

Leading Bounds on Micrometer to Picometer Fifth Forces from Neutron Star Cooling

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The equivalence principle and the inverse-square law of gravity could be violated at short distances (10^{-6} – 10^{-12} m) by scalars sporting a coupling g_N to nucleons and mass $\text{eV} \lesssim m_\phi \lesssim \text{MeV}$. We show for the first time that stringent bounds on the existence of these scalars can be derived from the observed cooling of nearby isolated neutron stars (NSs). Although NSs can only be used to set limits comparable to the classic supernova (SN) 1987A cooling bound in the case of pseudoscalars such as the QCD axion, the shallow temperature dependence of the scalar emissivity results in a huge enhancement in the effect of ϕ on the cooling of cold NSs. As we do not find evidence of exotic energy losses, we can exclude couplings down to $g_N \lesssim 5 \times 10^{-14}$. Our new bound supersedes all existing limits on scalars across 6 orders of magnitude in m_ϕ . These conclusions also extend to Higgs-portal models, for which the bound on the scalar-Higgs mixing angle is $\sin \theta \lesssim 6 \times 10^{-11}$.

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Introduction—The existence of novel light CP -even scalars ϕ would lead to scale-dependent departures from firmly established predictions of gravitational physics, like Newton's inverse-square law and the weak equivalence principle. An experimental effort has been devoted to searching for deviations from these principles for several decades; see, e.g., Refs. [1–3]. Such scalar particles—which can arise as dilatons [4,5] or radions in theories with extra dimensions [6]—could also constitute 100% of the dark matter content in our Universe if produced through, e.g., the misalignment mechanism [7–11], act as a portal with a rich dark sector [12], or be related to the hierarchy problem in the context of relaxion models [13].

Casimir measurements [14,15], microcantilevers [16], torsion-balance experiments [17–22], and satellite-borne accelerometers [23] are powerful probes of scalars with masses $m_\phi \lesssim 1$ eV, corresponding to deviations from the inverse-square law at distances larger than 1 μm . Nonetheless, astrophysical bounds are much more stringent at larger masses. The existence of a new scalar particle is expected to affect the lives of stars. After being emitted by the nucleons making up the stellar plasma, the subsequent

escape of the scalars out of the star constitutes an exotic cooling channel beyond what is usually assumed in standard evolutionary models [24–26]. Arguments of this type have been used in the past to set strong bounds on the scalar-nucleon coupling g_N . For example, the production of ϕ through resonant conversion from longitudinal plasmons would change the brightness of the tip of the red giant branch from what we observe, implying a severe limit of $g_N \lesssim 1.1 \times 10^{-12}$ [27]. Likewise, the exotic cooling due to scalar bremsstrahlung through electron-nucleus scattering would induce a deviation in the white-dwarf (WD) luminosity function, so that $g_N \lesssim 7 \times 10^{-13}$ [28]. For $m_\phi \gtrsim 10$ keV horizontal branch stars exclude a sliver of the parameter space [27], and at larger masses still ($m_\phi \gtrsim 100$ keV) the existence of scalars is constrained by the observed duration of the neutrino signal from supernova (SN) 1987A at Kamiokande II and IMB [29–31] (see however Ref. [32] for a recent comparison of standard neutrino cooling and SN 1987A data).

For the first time, we show that old neutron stars (NSs), such as some of the nearby isolated Magnificent Seven (M7) and PSR J0659, constrain $g_N \lesssim 5 \times 10^{-14}$, improving existing bounds by more than one order of magnitude. Analogously to NS bounds placed on axions [33–39], we derive bounds on scalar emission by comparing the predicted cooling curves of each NS with their measured ages and surface luminosities, fixing the equation of state (EOS) and the superfluidity model, while varying the uncertain NS mass and fraction of light elements in their

