Notes: 1.17-1.24.2022

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1 The code

Currently, I have made 4 codes for the bosonic ADM case and plan to make the same 4 codes for the fermionic case. As of right now, I just have one of those codes for the ADM fermionic case. So, the code I have for the bosonic ADM case are: A code deciding the central ADM values based on the desired central pressure fraction, a code that uses the ADM mass-fraction to find central ADM values, a code that assumes ADM is uniformly distributed in the NS, and a code that assumes each NS has the same ADM central values. All of these codes will be posted on the GitHub as they are finished.

2 Progress on using the HELIOS computing cluster

I have not done enough work on this to be able to report anything significant. I am going to most of tomorrow and this week putting the effort to understand how to work this.

3 Literature Review

3.1 The goal

The main reason for doing this is to see how feasible this project is given the recent published papers on the constraints of ADM in neutron stars.

3.2 Bosonic Dark Matter in Neutron Stars and its Effect on Gravitational Wave Signal-V.Sagun et al.[9]

3.2.1 Summary of the paper

They use only the mass measurements of J0348+0432 and J0740+6620, and tidal deformability constraint for a $1.4M_\odot$ ($\Lambda_{1.4} \leq 580$), and use a self-interacting bosonic dark matter equation of state via

$$P = \frac{m_\chi^4}{9\lambda}\left(\sqrt{1+\frac{3\lambda}{m_\chi^4}\rho} - 1\right)^2 \tag{1}$$

that comes from the Lagrangian

$$\mathcal{L} = \frac{1}{2}\partial^{\mu}\phi\partial_{\mu}\phi^{*} - \frac{m_{\chi}^{2}}{2}\phi\phi^{*} - \frac{\lambda}{4}(\phi\phi^{*})^{2} \tag{2}$$

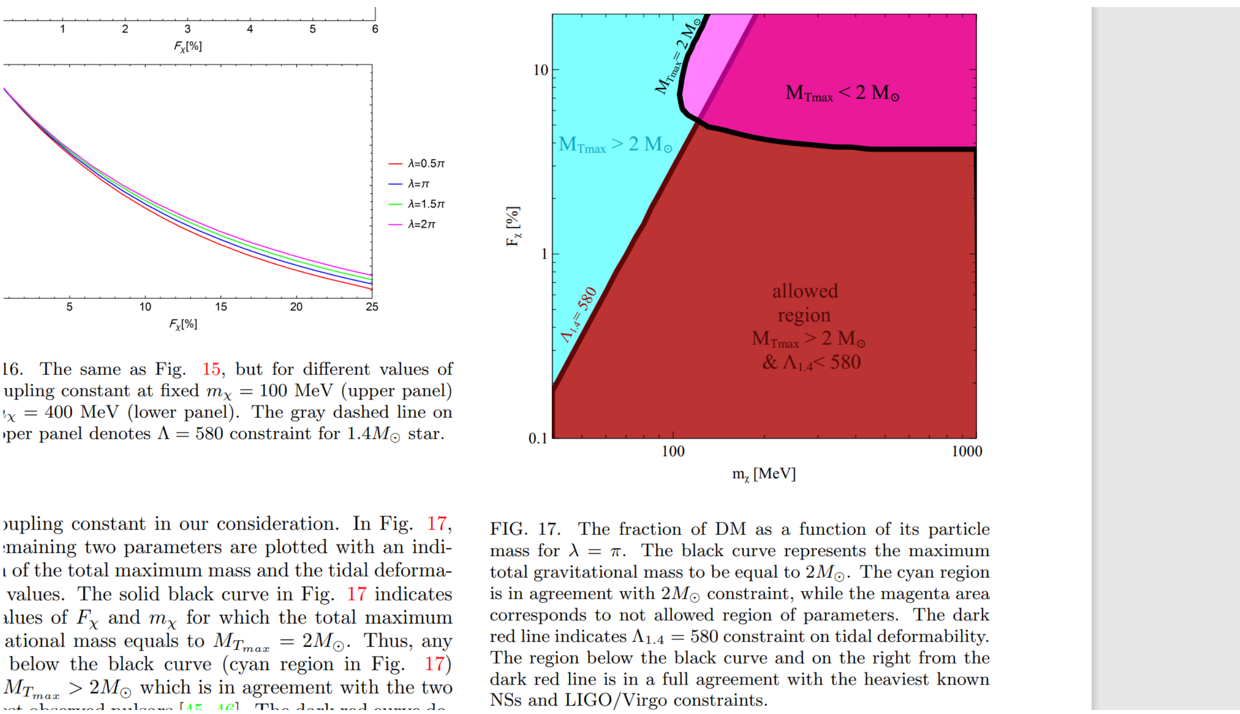

Figure 1: The main figure of [9] which aims to constrain the gravitational mass-fraction, F_χ.

This figure shows us that an allowed region in which both the total maximum mass $M_{max} \geq 2M_\odot$ and tidal deformability $\Lambda_{1.4} \leq 580$ constraints are satisfied is limited to relatively low DM fractions $F_\chi \leq 5\%$ at a fixed value of the self-coupling constant $\lambda = \pi$. This plot was made using sub-GeV dark matter particle mass.

3.3 Neutron stars: New constraints on asymmetric dark matter - V. Sagun et al. [7]

3.3.1 Summary of the paper

The authors of this paper use the non-interacting version of Nelson et al.'s fermionic ADM EOS and the reason why they do it is because the interaction term at most only accounts for 15% of the total value of the pressure/energy density. The baryonic EOS used is their own EOS called the IST EOS, which stands for induced surfact tension equation of state. Using the observational fact of the existence of the two heaviest known NSs (i.e., PSR J0348+0432, PSR J0740+6620) with the masses exceeding the two solar masses, the authors presented a new allowable range of masses of DM particles and their fractions inside the star. Our analysis is based on the ability of NSs to accumulate a sizeable amount of ADM, which can significantly reduce the mass of the host NS.Furthermore, they discussed the main stages of star evolution from the progenitor to the NS and their influence on the capturing rate of DM. Keeping in mind our limited understanding of the amount of DM in the proto-star cloud, impact of a supernova explosion and the proto-NS stages, NS in the most central parts of the Galaxy can maintain about 0.01% of DM from the total mass of the star. Based on this estimation we argue that measurements of a $2M_{\odot}$ NS in the center of the Milky Way will **constrain the upper mass of the particles of ADM below 60 GeV.**

Also they estimate how much dark matter could be in the two neutron stars. Thus, using the NFW profile for the dark matter distribution and baryonic matter density profile near those pulsars, they find $f_{\chi} = 1.60.4\%$ near PSR J0348+0432 and $f_{\chi} = 1.350.35\%$ near PSR J0740+6620. On the figure below these values are depicted as red, green and blue lines, respectively. For the Einasto profile the estimated fractions $f_{\chi} = 1.350.05\%, 1.120.049\%$ near PSR J0348+0432 and PSR J0740+6620, correspondingly.

