Constraints for weakly interacting light bosons
from existence of massive neutron stars

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Theories beyond the standard model include a number of new particles some of which might be
light and weakly coupled to ordinary matter. Such particles affect the equation of state of nuclear
matter and can shift admissible masses of neutron stars to higher values. The internal structure of
neutron stars is modified provided the ratio between coupling strength and mass squared of a
weakly interacting light boson is above $g^2/\mu^2 \sim 25$ GeV$^{-2}$. We provide limits on the couplings
with the strange sector, which cannot be achieved from laboratory experiments analysis. When the
couplings to the first family of quarks are considered the limits imposed by the neutron stars are not
more stringent than the existing laboratory ones. The observations on neutron stars give evidence
that equation of state of the $\beta$-equilibrated nuclear matter is stiffer than expected from many-body
theory of nuclei and nuclear matter. A weakly interacting light vector boson coupled predominantly
to the second family of the quarks can produce the required stiffening.

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Dark energy explains the accelerating expansion of the Universe. The density of dark energy $\rho_D \approx 3.8$ keV/cm$^3$
may correspond to a fundamental scale $\lambda_D = \rho_D^{1/4} \approx 8.5 \times 10^{-5}$ m [8, 9, 10, 11, 12, 13]. Theoretical schemes with ex-
tensions suggest modifications of gravity below $\lambda_D$ and a multitude of states with masses above $1/\lambda_D$ very
weakly coupled to members of multiplets of the standard model. Scales significantly below $\lambda_D$ represent the inter-
est for supersymmetric extensions of the standard model which include generally a number of new particles, such as
the leading dark matter candidate neutralino. Typically, new particles are expected with masses above sev-
eral hundred GeVs or even higher. However, light particles may exist also, such as a neutral very weakly coupled
spin-1 gauge $U$-boson [14] that can provide annihilation of light dark matter and be responsible for the 511 keV line
observed from the galactic bulge [6, 7].

Deviations from the inverse-square Newton’s law are parametrized often in terms of the exchanges by hypo-
thesetical bosons also. Constraints on the deviations from Newton’s gravity have been set experimentally in the
sub-millimeter scale [8, 9, 10, 11, 12, 13] and down to distances $\approx 10$ fm where effects of light bosons of extensions
of the standard model can be expected [14, 15, 16, 17, 18]. Constraints on the coupling constants from unobserved
missing energy decay modes of ordinary mesons are discussed in Ref. [19].

Bosons with small couplings escape detection in most laboratory experiments. However, bosons interacting
with baryons modify the equation of state (EOS) of nuclear matter. Their effect depends on the ratio between
the coupling strength and the boson mass squared, so a

weakly interacting light boson (WILB) may influence the structure of neutron stars even if its baryon couplings are
very small.

The effect of a vector boson on the energy density of nuclear matter can be evaluated by averaging the corre-
spanding Yukawa potential:

$$E_I = \frac{1}{2} \int dx_1 dx_2 \rho(x_1) g^2 e^{-\mu r} \rho(x_2),$$  \hspace{1cm} (1)

where $\rho(x_1) = \rho(x_1) \equiv \rho$ is the number density of homogeneously distributed baryons, $r = |x_2 - x_1|$, $g$ is the
coupling constant with baryons, and $\mu$ is the boson mass. A simple integration gives

$$E_I = V g^2 \rho^2 \frac{\mu^2}{2\mu^2},$$  \hspace{1cm} (2)

where $V$ is the normalization volume.

The coherent contribution to the energy density of nuclear matter from vector WILBs should be compared to that
from the ordinary $\omega$-mesons. In one-boson exchange potential (OBEP) models, the nucleon-nucleon repulsive
core at short distances $r \leq b = 0.4$ fm is attributed to $\omega$-meson exchanges. Respectively, the $\omega$-meson plays a fundamental
erole in nuclear matter EOS. In the mean-field approximation, the contribution of $\omega$-meson exchanges to the
energy has the form of Eq. [2], with $g$ and $\mu$ replaced by the $\omega$-meson coupling $g_\omega$ and the mass $\mu_\omega$.