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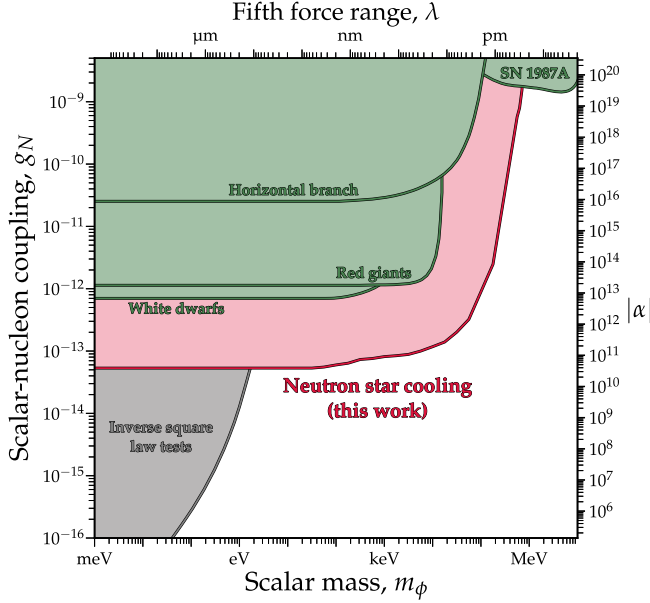


FIG. 1. Our new limit on the scalar-nucleon coupling g_N at 95% C.L. as a function of the scalar mass from neutron star cooling. We show the limit alongside other astrophysical bounds (green) [27,28,31] and laboratory tests of the inverse-square law (gray) [15]. For comparison with the conventional parametrization of fifth forces, we also show the coupling in terms of the equivalent strength of a Yukawa force relative to gravity $|\alpha|$ along the right-hand axis, and the range of that force $\lambda = m_\phi^{-1}$ along the top axis. We assume equal coupling to protons and neutrons.

envelopes. In contrast to the QCD axion, however, these constraints are dramatically stronger than those determined from SNe, as shown in Fig. 1. At $m_\phi \simeq 100$ keV, our new bound is more than 3 orders of magnitude stronger than the one obtained from SN 1987A. Although this might come as a surprise, it can be understood through simple arguments that we outline below. The main cause is the lower temperature of cold NSs, which strongly suppresses the rate of neutrino emission in comparison to the rate of scalar emission, making it much easier to spot this signal of exotic cooling.

When are supernovae better than cold neutron stars?—The celebrated exotic cooling bounds from SNe, first drawn on the QCD axion, are the paradigmatic application of this kind of argument. Broadly speaking, the argument relies on the idea that we expect a dynamical impact on a star’s evolution when the luminosity in the form of a new species becomes comparable to the dominant luminosity of the star. In the case of SNe this is due to neutrino emission, and for NSs—at least up to $\sim 10^5$ yr in age—this is still the case. This is why the use of cold NSs does not allow one to constrain any significant new portions of the QCD axion parameter space in comparison to SNe. In both cold NSs and hot protoneutron stars formed in the core of an SN, the emission of axions and of neutrinos depends on the temperature roughly in the same way. This is because

the emission of an axion or a neutrino pair comes with an associated flip of the spin of a nucleon. The amplitude for such a spin flip is always associated with a factor $\sim p_a/m_N$, as appears most naturally in the nonrelativistic Hamiltonian for a spin flip, which has the form $\sigma \cdot \mathbf{p}_a/m_N$, where σ is the spin operator. Since the momentum of the axion, or of the neutrino pair, grows in proportion to the temperature T , it follows that the neutrino and axion luminosities scale in the same way with temperature, and thus their ratio, L_a/L_ν , is roughly the same for SNe and cold NSs:

$$\left(\frac{L_a}{L_\nu}\right)_{\text{NS}} \sim \left(\frac{L_a}{L_\nu}\right)_{\text{SN}}. \quad (1)$$

This is why the values of the axion coupling constants that can be constrained are roughly the same for both of these sources.