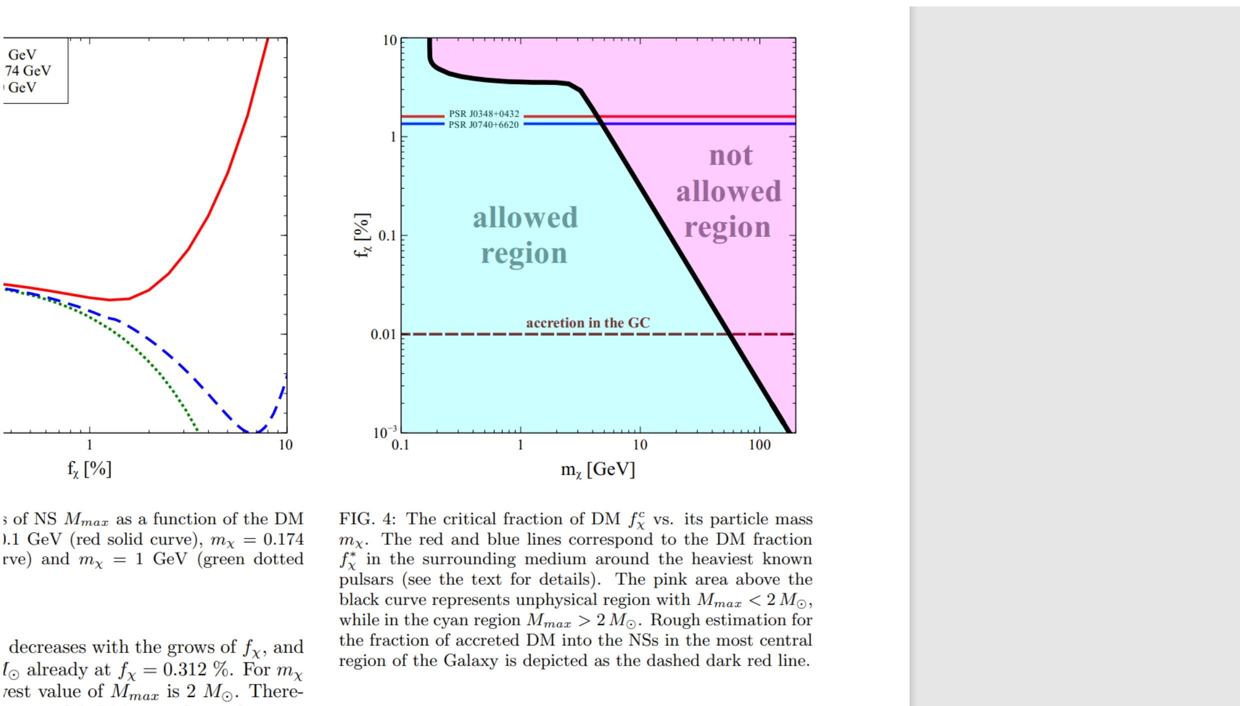

Figure 2: The main result of [7] which sets to put a constraint on the non-interacting version of Nelson et. al's fermionic EOS partile mass as well as mass-fraction.

3.4 Constraints on the fermionic dark matter from observations of neutron stars- V.Sagun et al. [10]

3.4.1 Summary of the paper

The dark matter EOS that they use is the non-interacting fermionic ADM EOS from Nelson et al. 2018 and their own IST EOS for the baryonic portion of the star. The main conclusions of this paper is that $\Lambda_{1.4M_{\odot}} \leq 800$ result from GW170817 event rejected a possibly of having an extended halo of light DM particles around compact stars, while the$2M_{\odot}$ limit shaped a range of allowed fractions of DM for higher particle's mass. Furthermore, they demonstrated how their estimate of the fraction of DM accumulated within a NS in the most central part of the Galaxy combined with future measurements of the $2M_{\odot}$ NS in that region can set the upper constraint on the mass of fermionic DM, which should not exceed 60 GeV.

