PROCEEDINGS OF SCIENCE

Pulsar Timing Constraints on New Mechanisms of Energy Loss in Neutron Stars

Susan Gardner[a,*]

[a] *Department of Physics and Astronomy, University of Kentucky, Lexington, KY 40506-0055, USA*

E-mail: susan.gardner@uky.edu

The neutron lifetime anomaly speaks to the possibility of exotic decay channels of the neutron. The very existence of neutron stars constrains the strength of such effects, and in this talk I develop how precisely determined energy-loss constraints, particularly anomalous binary-pulsar period lengthening, limit not only the total baryon loss rate across the star but also the parameters of the particle physics models that can produce such loss. To do this, we compute the new processes in the dense nuclear medium found at the core of a neutron star, employing the techniques of relativistic mean-field theory. Focusing on scenarios in which the dark-sector particles do not accumulate in the star, we extract limits on in-vacuum exotic neutron decays, and we determine them for various equations of state, noting their implications.

The XVIth Quark Confinement and the Hadron Spectrum Conference (QCHSC24)
19-24 August, 2024
Cairns Convention Centre, Cairns, Queensland, Australia

*Speaker

https://pos.sissa.it/

PoS(QCHSC24)223

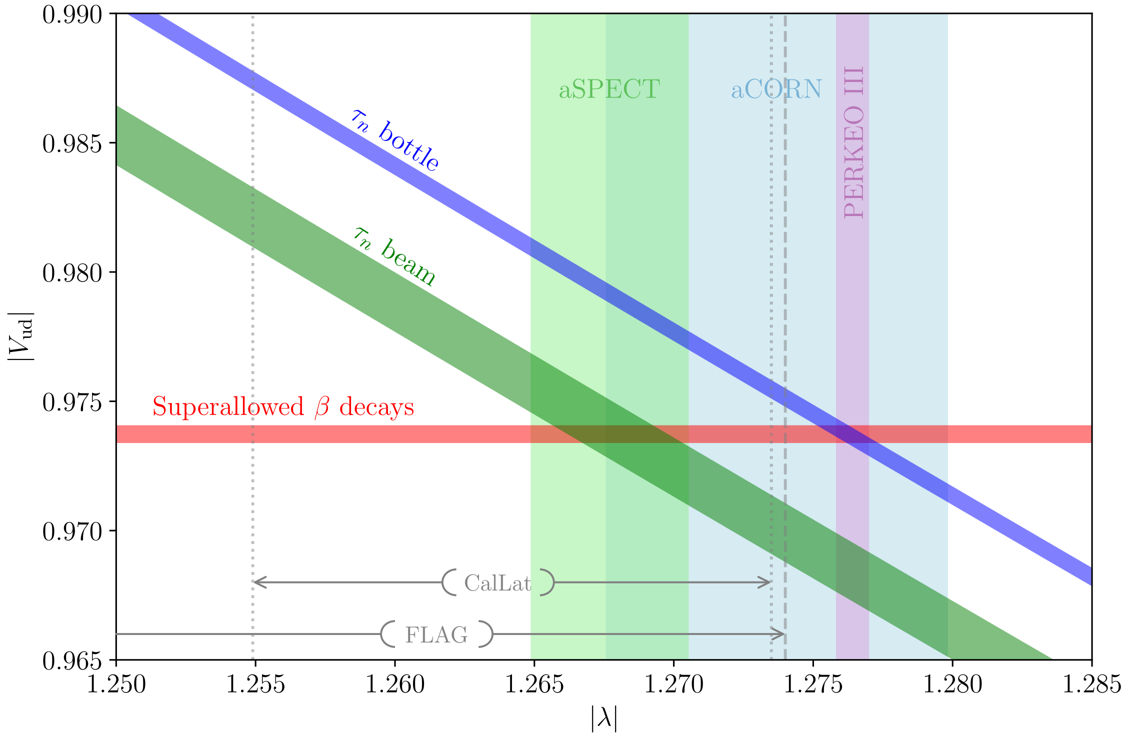

Figure 1: The SM correlation between the CKM matrix element $|V_{ud}|$ versus the axial-vector to vector coefficient ratio $|\lambda| = |g_A/g_V|$ is presented, utilizing the averaged neutron lifetime values from bottle (blue) and beam (green) methods. Vertical bands illustrate $|\lambda|$ determinations from a (aSPECT and aCORN) and A (PERKEO III) decay correlation measurements. Additionally, lattice QCD computations of g_A are shown as gray lines. Figure taken from [3], to which we refer for all details.

1. Introduction

Observations of pulsar timing in neutron-star systems provide sensitive energy-loss constraints that open new windows on exotic mechanisms of neutron disappearance. Baryon number violation (BNV) appears in many models of physics beyond the Standard Model (SM), and here we consider *apparent* BNV in which a neutron disappears to a final state with non-SM particles and no baryons [1]. In this contribution, drawn from [1–3], we describe the motivations for studying such exotic decays, noting the connections to new-physics mechanisms to generate dark matter and the cosmic baryon asymmetry [4–13]. This and the existence of precisely determined energy-loss constraints in neutron stars, particularly through pulsar-timing observations in binary-pulsar systems [14, 15], limit not only the total baryon loss rate across the star but also the parameters of the particle physics models that can produce such loss [1, 2, 16, 17]. Here we outline how this is realized concretely.

