalism for stellar capture of dark matter was set up by Gould [97, 98, 100] in the late 80’s, and has remained quite successful to this day, with many authors continuing to build upon these foundations over time [99, 101, 102].

Once the dark matter is captured, it will continue to scatter with the stellar constituents until it thermalises within the core of the Sun, collecting with an isothermal sphere. The radius of this sphere can be found by applying the virial theorem, with the gravitational potential given by

$$\Phi(r) = - \int_r^\infty \frac{GM_\odot(r')}{r'^2} dt', \quad (1.28)$$

$$\approx \frac{2}{3}\pi G\rho_{\odot,c}r^2, \quad (1.29)$$

assuming the density of the Sun within this region is constant, $\rho_{\odot,c}$. The resulting radius is

$$r_{\text{iso}}^2 = \frac{3T_{\odot}}{2\pi G m_{\text{DM}} \rho_{\odot}}. \quad (1.30)$$

The dark matter number density will follow a Gaussian profile,

$$n_{\text{iso}}(r) = n_0 \exp\left(-\frac{m_{\text{DM}}\Phi(r)}{T_{\odot}}\right), \quad (1.31)$$

$$= n_0 \exp(-r^2/r_{\text{iso}}^2), \quad (1.32)$$

where n_0 is a normalisation constant fixed by requiring that the total number of dark matter particles is

$$N_{\text{DM}} = \int d^3r n_{\text{iso}}(r). \quad (1.33)$$

In addition, dark matter velocity will follow a Maxwell-Boltzmann distribution,

$$f_{\text{MB}}(v) = 4\pi \left(\frac{m_{\text{DM}}}{4\pi T_{\odot}}\right)^{3/2} v^2 \exp\left[-\frac{m_{\text{DM}}v^2}{4T_{\odot}}\right]. \quad (1.34)$$

The time evolution of the total number of dark matter particles within the Sun is governed by three processes. Capture acts to increase the number over time, while annihilation and evaporation will reduce this number over time. This is described by the differential equation

$$\frac{dN_{\text{DM}}}{dt} = C - EN_{\text{DM}} - AN_{\text{DM}}^2, \quad (1.35)$$

where C and E are the capture and evaporation rates respectively, with A being related to the annihilation rate, Γ_{ann} through

$$\Gamma_{\text{ann}} = \frac{1}{2} \int dr^3 n_{\text{iso}}^2(r) \langle \sigma_{\text{ann}} v \rangle \quad (1.36)$$

$$\equiv \frac{1}{2} A N_{\text{DM}}^2, \quad (1.37)$$

where the factor of 1/2 accounts for each annihilation removing two dark matter particles from the Sun.

In this context, evaporation refers to the process in which dark matter can be ejected back out of the Sun by up-scattering¹⁰ off an energetic constituent. This

¹⁰Up-scattering refers to the interactions in which the dark matter gains rather than loses energy.

becomes increasingly important for lighter dark matter masses, as less energy will be required to boost the dark matter above the local escape velocity. Below a certain mass, the capture and evaporation come into equilibrium, and a net-zero amount of dark matter is contained within the Sun. This critical mass places a lower bound on the dark matter mass that can be probed through stellar capture and is named the evaporation mass, m_{evap} .

There are three regimes we are interested in solving this equation for. The simplest case is when evaporation and annihilation are both negligible, then the solution is simply,

$$N_{\text{DM}}(t) = Ct, \quad (1.38)$$

indicating that the dark matter will simply continue to grow over time.

Next, assume that annihilations are negligible ($A = 0$), while capture and evaporation are present. The result is

$$N_{\text{DM}}(t) = Ct \left(\frac{1 - e^{-Et}}{Et} \right), \quad (1.39)$$

where the first factor is the number of captured dark matter if evaporation is negligible. From this, we can estimate the evaporation mass by asking when the evaporation rate is large enough to cause a significant reduction in the number of captured dark matter particles relative to the $E = 0$ case. This can be expressed formally as [101]

$$\frac{1}{N_{\text{DM}}(m_{\text{evap}})} \left| N_{\text{DM}}(m_{\text{evap}}) - \frac{C(m_{\text{evap}})}{E(m_{\text{evap}})} \right| = \alpha, \quad (1.40)$$

where α is the fraction of evaporated dark matter, taken to be $\sim 10\%$.

Finally, consider the case in which evaporation can be neglected, $m_{\text{DM}} \gtrsim m_{\text{evap}}$. The solution in this regime is

$$N_{\text{DM}}(t) = \sqrt{\frac{C}{A}} \tanh(\sqrt{CA}t) \xrightarrow{t \rightarrow \infty} \sqrt{\frac{C}{A}}, \quad (1.41)$$

that reaches an equilibrium state between capture and annihilation for times longer than the characteristic scale, $t_{\text{eq}} = 1/\sqrt{CA}$. This state is known as capture-annihilation equilibrium.

The signals searched for depend on whether the dark matter can annihilate or not. If the dark matter is asymmetric, it cannot annihilate, and we can set $A = 0$ in Eq. 1.35. This leads to the population continuing to grow over time, with $N_{\text{DM}}(t) = Ct$ if evaporation is negligible. A large enough population of captured dark matter can alter the energy transport within the Sun, leading to the modifications of the solar neutrino flux, or even the solar structure itself [87, 103–105].

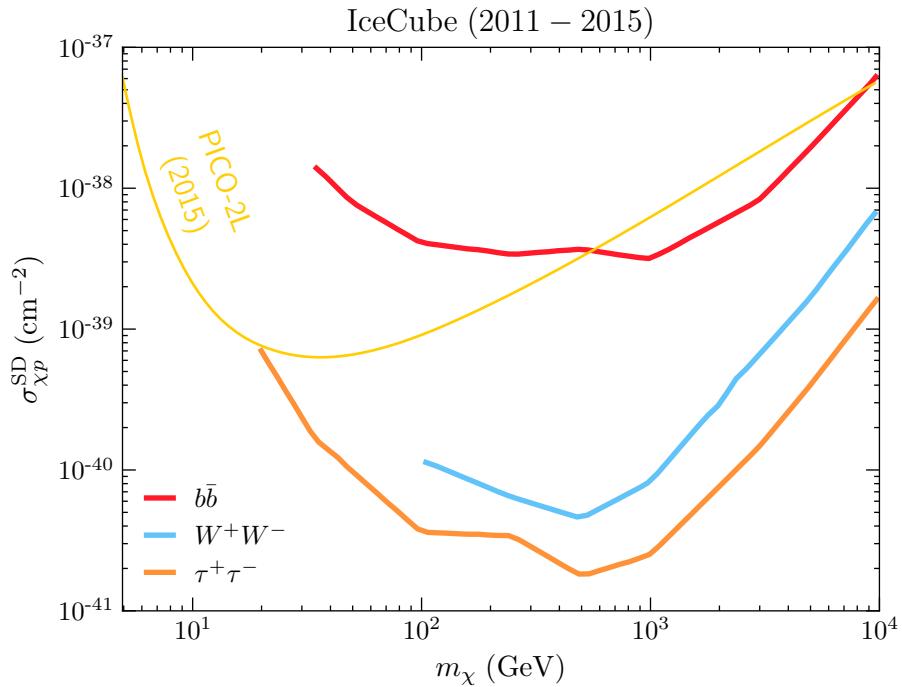


Figure 1.6: Limits on the SD dark matter-proton cross-section from the IceCube collaboration assuming 100% branching fraction to $b\bar{b}$ (red), W^+W^- (blue) or $\tau^+\tau^-$ (orange) final states. Also shown is the result from the PICO-2L DD experiment. This plot was recreated with data taken from Ref. [76].

Instead, if the dark matter can annihilate an equilibrium will eventually be reached between the capture and annihilation rates, and the total number of dark matter particles will be constant. If the annihilation products can escape the Sun, they can be searched for by various experiments depending on the nature of the final states. These could be neutrinos produced from the decays of other charged annihilation products [79–81, 106, 107], or to some other long-lived state that can escape the Sun and decay into visible states [108–112].

In comparison to DD searches, interpretation of indirect detection data will require additional model-dependent assumptions, namely the relevant annihilation channels of the dark matter. The most general limits can be placed by assuming that the dark matter only has a single annihilation channel, i.e. annihilation to a $\tau^+\tau^-$ final state 100% of the time. Under these assumptions, limits on the SD dark matter-proton cross-section have been placed that exceed current DD constraints, due to the rather large abundance of Hydrogen within the Sun. Constraints from the IceCube collaboration are shown in Fig. 1.6.

As stated above, the range of dark matter masses that can be probed by Solar capture is limited by the evaporation mass of ~ 3 GeV. Additionally, as with direct

detection, interactions that are suppressed by the momentum transfer/velocity of the dark matter will result in a significantly smaller capture rate and hence a smaller flux of annihilation products, resulting in weaker limits. These constraints also rely on the annihilation rate being sufficiently fast such that capture-annihilation equilibrium is reached within the lifetime of the Sun. If the annihilation cross-section is p -wave suppressed by the velocity of the annihilating dark matter, then this equilibrium may not be achieved. Should this be the case, then no limits can be placed as no flux of annihilation products to detect.

Overcoming the first of these issues requires either a colder star or one that is much heavier to decrease the evaporation mass. The second requires dark matter to scatter with the constituent material at relativistic energies to overcome the suppression in the cross-sections. Finally, the p -wave suppression can be alleviated if the dark matter annihilates within a very small volume in the core of the star, boosting the annihilation rate. Fortunately, there exist objects that can achieve all of these requirements, allowing for a wider variety of dark matter models to be explored than direct detection or traditional indirect detection experiments. These objects are known as compact objects, namely neutron stars and white dwarfs.

1.5 Compact Objects as Dark Matter Probes

The main goal behind this work is to explore how compact objects can be used to probe a wide variety of dark matter interactions that terrestrial direct detection experiments are insensitive to. By compact objects, we are referring to Neutron Stars (NSs) and White Dwarfs (WDs), and not Black Holes that also fall into this category.

Compact objects offer a unique laboratory for studying dark matter and its interactions with the Standard Model in environments unachievable anywhere else in the Universe. They generate strong gravitational fields and are composed of incredibly dense matter, with NSs reaching super-nuclear densities in their central cores. The capture rate within these objects is therefore enhanced due to these properties, with benefits over solar capture including:

- **Gravitational focusing of the DM flux:** The strong gravitational field will increase the impact parameter of the infalling dark matter. This increases the effective size of the capturing body, increasing the flux of dark matter passing through it.
- **Relativistic Interaction Energies:** In general, the infalling dark matter will be accelerated to (semi-)relativistic velocities ($\sim 0.2 - 0.7c$). Moreover,

the stellar constituents will also have relativistic energies. As such, interactions that are momentum/velocity dependent will suffer far less suppression than in DD experiments.

- **Large Number of Targets:** The extremely high densities of these objects correspond to a considerable number of targets for scattering to occur. This allows these objects to probe very small scattering cross-sections, with NSs in particular expected to reach as low as $\sim 10^{-45} \text{ cm}^2$.
- **Low Evaporation Masses:** Relative to the Sun, the evaporation mass in compact objects can be quite low, on the order of keV in some cases. This is due in part to the increased gravitational strength, but mainly to the significantly lower temperatures in old compact objects.

In the past, capture in NSs has been applied primarily in the context of seeding gravitational collapse into black holes [113–119], and the modifications of NS merger rates as well as the gravitational wave signatures of these mergers [120–123]. Capture in WDs has also been considered, with a variety of different applications of the capture process [124–129].