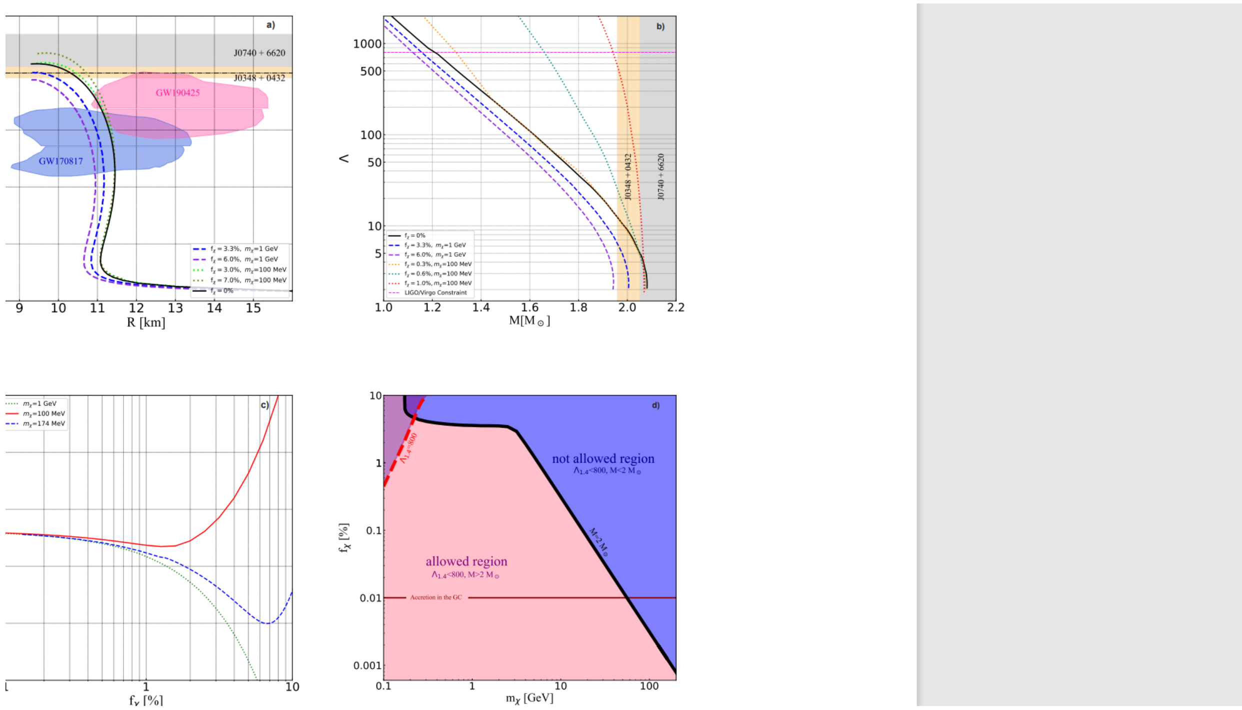

Figure 3: Panels b and d are the figures which yield the main result of [10]. The horizontal magenta colored line in b) is the upper limit on the tidal deformability constraint of a $1.4M_{\odot}$ NS where $\Lambda_{1.4M_{\odot}} \leq 800$ set by the LIGO/Virgo collaboration.

3.5 Constraining exotic compact stars composed of bosonic and fermionic dark matter with Gravitational Wave events- S.Wystub

3.5.1 Summary of the paper

This paper [12] is not so relevant despite the title since they are talking about using gravitational wave measurements to constrain compacts objects that contain only dark matter and no baryonic matter. If we look into this, then we can look at it. For now, it is not important I believe.

3.6 Effects of dark matter on the nuclear and neutron star matter - H.C. Das [4]

3.6.1 Summary of the paper

The dark matter model they use is a fermionic dark matter particle of mass $200\,GeV$ that interacts with the standard model and itself via the standard model Higgs. They also pick a constant self-interaction strength and fixed proton-Higgs form factor f. In this paper, they study of the impact of dark matter with varying Fermi momenta (k_F^{DM}, which essentially is saying that each star could have the same central number density of dark matter ($n_\chi(r = 0)$). They also consider rotating NS and how dark matter impacts the moment of inertia of those types of stars. The pulsars PSR J1614-2230 and PSR J0740+6620.

They find softer EoS with the increasing DM momentum,i.e. the energy density increases with k_F^{DM} without adding much to the pressure. The influence of DM on effective mass, symmetry energy, L-coefficient and K_{sym} are not much change with the variation of k_F^{DM} due to the small contributions of the Higgs field. However, some other derivatives of S (Qsym) and E (K) affected significantly by DM. These effects contribute to the mass, radius and moment of inertia of stellar object like a NS. Also, the variation of ϵ, K and Qsym due to DM not only affect the structure of NS but also significantly influence on the cooling effect of newly born NS after a supernova explosion.

3.7 Dark matter admixed neutron star as a possible compact component in the GW190814 merger event- H.C Das [2]

3.7.1 Summary of the paper

The ADM model is the same model as mentioned before and they the same parameters were used as well. As for the nuclear EOS they choose 6 different EOSs, but I think they are all very similar in construction given that they all begin with NL. To be precise the EOSs are NL3,NL3*. NL1,NL-SH,NL3-II,NL-RA1.

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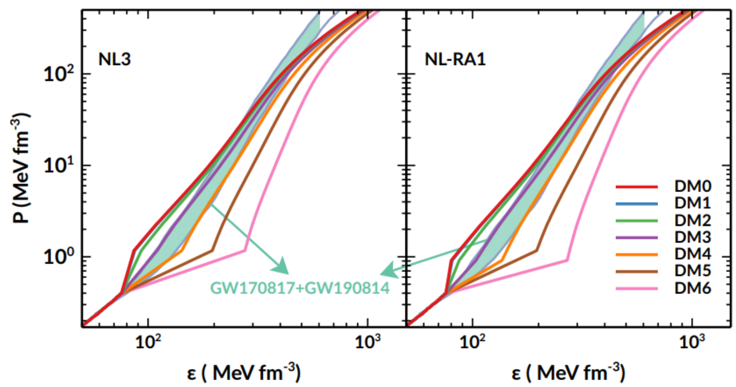

FIG. 1. The EOS are shown for NL3 and NL-RA1 with DM Fermi momenta 0–0.06 GeV. The joint constraints from the gravitational wave data GW170817 and GW190814 in shaded region are adopted from Ref. [1].

Figure 4: Each curve represents a the EOS in the top left of the plot with dark matter with different dark matter Fermi momenta 0-0.06 GeV (i.e each with different uniform dark matter number density inside the neutron star).

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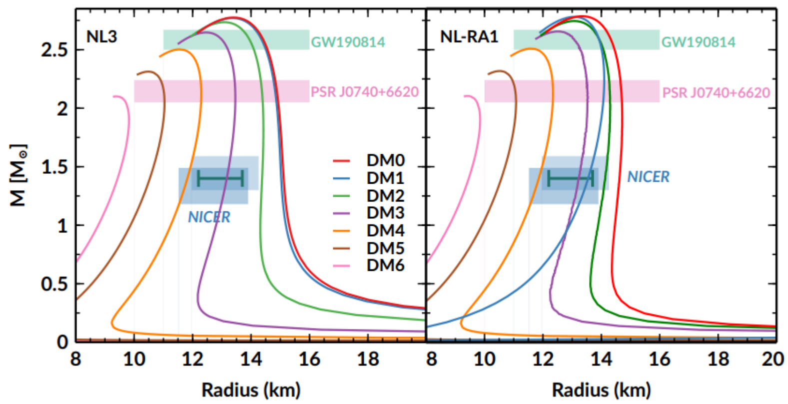

FIG. 3. The $M - R$ relations for NL3 and NL-RA1 with different DM Fermi momenta. The horizontal bars represent the maximum mass constraints from the PSR J0740+6620 (light pink) and the GW190814 event (dark cyan). The NICER data are also shown with two boxes from two different analyses [20, 21]. The double-headed green line represents the radius constraints by the GW190814 [1] for 1.4 $M_\odot$ NS.