2. From the neutron lifetime puzzle to dark decays and late-scale co-genesis

An intriguing anomaly of decades-long standing lies in determinations of the neutron lifetime, in that its measured value depends on how it is measured. Certainly there is only one neutron

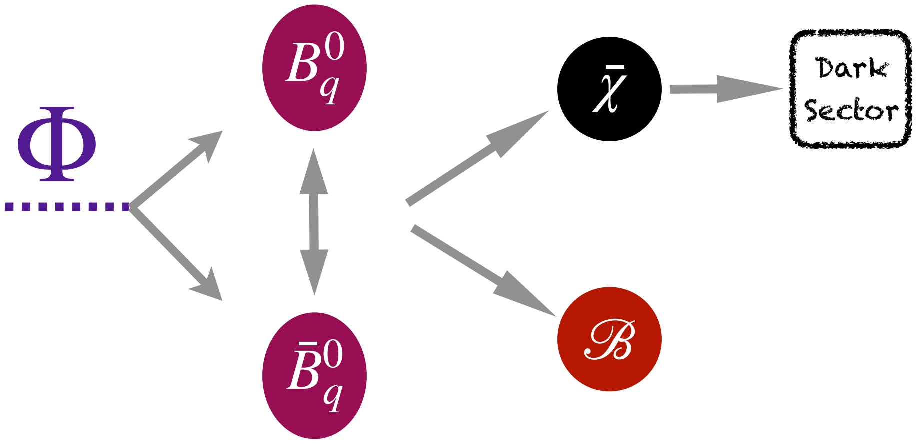

Figure 2: A schematic illustration of B-mesogenesis [8], a late-scale dark co-genesis model. Here a scalar Φ, produced out of equilibrium, decays and hadronizes to a $B_q^0 \bar{B}_q^0$ pair, with $q \in d, s$. The pair mixes, in the presence CP violation, and, finally, a B meson decays preferentially to $B \to \mathcal{B}\bar{\chi}$, a baryon $\mathcal{B}$ - dark anti-baryon $\bar{\chi}$ pair. Since $\bar{\chi}$ carries $\mathcal{B} = -1$ the $\mathcal{B}\bar{\chi}$ final states do not break baryon number, yet this scenario produces a baryon asymmetry in the visible sector. The produced $\bar{\chi}(\chi)$ decays to other dark sector states, which can function as dark-matter candidates. Figure taken from [3].

lifetime, and the numerical difference from the different methods is about a 1% effect. Perhaps the neutron decays to a non-SM final-state, explaining why counting "living" neutrons (as in the bottle method), rather than "dead" ones (i.e., decay products, as in the beam method) [18], yields a shorter lifetime [19, 20], though severe constraints on this scenario arise from the measured $V - A$ structure of the SM weak currents in neutron decay [21] and the observed neutron star masses [22–24]. Recent neutron lifetime and decay measurements and computations are compiled in Fig. 1. Yet, even so, the rate of baryon disappearance to exotic final states is apparently allowed to be grossly larger than that of neutron decay with BNV to SM final states. Intriguingly, a model with a baryon-number-carrying scalar that produces $n \to \chi\gamma$ [19], where χ is a dark baryon, also operates as a dynamical ingredient in "B-mesogenesis" — a low-scale, dark co-genesis model [8, 12].

BNV is one of the Sakharov conditions for baryogenesis in the early Universe [25], but in low-scale baryogenesis models with "hidden" sectors that explain both dark matter and the cosmic baryon asymmetry, as in, e.g., [4, 7, 8], the noted conditions can be sufficient, rather than necessary. A common feature of such scenarios is a generalized definition of baryon number, across visible and hidden sectors [5]. Even in the event that the total such baryon number is zero, a cosmic baryon asymmetry arises from generating net baryon number in the visible sector, making processes that link baryons and hidden-sector baryons necessary. These models are also seemingly insensitive to the increasingly severe experimental limits on the permanent electric dipole moments of the neutron and electron [26, 27], in that they can yield baryogenesis even in the absence of sources of CP violation beyond the SM. A concrete illustration is provided in Fig. 2. There, out-of-equilibrium decays of a scalar to a $B\bar{B}$ meson pair, with CP violation, yields B (or $\bar{B}$) decay to $\mathcal{B}\bar{\chi}$ ($\bar{\mathcal{B}}\chi$). A rate excess in the channel with a SM baryon $\mathcal{B}$ generates the cosmic baryon asymmetry. To do this, a dark-sector interaction must be chosen to mediate χ decay, to avoid washout and to generate a dark-matter candidate — and different choices and neutron-star scenarios [3] are possible. Following

[8, 11], we introduce a dark baryon χ and baryon-number carrying scalars Y_{Y}, transforming as $(\bar{3}, 1, \mathrm{Y})$ under $\mathrm{SU(3)} \times \mathrm{SU(2)_L} \times \mathrm{U(1)_Y}$, to yield either

$$\mathcal{L}_{Y_{\frac{2}{3}}} \supset -y_{d_a d_b} \epsilon_{\alpha\beta\gamma} Y^{\alpha}_{\frac{2}{3}} d^{\beta}_{a} d^{\gamma}_{b} - y_{\chi u_c} Y^{\alpha *}_{\frac{2}{3}} \chi^{c} u^{\alpha}_{c} + \mathrm{h.c.}\,, \tag{1}$$

or

$$\mathcal{L}_{Y_{-\frac{1}{3}}} \supset -y_{u_a d_b} \epsilon_{\alpha\beta\gamma} Y^{\alpha}_{-\frac{1}{3}} u^{\beta}_{a} d^{\gamma}_{b} - y_{\chi d_c} Y^{\alpha *}_{-\frac{1}{3}} \chi^{c} d^{\alpha}_{c} + \mathrm{h.c.}\,. \tag{2}$$