In recent years, dark matter induced heating of NSs has reemerged as a potential detection frontier [130–137]. It was shown that dark matter could reheat old, isolated NSs in our local neighbourhood¹¹ back up to temperatures that would cause them to radiate as blackbody peaked in the near-infrared. The aim is to locate the NSs with radio telescopes such as the Square-Kilometer-Array (SKA), and determine their age through their spin-down rate. Once located, the star’s temperature can be determined through observations from infrared telescopes such as the James Webb Space Telescope (JWST). Knowing the age of the star allows us to compare its observed temperature to that predicted by models of neutron star cooling. A discrepancy between these two temperatures can indicate whether an additional heating source is present within the star.

This heating occurs in two stages. The dark matter will first kinetically heat the star through the scattering events that result in both its capture and thermalisation. We define *kinetic heating* to have been achieved once the dark matter has deposited 99% of its initial kinetic energy into the star. If the dark matter can annihilate, and assuming these annihilation products remain trapped within the star, its mass energy will be transferred to the star, further increasing the temperature of the star. In order for this *annihilation heating* to be efficient, capture-annihilation equilibrium must be achieved on a timescale shorter than the age of the star. These processes are illustrated in Fig. 1.7, with the temperatures shown assume a NS in our local neighbourhood.

¹¹Local neighbourhood refers to the region within $\sim 1 \text{ kpc}$ of the Sun.

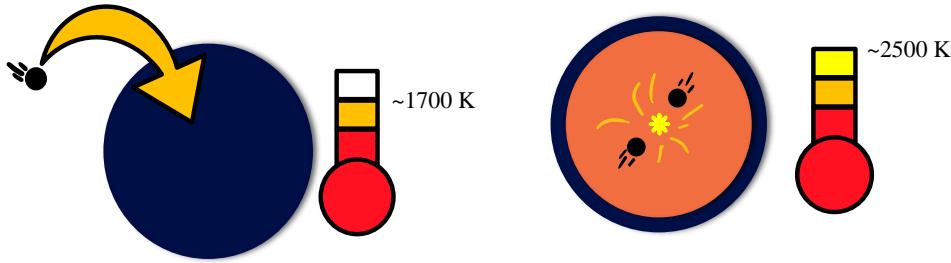


Figure 1.7: Illustration of DM-induced heating of compact objects. **Left:** kinetic heating due to DM scattering, raising the temperature to ~ 1700 K. **Right:** Annihilation heating contributes an additional ~ 800 K. This image is inspired by Ref. [130].

It is important to keep track of all the timescales involved in the heating process so that we can accurately determine the full extent of dark matter-induced heating. These timescales are the age of the star, t_* , the kinetic heating time, t_{kin} , and the capture-annihilation heating timescale, t_{eq} . In order for maximal heating to be achieved, we require $t_{\text{kin}} + t_{\text{eq}} < t_*$.

To accurately project how sensitive neutron star heating to dark matter interactions, one first requires an accurate calculation of the capture rate. However, existing calculations have relied on the formalism set up by Gould for capture in the Sun without fully accounting for the extreme physics present in these objects. Developing a consistent formalism for dark matter capture in compact objects, based on the Gould formalism, and applying this to dark matter induced heating is at the heart of this thesis.

1.6 Thesis Outline

Following this introduction, Chapter ?? covers the prerequisite knowledge of compact objects required for the remainder of this work. This includes a detailed overview of the general structure equations of relativistic stars, followed by details of the internal structure of both white dwarfs and neutron stars.

Chapters ?? and ?? of this thesis are devoted to reformulating Gould's capture formalism to account for the physics specific to compact objects in a self-consistent manner. These include a relativistic treatment of the kinematics, using General Relativity to calculate the correct dark matter flux passing through the star, and accounting for Pauli blocking of the final state target using Fermi-Dirac statistics for the stellar constituents. In addition, we incorporate the internal structure of these objects by calculating the radial profiles for the relevant microscopic quantities (e.g.,

chemical potentials and number densities) via the adoption of a realistic equation of state.

Further considerations are required when considering dark matter interactions with the baryonic matter inside NSs. Due to the high density of the NS interior, the baryons undergo strong self-interactions and should not be treated as a free Fermi gas. Instead, adopting an equation of state that accounts for these interactions is required. These interactions modify the mass of the baryons, leading them to obtain an effective mass smaller than their value in vacuum. Furthermore, as we will see, the dark matter may interact with the baryons with momentum transfers on the order of 10 GeV. This is high enough that the dark matter will begin to resolve the internal structure of the baryon. To account for this, the momentum dependence of the baryon form factors that are typically neglected in direct detection and solar capture must be reintroduced.

This formalism is made in preparation for a thorough analysis of the timescales involved in the dark matter heating of compact objects, covered in Chapter ???. The energy deposited in both the kinetic and annihilation heating stages does not occur instantaneously, and the timescales involved in them need to be compared to the age of the star in question. We will define kinetic heating timescale as the time required for dark matter to deposit 99% of its initial kinetic energy into the star. For annihilation heating to occur, the dark matter must reach a state of capture-annihilation equilibrium within the stellar core. In standard calculations of this timescale, the dark matter must first become thermalised with the star. Only then can annihilations occur efficiently enough to heat the star.

We will work with the EFT operators in Table 1.1 that describe Dirac fermion dark matter interacting with Standard Model fermions. Each operator will be studied in isolation, i.e., by considering a Lagrangian that contains only one of the operators rather than a linear superposition of multiple. This way, we can analyse specific types of interactions independently, allowing us to take as model-independent an approach to the phenomenology as possible.

We present our concluding remarks on this thesis in Chapter ???

2

A Primer on Compact Objects

Within the cores of stars, there exists a delicate balance between the gravitational forces pulling the matter inward, and the outward pressure generated by the thermonuclear fusion of light elements. This process begins as is fused to form helium. Eventually, the hydrogen is depleted, allowing gravity to temporarily overcome the outward pressure leading to the core to begin contracting. As this occurs, the gravitational potential energy is converted to thermal energy and the core eventually becomes hot enough to facilitate helium burning.

This cycle can continue as heavier and heavier elements are formed within the ever-increasingly hot stellar core. Lighter stars cannot reach the temperature required to fuse light elements such as helium and carbon, ending the cycle there. If the star is heavy enough, iron will eventually be formed from the burning of silicon. As the fusion of iron nuclei is an endothermic process, it will not occur spontaneously, ending the cycle in heavy stars. Without a fuel source, the core will collapse under its own gravity, leading to the death of the star.

What comes after this collapse depends on the mass of the progenitor star. Very light stars, $\lesssim 0.5M_{\odot}$, have lifetimes much longer than the age of the universe, and so are uninteresting to our current discussion. Moderately heavy stars, $1M_{\odot} \lesssim M_{\star} \lesssim 8M_{\odot}$, will continue burning fuel until the outer layers of the star are dispersed as it expands, leaving a core comprised of helium, carbon and oxygen with small abundance of heavier elements. The core will begin to collapse until the Fermi degeneracy of the ultrarelativistic electrons is great enough to reestablish equilibrium, resulting in a White Dwarf (WD) [138].

Heavy stars, $\gtrsim 8M_{\odot}$, spectacularly end their lives in a type-II supernova event. This occurs when the core of the star exceeds the Chandrasekhar mass of $1.4M_{\odot}$, which cannot be supported by electron degeneracy pressure. The core itself will then collapse, leading to a shockwave that ejects the majority of the mass of the star.

All that will remain is an extremely dense core supported by neutron degeneracy pressure, a Neutron Star (NS) [139]. If the star was so massive that the gravitational forces overcome even the neutron degeneracy pressure, then the core collapses into a black hole.

These stellar corpses, white dwarfs, neutron stars, and black holes, are collectively known as compact objects. They have masses similar to or larger than the Sun, that is compressed into much smaller bodies with significantly larger surface gravities. These objects do not have a source of fuel, and spend the rest of their lives cooling through the emission of photons and neutrinos. For the remainder of this thesis, we will only be interested in white dwarfs and neutron stars and will collectively refer to these as compact objects, excluding black holes from this term.

This chapter is dedicated to discussing the aspects of the structure, composition, and observational status of these objects relevant to this work¹.

2.1 Structure Equations from General Relativity

The highly dense matter comprising neutron stars and white dwarfs leads to extremely strong gravitational fields being produced by the stars. As such, modeling the structure of these objects falls into the domain of General Relativity (GR). Here we review the structure of static, spherically symmetric compact objects, following Refs. [140–142].

First, the static nature of the star means that the components of the metric are functions only of the spacial coordinates and not of time. Together with the assumption that the mass distribution of the star is spherically symmetric leads to a Schwarzschild-like metric of the form

$$ds^2 = -d\tau^2 = -B(r)dt^2 + A(r)dr^2 + r^2d\Omega^2, \quad (2.1)$$

with $d\tau$ the proper time interval, and $A(r)$, $B(r)$ being functions only of the radial coordinate that are often written as

$$A(r) = e^{2\Lambda(r)}, \quad B(r) = e^{2\Phi(r)}. \quad (2.2)$$

These functions are subject to the condition that at distances far from the star, $r \rightarrow \infty$, space-time must become flat, which translates to the boundary conditions

$$\lim_{r \rightarrow \infty} A(r) = \lim_{r \rightarrow \infty} B(r) = 1. \quad (2.3)$$

¹As this work is written from the perspective of a particle physicist, I wish to apologise to my astrophysics colleagues for what is to come.

The matter that comprises the star is modeled as a perfect fluid, meaning we are neglecting any shear stresses and energy transport within the star. Such a fluid is described by its pressure $P(r)$, density $\rho(r)$, and baryonic number density, $n_b(r)$, as well as the 4-velocity of the fluid $u^\mu(r)$. Being static, the only non-zero component of this velocity is the time component, which is fixed by the normalisation condition $g_{\mu\nu}u^\mu u^\nu = -1$ to be $u^t = 1/\sqrt{B(r)}$. These quantities are used to construct the stress-energy tensor of the star, which takes the form

$$T^{\mu\nu} = (\rho + P)u^\mu u^\nu + Pg^{\mu\nu}. \quad (2.4)$$

The microphysics underlying the matter interactions are encoded in an equation of state (EoS) relating the various thermodynamic quantities. This is typically expressed by providing the pressure as a function of the density, $P(\rho)$. It is often more convenient to parameterise the EoS by the number density of baryons, and the entropy per baryon s , such that

$$P = P(n_b, s), \quad \rho = \rho(n_b, s). \quad (2.5)$$

The dependence on s turns out to be trivial in most scenarios involving compact objects, such as those considered here. The pressure in these stars arises from the degeneracy of the nucleons in NSs or the electrons in WDs, rather than from the thermal motion of the constituents as in main sequence stars. These thermal degrees of freedom will be frozen out at temperatures lower than the Fermi energy of the system, which is typically around $E_F \sim 10$ MeV in NSs or ~ 1 MeV in WDs, and correspond to temperatures of $T_\star \sim 10^{11}$ K and $\sim 10^{10}$ K respectively. As these objects are expected to cool well below these temperatures quickly after formation [143–145], the entropy can be taken to be zero throughout the star. This allows us to reduce the two-parameter EoS to a simpler one-parameter one,

$$P = P(n_b, s = 0) = P(n_b), \quad \rho = \rho(n_b, s = 0) = \rho(n_b). \quad (2.6)$$

The structure of the star is therefore dictated by the quantities $A(r)$, $B(r)$, $P(r)$, $\rho(r)$, and $n_b(r)$. This system is determined by applying the Einstein field equations, $G^{\mu\nu} = 8\pi T^{\mu\nu}$, together with the energy-momentum conservation, $T^{\mu\nu}_{;\nu} = 0$, the EoS relations Eqs. 2.6, and the appropriate boundary conditions. The structure equations that come out of this analysis were first discovered concurrently by Tolman [146] and by Oppenheimer and Volkoff [147], and so are known as the TOV equations. They take the form

$$\frac{dP}{dr} = -\rho(r)c^2 \left[1 + \frac{P(r)}{\rho(r)c^2} \right] \frac{d\Phi}{dr}, \quad (2.7)$$

$$\frac{d\Phi}{dr} = \frac{GM(r)}{c^2 r^2} \left[1 + \frac{4\pi r^3 P(r)}{M(r)c^2} \right] \left[1 - \frac{2GM(r)}{c^2 r} \right]^{-1}, \quad (2.8)$$

$$\frac{dB}{dr} = 2B(r) \frac{d\Phi}{dr}, \quad (2.9)$$

where $M(r)$ is related to the metric factor $A(r)$ through

$$A(r) = \left[1 - \frac{GM(r)}{c^2 r} \right]^{-1}, \quad (2.10)$$

and is interpreted as the mass contained within a radius r . It obeys the mass equation

$$\frac{dM}{dr} = 4\pi r^2 \rho(r), \quad M(0) = 0, \quad (2.11)$$

that arises from the $\mu = \nu = 0$ component of the Einstein field equations. These equations are the general relativistic versions of the hydrostatic equilibrium equations of regular stellar structure, with Eq. 2.7 reducing to the familiar

$$\frac{dP}{dr} = -\frac{GM(r)}{r^2} \rho(r), \quad (2.12)$$

in the Newtonian limit, $GM(r)/c^2 r \ll 1$.