Therefore, at present, cold NSs have primarily acted as an independent means, with complementary systematic uncertainties, to exclude coupling strengths comparable to the ones tested by SNe. The argument above provides a reason for this, but it also sheds light on its unique dependence on the axial mechanism of axion emission. Different emission mechanisms can exhibit characteristically different temperature dependencies, which we can understand with simple arguments. We focus on the case of a scalar particle coupling to nucleons here, which is the most promising target for neutron-star-like environments given the densities close to nuclear saturation. When emitting a scalar particle, the spin of the nucleon does *not* flip, so there is no suppression from the scalar momentum. On the other hand, the emission of scalar radiation from a system of nonrelativistic particles can happen only in proportion to their quadrupole moment, rather than to their charge. In the reaction $NN \rightarrow NN$ (we take identical nucleons for the moment), both the total charge (i.e., number of nucleons) and current (i.e., flux of nucleons) are conserved, with only their quadrupole moment allowed to change, which is required for the radiation of scalar particles. It follows that the radiation rate will be suppressed by a factor $\sim (p_N/m_N)^4$; crucially, this suppression factor depends on the nucleons’ momentum, rather than the scalar’s. In an SN, where nucleons are usually only mildly degenerate, their typical momentum is of order $p_N \sim \sqrt{m_N T}$, so coincidentally the suppression factor $\sim (p_N/m_N)^4 \sim (T/m_N)^2$ turns out to be comparable to that for axion and neutrino emission. But in cold NSs, thanks to their large degeneracy, scalar emission is enhanced substantially in comparison to neutrinos. This simple argument suggests that

$$\left(\frac{L_\phi}{L_\nu}\right)_{\text{NS}} \sim \left(\frac{L_\phi}{L_\nu}\right)_{\text{SN}} \frac{p_{N,\text{NS}}^4}{m_N^2 T_{\text{NS}}^2} \sim 10^7 \left(\frac{L_\phi}{L_\nu}\right)_{\text{SN}}, \quad (2)$$

where $T_{\text{NS}} \sim 10$ keV is the typical temperature for NSs with ages $\sim 10^5$ yr and $p_{N,\text{NS}} \sim 200$ MeV is the typical

nucleon Fermi momentum in nuclear matter at nuclear saturation density $\rho \sim \text{few} \times 10^{14} \text{ g cm}^{-3}$. Such a huge enhancement implies that NSs should be much better test beds for the emission of scalar radiation than SNe. Since the luminosity grows in proportion to the coupling of the new species, we expect an improvement of around 3–4 orders of magnitude in the bounds on scalar particles from cold NSs.

To complement our arguments, we may also notice that if the new scalar particle couples with different strengths to protons and neutrons, one may well have an additional enhancement. While the total charge associated with the scalar field is conserved in $np \rightarrow np$ scattering, the current (i.e., flux of protons or flux of neutrons) is not necessarily conserved. Therefore, one can have an even stronger enhancement, because the scalar radiation rate is suppressed only by a dipole factor $\sim (p_N/m_N)^2$, so that we may have

$$\left(\frac{L_\phi}{L_\nu}\right)_{\text{NS}} \sim \left(\frac{L_\phi}{L_\nu}\right)_{\text{SN}} \frac{p_{N,\text{NS}}^2}{T_{\text{NS}}^2} \sim 10^8 \left(\frac{L_\phi}{L_\nu}\right)_{\text{SN}}. \quad (3)$$

These simple arguments, based on the microphysics of the emission process, point toward NSs as ideal probes of scalar emission. We now proceed to a discussion of how our resulting constraint, shown in Fig. 1, is derived.