The Roman subscripts are generational indices, and a dark-sector interaction

$$\mathcal{L}_{\mathrm{dark}} \supset y_d \bar{\chi} \phi_B \xi + \mathrm{h.c.} \tag{3}$$

permits χ decay, where ϕ_B is a scalar and ξ is a Majorana fermion. Constraining the flavor-structure of the possible couplings is a key path to determining the viability of the new-physics mechanism [2, 11]. In a neutron star, we consider the scenario $m_\xi > m_\chi > m_{\phi_B}$, particularly so that the induced decay shown in Fig 3 does not occur (though we note [28] for a study in a scenario in which it does) but $\chi - \chi$ annihilation does, yielding light decay products that can escape the star [2].

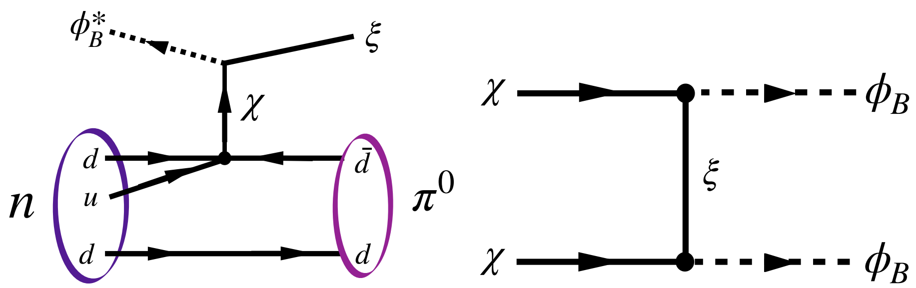

Figure 3: Feynman diagram contributing to induced neutron decay (left) via our dark sector interaction and to χ-χ annihilation (right), taken from [2].

At very low energies, these models lead to $n - \chi$ mixing at some strength $\varepsilon_{n\chi}$. If dark-sector particles do not accumulate in the star, so that, rather, they decay into particles that escape the star, its structure is approximately fixed by its central energy density ε_c, as per the solution to the TOV equations for a star with a fixed equation of state (EoS) in the SM. Supposing a quasi-equilibrium condition $\Gamma_{\mathrm{BNV}} \ll \Gamma_{\mathrm{weak}}$, where the latter characterizes the URCA rates, this implies that as ε_C changes from n disappearance, the structure of the star is still fixed by SM physics [1]. Thus, given a rate of change of $\mathcal{B}$, we can predict changes in the macroscopic parameters of the star and limit microscopic (dark-decay) models using relativistic mean-field (RMF) theory models [29, 30] in hadronic degrees of freedom adapted to describe neutron stars in β equilibrium [31, 32]. Using a suitable hidden-sector choice, we have followed this path to find severe constraints on $n - \chi$ mixing, setting limits on the possible parameter space in $\varepsilon_{n\chi}$ and M_χ.

3. Limiting exotic neutron loss with energy-loss constraints in neutron stars

Energy loss in neutron stars can be studied in different ways, through observational studies of individual pulsars vis-a-vis their spin-down or cooling rates or through observations of pulsars