The radius of the star, R_\star , is identified as the point at which the pressure and density vanish, $P(R_\star) = \rho(R_\star) = 0$. In the region outside the star, $r > R_\star$, the total mass remains constant at the mass of the star, $M(r \geq R_\star) = M_\star$, and so the only non-trivial structure functions in this region are the metric factors. Solving Eq. 2.9 with $P(r) = 0$ and constant $M(r)$ for $B(r)$ becomes elementary while the result for $A(r)$ is trivial, leaving us with

$$A(r) = \left[1 - \frac{GM_\star}{c^2 r} \right]^{-1}, \quad B(r) = 1 - \frac{GM_\star}{c^2 r}, \quad \text{for } r > R_\star, \quad (2.13)$$

and the metric reduces to the familiar Schwarzschild metric outside the star. Continuity of the metric at $r = R_\star$ enforces a second boundary condition for $B(r)$,

$$B(R_\star) = 1 - \frac{GM_\star}{c^2 R_\star}. \quad (2.14)$$

The final boundary condition required is the central pressure $P(0) = P_c$, or equivalently the central density/baryon number density. This is the only free parameter in the system and hence, for a given EoS, uniquely determines the stellar structure. All stars generated by an EoS can therefore be represented as a one-parameter sequence, typically represented as the mass-radius relation for the model.

Given all the above, we can write a simple recipe for constructing a model of a compact object:

1. Select an EoS to describe the constituent matter.

2. Specify the central pressure of the star, P_c .
3. Integrate the coupled system of differential equations 2.7, 2.8, 2.11 from the centre of the star outward until the pressure vanishes.
4. Use the boundary condition Eq. 2.14 to normalise the metric function $B(r)$.

In general, additional quantities will be present in the EoS, such as chemical potentials and the speed of sound, that may be subject to additional constraints. These quantities will need to be calculated at each step of the integration alongside the other structure functions.

2.2 White Dwarfs

The fate of main sequence stars of mass below $M_\star \lesssim 8M_\odot$ is to end their lives as a white dwarf. Consequently, these compact stellar remnants, which are supported against gravitational collapse by electron degeneracy pressure, are the most abundant stars in the Galaxy ($\gtrsim 90\%$). They are born at very high temperatures and cool down over billions of years. Observations of the coldest WDs therefore contain information on the star formation history of the Galaxy.

The vast majority of observed WDs are composed primarily of carbon and oxygen, plus small traces of elements heavier than helium. At the extremely high densities found in WDs, $\rho_\star \sim 10^6 - 10^{10} \text{ g cm}^{-3}$, electrons are strongly degenerate and determine the WD equation of state (EoS) and internal structure. The stellar core resembles a Coulomb lattice of ions surrounded by the degenerate electron gas, implying that the WD core is isothermal and a very good thermal conductor. The degenerate core is enclosed by a thin envelope that accounts for $\lesssim 1\%$ of the total mass [148].

The outer layers form an atmosphere that is rich in lighter elements such as hydrogen or helium, where the exact composition depends on the evolution of the WD progenitor and changes as the WD cools. This atmosphere is non-degenerate and extremely opaque to radiation, with an EoS that is subject to finite temperature effects. We limit our discussion to the core region of the WD that accounts for the vast majority of its mass.

2.2.1 The FMT Equation of State

In the limit of zero temperature, the simplest way to obtain the WD EoS is to assume an ideal Fermi gas of degenerate electrons, for a WD that is primarily composed of a single element. Corrections to the non-interacting electron picture

were introduced early by Salpeter [149]. By introducing the Wigner-Seitz (WS) cell approximation and assuming point-like nuclei, Salpeter obtained an analytical EoS that accounts for interactions between electrons and ions as well as other Coulomb corrections. These corrections, in general, depend on the chemical composition of the star.

More recently, it has been shown that the treatment of matter at high pressures presented by Feynman, Metropolis and Teller [150] can be extended to consistently take into account weak interactions and relativistic effects [151, 152], and incorporates Coulomb corrections in a more natural manner than the Salpeter EoS. The resulting Feynman-Metropolis-Teller (FMT) EoS is obtained by considering a relativistic Thomas-Fermi model within Wigner-Seitz cells of radius R_{WS} . For degenerate, relativistic, electrons, the equilibrium condition is that the Fermi energy, E_e^F , is constant within the cell,

$$E_e^F = \sqrt{(p_e^F)^2 + m_e^2} - m_e - eV(r) = \text{constant}, \quad (2.15)$$

where $V(r)$ is the Coulomb potential inside the cell, p_e^F is the electron Fermi momentum, m_e is the electron mass and e is the electric charge. To obtain an integrable solution for the energy density near the origin, it is necessary to introduce a finite size for the nucleus, with radius $R_c = \Delta\lambda_\pi Z^{1/3}$, where λ_π is the pion Compton wavelength, $\Delta \approx (r_0/\lambda_\pi)(A/Z)^{1/3}$, Z is the proton number, A is the atomic mass, and r_0 is an empirical constant ~ 1.2 fm. The proton and electron number densities inside the cell are then given by

$$n_p = \frac{(p_p^F)^3}{3\pi^2} = \frac{3Z}{4\pi R_c^3} \theta(R_c - r) = \frac{3}{4\pi} \left(\frac{1}{\Delta\lambda_\pi} \right)^3 \theta(R_c - r), \quad (2.16)$$

$$n_e = \frac{(p_e^F)^3}{3\pi^2} = \frac{1}{3\pi^2} \left[\hat{V}^2(r) + 2m_e \hat{V}(r) \right]^{3/2}, \quad (2.17)$$

$$\hat{V}(r) = eV(r) + E_e^F. \quad (2.18)$$

The Coulomb potential satisfies the Poisson equation

$$\nabla^2 V(r) = -4\pi e[n_p(r) - n_e(r)], \quad (2.19)$$

with requiring global charge neutrality of the cell enforcing the boundary conditions

$$\left. \frac{dV}{dr} \right|_{r=R_{\text{WS}}} = V(R_{\text{WS}}) = 0. \quad (2.20)$$

In practice, it is beneficial to work with dimensionless quantities, and so we define $x = r/\lambda_\pi$ and $\chi(r) = r\hat{V}(r)$, such that $x_c = R_c/\lambda_\pi$ and $x_{\text{WS}} = R_{\text{WS}}/\lambda_\pi$. Using

these expressions results in the relativistic Thomas-Fermi equation

$$\frac{1}{3x} \frac{d^2\chi}{dx^2} = -\frac{\alpha_{\text{EM}}}{\Delta^3} \theta(x_c - x) + \frac{4\alpha_{\text{EM}}}{9\pi} \left[\frac{\chi^2(x)}{x^2} + 2 \frac{m_e}{m_\pi} \frac{\chi(x)}{x} \right]^{3/2}, \quad (2.21)$$

with the boundary conditions

$$\chi(0) = 0, \quad \left. \frac{d\chi}{dx} \right|_{x_{\text{WS}}} = \frac{\chi(x_{\text{WS}})}{x_{\text{WS}}}. \quad (2.22)$$

By solving these equations, we can obtain the relevant thermodynamic quantities, namely the electron and proton number densities, electron chemical potential, and the energy and pressure of the cell. The electron chemical potential is obtained by evaluating Eq. 2.15 at the cell radius, noting that the Coulomb potential must vanish there, which results in the usual expression²

$$\varepsilon_{F,e} = \sqrt{(p_e^F)^2 + m_e^2} - m_e. \quad (2.23)$$

The energy and pressure of the cell can then be obtained following the analysis presented in ref. [152]. The cell energy gains contributions from the nuclear mass, electron kinetic energy, and Coulomb interactions, such that

$$E_{\text{tot}} = M_N + E_k + E_C, \quad (2.24)$$

$$E_k = \int_0^{R_{\text{WS}}} 4\pi r^2 [\mathcal{E}_e(r) - m_e n_e(r)] dr, \quad (2.25)$$

$$E_C = \frac{1}{2} \int_{R_c}^{R_{\text{WS}}} 4\pi r^2 e [n_p(r) - n_e(r)] V(r) dr, \quad (2.26)$$

where

$$\mathcal{E}_e(r) = \frac{1}{\pi^2} \int_0^{p_e^F} p^2 \sqrt{p^2 + m_e^2} dp, \quad (2.27)$$

is the electron energy density, and M_N is the mass of the nucleus. The energy density of the cell is then simply

$$\rho_{\text{WS}} = \frac{E_{\text{tot}}}{V_{\text{WS}}}, \quad (2.28)$$

where $V_{\text{WS}} = 4\pi R_{\text{WS}}/3$ is the volume of the WS cell. The only contribution to the internal cell pressure comes from the electrons,

$$P_e(r) = \frac{1}{3\pi^2} \int_0^{p_e^F} \frac{p^4}{\sqrt{p^2 + m_e^2}} dp, \quad (2.29)$$

²We use the symbol $\varepsilon_{F,i}$ to represent the chemical potential minus the mass of a particle species i , reserving $\mu_{F,i}$ for the full chemical potential.

EoS	WD₁	WD₂	WD₃	WD₄
ρ_c [g cm ⁻³]	1.47×10^6	3.84×10^7	3.13×10^8	2.31×10^{10}
M_\star [M_\odot]	0.440	1.000	1.252	1.384
R_\star [km]	9.39×10^3	5.38×10^3	3.29×10^3	1.25×10^3
$v_{\text{esc}}(R_\star)$ [km/s]	3.72×10^3	7.03×10^3	1.01×10^4	1.71×10^4

Table 2.1: Four configurations for white dwarfs composed of carbon, with an FMT EoS. Shown are the central densities, ρ_c , stellar mass M_\star and radius R_\star , and escape velocity at the edge of the WD, v_{esc} .

with the total pressure of the cell being $P_{\text{tot}} = P_e(R_{\text{WS}})$. Finally, the EoS is then obtained by solving Eq. 2.21 for various cell radii, yielding a relation between $E_{\text{tot}}(R_{\text{WS}})$ and $P_{\text{tot}}(R_{\text{WS}})$ parameterised by the radius of the Wigner-Seitz cell.