The $NN$ interactions are described with $g^2_\omega / \mu^2_\omega = 175$ GeV$^{-2}$ [20]. The relativistic mean field (RMF) model
[21] gives $g^2_\omega / \mu^2_\omega = 196$ GeV$^{-2}$. The compression modulus of nuclear matter $K = 210 \div 300$ MeV is consistent
with $g_{σ}^{2}/μ_{σ}^{2} = 125 \pm 180 \text{ GeV}^{-2}$ \cite{22}. Stiff RMF models use $g_{σ}^{2}/μ_{σ}^{2}$ up to 300 GeV$^{-2}$ \cite{23}. If we wish to stay within current limits and do not want to modify the internal structure of neutron stars qualitatively, as described by realistic models of neutron stars, one has to require that vector WILBs fulfill constraint

$$\frac{g_{σ}^{2}}{μ_{σ}^{2}} < \frac{g_{σ}^{2}}{μ_{σ}^{2}} \approx 200 \text{ GeV}^{-2}. \quad (3)$$

A similar reasoning applies to scalar WILBs which have to compete with the standard $σ$-meson exchange. In OBEP models, the long-range attraction between nucleons is attributed to $σ$-meson exchanges. The contribution of the $σ$-mesons to the interaction energy has the form of Eq.\,(2), with $g$ and $μ$ replaced by the $σ$-meson coupling $g_{σ}$ and the mass $μ_{σ}$. The sign of the contribution must be negative because of the attraction. Also, $ρ$ should be replaced by the scalar density. In RMF models, the $σ$-meson mean field decreases the nucleon mass. The effect depends on the ratio $g_{σ}^{2}/μ_{σ}^{2}$ also and produces an additional decrease of the energy at fixed volume and baryon number. The empirical values of the ratio $g_{σ}^{2}/μ_{σ}^{2}$ are 40 $\div$ 60% higher than those of the $ω$-meson \cite{20,21,22,23}. The internal structure of neutron stars is not modified significantly provided the coupling strength $g$ and mass $μ$ of scalar WILBs fulfill constraint

$$\frac{g_{σ}^{2}}{μ_{σ}^{2}} < \frac{g_{σ}^{2}}{μ_{σ}^{2}} \approx 300 \text{ GeV}^{-2}. \quad (4)$$

The deviations from the Newton’s gravitational potential are usually parametrized in the form

$$V(r) = -\frac{Gm_{1}m_{2}}{r} \left(1 + α_{G}e^{-r/λ}\right). \quad (5)$$

The second Yukawa term can be attributed to new bosons with $Gm^{2}α_{G} = ±g^{2}/(4π)$ and $λ = 1/μ$, where $+/−$ stands for scalar/vector bosons and $m$ is the proton mass.

On Fig. 1 we show regions in the parameter spaces $(g^{2}, μ)$ and $(α_{G}, λ)$ allowed for WILBs by the constraint \cite{3}. The constraint for scalar bosons is close to \cite{3}. Constraints from other works \cite{10,11,12,13,14,15,16,17,18} are shown also.

An increase of $g$ (a decrease of $μ$) of scalar WILBs increases the negative contribution to pressure, makes EOS of nuclear matter softer, makes neutron stars less stable against gravitational compression. The ratio $g^{2}/μ^{2}$ cannot be increased significantly above the limit \cite{4}, since the maximum mass of the neutron star sequence cannot be moved below masses of the observed pulsars.

An increase of $g$ (a decrease of $μ$) of vector WILBs, conversely, increases the positive contribution to pressure, makes EOS of nuclear matter stiffer, makes neutron stars more stable against gravitational compression and drives the maximum mass of neutron stars up.

In case of vector bosons, it is less obvious what kind of the observables confronts to high ratios $g^{2}/μ^{2}$.