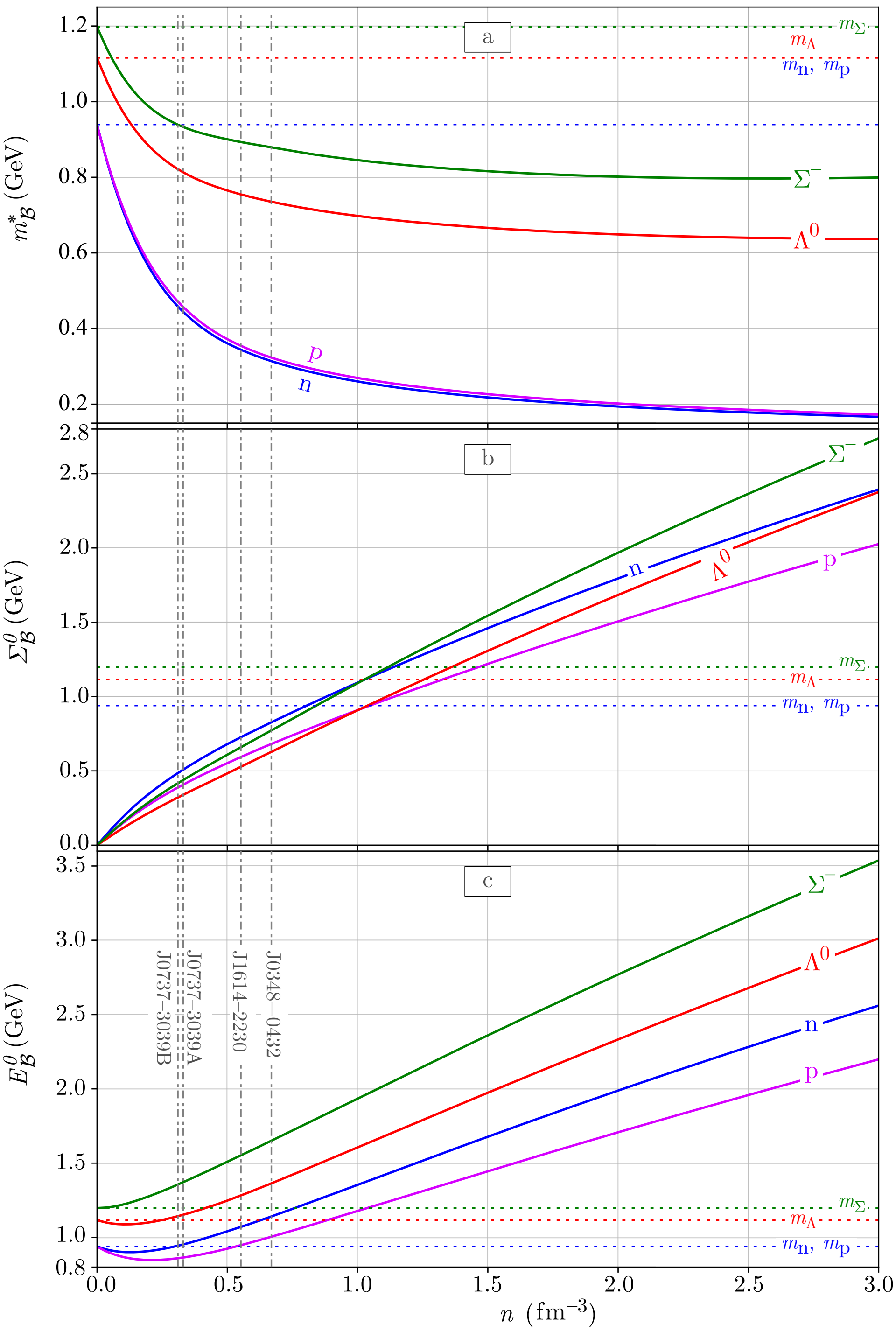

Figure 4: Variations in baryonic properties in the neutron star for the "DS(CMF)-1" EoS [31, 33] as functions of density. (**a**) Effective masses of various baryons. (**b**) Vector self-energies of the baryons in the nuclear matter frame. (**c**) Range of center-of-mass frame energies for the baryons. Vertical lines in all panels represent the central number densities of particular pulsar systems, while horizontal lines correspond to the vacuum masses of the respective baryons. Taken from [2], to which we refer for all details.

in binary systems. Here we focus on the observed relative rate of orbital period change $\dot{P}_b/P_b$ determined from pulsars in binary systems, which have yielded remarkably precise tests of general relativity [14, 15]. Variations in $\dot{P}_b/P_b$ can be sourced by either intrinsic effects, such as gravitational radiation or neutron-star energy loss, or extrinsic effects generated by the motion of the binary pulsar with respect to the solar system barycenter [34]. The contribution from gravitational radiation is long known [35], and we use [36] to assess the extrinsic effect due to the Galactic potential. Thus the difference of the observed and computed energy-loss effects from gravitational radiation and external forces allows us to set limits on the possibility of neutron-star energy loss, which we shall interpret in terms of a limit on anomalous baryon loss and finally as a limit on the rate for neutron dark decays, such as $n \to \chi\gamma$.

Tens of binary pulsars with measured P_b and $\dot{P}_b$ are known [37], and we choose systems in which there is no apparent mass transfer between the components and for which the individual masses are known. Binary systems with different pulsar masses allow us to sample different portions of $n - \chi$ mixing parameter space with m_χ. We find the strongest limits come from double pulsar binary systems, so that using J0737-3039A/B [38], e.g., we find a 2σ limit on $\dot{B}/B$ (from BNV) of $4.0 \times 10^{-13}\,\mathrm{yr}^{-1}$ [1, 2].

4. Assessing particle decays in the core of a neutron star

Dense-matter environments offer new opportunities to probe non-SM physics. Here we model that medium using the covariant hadronic model of [31] and work in its RMF limit, implying that the medium effects can be addressed through shifts in the baryon momenta and masses that change as a function of density. Finally, the baryons in neutron stars in the nuclear matter (n.m.) rest frame have a lower effective mass $m^*_{\mathcal{B}}$ and a higher self-energy $\Sigma^0_{\mathcal{B}}$ at high densities, but their rest energies $E^0_{\mathcal{B}}$ can be much higher than their rest masses, as shown in Fig. 4. The properties of a weakly-coupled dark baryon are not modified by those medium shifts, however, so that the medium effects change the allowed phase space of a baryon dark decay, such as $\mathcal{B} \to \chi\gamma$, opening access to χ masses that would not otherwise be accessible. We find it convenient to compute the decaying baryon width in the center of velocity (c.v.) frame because the in-medium baryon is not moving, but we compute the rate of change of the local baryon density with proper time in the n.m. frame, as then the matter is at rest [2]. Integrating these outcomes over the density profile of the star, we limit the $\varepsilon_{\mathcal{B}\chi}$ mixing parameter with m_χ, given the limits we determine on the anomalous energy loss in each pulsar system we consider.