Different WD configurations can be obtained, assuming a non-rotating spherically symmetric star, by solving the Tolman-Oppenheimer-Volkoff (TOV) equations [146, 147] coupled to the FMT EoS with different initial conditions for the pressure at the centre of the star. In Fig. 2.1 we show radial profiles for n_e (top left), $\varepsilon_{F,e}$ (top right), and escape velocity v_{esc} (bottom) for the carbon WDs in Table 2.1. Note that the difference in radius between the lightest and heaviest WD in Table 2.1 spans almost one order of magnitude, while the electron number densities in the core can vary up to 4 orders of magnitude (see top left panel). As expected, electrons are more degenerate in more compact WDs and become relativistic (see top right panel). The escape velocity can reach $\mathcal{O}(0.1 c)$ at the interior of the most compact WDs, while for very low mass WDs it can be as low as $\sim 0.003 c$.

The mass-radius relations obtained from a zero-temperature EoS begin to deviate from observations for low-mass WDs. To address this discrepancy, finite temperature effects can be introduced to the EoS [153]. The extension to finite temperatures is made by reintroducing the temperature dependence in the Fermi-Dirac distributions. Now, the electron chemical potential is no longer simply the Fermi energy of the system due to thermal corrections. Define the finite temperature Fermi-Dirac integrals of degree s as

$$F_s(\eta, \beta) = \int_0^\infty \frac{t^s \sqrt{1 + (\beta/2)t}}{1 + e^{t-\eta}} dt, \quad (2.30)$$

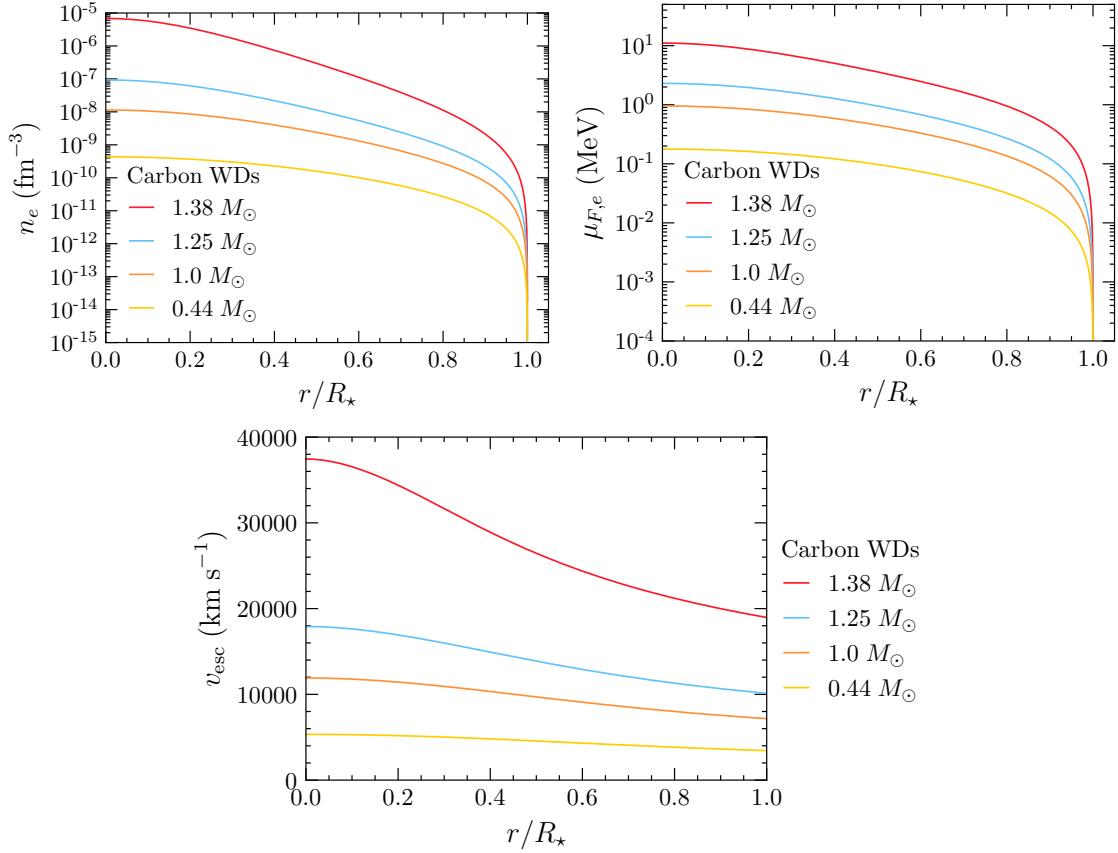


Figure 2.1: Electron number density (top left), chemical potential (top right), and escape velocity (bottom) radial profiles for the carbon WDs with FMT EoS in Table 2.1. The radial distance of each profile has been normalised to the radius of the star.

where we define the dimensionless quantities

$$t = \frac{E_e - m_e}{T_\star}, \quad (2.31)$$

$$\eta = \frac{\varepsilon_{F,e}}{T_\star}, \quad (2.32)$$

$$\beta = \frac{T_\star}{m_e}, \quad (2.33)$$

for a star at temperature T_\star . The Thomas-Fermi equilibrium condition within the WS cell is now given by

$$\varepsilon_{F,e}(r) - eV(r) = T_\star\eta(r) - eV(r) = \text{constant}, \quad (2.34)$$

with the Coulomb potential vanishing at the boundary of the cell as before. We

now make the change of variables into the dimensionless quantities $\chi/r = \varepsilon_{F,e}/(\hbar c)$ and $x = x/x_{\text{WS}}$ so that the Poisson equation 2.19 becomes

$$\frac{d^2\chi}{dx^2} = -4\pi\alpha_{\text{EM}}x \left(\frac{3}{4\pi\Delta^3} \theta(x_c - x) - \frac{\sqrt{2}}{\pi^2} \left(\frac{m_e}{m_\pi} \right)^2 [F_{1/2}(\eta, \beta) + \beta F_{3/2}(\eta, \beta)] \right), \quad (2.35)$$

$$\eta(x) = \left(\frac{1}{\lambda_\pi T_\star} \right) \frac{\chi(x)}{x}, \quad (2.36)$$

with the same boundary conditions as in Eq. 2.22.

The total energy of the cell remains very similar to the zero-temperature case, the main differences being it gains a contribution from the thermal motion of the nucleus,

$$E_{\text{th}} = \frac{3}{2}T_\star, \quad (2.37)$$

and that the electron energy density is now given by

$$\mathcal{E}_e = m_e n_e + \frac{\sqrt{2}}{\pi^2} m_e^4 \beta^{5/2} [F_{3/2}(\eta, \beta) + \beta F_{5/2}(\eta, \beta)]. \quad (2.38)$$

The pressure of the cell will now gain contributions from the motion of the nucleus as well as the electron, such that the total pressure is

$$P_{\text{tot}} = P_N + P_e, \quad (2.39)$$

$$P_N = \frac{2}{3} \frac{E_{\text{th}}}{V_{\text{WS}}} = \frac{T_\star}{V_{\text{WS}}}, \quad (2.40)$$

$$P_e = \frac{2^{3/2}}{3\pi} m_e^4 \beta^{5/2} [F_{3/2}(\eta(x_{\text{WS}}), \beta) + \beta F_{5/2}(\eta(x_{\text{WS}}), \beta)]. \quad (2.41)$$

In Fig. 2.2 we show the Mass-Radius relations obtained from the zero temperature FMT EoS together with several finite temperature configurations. As can be seen, the deviations from the zero temperature approximation begin at rather high temperatures, $T_\star \gtrsim 10^7$ K, for masses $\lesssim 0.6M_\odot$. Additionally, we show a random selection of 20,000 WDs presented in the Gaia early data release 2 (EDR2) report [154] as the yellow-red dots. The colour of the dot represents the internal temperature of the corresponding WD. The core temperature must be determined from the observed effective surface temperature of the star³, with the relation between the two depending on the composition of the WD atmosphere. To obtain

³The effective temperature is the temperature that characterises the surface of the star. Assuming that WDs are perfect blackbody emitters, the luminosity will be $L_\gamma = 4\pi\sigma_{SB} R_\star^2 T_{\text{eff}}^4$, where σ_{SB} is the Stefan–Boltzmann constant.

the central temperature from the reported effective temperatures, we use the WD cooling sequences generated in Ref. [145]⁴ assuming a thin hydrogen atmosphere. In general, there is good agreement between the mass-radius relations derived from the finite temperature FMT EoS and the observed internal temperatures of the WDs.

Given the non-linear nature of the differential equations that describe the FMT EoS (both at zero and finite temperatures), solving the system is a numerically challenging task. As there are no publically available resources to help solve these systems, a significant amount of time was put into solving this problem. As such, we have outlined in Appendix B the method employed in numerically solving the differential equations.

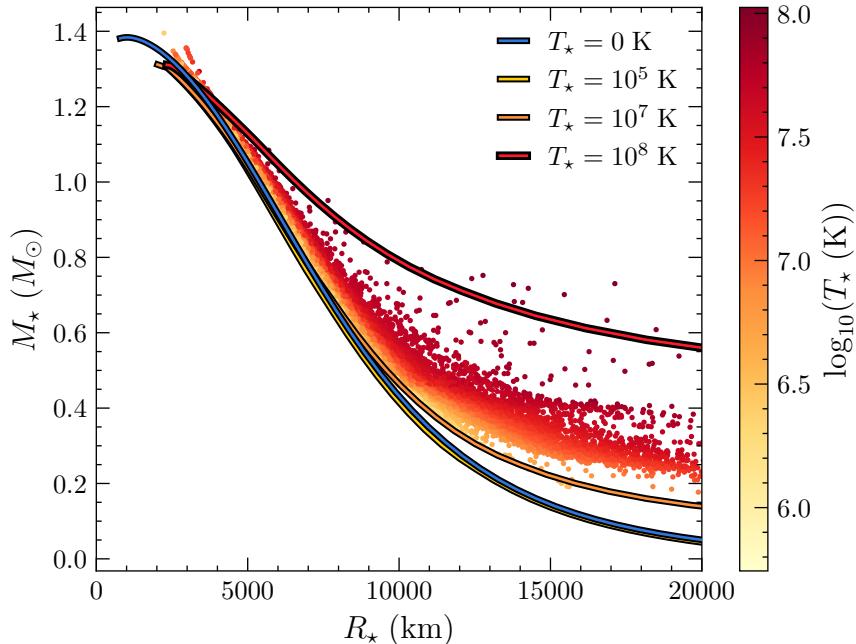


Figure 2.2: Mass-Radius relation of WDs calculated from the FMT EoS in the zero temperature approximation (dark blue), at 10^5 K (yellow), 10^7 K (orange), and 10^8 K (red), together with observed WDs from Gaia EDR2 observations [154] (light blue dots).

⁴The cooling sequence data can be obtained from [this cite](#).

2.2.2 Observational Status

The rate at which the energy of the WD core is radiated away is determined by the outer non-degenerate layers of the atmosphere. Spectroscopic observations shed light on the composition of these layers and can be used to classify WDs in terms of \sim six spectral types. Most of the observed WDs lie in the DA (hydrogen-rich) and DB (helium-rich) categories. Note that as WDs slowly cool, they undergo spectral evolution. There is a well-defined relation between their luminosity and age (cooling time) that, together with recent breakthroughs in theory and observations, allow us to estimate the age of the stars within the solar neighbourhood and to date the nearest star clusters [155–159].