![FIG. 1: (color online) Constraints on the coupling strength with nucleons $g^{2}/(4π)$ and the mass $μ$ (equivalently $α_{G}$ and $λ$) of hypothetical weakly interacting light bosons: $I$ are constraints from Ref. \cite{10}. 2 - from Ref. \cite{11}. 3 - from Ref. \cite{12}. 4 - from Ref. \cite{13}. 5 and 10 are constraints from low-energy n$−\text{208Pb}$ scattering, \cite{16} and \cite{14}, respectively. 6 - from Ref. \cite{17}. 7 - from Ref. \cite{15}. 8 and 9 are constraints from spectrosopy of antiproton atoms \cite{16}. 11 and 12 are constraints from near-forward $pn$ scattering for vector and scalar bosons, respectively \cite{18}. The axes are in the $log_{10}$ scale. The internal structure of neutron stars is not modified qualitatively provided the boson coupling strengths with baryons and masses lie at $g^{2}/μ^{2}$ $< 200 \text{ GeV}^{-2}$ beneath the highlighted area 13.]

Realistic models of nuclear matter are based on the nucleon-nucleon scattering data. They split into soft and stiff models according to the rate the pressure increases with the density. The soft models correspond to low maximum masses of neutron stars $\sim 1.6 \text{ M}_{⊙}$, while the stiff models give the upper limit around $\sim 2.6 \text{ M}_{⊙}$.

The problem on the softness of nuclear EOS has received new interest due the analysis of strange particle production in heavy-ion collisions. The data at different bombarding energies lead to the conclusion that EOS of nuclear matter must be soft at densities two to three times of the saturation density \cite{21,25,26}. Data on the transverse and elliptic flows in heavy-ion collisions suggest a soft EOS around the saturation, too \cite{27}.

Last years observations of pulsars with high masses have been reported. The most massive pulsars are PSR B1516+02B in the globular cluster M5 with the mass of $1.96±0.09 \text{ M}_{⊙}$ and PSR J1748-2021B in the globular cluster NGC 6440 with the mass of $2.74 ± 0.22 \text{ M}_{⊙}$ \cite{28}. The mass of rapidly rotating neutron star in the low mass X-ray binary 4U 1636-536 is estimated to be $M = 2.0 ± 0.1 \text{ M}_{⊙}$ \cite{29}. The mass and radius of the X-ray source EXO 0748-676 are constrained to $M ≥ 2.10 ± 0.28 \text{ M}_{⊙}$ and $R ≥ 13.8 ± 1.8 \text{ km}$ \cite{30}. The observations on neutron stars suggest that EOS of the $β$-equilibrated nuclear matter is stiff.

The controversy between the conclusions on the softness of nuclear matter as derived from the laboratory experiments and on the stiffness of the $β$-equilibrated
nuclear matter as derived from the astrophysical observations has been of interest since after the discovery of millisecond pulsars [31–32] and earlier [33].

Current models use to match EOS of neutron matter with a soft EOS at the saturation density and a stiff EOS at higher densities. Such models are in the qualitative agreement with laboratory and astrophysical data [34].

High densities provide favorable conditions for the occurrence of exotic forms of nuclear matter: pion, kaon, and dibaryon condensates, quark matter. New degrees of freedom make EOS softer, pushing the maximum mass of neutron stars down. The recent astrophysical observations seem to exclude the softest EOS e.g. based on the classical Reid soft core model [35] and make it problematic to accommodate the exotic forms of nuclear matter with masses and radii of the observed pulsars [30] (see however [36]).

The in-medium masses of vector mesons depend on the density. Assuming $\mu$ is a function of $\rho$ and using Eq. (2), one may evaluate the $\omega$-meson contribution to pressure:

$$P_\omega = \frac{g^2 \rho^2}{2\mu^2} \left( 1 - \frac{2\rho}{\mu} \frac{\partial \mu}{\partial \rho} \right). \quad (6)$$

A positive shift of the $\omega$-meson mass decreases the pressure and leads to a softer EOS, whereas a negative shift leads to a stiffer EOS. The data on the dilepton production in heavy-ion collisions do not give evidence for significant mass shift [37], so the observed stiffness of the $\beta$-equilibrated nuclear matter can hardly be attributed to in-medium modifications of the vector mesons.