5. Dark decay limits from energy-loss constraints in pulsar binaries

Finally, combining the various results, we report the 2σ exclusion limits on the $\varepsilon_{\mathcal{B}\chi}$ mixing parameters with m_χ as a function of the pulsar system chosen in Fig. 5. We also compare the 2σ exclusion limits on the vacuum branching fraction $\mathcal{B} \to \chi\gamma$ as a function of m_χ with the outcomes of terrestrial searches for BNV in Fig. 6. Finally, we show the limits on $n - \chi$ mixing and on the branching ratio for $n \to \chi\gamma$ in the mass region specific to neutron lifetime anomaly in Fig. 7. It is apparent that the limits on dark decay rates afforded by neutron stars are severe.

PoS(QCHSC24)223

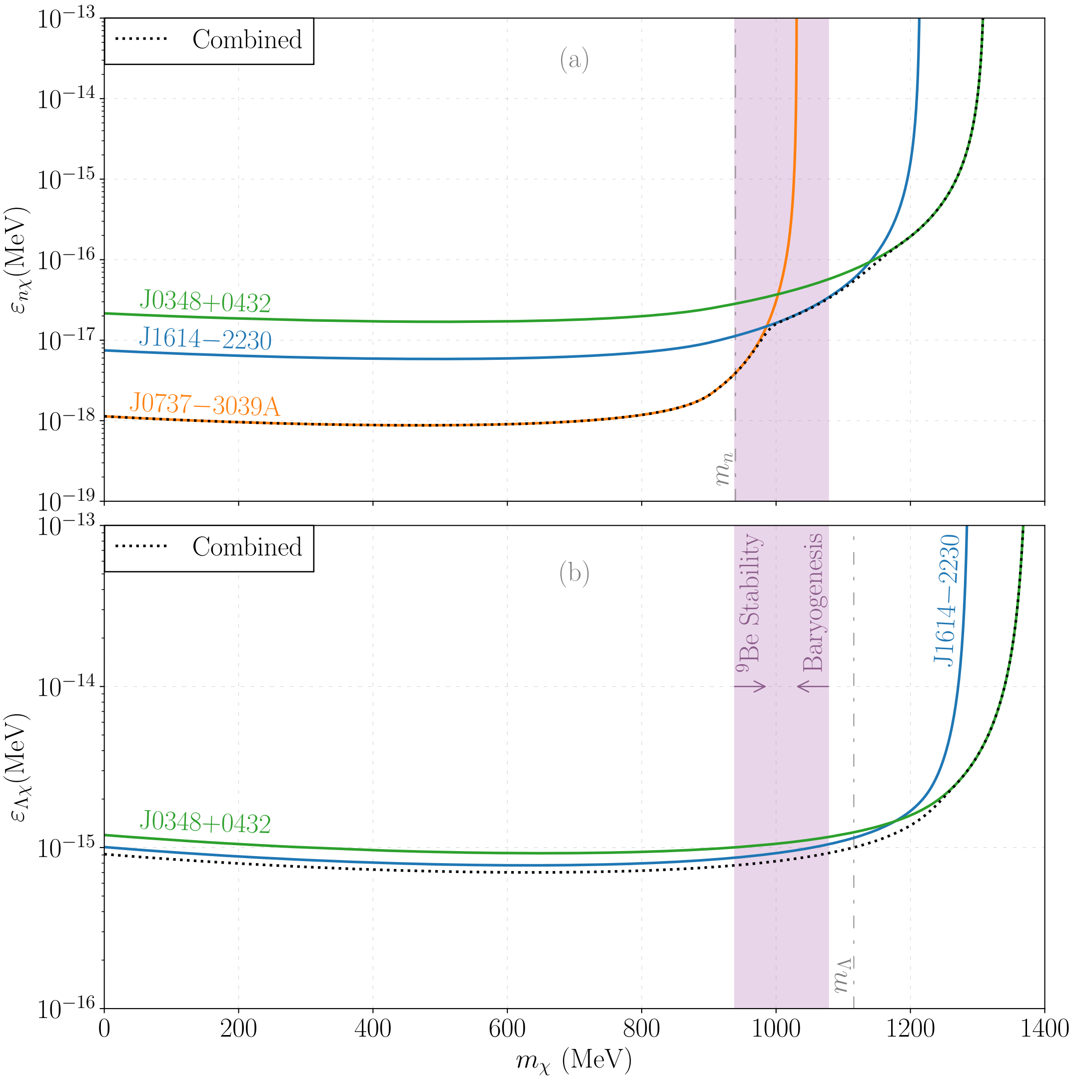

Figure 5: Two-σ exclusion constraints on the mixing parameters for baryon-dark baryon interactions based on the DS(CMF)-1 EoS [2] and our dark sector choice. The vertical purple band indicates the range for the dark baryon mass (m_χ) required by nuclear stability and successful baryogenesis. (**a**) Neutron (n)-dark baryon (χ) interaction constraints as functions of m_χ. The colored lines represent the exclusion limits from the pulsars in PSR J0348+0432 (green), PSR J1614–2230 (blue), and pulsar A in the double pulsar system PSR J0737–3039A/B (orange), with the combined limits depicted by a dotted black curve. The vertical dashed lines mark the vacuum rest mass of the neutron. (**b**) Similar constraints for the Λ-χ interaction, using the same color scheme and presentation with the vertical dashed line representing the vacuum rest mass of the Λ hyperon. The vertical lines denote the central densities of the pulsars that we consider in this study. Taken from [2], to which we refer for all details.