Over the past few decades, WDs have been extensively observed using photometry and spectroscopy. Most of the WDs have been discovered by large area surveys, such as the Sloan Digital Sky Survey (SDSS) [160]. However, these local samples are dominated by young WDs with relatively high effective temperatures ($T_{\text{eff}} \gtrsim 10^4$ K) [161–165]. Recently, the local volume sample of nearby stars within ~ 100 pc has been catalogued by the Gaia spacecraft [166, 167], an astrometric mission. New WD candidates have been identified [154], followed by dedicated spectroscopic observations [168, 169], increasing the local sample of cool WDs ($T_{\text{eff}} \lesssim 5000$ K).

On the other hand, globular clusters (GCs) are the oldest known stellar systems in the Galaxy. Among them is Messier 4 (M4), also classified as NGC 6121, which is the closest globular cluster to Earth being ~ 1.9 kpc away [170–172]. The age of M4, 11.6 Gyr, has been estimated using observations of faint cold WDs with the Hubble Space Telescope (HST) [155, 157]. This HST data, corrected for reddening and extinction, was converted into luminosities and effective temperatures in ref. [126]. From these calculations, it is possible to infer WD radii and their corresponding masses by assuming a mass-radius relation.

2.3 Neutron Stars

Being the end product of massive, $\gtrsim 8M_{\odot}$, stars, there are significantly fewer NSs than the WDs discussed above. As their name suggests, they are composed primarily of neutrons, which provide the degeneracy pressure required to prevent the gravitational collapse of the star. The internal structure of an NS is significantly more complicated than that of a WD. Broadly speaking, an NS can be divided into five main regions. We give an overview of the important features of each of these regions, and point the reader to Refs. [173–180] for more indepth discussions. Working from the outside in, these regions are:

Atmosphere

The atmosphere is an extremely thin layer of plasma that makes up less than 1% of the NS mass. However, it plays an extremely important role as the observed spectrum radiation emitted by the star must pass through this region [174, 175].

Outer Crust

The outer crust is the thin layer of ionized Iron-56 nuclei that extends down until the density reaches the neutron drip point, $\rho_\star = \rho_{\text{ND}} \sim 4.3 \times 10^{11} \text{ g cm}^{-3}$. This is the density at which neutrons begin to drip from the nuclei as their chemical potentials approach zero. The ionized electrons form a non-relativistic but degenerate gas, with their chemical potentials increasing as the density increases. This leads to the “neutronisation” of the nuclei as the beta-capture of electrons by protons increases.

Inner Crust

The density within the inner crust spans the range between $\rho_{\text{ND}} \lesssim \rho_\star \lesssim 0.5\rho_0$, with $\rho_0 \sim 2.8 \times 10^{14} \text{ g cm}^{-3}$ the nuclear saturation density (i.e. the density of nuclear matter) [174, 175, 181]. Here, the neutrons that have dripped from the nuclei will potentially form a superfluid. Towards the crust-core boundary, the nuclear lattice begins taking on interesting topological structures that are distinguished by the configuration of the voids in the lattice. These are known as the so-called *pasta phases* [182–184] of nuclear matter:

- 2D void cylinders creating spaghetti structures of nuclei
- Planar voids with slabs of nuclei forming lasagna sheets
- 3D cylindrical voids leading to thin 2D cylinders of nuclear ziti
- 3D spherical voids enclosed by ravioli
- 2D circular voids in sheets of Swiss cheese

Eventually, towards the crust-core interface the nuclear matter transitions into a uniform medium⁵.

⁵The nuclear minestrone, if you will

Outer Core

Once densities go above $0.5\rho_0$, the nuclear clusters will dissolve into a homogenous fluid that is composed of neutrons, protons, electrons, and muons known as *npeu* matter. The relative abundances of the species, $Y_i = n_i/n_b$, are dictated by the conditions of electrical neutrality and beta-equilibrium. Charge neutrality dictates that the abundances of the charged particles obeys

$$Y_p = Y_e + Y_\mu, \quad (2.42)$$

while beta-equilibrium refers to the balance between the weak decays of neutrons and the electron/muon capture by the protons,



with $\ell = e, \mu$. Muons will begin to replace electrons in these reactions once the electron chemical potential exceeds the mass of the muon, $\mu_{F,e} \gtrsim m_\mu = 105.7 \text{ MeV}$. As neutrinos are assumed to escape the NS once produced, the relation between the chemical potential of the leptons is simply

$$\mu_{F,e} = \mu_{F,\mu}, \quad (2.45)$$

on the chemical potentials. The outer core region ends once the density reaches $\rho_* \sim 2\rho_0$, and we transition into the inner core.

Inner Core

The densities within the inner cores of NSs extend between $2\rho_0 \lesssim \rho_* \lesssim (10 - 15)\rho_0$ and are hence a mystery to this day. As the density exceeds well above any material that can be produced in a laboratory, the exact composition of this region is unknown and depends on the equation of state one adopts to describe it. Some of the more well-known candidates are

- The appearance of hyperonic matter, i.e. nucleons containing a valence strange quark. These appear once the neutron chemical potential equals the Λ^0 hyperon, with the Ξ^- appearing once its chemical potential equals the sum of the chemical potentials of the neutrons and electrons [176, 185].
- Pion/Kaon condensates. These are Bose-Einstein condensates of pion/kaon-like excitations [186–191].
- A quark-gluon plasma comprised of deconfined u , d and s quarks and gluons [192–194].

2.3.1 Observational Status

Unlike the WDs discussed above, there are much fewer NS observations that constrain the EoS. However, recent years have seen significant strides in furthering our understanding of matter at super-nuclear densities, both from a theory and observational standpoint. On the theoretical side, these advances come from developments in chiral EFT allowing more detailed modelling of nuclear interactions [195–197], while the observational data has been bolstered thanks to the onset of gravitational wave astronomy due to the LIGO-VIRGO experiment [198–200] and the launch of the Neutron star Interior Composition Explorer (NICER) X-ray timing instrument.

Ultimately, what is needed to further constrain the NS EoS are more precise observations of NS masses and radii, which can be obtained from various observational techniques. NS masses have historically been much easier to measure than their radii. In particular, masses of NSs in binary systems can be precisely determined as the underlying gravitational theories are well-understood today [178, 179, 201–203]. The radii must be determined by assuming the NSs emit a blackbody spectrum, however, this method is only reliable for cool NSs where the atmospheric models are well understood [203].

The NICER experiment can provide much more precise measurements of NS radii than previous methods. This is achieved by measuring the X-ray pulse profiles of pulsars, that are sensitive to how light bends around the star. This provides information on the compactness of the star, $GM_\star/R_\star c^2$, that can be used to determine M_\star and R_\star given that the mass can usually be determined through other means. The heaviest NS observed to date, the millisecond pulsar PSR J0740+6620 [204, 205], had its mass determined by measuring the relativistic Shapiro time delay [206]⁶ of the radio signal, allowing the radius to be obtained once the compactness was measured [207]. Refined analyses result in a mass of $2.08 \pm 0.07 M_\odot$ [208] and a radius of $12.39^{+1.30}_{-0.98}$ km [205] or $13.71^{+2.61}_{-1.50}$ km [204] at 68% confidence levels.

Gravitational wave astronomy offers an alternative and independent determination of NS masses and radii to the electromagnetic observations above. The best candidate events for this analysis are NS binary mergers, though these are expected to be an uncommon occurrence. As the NSs inspiral toward each other, they will begin to deform due to the tidal forces they induce on one another [209]. This deformation will alter the waveform observed at the detectors, with the shift in the phase of the waveform depending on the mass ratio, $q = M_2/M_1 < 1$, the chirp mass of the system, $\mathcal{M}_{\text{chirp}} = (M_1 M_2)^{3/5} / (M_1 + M_2)^{1/5}$, and a combination of the tidal deformabilities, $\tilde{\Lambda}$. The latter refers to how susceptible the star is to deformation due to tidal forces acting upon it, with larger values corresponding to less compact objects. Comparing the observed waveform to that determined from

⁶This refers to the time it takes for light to move out of a gravitational well taking longer than the naive Newtonian prediction due to the curvature of space-time.

precise numerical simulations allows constraints to be placed on these parameters, and ultimately on the masses and radii of the merging NSs.

Furthermore, the electromagnetic emission from the remnant object provides information about the maximum mass an NS can achieve. If the mass of the remnant object is too large, it will collapse into a black hole, and it is highly unlikely that a gamma-ray burst will occur. If the remnant does not immediately collapse, then its mass and how it is rotating determines whether it will be hydrodynamically stable, unstable, or metastable against gravitational collapse. A remnant that undergoes differential rotation⁷ can support heavier masses than one that is uniformly rotating. Hence, the afterglow spectrum can inform us as to how the star is rotating. Comparing the maximum mass supported by this rotation to the initial mass after inspiral yields an upper bound on the maximum NS mass achievable.

To date, the only confirmed NS-NS merger is the merger event GW170817 observed at LIGO-VIRGO in 2017 [199, 200], with the gamma-ray burst counterpart signal observed at the Fermi Gamma-ray Burst Monitor and INTEGRAL satellite [198]. These observations led to the constraint that the radius of a $1.4M_{\odot}$ NS has an upper bound of $R_{1.4} < 13.3$ km [210, 211], and that the maximum NS mass must be $M_{\text{NS,MAX}} < 2.18M_{\odot}$ [198].

2.3.2 Neutron Star Equations of State

Given the scarce constraints that have been placed on the NS mass-radius relation, there are numerous equations of state in the literature that can be used to incorporate the internal structure into our calculations. In this work, we adopt two different EoSs, which we detail here.

The Brussels-Montreal EoS

The first family of EoSs adopted in this work are based on the Brussels-Montreal (BSk) energy density functionals [212–217], for cold, non-accreting NSs. In these models, the density-dependent nucleon interactions are accounted for via a mean-field approximation in either the Hartree-Fock (HF) or Hartree-Fock-Bogoliubov (HFB) formalism⁸, through effective Skyrme type forces [218, 219]. The BSk EoS family are unified EoSs, meaning they describe all the regions of the NS interior using the single effective Hamiltonian. Furthermore, the authors provide public FORTRAN subroutines that implement fits to the EoS quantities such as the pressure

⁷This is when components of the star at different latitudes have different angular velocities.

⁸The HF method accounts for the energy associated with nucleon pairings, while the HFB method neglects this contribution.

EoS	BSk24-1	BSk24-2	BSk24-3	BSk24-4
ρ_c [g cm $^{-3}$]	5.94×10^{14}	7.76×10^{14}	1.04×10^{15}	1.42×10^{15}
M_\star [M_\odot]	1.000	1.500	1.900	2.160
R_\star [km]	12.215	12.593	12.419	11.965
$B(R_\star)$	0.763	0.648	0.548	0.467
$c_s(0)$ [c]	0.511	0.628	0.734	0.835

Table 2.2: Benchmark NSs, for four different configurations of the equations of state (EoS) for cold non-accreting neutron stars with Brussels–Montreal functionals BSk24 [217]. EoS configurations are determined by the central mass-energy density ρ_c .

and density as functions of the baryon number density, allowing straightforward implementation of the EoS.

The authors provide these fits to seven configurations of the BSk EoS, labeled BSk19-26. Of these, the older BSk19-21 functionals were fitted to older atomic mass data that has since been updated in the newer models, BSk22-26. The mass-radius relation predicted by a selection of these models is shown in Fig. 2.4 by the blue lines. Missing are the BSk20 and 21 models, as they give very similar results to the 26 and 24 models respectively. The BSk19 EoS is partially ruled out from the lower bound on NS radii obtained from the electromagnetic counterpart of the GW170817 event [220], while BSk22 is ruled out from constraints on the tidal deformability from the same event [221]. Additionally, BSk22 does not support the presence of direct Urca⁹ processes in NSs described by this EoS. These processes are required to explain observations of a small population of NSs that have cooled to temperatures below those predicted by the “minimal cooling paradigm” [222, 223]. On the other hand, the BSk26 functional predicts that all stable NSs will support direct Urac processes. This goes against the current observational evidence that a majority of NSs are well modeled by the minimal cooling paradigm, ruling the EoS out. Of the remaining two models, BSk24 and 25, we choose to adopt BSk24 as it gives slightly better fits to NS mass data than that of BSk25.