Figure 5: Each curve represents a the EOS in the top left of the plot with dark matter with different dark matter Fermi momenta 0-0.06 GeV (i.e each with different uniform dark matter number density inside the neutron star).

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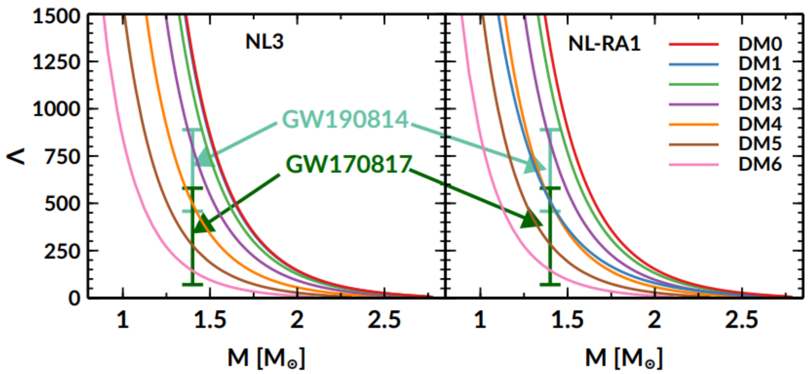


FIG. 4. (colour online) The tidal deformability of the NS with the mass for NL3 and NL-RA1 parameter set for different DM Fermi momenta. The dark cyan (green) line implies the constraint given by GW190814 (GW170817) data for 1.4 $M_\odot$ NS.

Figure 6: Each curve represents a the EOS in the top left of the plot with dark matter with different dark matter Fermi momenta 0-0.06 GeV (i.e each with different uniform dark matter number density inside the neutron star).

From the above figures their conclusions from this work is that the addition of dark matter to the EOS the EOS becomes softer and reduces the mass, radius, and tidal deformability. They note that their DM3 and DM4 passes "well through the joint constraint" of the gravitational waves. They also mention that the masses and radii are well consistent with gravitational wave data for the DM3. Lastly, they state that the radii of DM3 and DM4 are constrained well with the NICER results that they used.

3.8 Dark matter effects on the compact star properties- H.C Das [3]

3.8.1 Summary of the paper

Essentially this is the same paper as previous, but they use new measurements and show how DM3 and DM5 (same meaning as they meant last paper) impact the electric/magnetic tidal love numbers and magnetic tidal deformability as well. However, they do not compare those plots to any data. Below are the same plots as last paper, but with the new measurements.

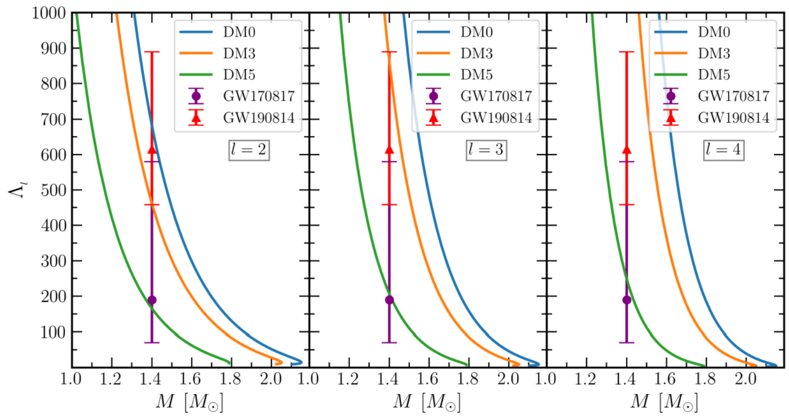


Figure 3. Same as Fig. 2, but for dimensionless electric tidal deformability. The purple colour error bar represent the constraint on $\Lambda_{1.4}$ given by LIGO/Virgo [1,55] from the BNS merger event GW170817 with, $\Lambda_{1.4} = 190^{+390}_{-70}$. The red colour error bar represents the $\Lambda_{1.4}$ constraints from the GW190814 event under the assumption of NSBH scenario with, $\Lambda_{1.4} = 616^{+273}_{-158}$ [56].

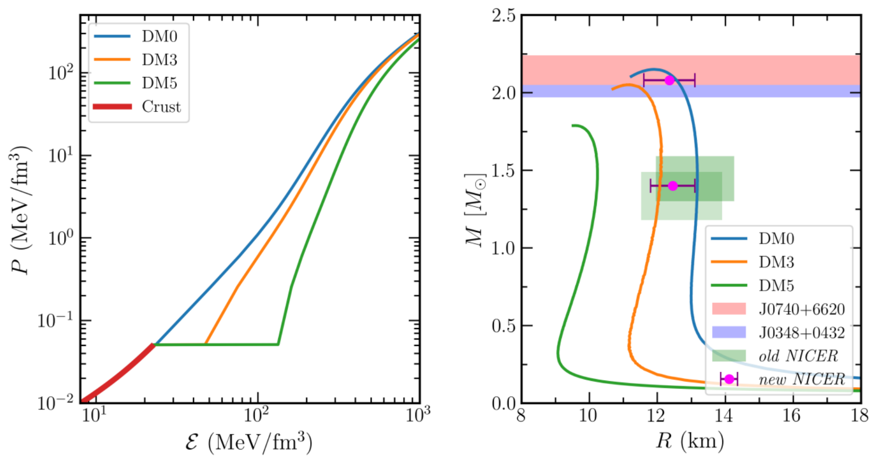


Figure 1. *Left:* EoSs for unified IOPB-I EoS (IOPB-I-U) with different DM percentage. The red line represents the IOPB-I crust calculated in Ref. [31]. *Right:* $M - R$ profiles for DM admixed NS. Different massive pulsars constraints such as MSP J0740+6620 by Cromartie *et al.* [49], and PSR J0348+0432 by Antoniadis *et al.* [50] are overlaid with different colour bars. Both old NICER [51,52] constraints for canonical star and new NICER limit for both 1.40 and 2.08 $M_\odot$ are also depicted [53].