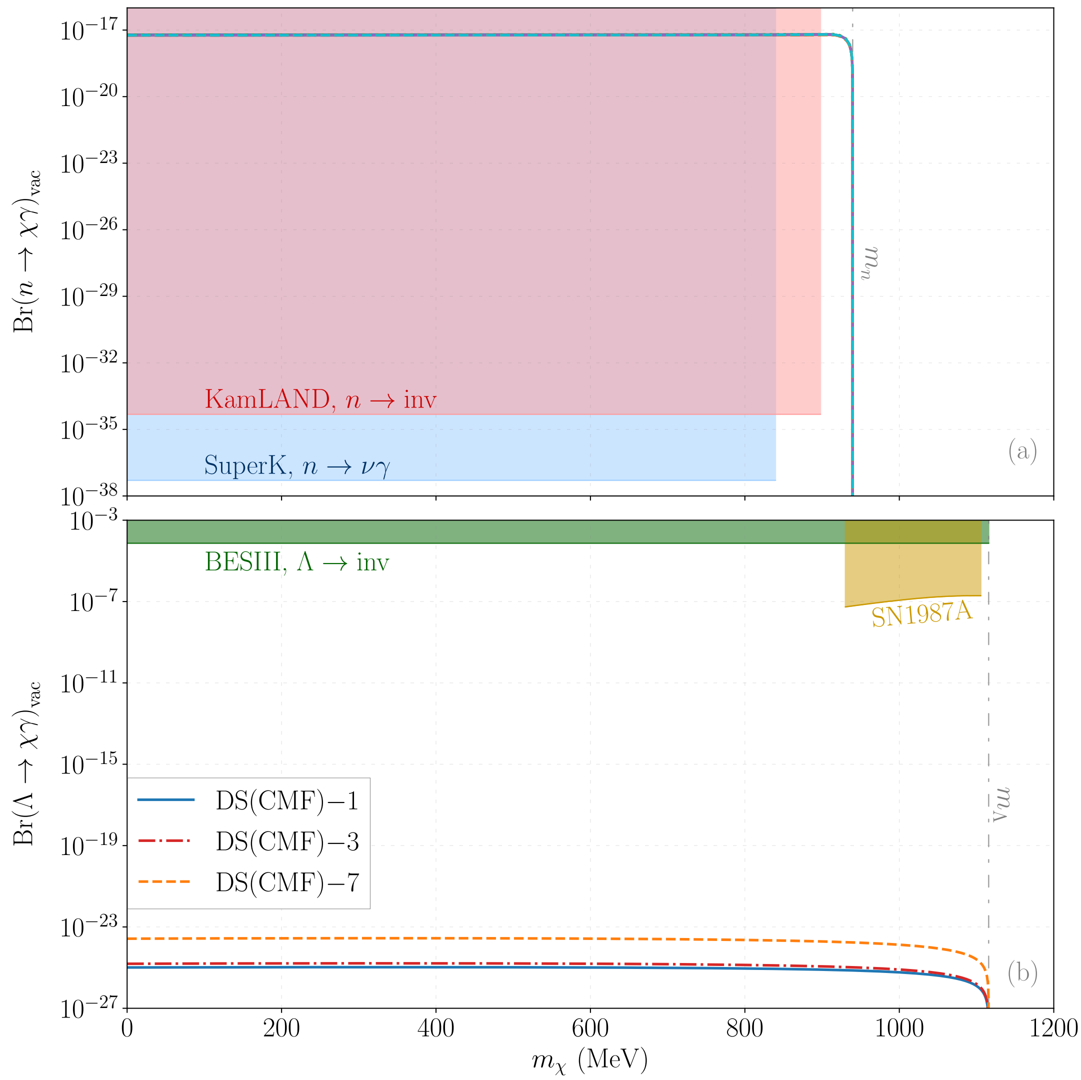

Figure 6: Two-σ exclusion limits on the vacuum branching fraction for $\mathcal{B} \to \chi\gamma$ processes are depicted in panels **(a)** for neutrons and **(b)** for Λ baryons. The blue region represents limits from SuperKamiokande [39]. We highlight that the KamLAND constraint (red) [40] is pertinent to our study of $n \to \chi\gamma$ decay, as the prompt photon would not pass the correlation cuts and would remain undetected. Panel (b) also presents limits from neutron star studies for the DS(CMF) family of EoSs in order of increasing severity, along with constraints from the BES-III experiment (green) [41], noting that the γ in this case would also be undetected, and the SN1987A limits (gold) [11]. Taken from [3], to which we refer for all details.

6. Summary

Neutron stars offer an enormous baryon reservoir in which dark-decay processes can be probed, with some 10^{57} neutrons expected in a typical neutron star [43] — a number far larger than the volume of any terrestrial proton-decay experiment [1]. This and the existence of precisely determined energy-loss constraints in neutron stars, particularly through pulsar-timing observations in binary-pulsar systems [15], limit not only the total baryon loss rate across the star but also the