Scalars from cold neutron stars: Data analysis and constraints—Under typical conditions expected for an NS with age $\sim 10^5$ yr, the emission of scalars with masses $m_\phi \lesssim 30$ keV opens an efficient energy-loss channel in addition to neutrino and photon emission, which would accelerate the NS cooling rate. The total energy balance requires that

$$C \frac{dT_c^\infty}{dt} = -L_\gamma^\infty - L_\nu^\infty - L_\phi^\infty + H, \quad (4)$$

where the photon luminosity is related to the surface temperature T_s^∞ as $L_\gamma^\infty = 4\pi R_\infty^2 (T_s^\infty)^4$. Here t is the time, C and T_c^∞ are the heat capacity and temperature of the NS interior, respectively, and the superscript ∞ refers to quantities as measured by a distant observer. The final term H accounts for surface heating due to the surrounding magnetic field. We assume here $H = 0$ —Ohmic heating from magnetic field decay might affect our constraints by $\sim 50\%$, as shown in Ref. [38]. Furthermore, we do not take into account other potential sources of stellar heating, e.g., rotochemical heating, vortex creep heating, and crust cracking [40], which might possibly induce uncertainties comparable to those related to Ohmic heating. It should be noted that the theoretical modeling of such effects still requires work and none of them has yet been firmly confirmed experimentally.

In the nucleon-rich interior of the NS, scalar production is dominated by the nucleon coupling $\mathcal{L} \supset g_N \phi \bar{N}N$, where

$N = p, n$ for neutrons and protons, respectively. The main emission channel is NN bremsstrahlung $N + N \rightarrow N + N + \phi$ [29]. We reevaluate the scalar bremsstrahlung emission rate here, going beyond the usual one-pion exchange (OPE) or soft approximations employed in previous works. Nucleon scattering is described by employing the effective interaction potential already employed in Refs. [41,42] to compute neutrino emissivities from NSs. The code we use to model the NS evolution, NSCool [43], adopts the same framework to determine neutrino emission, so that our treatment of the exotic production is on par with that of standard processes. The potential has a long-range OPE interaction, reduced at large momentum exchange with a phenomenological ρ meson exchange, and a short-range component extracted from the Landau parameters of the nuclear matter. We detail the computation of the scalar emission in Supplemental Material (SM) [44].

If the scalar emission is too efficient, it competes with photon and neutrino cooling channels, potentially making the NSs cooler than expected for their age. We consider measurements of four of the M7 (see Refs. [38,55] for related works on M7 NSs), for which thermal luminosity and kinematic age data are available [56,57]. This list is enriched by PSR J0659, which is also older than $\sim 10^5$ yr and has available thermal luminosity measurements. All the relevant data for our analysis are reported in Table I.

We simulate the NS cooling curves using the public code NSCool [43], which tracks the cooling process of a one-dimensional NS model from a few seconds after its birth to several million years. In particular, NSCool solves the heat transport and energy balance equations in a full general relativity framework, determining the surface temperature $T_s(T_c)$ as a function of the temperature in the NS interior T_c . The NS model is determined by specifying the NS mass M_{NS} , the amount of light elements ΔM defining the envelope composition, the EOS modeling the NS interior, and the choice of superfluidity model. In the following we assume the Akmal-Pandharipande-Ravenhall (APR) EOS

TABLE I. Parameters of the neutron stars considered herein. Values of the core temperature T_c , the core density ρ_c , and the NS radius R are obtained from the best-fit models determined for each given NS.

Name	L_γ^∞ (10^{33} erg/s)	Age (Myr)	T_c (keV)	ρ_c (g cm^{-3})	R (km)
J1856 ^a	0.065 ± 0.015	0.42 ± 0.08	1.5	7.1×10^{14}	11.4
J1308 ^b	0.32 ± 0.06	0.55 ± 0.25	9.4	1.2×10^{15}	11.2
J0720 ^c	0.22 ± 0.11	0.85 ± 0.15	5.1	1.1×10^{15}	11.3
J1605 ^d	0.4 ± 0.1	0.44 ± 0.07	8.1	1.2×10^{15}	11.2
J0659 ^e	0.28 ± 0.14	0.35 ± 0.044	9.0	7.5×10^{14}	11.5

^a[58–60];

^b[61,62];

^c[63,64];

^d[65,66];

^e[57,67].