The realistic models of neutron matter discussed in Ref. [34] neglect hyperon channels e.g. reactions $\Sigma^- \rightarrow n + e^- + \bar{\nu}_e$. In RMF models [22,35,39], the $\beta$-equilibrium of hyperons drops the limiting mass by $0.5 \div 0.8 M_\odot$. This result is in accord with hypernuclear data and other recent calculations [40,41,42]. The inclusion of the $\beta$-equilibrium for all baryons brings difficulties in reproducing the observed masses of neutron stars.

Coming back to vector WILBs, we see that their existence is desirable to provide additional stiffening of the $\beta$-equilibrated nuclear matter.

The Compton wavelength of WILBs is assumed to be greater than the radius of nuclei e.g. $1/\mu > R \approx 7$ fm $\approx (30 \text{ MeV})^{-1}$ for the lead. The contribution of WILBs to the binding energy of nuclei then equals $\sim A^2 g^2 / R$ like for photons. Since $g^2/(4\pi)$ is much smaller than the fine structure constant, the effect of WILBs on nuclei is negligible. Above $\sim 10^2$ MeV the coupling constant of WILBs is close to unity, so WILBs are there neither weekly interacting nor light.

WILBs thus do not modify observables in laboratory experiments on hypernuclear physics, nuclear structure and heavy-ion collisions, since their baryon couplings are very small. The characteristic scale of the parameters of these particles is fixed by the upper limit [3].

The mass-radius relations for non-rotating neutron stars are shown on Fig. 2 for four values of the ratio $g^2/\mu^2 = 0, 25, 50$ and $100 \text{ GeV}^{-2}$ of a flavor-singlet vector WILB. At densities below $\rho_{drip} = 4.3 \times 10^{11}$ g/cm$^3$ the matter represents an atomic lattice. WILBs do not modify properties of nuclei and the Baym-Pethick-Sutherland EOS [43], accordingly. At densities $\rho_{drip} < \rho < \rho_{nucu} = 2.8 \times 10^{14}$ g/cm$^3$, atomic lattice coexists with neutron liquid. The matter at $\rho_{drip} < \rho < \rho_{nucu}$ is described by the Baym-Bethe-Pethick EOS [44]. Above $\rho_{nucu}$, nuclei dissolve and the matter is described by the $\beta$-equilibrated hyperon liquid with the compression modulus $K = 300$ MeV [22]. WILBs contribute to the energy density and pressure above $\rho_{drip}$, as described by Eqs. (2) and (6) with $\mu \partial \mu / \partial \rho = 0$, through the spatially extended nucleon and hyperon liquid components of the neutron star matter. The vector WILBs give equal contributions to the chemical potentials of the octet baryons and do not violate the chemical $\beta$-equilibrium [33]. The inclusion of such vector bosons does therefore not change composition of the neutron star matter.

The highlighted area at the upper left corner of Fig. 2 excludes within general relativity the radii of neutron stars below the Schwarzschild radius. The causal limit excludes the area $R \lesssim 3GM$ [45]. The rotation speed
limit curves are constructed using the modified Keplerian rate \( v_{\text{max}} \approx 1045 \left( M/M_\odot \right)^{1/2} (10 \text{ km}/R)^{3/2} \text{ Hz} \), which accounts for the deformation of rotating neutron stars and effects of general relativity [46].

It is seen from Fig. 2 that, despite we selected EOS with the high compression modulus, the neutron star sequence with \( g^2/\mu^2 = 0 \) contradicts to the mass measurement of PSR B1516+02B. It gives a very low mass of the neutron star from the blackbody radiation radius constraint also, which confronts with the lower limit of \( \sim 0.85 \text{ M}_\odot \) for masses of protoneutron stars [59].