We use the BSk24 EoS to generate four benchmark NSs with masses of 1, 1.5, 1.9 and 2.16 M_\odot , with the central density ρ_c , stellar mass, radius, metric factor $B(R_\star)$ and central speed of sound $c_s(0)$ in Table 2.2. Radial profiles of the baryon number density $n_b(r)$, metric factor $B(r)$, neutron chemical potential $\varepsilon_{F,n}(r)$, and neutron abundance $Y_n(r)$, are shown in Fig. 2.3.

While BSk24 and 25 lie well within current observational constraints, they are minimal models in that they only account for $npe\mu$ matter, and do not incorpo-

⁹This is another name given to the reactions in Eqs. 2.43, 2.44

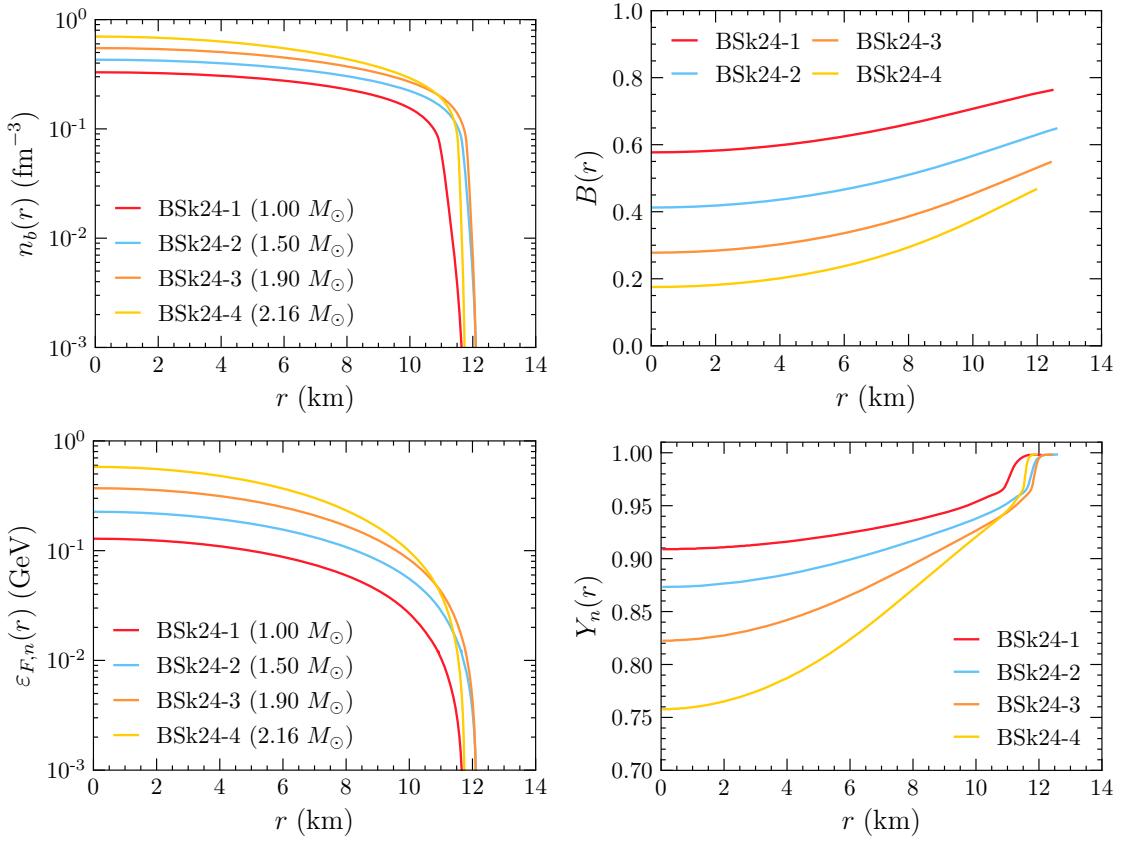


Figure 2.3: Radial profiles of the baryon number density (top left), metric factor $B(r)$ (top right), neutron chemical potential (bottom left), and neutron abundance (bottom right) for the four benchmark NS of the BSk24 EoS in Table 2.2.

rate any exotic species within the NS core. This is problematic as it is highly likely that hyperonic matter will appear in the cores of NS heavier than $\sim 1.7 M_\odot$. Additionally, the Skyrme forces that describe the nuclear interaction are treated non-relativistically, while the nucleons in heavier stars can become semi-relativistic. To address these concerns, later works [224, 225] adopted the Quark-Meson Coupling (QMC) EoS.

The Quark-Meson Coupling EoS

The second EoS adopted is based on the QMC model of Refs. [226–229], in which baryons are described as bags of three valence quarks, with the bags themselves modeled by the MIT bag model [230]. The interactions among the baryons are described by the exchange of mesons between the valence non-strange quarks and

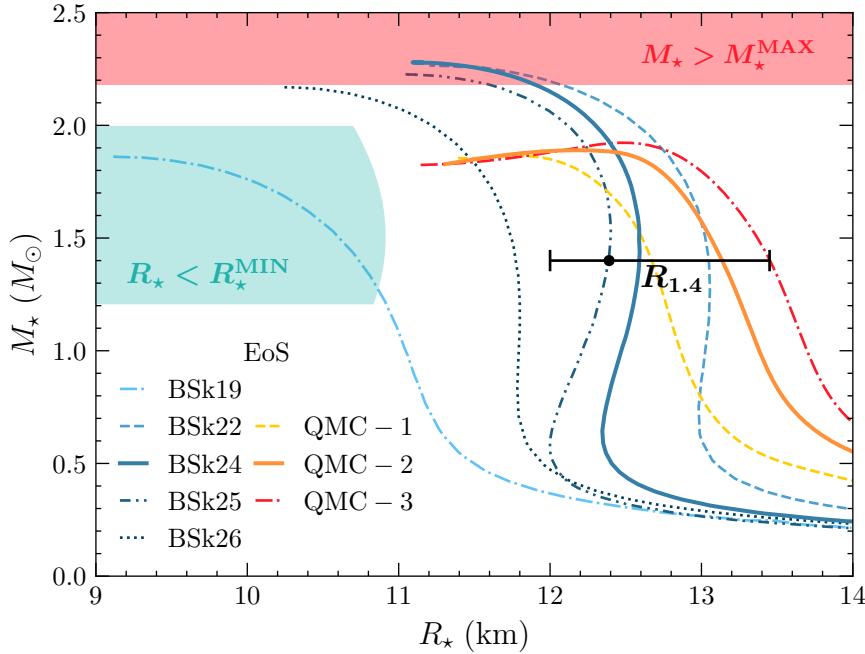


Figure 2.4: Neutron Star Mass-Radius relation predicted by the BSk (blue lines) and QMC (red lines) EoSs. Constraints obtained from the gravitational wave event GW170817 are shown as the shaded regions, with the lower bound on the radius in turquoise, and the maximum NS mass possible in red. The line band labeled $R_{1.4}$ indicates the constraints on the radius of a $1.4 M_\odot$ NS.

are formulated within a relativistic mean-field Lagrangian. The exchange of the vector mesons acts as an overall shift to the energy of the baryons¹⁰. The scalar mean fields play a significantly more important role, modifying the effective mass of the baryons. The scalar (and also vector) couplings are density-dependent, leading to an effective mass of the baryons that varies throughout the NS. The density dependence of these couplings is equivalent to including repulsive three-body forces between the baryons and arises naturally in the QMC model through the in-medium modification of the baryonic structure [231, 232]. Additional details on the energy density and couplings of the QMC model adopted in this work are given in Appendix C.

The mass-radius relation of three different configurations of the QMC EoS, namely three different choices of the isovector coupling constant, are shown as the red lines in Fig. 2.4, obtained from Ref. [233]. Of these, QMCb lies within the constraints on the radius of a $1.4 M_\odot$ NS from GW170817, and can produce an NS

¹⁰A simple analogy for this is how the energy of an electron in an electromagnetic field is due to the exchange of photons, which are vector fields.

EoS	QMC-1	QMC-2	QMC-3	QMC-4
n_B^c [fm $^{-3}$]	0.325	0.447	0.540	0.872
M_\star [M_\odot]	1.000	1.500	1.750	1.900
R_\star [km]	13.044	12.847	12.611	12.109
$B(R_\star)$	0.772	0.653	0.588	0.535

Table 2.3: Benchmark NSs for four different configurations of the QMC equation of state. EoS configurations are determined by the central number density n_B^c .

of mass $1.908 \pm 0.016 M_\odot$, the currently preferred mass of PSR J1614-2230 obtained by the NANOGrav collaboration [234]¹¹.

The QMCb EoS data was provided by the authors of Ref. [233] for use in this work and will be referred to as simply the QMC EoS from here on. From this, we calculate the internal structure of four benchmark NSs, similar to Table 2.2 with the central baryon density replacing the central density and the speed of sound omitted. The top four plots in Fig. 2.5 show the radial profiles for the number densities of the neutrons and protons for each configuration on the left, with their effective masses shown on the right. The bottom two plots of the same figure show the number densities for each species within the heaviest star on the left, including leptons in dashed lines, with the effective masses for each of the baryons on the right. The replacement of high-momentum neutrons with low-momentum hyperons is clearly seen in the bottom left plot, as the neutron number density dips towards the centre of the massive star. As the densities are high enough for the charged hyperon Ξ^- to appear, the abundance of leptons decreases due to the requirement of charge neutrality, also seen in this plot.

¹¹As mentioned above, the current heaviest NS has a mass of $2.08 \pm 0.07 M_\odot$ though the implications of this on the QMC EoS are beyond the scope of this work.