3.9 Implications of feebly interacting dark sector on neutron star properties and constraints from GW170817 - A. Guha et. al [11]

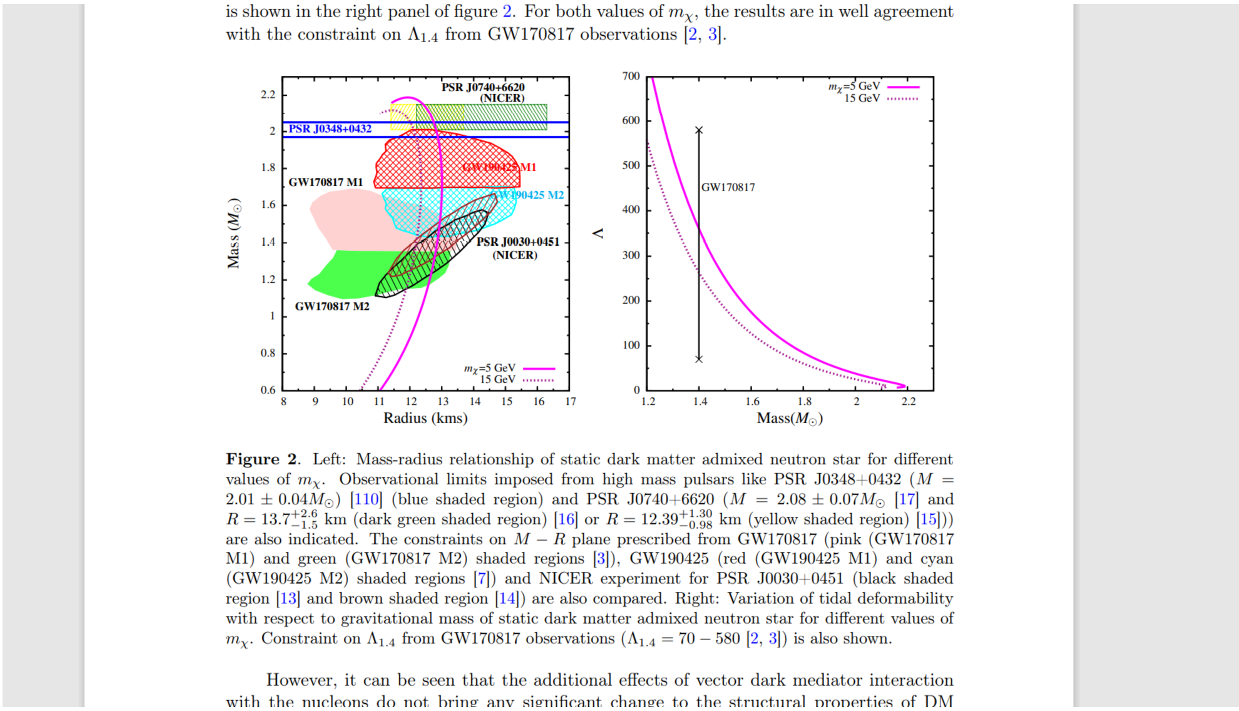
3.10 Feeble DM-SM interaction via new scalar and vector mediators in rotating neutron stars - A. Guha et. al [6]

3.10.1 Summary of the papers

I am going to put these two papers together as they do a very similar analysis the main differences is the dark matter model considered and one also considers rotating NSs at the end. Their study is very similar to the H.C Das papers given that they use same constant Fermi momenta (k_χ^F), but they use two different dark matter particle mass 5-20 GeV with 5 GeV increments. **Lastly, they are similar to the H.C Das papers in the respect that both [11, 6] assume "For the analysis we have assumed a constant density of fermionic DM throughout the NS and beyond."**. H.C Das et al ([4, 3, 2]) does not explicitly state this, but in order to have " DM0, DM3, and DM5 represent the DM Fermi momenta 0.00, 0.03, and 0.05 GeV respectively" one needs to have a constant number density.

The ADM model considered in [11] is a attractive self-interacting fermionic ADM particle that mediates with the standard model via some scalar mediator that also interacts with the Higgs. Although from Nelson et al. 2018 an interaction of ADM with the SM is going to be very very week according to SN1987A. The ADM model considered in [6] is the same as [11], but this time they include repulsive self-interactions via some vector mediator. Lastly, they both consider the same nuclear EOS which is $\sigma - \omega$ model for nuclear matter.

Even though they each look at observed data from J0030,J00740,J0348,GW170817,GW190425 the main result gathered from their works were that the main impacts of a ADM core with radius of the NS and that the parameter space in which they used were consistent with the data. However, they make no attempt to try to constrain any of the parameter space of the ADM model. Below are the figures used in each paper and I will caption each with a citation from each appropriate paper.



is shown in the right panel of figure 2. For both values of m_χ, the results are in well agreement with the constraint on $\Lambda_{1.4}$ from GW170817 observations [2, 3].

Figure 2. Left: Mass-radius relationship of static dark matter admixed neutron star for different values of m_χ. Observational limits imposed from high mass pulsars like PSR J0348+0432 ($M = 2.01 \pm 0.04 M_\odot$) [110] (blue shaded region) and PSR J0740+6620 ($M = 2.08 \pm 0.07 M_\odot$ [17] and $R = 13.7^{+2.6}_{-1.5}$ km (dark green shaded region) [16] or $R = 12.39^{+1.30}_{-0.98}$ km (yellow shaded region) [15])) are also indicated. The constraints on $M - R$ plane prescribed from GW170817 (pink (GW170817 M1) and green (GW170817 M2) shaded regions [3]), GW190425 (red (GW190425 M1) and cyan (GW190425 M2) shaded regions [7]) and NICER experiment for PSR J0030+0451 (black shaded region [13] and brown shaded region [14]) are also compared. Right: Variation of tidal deformability with respect to gravitational mass of static dark matter admixed neutron star for different values of m_χ. Constraint on $\Lambda_{1.4}$ from GW170817 observations ($\Lambda_{1.4} = 70 - 580$ [2, 3]) is also shown.