[68], built in the NSCool code, and the 0-0-0 superfluidity model, which assumes no superfluidity by setting excitation gaps to zero; we can rely in this case on the detailed study of Ref. [38], showing that the constraints on exotic emission may change by tens of percent between different model assumptions, well below the unavoidable uncertainties on the nuclear interaction model. The latter reasonably entails a factor 5–6 uncertainty on the emissivity, corresponding to a factor 2–3 uncertainty on the final constraints.

Conversely, the fraction of light elements in accreted envelopes ΔM may significantly affect the relation between the core and surface temperatures $T_s(T_c)$ during both the neutrino- and photon-dominated cooling phases, while the baryonic NS mass has a major role in determining the composition and the density of the core. To deal with these nuisance parameters, we vary ΔM over six log-spaced values from $\Delta M = 10^{-20} M_\odot$ (no light elements in accreted envelopes) to $\Delta M = 10^{-6} M_\odot$ (high concentration of light elements in accreted envelopes). For the NS mass, we take six linearly spaced values between $M_{\text{NS}} \in [1.0 M_\odot, 2.0 M_\odot]$. For each pair of $(\Delta M, M_{\text{NS}})$, we run a set of NS simulations while varying the scalar's mass and coupling. The set of simulated light curves describing the i th NS $L(m_\phi, g_N, \theta^i)$ is therefore parametrized in terms of the scalar's free parameters $\{m_\phi, g_N\}$ and our nuisance parameters $\theta^i = \{M_{\text{NS}}^i, \Delta M^i, t^i\}$, which characterize the NS model. For each NS, we then write down a likelihood function,

$$\mathcal{L}_i(\mathbf{d}_i | m_\phi, g_N, \theta^i) = \mathcal{N}[L(m_\phi, g_N, \theta^i) - L_0^i, \sigma_L^i] \times \mathcal{N}[t^i - t_0^i, \sigma_t^i], \quad (5)$$

where $\mathcal{N}(x, \sigma)$ is a zero-mean Gaussian distribution function with standard deviation σ . The data for the i th NS consists of $\mathbf{d}_i = \{L_0^i, \sigma_L^i, t_0^i, \sigma_t^i\}$, where σ_L^i and σ_t^i are the 1σ measurement uncertainties on the NS luminosity L_0^i and age t_0^i , respectively. From here, we can then construct a joint likelihood for the set of all NSs, $\mathcal{L}(\mathbf{d} | m_\phi, g_N, \theta)$, by taking the product of each individual NS's likelihood, where now $\mathbf{d} = \{\mathbf{d}_i\}_{i=1}^5$ and $\theta = \{\theta^i\}_{i=1}^5$ represent the full lists of NS data and their nuisance parameters.

To set upper limits on the allowed value of g_N , we calculate the profile likelihood ratio test statistic for exclusion limits [69] at a fixed value of m_ϕ ,

$$q(g_N; m_\phi) = \begin{cases} -2 \ln \frac{\mathcal{L}(\mathbf{d} | m_\phi, g_N, \hat{\theta})}{\mathcal{L}(\mathbf{d} | m_\phi, \hat{g}_N, \hat{\theta})} & g_N \geq \hat{g}_N \\ 0 & g_N < \hat{g}_N, \end{cases} \quad (6)$$

where $\hat{g}_N$ is the best-fit value of g_N and we use $\hat{\theta} = \{\hat{\theta}^i\}_{i=1}^5$ to denote the values of the nuisance parameters that maximize the likelihood function in which they appear. The 95% confidence level upper limit on the scalar-

nucleon coupling can then be found by satisfying $q(g_N^{95}; m_\phi) = 2.71$, assuming that Wilks's theorem holds [70].