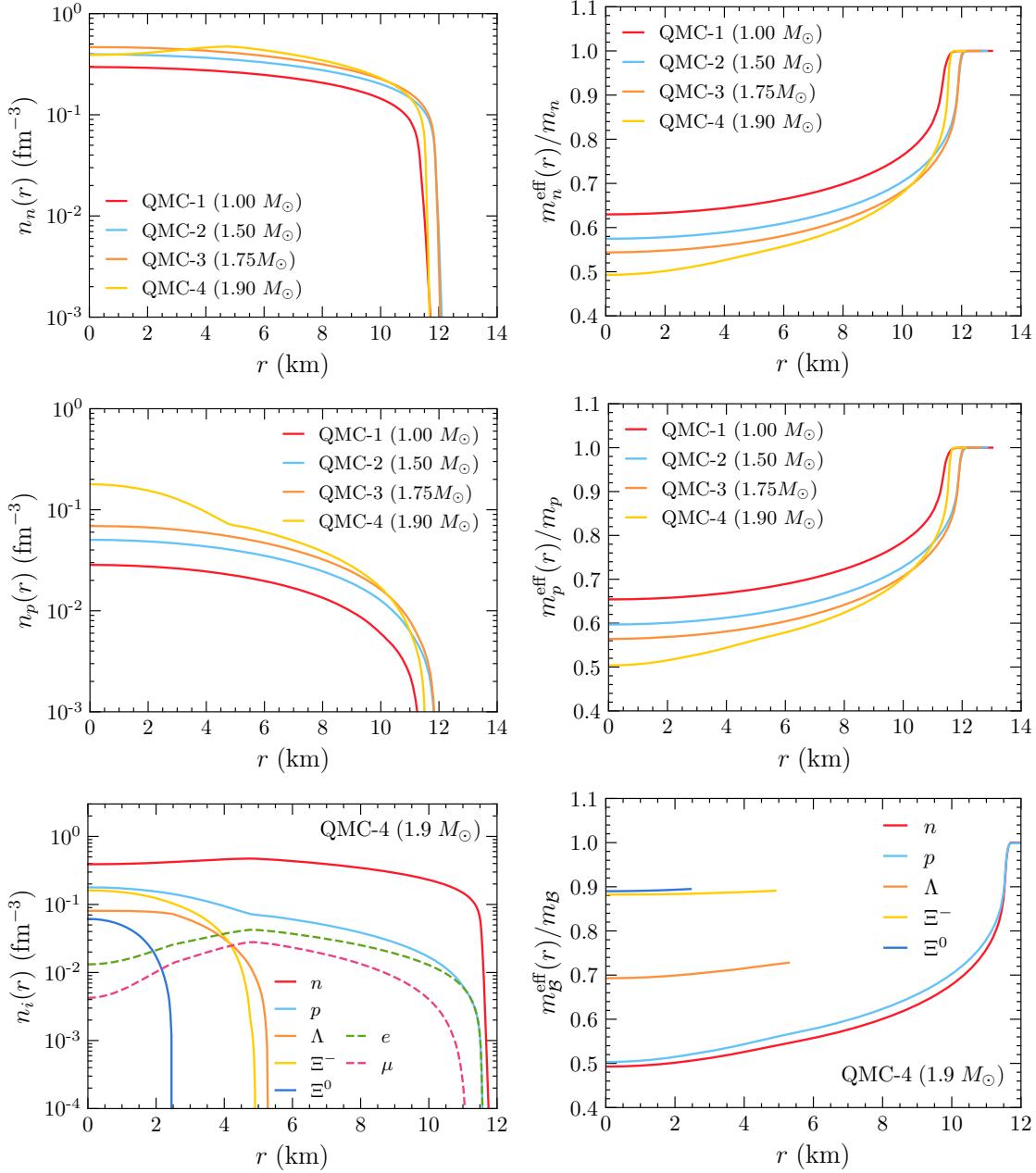


Figure 2.5: Number density profiles (left) and the ratio of the effective mass to the bare mass (right) for neutrons (top) and protons (middle) for benchmark configurations of the QMC EoS in Table 2.3. In the bottom panels, we show the same profiles for all species in the heaviest NS considered, QMC-4, which contains hyperonic matter.

A

Hadronic matrix elements for scattering operators

This appendix provides the hadronic matrix elements required for computing the dark matter-baryon couplings given in Eqs. 1.17-1.21, for both nucleons and hyperons.

A.1 Nucleons

The values of the hadronic matrix elements for neutrons and protons used in this paper are listed in Table 1.1. The values of $\Delta_q^{(p)}$ (and similarly for $\delta_q^{(p)}$) are obtained using isospin symmetry:

$$\Delta_u^N = \Delta_d^{N^\star}, \quad \Delta_s^N = \Delta_s^{N^\star}, \quad (\text{A.1})$$

where N^\star is the nucleon obtained interchanging $u \iff d$ quarks.

q	$f_{T_q}^{(n)}$ [235]	$f_{T_q}^{(p)}$ [235]	$\Delta_q^{(n)}$	$\delta_q^{(n)}$ [235]
u	0.0110	0.0153	-0.319 [236]	-0.230
d	0.0273	0.0191	0.787 [236]	0.840
s	0.0447	0.0447	-0.040 [237]	-0.046

Table A.1: Hadronic matrix elements for neutrons and protons.

A.2 Hyperons

To calculate the $f_{T_q}^{(\mathcal{B})}$ couplings for hyperons, we use the baryonic sigma terms from ref. [238], listed in Table A.2, in the following way

$$f_{T_{u,d}}^{(\mathcal{B})} = \frac{\sigma_{l\mathcal{B}}}{m_{\mathcal{B}}} \frac{m_{u,d}}{m_u + m_d}, \quad (\text{A.2})$$

$$f_{T_s}^{(\mathcal{B})} = \frac{\sigma_s}{m_{\mathcal{B}}}, \quad (\text{A.3})$$

where the first relation assumes

$$\frac{\sigma_u^{\mathcal{B}}}{m_u} = \frac{\sigma_d^{\mathcal{B}}}{m_d}. \quad (\text{A.4})$$

In addition, we assume

$$\sigma_u^{\mathcal{B}} = \sigma_d^{\mathcal{B}^*}, \quad \sigma_s^{\mathcal{B}} = \sigma_s^{\mathcal{B}^*}. \quad (\text{A.5})$$

For the dimension 6 operators where $c_q \propto m_q$, the nucleon couplings depend only on the following sum of the $f_{T_q}^{(\mathcal{B})}$ values

$$\sum_{q=u,d,s} f_{T_q}^{(\mathcal{B})} = \frac{\sigma_{l\mathcal{B}} + \sigma_s}{m_{\mathcal{B}}}, \quad (\text{A.6})$$

and hence exact values for the individual $f_{T_q}^{(\mathcal{B})}$ are unnecessary. The axial vector [238, 239] and tensor [240] couplings are listed in Table A.2.

\mathcal{B}	$\sigma_{l\mathcal{B}}$ (MeV)	σ_s (MeV)	Δ_u	Δ_d	Δ_s	δ_u	δ_d	δ_s
Λ^0	32 ± 4	176 ± 19	0	0	0.59	0	0	0.47
Ξ^0	13 ± 10	334 ± 21	-0.38	0	1.03	-0.22	0	0.9
Ξ^-	13 ± 10	334 ± 21	0	-0.38	1.03	0	-0.22	0.9

Table A.2: Sigma commutators for scalar interactions for each hyperon \mathcal{B} (first and second column). Spin matrix elements for axial vector [238, 239] and tensor interactions are given in the remaining columns. Tensor couplings for Ξ are taken from ref. [240], while those for Λ^0 are our estimates.

B

Solving the FMT EoS

Here we demonstrate how the nonlinear shooting method is used to solve the zero-temperature Feynman-Metropolis-Teller equation of state for white dwarfs. The same algorithm can be used to solve the finite temperature EoS.

To begin, define a function $f(x, \chi, \chi')$ to be

$$f(x, \chi, \chi') = \frac{d^2\chi}{dx^2} \quad (\text{B.1})$$

$$= -\frac{3x\alpha_{\text{EM}}}{\Delta^3}\theta(x_c - x) + \frac{4x\alpha_{\text{EM}}}{3\pi} \left[\frac{\chi^2(x)}{x^2} + 2\frac{m_e}{m_\pi} \frac{\chi(x)}{x} \right]^{3/2}, \quad (\text{B.2})$$

with the domain $0 \leq x \leq x_{\text{WS}}$. In general, the boundary conditions can be written as a set of linear equations

$$a_0\chi(0) - a_1\chi'(0) = \gamma. \quad (\text{B.3})$$

$$b_0\chi(0) + b_1\chi'(0) = \beta \quad (\text{B.4})$$

where in the present case the coefficients are simply

$$a_0 = 1, \quad a_1 = 0, \quad b_0 = 1, \quad b_1 = -x_{\text{WS}}, \quad \gamma = 0, \quad \beta = 0. \quad (\text{B.5})$$

We will remain as general as possible so that this method can be adapted easily to other systems while highlighting the key results for the current application.

This boundary value problem (BVP) can be related to an equivalent initial value problem (IVP) by parameterising the initial slope by the parameter s . We define for the function $u(x)$ to be a solution to this IVP such that

$$u''(x) = f(x, u, u'), \quad (\text{B.6})$$

with the initial conditions

$$u(0) = a_1 s - c_1 \gamma \quad (\text{B.7})$$

$$u'(0) = a_0 s - c_0 \gamma \quad (\text{B.8})$$

where the coefficients c_0 and c_0 are any constants that satisfy

$$a_1 c_0 - a_0 c_1 = 1. \quad (\text{B.9})$$

For the FMT case, we have $c_1 = -1$, and c_0 is a free parameter that can be set to 0, leaving

$$u(0) = 0 \quad (\text{B.10})$$

$$u'(0) = s - c_0. \quad (\text{B.11})$$

The solution to the IVP depends on the value of s , and so we write this as $u(x; s)$. This solution will also satisfy the original BVP if the s is a root of

$$b_0 u(b; s) + b_1 u'(b; s) - \beta = 0 \quad (\text{B.12})$$

$$\implies u(x_{\text{WS}}; s) - x_{\text{WS}} u'(x_{\text{WS}}; s) = 0 \quad (\text{FMT EoS}). \quad (\text{B.13})$$

It will be convenient to express this condition in terms of the roots of a function $\phi(s)$ defined as

$$\phi(s) = b_0 u(b; s) + b_1 u'(b; s) - \beta = 0. \quad (\text{B.14})$$

The IVP can be solved by reduction of order, changing it into a system of two first-order non-linear ODEs taken to be

$$u(x)' = v(x), \quad (\text{B.15})$$

$$v'(x) = f(x, u, v), \quad (\text{B.16})$$

with the initial conditions given in general by

$$u(a) = a_1 s - c_0 \gamma, \quad (\text{B.17})$$

$$v(a) = a_0 s - c_0 \gamma, \quad (\text{B.18})$$

and specifically here are

$$u(0) = 1, \quad (\text{B.19})$$

$$v(0) = s - c_0. \quad (\text{B.20})$$

We denote the solutions as $u(x; s)$ and $v(x; s)$, and re-express $\phi(s)$ in terms of these functions as

$$\phi(s) = b_0 u(b; s) + b_1 v(b; s) - \beta = 0. \quad (\text{B.21})$$

To solve the system numerically, we can define a grid consisting of J points

$$0 \leq x_j \leq x_{\text{ws}}, \quad 0 \leq j \leq J, \quad (\text{B.22})$$

and solve the system on this grid for some initial choice of s_0 . We represent the numerical solutions as vectors $U_j(s_0)$, $V_j(s_0)$, with $\phi(s)$ is then simply

$$\phi(s_0) = b_0 U_J(s_0) + b_1 V_J(s_0) - \beta. \quad (\text{B.23})$$

$$(\text{B.24})$$

As this choice of s_0 was essentially arbitrary, it will almost certainly not be a root. We can then use Newton's method to iteratively select the next s used to solve the system. In general, the next iteration of s given the previous choice is found through

$$s_{i+1} = s_i - \frac{\phi(s_i)}{\dot{\phi}(s_i)} \quad (\text{B.25})$$

where $\dot{\phi}(s) = \frac{\partial \phi}{\partial s}$.