However, it can be seen that the additional effects of vector dark mediator interaction with the nucleons do not bring any significant change to the structural properties of DM

Figure 7: The mass-radius and tidal deformability-mass plots from [11]

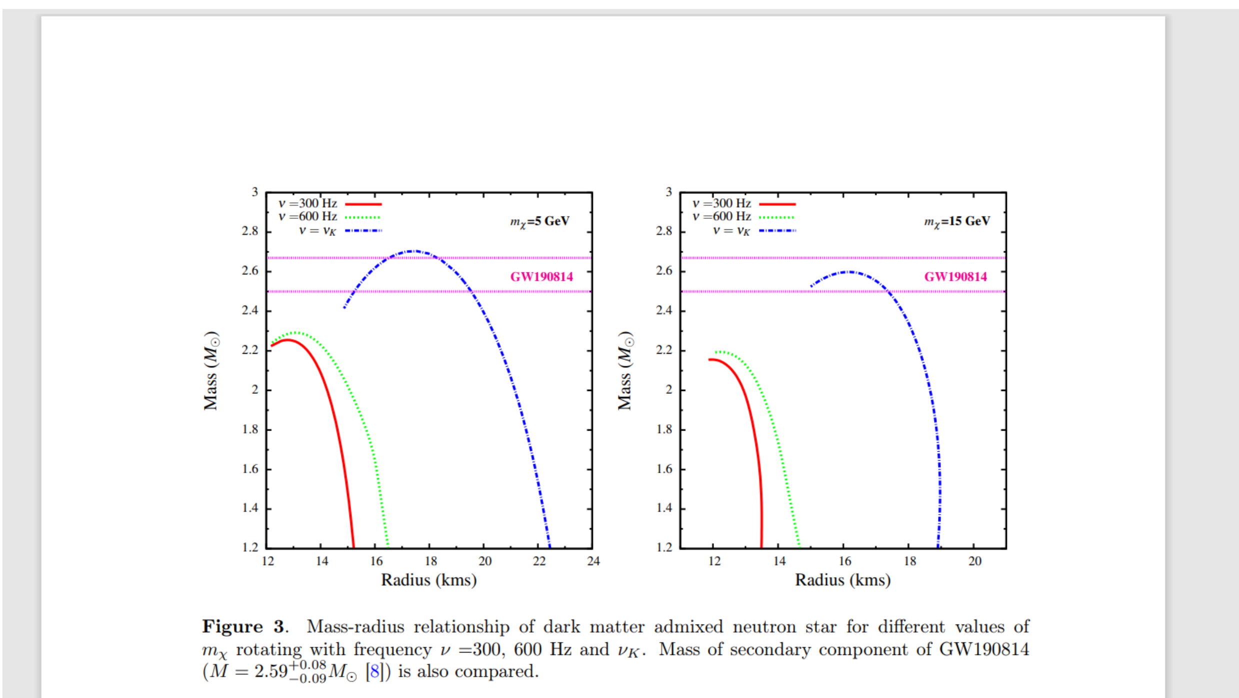


Figure 3. Mass-radius relationship of dark matter admixed neutron star for different values of m_χ rotating with frequency ν =300, 600 Hz and ν_K. Mass of secondary component of GW190814 ($M = 2.59^{+0.08}_{-0.09} M_\odot$ [8]) is also compared.

Figure 8: The incorporation of rotation frequency in mass-radius plots from [11]

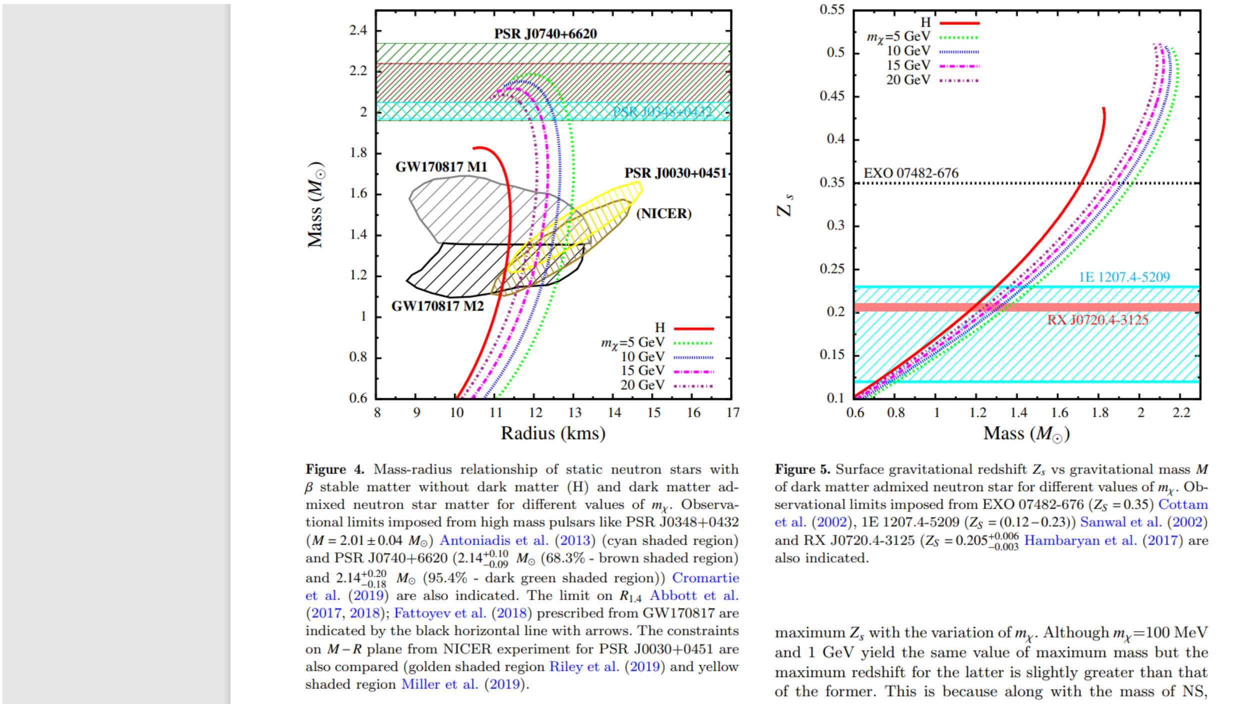


Figure 4. Mass-radius relationship of static neutron stars with β stable matter without dark matter (H) and dark matter admixed neutron star matter for different values of m_χ. Observational limits imposed from high mass pulsars like PSR J0348+0432 ($M = 2.01 \pm 0.04$ $M_\odot$) Antoniadis et al. (2013) (cyan shaded region) and PSR J0740+6620 ($2.14^{+0.10}_{-0.09}$ $M_\odot$ (68.3% - brown shaded region) and $2.14^{+0.20}_{-0.18}$ $M_\odot$ (95.4% - dark green shaded region)) Cromartie et al. (2019) are also indicated. The limit on $R_{1.4}$ Abbott et al. (2017, 2018); Fattoyev et al. (2018) prescribed from GW170817 are indicated by the black horizontal line with arrows. The constraints on $M-R$ plane from NICER experiment for PSR J0030+0451 are also compared (golden shaded region Riley et al. (2019) and yellow shaded region Miller et al. (2019).