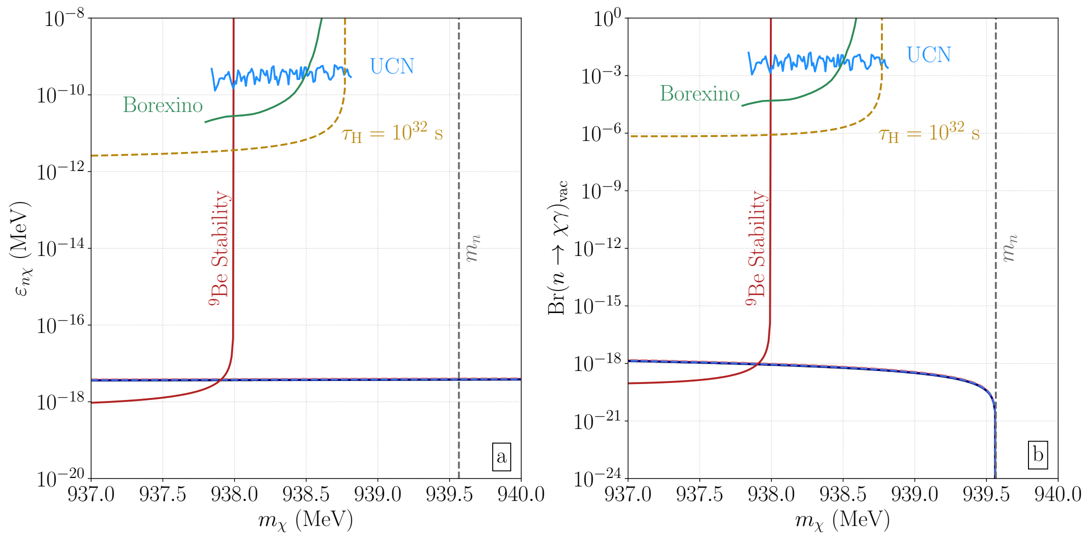

Figure 7: Exclusion limits at 2σ in blue on (a) $\varepsilon_{n\chi}$ and (b) the vacuum branching fraction for $n \to \chi\gamma$ in the particular χ mass region pertinent to an explanation of the neutron lifetime anomaly. Additional constraints and expected limits have been included as detailed in the text, after [42]. Figure taken from [2], to which we refer for all details.

parameters of the particle physics models that can produce such loss [2, 17]. Using a suitable hidden-sector choice, we have followed this path to find severe constraints on $n-\chi$ mixing, and thus to exclude this particular model as a fractional explanation of the neutron lifetime anomaly — and also to constrain the flavor structure of the couplings in the co-genesis model we have noted [2]. We note that futures studies of neutron-star heating may help in the identification of non-null results.

Acknowledgments

S.G. thanks Jeffrey Berryman and Mohammadreza Zakeri for their collaboration on the work presented here, and she acknowledges support from the U.S. Department of Energy, Office of Science, Office of Nuclear Physics under contract DE-FG02-96ER40989.

References

[1] J.M. Berryman, S. Gardner and M. Zakeri, *Neutron Stars with Baryon Number Violation, Probing Dark Sectors*, *Symmetry* **14** (2022) 518 [2201.02637].

[2] J.M. Berryman, S. Gardner and M. Zakeri, *How macroscopic limits on neutron-star baryon loss yield microscopic limits on non-standard-model baryon decay*, *Phys. Rev. D* **109** (2024) 023021 [2305.13377].

[3] S. Gardner and M. Zakeri, *Probing Dark Sectors with Neutron Stars*, *Universe* **10** (2024) 67 [2311.13649].

[4] H. Davoudiasl, D.E. Morrissey, K. Sigurdson and S. Tulin, *Hylogenesis: A Unified Origin for Baryonic Visible Matter and Antibaryonic Dark Matter*, *Phys. Rev. Lett.* **105** (2010) 211304 [1008.2399].

[5] H. Davoudiasl and R.N. Mohapatra, *On Relating the Genesis of Cosmic Baryons and Dark Matter*, *New J. Phys.* **14** (2012) 095011 [1203.1247].

[6] H. Davoudiasl, *Nucleon Decay into a Dark Sector*, *Phys. Rev. Lett.* **114** (2015) 051802 [1409.4823].

[7] R. Allahverdi, P.S.B. Dev and B. Dutta, *A simple testable model of baryon number violation: Baryogenesis, dark matter, neutron–antineutron oscillation and collider signals*, *Phys. Lett. B* **779** (2018) 262 [1712.02713].

[8] G. Elor, M. Escudero and A. Nelson, *Baryogenesis and Dark Matter from B Mesons*, *Phys. Rev. D* **99** (2019) 035031 [1810.00880].

[9] S. Fajfer and D. Susič, *Colored scalar mediated nucleon decays to an invisible fermion*, *Phys. Rev. D* **103** (2021) 055012 [2010.08367].

[10] G. Elor and R. McGehee, *Making the Universe at 20 MeV*, *Phys. Rev. D* **103** (2021) 035005 [2011.06115].

[11] G. Alonso-Álvarez, G. Elor, M. Escudero, B. Fornal, B. Grinstein and J. Martin Camalich, *Strange physics of dark baryons*, *Phys. Rev. D* **105** (2022) 115005 [2111.12712].

[12] G. Alonso-Álvarez, G. Elor and M. Escudero, *Collider signals of baryogenesis and dark matter from B mesons: A roadmap to discovery*, *Phys. Rev. D* **104** (2021) 035028 [2101.02706].

[13] F. Elahi, G. Elor and R. McGehee, *Charged B mesogenesis*, *Phys. Rev. D* **105** (2022) 055024 [2109.09751].

[14] R.A. Hulse and J.H. Taylor, *Discovery of a pulsar in a binary system*, *Astrophys. J. Lett.* **195** (1975) L51.

[15] J.M. Weisberg and Y. Huang, *Relativistic Measurements from Timing the Binary Pulsar PSR B1913+16*, *Astrophys. J.* **829** (2016) 55 [1606.02744].