However, $\dot{\phi}(s)$ is trivial to calculate, as it depends on the functions $u(x; s)$ and $v(x; s)$. We must therefore define an additional set of functions,

$$\xi(x) = \frac{\partial u(x; s)}{\partial s}, \quad (\text{B.26})$$

$$\eta(x) = \frac{\partial v(x; s)}{\partial s}, \quad (\text{B.27})$$

that results in the additional ODEs that must be solved alongside the original two,

$$\xi' = \eta, \quad (\text{B.28})$$

$$\eta' = p(x; s)\eta + q(x; s)\xi, \quad (\text{B.29})$$

with the p and q functions given by

$$p(x; s) = \frac{\partial f}{\partial v}, \quad (\text{B.30})$$

$$q(x; s) = \frac{\partial f}{\partial u}. \quad (\text{B.31})$$

The initial conditions for these equations are

$$\xi(a) = a_1, \quad (\text{B.32})$$

$$\eta(a) = a_0, \quad (\text{B.33})$$

For the application to the FMT EoS, these functions are given explicitly by

$$p(x; s) = 0. \quad (\text{B.34})$$

$$q(x; s) = \frac{4\alpha_{\text{EM}}}{\pi} \left(\frac{u^2}{x^2} + 2 \frac{m_e u}{m_\pi x} \right)^{1/2} \left(\frac{u}{x} + \frac{m_e}{m_\pi} \right), \quad (\text{B.35})$$

Thus we can now express $\dot{\phi}(x)$ in terms of these new functions as

$$\dot{\phi}(s) = b_0 \xi(b; s) + b_1 \eta(b; s). \quad (\text{B.36})$$

$$(\text{B.37})$$

The complete system of ODEs needed to solve the IVP is given by

$$u' = v, \quad (\text{B.38})$$

$$v' = -\frac{3x\alpha_{\text{EM}}}{\Delta^3} \theta(x_c - x) + \frac{4x\alpha_{\text{EM}}}{3\pi} \left(\frac{u^2}{x^2} + 2 \frac{m_e u}{m_\pi x} \right)^{3/2}, \quad (\text{B.39})$$

$$\xi' = \eta \quad (\text{B.40})$$

$$\eta' = \frac{4\alpha_{\text{EM}}}{\pi} \left(\frac{u^2}{x^2} + 2 \frac{m_e u}{m_\pi x} \right)^{1/2} \left(\frac{u}{x} + \frac{m_e}{m_\pi} \right) \xi \quad (\text{B.41})$$

with the conditions

$$u(0) = 0, \quad v(0) = s_i, \quad (\text{B.42})$$

$$\xi(0) = 0, \quad \eta(0) = 1, \quad (\text{B.43})$$

where s_i is the i th iteration of s found by via

$$s_{i+1} = s_i - \frac{u(x_{\text{WS}}; s_i) - x_{\text{WS}} v(x_{\text{WS}}; s_i)}{\xi(x_{\text{WS}}; s_i) - x_{\text{WS}} \eta(x_{\text{WS}}; s_i)}. \quad (\text{B.44})$$

The initial “guess” of s_0 that starts the loop should be chosen wisely to be somewhat close to the true value. The final system is found once the absolute value of $\phi(s_i)$ falls below the tolerance specified,

$$|\phi(s_i)| < \varepsilon_{\text{tol}}, \quad (\text{B.45})$$

with standard values of $\varepsilon_{\text{tol}} = 10^{-4}$.

Once the system is solved, we re-associate $u(x)$ with $\chi(x)$ and the pressure, density and chemical potential profiles within the cell can be obtained.

Depending on the algorithm used in solving the IVP, the Jacobian matrix may be required and is given by

$$J = \begin{pmatrix} 0 & 1 & 0 & 0 \\ \frac{4\alpha_{\text{EM}}}{\pi} \left(\frac{u^2}{x^2} + 2 \frac{m_e u}{m_\pi x} \right)^{1/2} \left(\frac{u}{x} + \frac{m_e}{m_\pi} \right) & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ \frac{8\alpha_{\text{EM}}\xi}{\pi x} \frac{\left(\frac{u^2}{x^2} + 2 \frac{m_e u}{m_\pi x} + \frac{m_e^2}{2m_\pi^2} \right)}{\left(\frac{u^2}{x^2} + 2 \frac{m_e u}{m_\pi x} \right)^{1/2}} & 0 & \frac{4\alpha_{\text{EM}}}{\pi} \left(\frac{u^2}{x^2} + 2 \frac{m_e u}{m_\pi x} \right)^{1/2} \left(\frac{u}{x} + \frac{m_e}{m_\pi} \right) & 0 \end{pmatrix}, \quad (\text{B.46})$$

as well as the vector of the second derivatives

$$\frac{\partial}{\partial x} \begin{pmatrix} u' \\ v' \\ \xi' \\ \eta' \end{pmatrix} = \begin{pmatrix} 0 \\ -\frac{3\alpha_{\text{EM}}}{\Delta^3} \theta(x_c - x) - \frac{8\alpha_{\text{EM}}}{3\pi} \left(\frac{u^2}{x^2} + 2 \frac{m_e u}{m_\pi x} \right)^{1/2} \left(\frac{u^2}{x^2} + \frac{m_e u}{2m_\pi x} \right) \\ 0 \\ -\frac{8\alpha_{\text{EM}}\xi}{\pi x^2} \frac{\left(\frac{u^2}{x^2} + 2 \frac{m_e u}{m_\pi x} + \frac{m_e^2}{2m_\pi^2} \right)}{\left(\frac{u^2}{x^2} + 2 \frac{m_e u}{m_\pi x} \right)^{1/2}} \end{pmatrix}. \quad (\text{B.47})$$

C

QMC Equation of State Functionals

Under the assumption of beta equilibrium throughout the entire NS, the energy density functional, which is the sum of the Hartree and Fock terms, $\epsilon = \epsilon_{\text{Hartree}} + \epsilon_{\text{Fock}}$, in the QMC EoS was derived Ref. [233]. The Hartree term is given by

$$\begin{aligned} \epsilon_{\text{Hartree}} = & \frac{m_\sigma^2 \sigma^2}{2} + \frac{m_\omega^2 \omega^2}{2} + \frac{m_\rho^2 b^2}{2} + \frac{m_\delta^2 \delta^2}{2} \\ & + \frac{1}{\pi^2} \sum_{\mathcal{B}} \int_0^{k_F^\mathcal{B}} k^2 \sqrt{k^2 + m_i^{\text{eff}}(\sigma, \delta)^2} dk \\ & + \frac{1}{\pi^2} \sum_L \int_0^{k_F^L} k^2 \sqrt{k^2 + m_L^2} dk, \end{aligned} \quad (\text{C.1})$$

Here σ, ω, b and δ denote the isoscalar scalar and vector fields and the isovector vector and scalar fields, respectively. The sums run over the full baryon octet $\mathcal{B} = (n, p, \Lambda^0, \Sigma^{0,\pm}, \Xi^{0,-})$ and leptons $L = (e^-, \mu^-)$. The meson mean field equations

are

$$m_\sigma^2 \sigma = \frac{1}{\pi^2} \sum_{\mathcal{B}} (-\partial_\sigma m_i^{\text{eff}}(\sigma, \delta)) \int_0^{k_F^\mathcal{B}} k^2 \frac{m_i^{\text{eff}}(\sigma, \delta)}{\sqrt{k^2 + m_i^{\text{eff}}(\sigma, \delta)^2}} dk, \quad (\text{C.2})$$

$$m_\omega^2 \omega = \sum_{\mathcal{B}} n_{\mathcal{B}} g_\omega \left(1 + \frac{s_{\mathcal{B}}}{3} \right) = \sum_{\mathcal{B}} n_{\mathcal{B}} g_\omega^\mathcal{B}, \quad (\text{C.3})$$

$$m_\rho^2 b = \sum_{\mathcal{B}} n_{\mathcal{B}} g_\rho t_{3\mathcal{B}} = \sum_{\mathcal{B}} n_{\mathcal{B}} g_\rho^\mathcal{B}, \quad (\text{C.4})$$

$$m_\delta^2 \delta = \sum_{\mathcal{B}} (-\partial_\delta m_i^{\text{eff}}(\sigma, \delta)) \frac{1}{\pi^2} \int_0^{k_F^\mathcal{B}} k^2 \frac{m_i^{\text{eff}}(\sigma, \delta)}{\sqrt{k^2 + m_i^{\text{eff}}(\sigma, \delta)^2}} dk. \quad (\text{C.5})$$

The Fock terms take the form

$$\begin{aligned} \epsilon_{\text{Fock}} &= \frac{1}{(2\pi)^6} \sum_{\mathcal{B}} \int_{k_1, k_2} \frac{\partial_\sigma m_i^{\text{eff}}(\sigma, \delta)^2}{(\vec{k}_1 - \vec{k}_2)^2 + m_\sigma^2} \left[\frac{m_i^{\text{eff}}(\sigma, \delta)}{\sqrt{k_1^2 + m_i^{\text{eff}}(\sigma, \delta)^2}} \right] \left[\frac{m_{\mathcal{B}'}^{\text{eff}}(\sigma, \delta)}{\sqrt{k_2^2 + m_{\mathcal{B}'}^{\text{eff}}(\sigma, \delta)^2}} \right] \\ &\quad + \frac{1}{(2\pi)^6} \sum_{\mathcal{B}, \mathcal{B}'} \int_{k_1, k_2} \frac{Z_{t_{3\mathcal{B}} t_{3\mathcal{B}'}}}{(\vec{k}_1 - \vec{k}_2)^2 + m_\delta^2} \left[\frac{m_i^{\text{eff}}(\sigma, \delta)}{\sqrt{k_1^2 + m_i^{\text{eff}}(\sigma, \delta)^2}} \right] \left[\frac{m_{\mathcal{B}'}^{\text{eff}}(\sigma, \delta)}{\sqrt{k_2^2 + m_{\mathcal{B}'}^{\text{eff}}(\sigma, \delta)^2}} \right] \\ &\quad - \frac{1}{(2\pi)^6} \sum_{\mathcal{B}} \int_{k_1, k_2} \frac{g_\omega^{\mathcal{B}^2}}{(\vec{k}_1 - \vec{k}_2)^2 + m_\omega^2} - \sum_{\mathcal{B}, \mathcal{B}'} \int_{k_1, k_2} \frac{g_\rho^2 I_{t_{3\mathcal{B}} t_{3\mathcal{B}'}}}{(\vec{k}_1 - \vec{k}_2)^2 + m_\rho^2}, \end{aligned} \quad (\text{C.6})$$

where we have defined for convenience

$$I_{t_{3\mathcal{B}} t_{3\mathcal{B}'}} = \delta_{t_{3\mathcal{B}}, t_{3\mathcal{B}'}} + (\delta_{t_{3\mathcal{B}}, t_{3\mathcal{B}'}+1} + \delta_{t_{3\mathcal{B}'}, t_{3\mathcal{B}}+1}) t_{\mathcal{B}} \quad (\text{C.7})$$

and

$$\begin{aligned} Z_{t_{3\mathcal{B}} t_{3\mathcal{B}'}} &= \partial_\delta m_i^{\text{eff}}(\sigma, \delta) \partial_\delta m_{\mathcal{B}'}^{\text{eff}}(\sigma, \delta) \delta_{t_{3\mathcal{B}}, t_{3\mathcal{B}'}} \\ &\quad + g_\delta^{\mathcal{B}}(\delta, \sigma) g_\delta^{\mathcal{B}'}(\delta, \sigma) (\delta_{t_{3\mathcal{B}}, t_{3\mathcal{B}'}+1} + \delta_{t_{3\mathcal{B}'}, t_{3\mathcal{B}}+1}) t_{\mathcal{B}}. \end{aligned} \quad (\text{C.8})$$

The chemical potentials for each species are defined as

$$\mu_{F,i} = \frac{\partial \epsilon}{\partial n_i}. \quad (\text{C.9})$$

The relevant coupling constants of the scalar and vector mesons to the baryons, as well as the meson masses and the resulting nuclear matter properties are given in ref. [233].

The density dependent scalar couplings are calculated by solving the MIT bag model [230] equations of motion in the scalar fields and thus our calculation includes

the self-consistent adjustment of the internal structure of the baryons in the medium at the corresponding local density [226, 227, 229]. The density dependence of these couplings is equivalent to the inclusion of repulsive three-body forces between all of the baryons, which arise naturally once allowance is made for the modification of baryon structure in the medium, without any new parameters [231, 232].