Figure 5. Surface gravitational redshift Z_s vs gravitational mass M of dark matter admixed neutron star for different values of m_χ. Observational limits imposed from EXO 07482-676 ($Z_S = 0.35$) Cottam et al. (2002), 1E 1207.4-5209 ($Z_S = (0.12-0.23)$) Sanwal et al. (2002) and RX J0720.4-3125 ($Z_S = 0.205^{+0.006}_{-0.003}$ Hambaryan et al. (2017) are also indicated.

maximum Z_s with the variation of m_χ. Although m_χ=100 MeV and 1 GeV yield the same value of maximum mass but the maximum redshift for the latter is slightly greater than that of the former. This is because along with the mass of NS,

Figure 9: The mass-radius plot from [6]. Please ignore the plot to the right as they were also considering gravitational redshift versus mass. Unless we also wish to look into this type of constraint (if the data is available.)

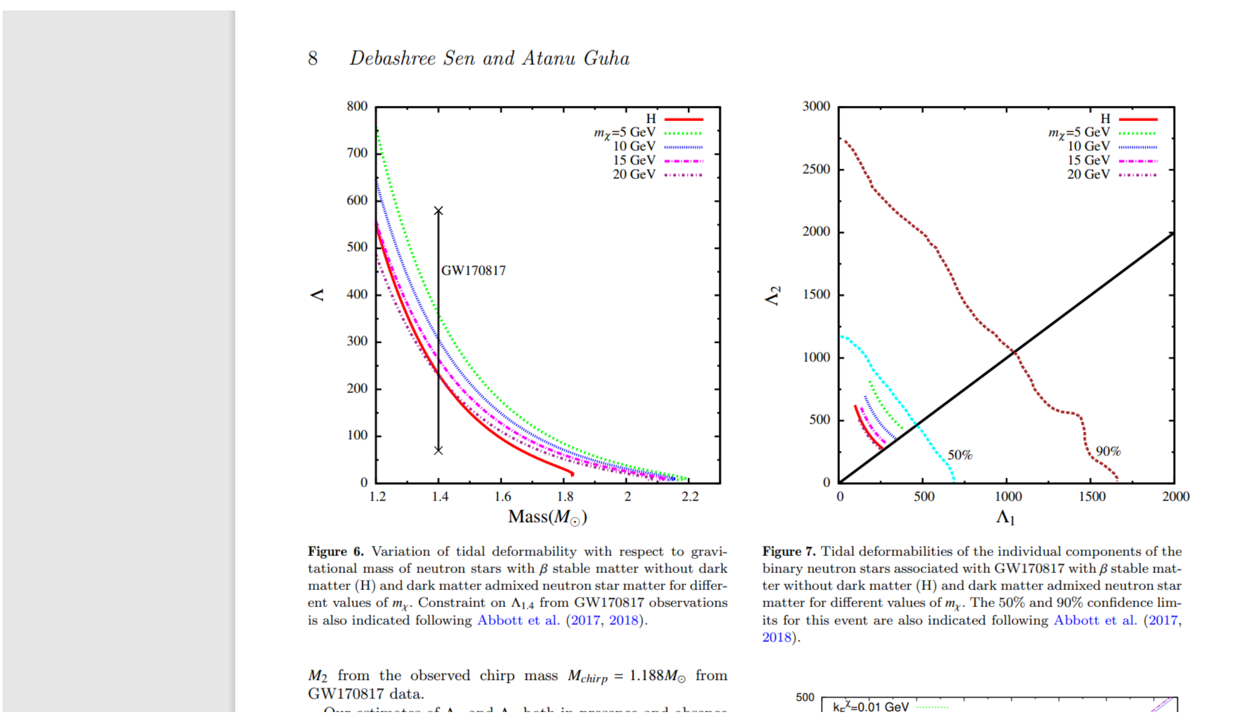

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Figure 6. Variation of tidal deformability with respect to gravitational mass of neutron stars with β stable matter without dark matter (H) and dark matter admixed neutron star matter for different values of m_χ. Constraint on $\Lambda_{1.4}$ from GW170817 observations is also indicated following Abbott et al. (2017, 2018).

Figure 7. Tidal deformabilities of the individual components of the binary neutron stars associated with GW170817 with β stable matter without dark matter (H) and dark matter admixed neutron star matter for different values of m_χ. The 50% and 90% confidence limits for this event are also indicated following Abbott et al. (2017, 2018).

M_2 from the observed chirp mass $M_{chirp} = 1.188 M_\odot$ from GW170817 data.

Figure 10: The tidal deformability-mass plots from [6]