The value of \( g^2/\mu^2 \approx 10 \text{ GeV}^{-2} \) gives the maximum mass slightly above 3.0 M_\odot. However, the neutron star sequence does not cross the rotation speed limits, while the red shift remains always below \( z = 0.35 \). The upper bound [3] is thus critical for the internal structure of neutron stars [54].

The vector WILBs increase the minimum and maximum mass limits and radii of neutron stars and are able to bring in the agreement models of hyperon matter which are soft with the astrophysical observations on neutron stars which require a stiff EOS. The ratio \( g^2/\mu^2 \approx 50 \text{ GeV}^{-2} \) might be reasonable. Such a value, however, clearly contradicts to the laboratory constraints shown on Fig. 1 in the entire mass range \( \mu = 10^{-9} \) to \( 10^2 \text{ MeV} \).

The in-medium modification of masses of vector bosons modify EOS. Vector WILBs can be compared to the \( \omega \)-meson where \( |\delta \mu_\omega/\mu_\omega| \lesssim 0.1 \) above the saturation density [37]. A vector WILB mass shift can be estimated as \( |\delta \mu^2| \approx g^2/\mu^2 \). The in-medium modification is small provided \( |\delta \mu^2| \lesssim \mu^2 \). The laboratory constraints shown on Fig. 1 do not apply to WILBs coupled to hyperons. A vector WILB coupled predominantly to the second family of the quarks makes hyperon matter EOS stiffer also. It contributes differently to chemical potentials of the octet baryons and suppresses the hyperon content of the neutron star matter due the additional repulsion. One can expect the ratio \( g^2/\mu^2 \) should be close to or higher than that estimated above (\( \sim 50 \text{ GeV}^{-2} \)). In such a scenario, nuclear matter without hyperons can be treated as reasonable approximation for the modeling structure of neutron stars in the \( \beta \)-equilibrium also e.g. on line with Ref. [34] where models with the blocked hyperon channels are shown to be in the qualitative agreement with the laboratory and astrophysical constraints.

Gauge bosons interact with the conserved currents only, but flavor is not conserved. A WILB coupled to the second family of the quarks cannot be a gauge boson, so it does not arise naturally in the current theoretical schemes. Here, we do not have a goal whatsoever to go beyond the phenomenological analysis.

Hypernuclear data restrict \( NY \) potentials, whereas the interaction between hyperons YY is not known experimentally. The stiffness of the hyperon matter might also be attributed to the \( \phi(1020) \)-meson exchange, whose coupling to the nonstrange baryons is suppressed according to the Okubo-Zweig-Iizuka rule (see, however, [50]).

Summarizing, we have assumed the existence and derived constraints for a new boson that couples to nuclear matter. Such a particle contributes, by its coherent force among nuclear constituents, to a modified EOS and affects the structure of neutron stars. The neutron stars exclude scalar bosons with the coupling strengths and masses above the line 13 on Fig. 1, whereas in a narrow band below it and above a vector boson coupled to quarks of the second family could modify the EOS in a direction favored by the observed masses and radii of neutron stars. The astrophysical constraints in the non-strange sector are less stringent than the most accurate laboratory ones. They are unique, however, for scalar WILBs in the strange sector. The region of validity of the astrophysical constraints extends from \( \lambda \sim 10 \text{ fm} \) to about 10 km. Detailed studies of manifestations of new bosons in astrophysics, physics of neutron stars, and hadron decays to energy missing channels can shed more light on the existence of WILBs and their possible effect on the structure of neutron stars.

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We do not discuss the gravitational mass - baryon mass relationship for PSR J0737-3039 (B) [47], since majority of realistic models fail to reproduce it. None of the neutron star models with WILBs fits the radiation radius $R_{\text{rad}} = 12.8 \pm 0.4$ km of an X-ray source in the globular cluster M13 [48]. Also, the rotation speed limit from the X-ray transient XTE J1739-285 that favors a soft EOS and the mass of pulsar PSR J1748-2021B that favors a very stiff EOS are nearly mutually exclusive. These data need confirmation.

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