[16] I. Goldman, R.N. Mohapatra and S. Nussinov, *Bounds on neutron-mirror neutron mixing from pulsar timing*, *Phys. Rev. D* **100** (2019) 123021 [1901.07077].

[17] R. Allahverdi, A. Thompson and M. Zakeri, *Insights from binary pulsars and laboratories into baryon number violation: Implications for GeV dark matter*, *Phys. Rev. D* **110** (2024) 115010 [2409.08178].

[18] F.E. Wietfeldt and G.L. Greene, *Colloquium: The neutron lifetime*, *Reviews of Modern Physics* **83** (2011) 1173.

[19] B. Fornal and B. Grinstein, *Dark Matter Interpretation of the Neutron Decay Anomaly*, *Phys. Rev. Lett.* **120** (2018) 191801 [1801.01124].

[20] Z. Berezhiani, *Neutron lifetime and dark decay of the neutron and hydrogen*, *LHEP* **2** (2019) 118 [1812.11089].

[21] A. Czarnecki, W.J. Marciano and A. Sirlin, *Neutron Lifetime and Axial Coupling Connection*, *Phys. Rev. Lett.* **120** (2018) 202002 [1802.01804].

[22] G. Baym, D.H. Beck, P. Geltenbort and J. Shelton, *Testing Dark Decays of Baryons in Neutron Stars*, *Phys. Rev. Lett.* **121** (2018) 061801 [1802.08282].

[23] D. McKeen, A.E. Nelson, S. Reddy and D. Zhou, *Neutron stars exclude light dark baryons*, *Phys. Rev. Lett.* **121** (2018) 061802 [1802.08244].

[24] T.F. Motta, P.A.M. Guichon and A.W. Thomas, *Implications of Neutron Star Properties for the Existence of Light Dark Matter*, *J. Phys. G* **45** (2018) 05LT01 [1802.08427].

[25] A.D. Sakharov, *Violation of CP Invariance, C asymmetry, and baryon asymmetry of the universe*, *Pisma Zh. Eksp. Teor. Fiz.* **5** (1967) 32.

[26] C. Abel et al., *Measurement of the Permanent Electric Dipole Moment of the Neutron*, *Phys. Rev. Lett.* **124** (2020) 081803 [2001.11966].

[27] T.S. Roussy et al., *An improved bound on the electron's electric dipole moment*, *Science* **381** (2023) adg4084 [2212.11841].

[28] J. Berger and G. Elor, *Dark Matter Induced Nucleon Decay Signals in Mesogenesis*, 1, 2023.

[29] J.D. Walecka, *A Theory of highly condensed matter*, *Annals Phys.* **83** (1974) 491.

[30] B.D. Serot and J.D. Walecka, *The Relativistic Nuclear Many Body Problem*, *Adv. Nucl. Phys.* **16** (1986) 1.

[31] V. Dexheimer and S. Schramm, *Proto-Neutron and Neutron Stars in a Chiral SU(3) Model*, *Astrophys. J.* **683** (2008) 943 [0802.1999].

[32] CompOSE Core Team collaboration, *CompOSE Reference Manual*, *Eur. Phys. J. A* **58** (2022) 221 [2203.03209].

[33] V. Dexheimer, *The Relativistic SU(3) Chiral Mean Field (CMF) equation of state. (DS(CMF)-1)*, 2021.

[34] T. Damour and J.H. Taylor, *On the Orbital Period Change of the Binary Pulsar PSR 1913+16*, *Astrophys. J.* **366** (1991) 501.

[35] P.C. Peters, *Gravitational radiation and the motion of two point masses*, *Phys. Rev.* **136** (1964) B1224.

[36] K. Lazaridis, N. Wex, A. Jessner, M. Kramer, B.W. Stappers, G.H. Janssen et al., *Generic tests of the existence of the gravitational dipole radiation and the variation of the gravitational constant*, *Monthly Notices of the Royal Astronomical Society* **400** (2009) 805 [https://academic.oup.com/mnras/article-pdf/400/2/805/3326717/mnras0400-0805.pdf].

[37] R.N. Manchester, G.B. Hobbs, A. Teoh and M. Hobbs, *The Australia Telescope National Facility pulsar catalogue*, *Astron. J.* **129** (2005) 1993 [astro-ph/0412641].

[38] M. Kramer, I.H. Stairs, R.N. Manchester, N. Wex, A.T. Deller, W.A. Coles et al., *Strong-field gravity tests with the double pulsar*, *Phys. Rev. X* **11** (2021) 041050.

[39] Super-Kamiokande collaboration, *Search for Nucleon and Dinucleon Decays with an Invisible Particle and a Charged Lepton in the Final State at the Super-Kamiokande Experiment*, *Phys. Rev. Lett.* **115** (2015) 121803 [1508.05530].

[40] KamLAND collaboration, *Search for the invisible decay of neutrons with KamLAND*, *Phys. Rev. Lett.* **96** (2006) 101802 [hep-ex/0512059].

[41] BESIII collaboration, M. Ablikim et al., *Search for Invisible Decays of the* Λ *Baryon*, 10, 2021.

[42] D. McKeen and M. Pospelov, *How long does the hydrogen atom live?*, 3, 2020.

[43] G. Baym and C. Pethick, *Neutron Stars*, *Ann. Rev. Nucl. Part. Sci.* **25** (1975) 27.