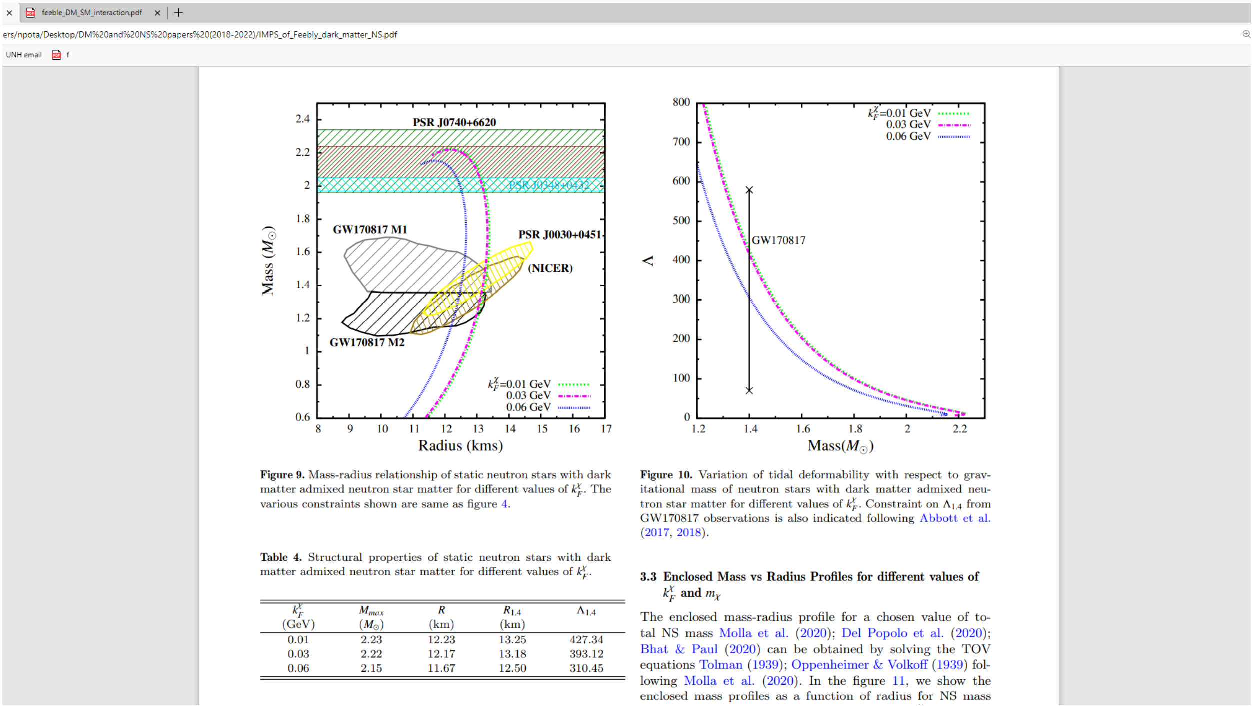

Figure 9. Mass-radius relationship of static neutron stars with dark matter admixed neutron star matter for different values of k_F^χ. The various constraints shown are same as figure 4.

Figure 10. Variation of tidal deformability with respect to gravitational mass of neutron stars with dark matter admixed neutron star matter for different values of k_F^χ. Constraint on $\Lambda_{1.4}$ from GW170817 observations is also indicated following Abbott et al. (2017, 2018).

Table 4. Structural properties of static neutron stars with dark matter admixed neutron star matter for different values of k_F^χ.

k_F^χ (GeV)	M_{max} ($M_\odot$)	R (km)	$R_{1.4}$ (km)	$\Lambda_{1.4}$
0.01	2.23	12.23	13.25	427.34
0.03	2.22	12.17	13.18	393.12
0.06	2.15	11.67	12.50	310.45

3.3 Enclosed Mass vs Radius Profiles for different values of k_F^χ and m_χ

The enclosed mass-radius profile for a chosen value of total NS mass Molla et al. (2020); Del Popolo et al. (2020); Bhat & Paul (2020) can be obtained by solving the TOV equations Tolman (1939); Oppenheimer & Volkoff (1939) following Molla et al. (2020). In the figure 11, we show the enclosed mass profiles as a function of radius for NS mass

Figure 11: The mass-radius and tidal deformability-mass plots from [6] using different Fermi momenta instead of different masses. **Note** this approach assumes a uniform number density distribution within the neutron star.

3.11 Dark matter admixed neutron star properties in the light of gravitational wave observations: a two fluid approach- Apran Das [1]

3.11.1 Summary of the paper

This paper was interesting as it uses a different ADM model where dark matter has two mediators (as shown [5]) which supposes ADM has a scalar and vector mediator. However, this is similar to a model where one simply says this scalar mediator is the Higgs. They also use Bayesian Parameter optimization for the dark matter properties of the scalar and vector mediator interaction strengths, total dark matter particle mass, and dark matter fraction defined by $\frac{\epsilon_{ADM}(r=0)}{\epsilon_{Baryons}(r=0)}$. Although, what they did was interesting the paper did not give anything new and simply concluded that these results are model independent and that a model independent study should be done. Below is the table that was shown in the conclusion

Data		Parameters		
	value		Flat Prior	Posterior
NS maximum mass ($M_\odot$)	2.01 ± 0.04 [70]	c_{sd} (Gev^{-1})	$1-7$	$3.90^{+0.82}_{-0.70}$
$R_{1.4}$ (Km.)	11.3 ± 1.0 [71–74]	c_{vd} (Gev^{-1})	$10-14$	$11.88^{+0.53}_{-0.46}$
$\Lambda_{1.4}$	70-580 [75]	M_D (MeV)	$200-1200$	$730.57^{+132.87}_{-103.93}$
		f_D	$0.0-0.25$	$0.08^{+0.03}_{-0.02}$

TABLE II: Table of information considered for the estimation of the unknown parameters in the dark matter sector along with the optimized parameters using the Bayesian parameter optimization. Here ± indicates the error in the values of various quantities.

to the nuclear matter, parameters in the density dependent dark matter sector are not fixed. Using the Bayesian

4 My thoughts on the feasibility of this project after this review

To begin, I would like to say that I believe that our project is still feasible. The thoughts I have on this are varied and would like to discuss this with everyone on Wednesday. Also, I would like to say that I don't think that these directions are mutually exclusive and we could certainly do them all in some fashion.

1. The first thought I have on this is that we set constraints on ADM parameters in each NS that we have access to and treat each with a case by case basis. Then we create a plot of interaction strength vs. ADM particle mass, similar to that of [8], but we take into account of the total mass of the resulting ADM admixed NS to ensure that the maximum mass of the mass-radius is still above $2\,M_\odot$. Lastly, we place the appropriate constraints that we got from the NS onto this plot as well. I am unsure if it is possible to set constraints on the ADM parameters, but if we can produce a table similar to that of [1] for each available NS then that could be useful to hopefully add more constraints to the mentioned plot. Also, I think we could consider figures for the cases purely core and halo cases.

2. The other thought I have on this is that we try to constrain the dark matter pressure fraction vs. interaction strength for bosonic and fermionic dark matter. We also could add in the constraints of the maximum mass of the mass-radius as well as the ADM parameters constraints from NSs in (1).

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