We note that the analysis of axion-induced cooling of NSs in Ref. [38] found that a full Monte Carlo simulation of the distribution of q differed from that of the asymptotic χ^2 distribution, which is assumed when naively applying Wilks's theorem—this entailed a $\sim 50\%$ shift in the resulting upper limit on the axion mass. However, we emphasize that this is a minor discrepancy when compared to the dominant systematic uncertainties due to the nuclear interaction model, which are at the level of a factor 4–5 in the emissivity and therefore a factor 2 in the constraints.

Our nuclear interaction model follows the historical setup of Ref. [41], in which the long-range interaction is modeled as an OPE, potentially modified by a phenomenological ρ meson exchange, and the short-range interaction is extracted from the Landau parameters of heavy nuclei. However, such Landau parameters refer to symmetric nuclear matter, whereas NSs are largely neutron dominated. Even the long-range component of the potential has been shown to suffer large renormalization in dense nuclear matter [71–77]. The quenching of the axion coupling in dense matter also cannot be accurately anticipated; the Brown-Rho scaling, adopted in, e.g., Ref. [38], is mostly a qualitative conjecture to capture the leading features of this phenomenon. Therefore, a fair assessment is that these techniques primarily capture the order of magnitude and the temperature dependence of the emissivity, and are the dominant source of uncertainty on the constraints we find, making efforts to correct for more minor 10%–50% discrepancies unnecessary. Fortunately, our constraints supersede previous ones by much more than these estimated uncertainties.

Our resulting limit is shown in Fig. 1. We exclude $g_N \lesssim 5 \times 10^{-14}$ for masses $m_\phi \lesssim 100$ eV, overtaking previous constraints from the WD luminosity function [28] by more than one order of magnitude. Remarkably, our limits dominate over all the previous astrophysical limits for $m_\phi \lesssim 700$ keV, improving upon the SN cooling bound by ~ 4 orders of magnitude. For the SN constraints, we use the results of Ref. [31]; these rely primarily on resonant emission, rather than bremsstrahlung emission; however, the two are comparable in order of magnitude, so that our estimates for the expected improvement in the NS cooling constraints still hold.

Discussion and outlook—At the microscopic level, searches for deviations from the inverse-square law and the weak equivalence principle can be seen as testing for novel Yukawa interactions arising from the exchange of low-mass bosons. By capitalizing on the low temperatures and high densities of cooling isolated NSs, we have obtained the most stringent bounds to date on exotic scalars ϕ with mass $\text{eV} \lesssim m_\phi \lesssim \text{MeV}$ coupled to nucleons. We exclude couplings down to $g_N \lesssim 5 \times 10^{-14}$, which in terms

of the equivalent strength of the Yukawa force with respect to gravity means $|\alpha| = g_N^2/4\pi G_N m_N^2 \lesssim 4 \times 10^{10}$, with an improvement over the previous bounds on the latter by more than 2 orders of magnitude. Our bounds are now leading for scalars mediating a fifth force over micrometer to picometer distances—an especially challenging range to probe experimentally—emphasizing the complementary nature of astrophysical probes of new physics.

These bounds are also relevant for CP -violating axion interactions [78–92], as we detail in SM [44], where we compare our bound against the landscape of constraints from Refs. [14,15,17–21,23,93–138]. We may also translate our limits to, e.g., models with a Higgs portal where $g_N \simeq 8 \times 10^{-4} \sin \theta$. Our bound of $\sin \theta \lesssim 6 \times 10^{-11}$ surpasses the existing limits that rely on the scalar-electron coupling.

While in this Letter we have focused on scalars, fifth forces between baryons might be mediated by new gauge bosons—although in this case, one would need an additional coupling to leptons to guarantee anomaly cancellation. NSs might also constitute our best laboratory for exploring this class of models. Likewise, NSs can be the ideal probe of dark sector particles produced through baryonic interactions. We leave the question of how these cold compact stars fare compared to other probes to future work.

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Data availability—The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be

prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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