Is there a supernova bound on axions?

Nitsan Bar, Kfir Blum, and Guido D’Amico

1 Weizmann Institute of Science, Rehovot, Israel 7610001
2 Theory department, CERN, CH-1211 Geneva 23, Switzerland
3 Stanford Institute for Theoretical Physics, Stanford University, Stanford, CA 94306, USA

We present a critical assessment of the SN1987A supernova cooling bound on axions and other light particles. Core-collapse simulations used in the literature to substantiate the bound omitted from the calculation the envelope exterior to the proto-neutron star (PNS). As a result, the only source of neutrinos in these simulations was, by construction, a cooling PNS. We show that if the canonical delayed neutrino mechanism failed to explode SN1987A, and if the pre-collapse star was rotating, then an accretion disk would form that could explain the late-time ($t \gtrsim 5$ sec) neutrino events. Such accretion disk would be a natural feature if SN1987A was a collapse-induced thermonuclear explosion. Axions do not cool the disk and do not affect its neutrino output, provided the disk is optically-thin to neutrinos, as it naturally is. These considerations cast doubt on the supernova cooling bound.

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II. PREVIOUS WORK

Raffelt \[7, 8\] reviewed the SN1987A bound on axions and suggested the following criterion to define the axion bound, based on the time duration of the burst:

\[
\epsilon_a < 10^{19} \text{ erg/g/s.}
\] (1)

Here \(\epsilon_a\) is the axion emissivity which, in Eq. \(1\), is to be evaluated at reference temperature \(T = 30\) MeV and density \(\rho = 3 \times 10^{14} \text{ g/cm}^3\). Eq. \(1\) was introduced as a simple, effective means to formulate the axion bound. To substantiate it, Raffelt \[7\] refers to the numerical simulations of Mayle et al \[47, 48\] and of Burrows, Turner, and Brinkmann \[49\]. We therefore discuss these numerical works in some detail.

Ref. \[48\] (updating \[47\]) studied core collapse in 1D simulations including axions. The axion bound was defined to correspond to the value of \(f_a\) with which the neutrino burst duration extends over > 7 sec. This timing requirement implied total energy emission in axions of \(E_a = \int dt L_a < 3 \times 10^{53}\) erg. Two points are important to note about the simulations of \[47, 48\]:

- There was no supernova explosion in the simulations.
- The simulations included only the central \(M = 1.64\) \(M_\odot\) iron core of the star, discarding the stellar envelope outside of it. The time it takes the outermost mass coordinate of \[47, 48\] to fall onto the PNS is \(t_{\text{in}} \approx 0.4 (1.64\ M_\odot/M)^{\frac{1}{2}} \left(r/2 \times 10^8 \text{ cm}\right)^{\frac{3}{2}}\) sec, where \(r \approx 2 \times 10^8\) is a typical radial coordinate for this value of \(M\). Therefore, on times \(t \gtrsim 1\) sec or so, the simulations left out of the calculation the accretion of the envelope outside of the iron core.

Inspecting the neutrino luminosity in the calculations of \[48\] (see Fig. 3 there), one notices that the neutrino luminosity during \(t < 2.5\) sec is insensitive to axion emission for whatever value of \(f_a\). At \(t > 2.5\) sec axion cooling starts to affect the neutrino signal, but by \(t = 5\) sec the neutrino luminosity is still only reduced by a factor of \(\sim 2\) compared to the no-axion simulation; such minor suppression would be perfectly compatible with the SN1987A data (see Fig. \(1\)). At \(t > 5\) sec, the neutrino luminosity in simulations with \(f_a\) in the excluded range goes significantly below the no-axion case, falling to \(L_{\nu_e} < 10^{51}\) erg/s at \(t \approx 7\) sec. If the PNS was the only source of neutrinos, then this behaviour would indeed be inconsistent with the neutrino events around \(t \sim 10\) sec.
The second suite of simulations referred to by [7] is that of Burrows, Turner, and Brinkmann [49], based on the numerical framework of [50, 51]. Again, the simulations (with and without an axion emission) did not involve a supernova explosion. The explicit initial conditions contained only the iron core with a mass of \( M = 1.3 \, M_\odot \). Ref. [49] did include a treatment of accretion, but that was not calculated from an actual stellar profile. Instead, an effective accretion rate was specified by \( \dot{M} = M_0 e^{-t/\tau} \). Three models were studied: model A, with \( M_0 = 1 \, M_\odot / s \), and models B and C, with \( M_0 = 0.4 \, M_\odot / s \). All three models used \( \tau = 0.5 \, \text{sec} \). With these parameters the accretion rate in all three models dropped below \( 10^{-3} \, M_\odot / s \) within less than 2.8 seconds, effectively eliminating the accretion component of the neutrino luminosity that, as we show in Sec. IIII, requires \( M \gtrsim 0.05 \, M_\odot / s \) to accommodate the SN1987A data. With this treatment, effectively limiting the simulations to contain a bare cooling PNS at \( t \gtrsim 2 \, \text{sec} \), Ref. [49] found an axion bound that was approximately consistent with the results of [58] (after proper matching of the axion couplings [7]).

Proceeding from Raffelt 90’s [7] to more recent analyses, the strategy remained the same: the emission of new particles was calculated in simulations of PNS cooling, without a supernova explosion. Ref. [52] simulated a bare PNS read-off from a core-collapse simulation at \( t = 0.5 \, \text{sec} \). Ref. [54] (see also [53]) used simulations in which an explosion was triggered by artificially enhancing the heat deposition due to neutrinos behind the stalled shock. The artificial heating rates were tuned such that by \( t = 0.5 \, \text{sec} \), the shock progressed out to \( \sim 1000 \, \text{km} \), thereby eliminating the accretion luminosity component. Refs. [11, 54] used simulations from [55] in which an explosion was set-off artificially at \( t = 0.1 \, \text{sec} \), after which the envelope above the PNS was removed by hand.

To conclude this section, the Raffelt criterion [7] is based on the assumption that the non-exploding simulations must somehow be missing some key aspect of the physics, and the DvM must trigger an explosion on time \( t \lesssim 2 \, \text{sec} \) after core collapse. The explosion is assumed to strip-off the envelope of the star, leaving the cooling PNS as the only source of neutrinos. Following this logic, all of the analyses and reanalyses of the supernova axion bound effectively involved simulations of bare PNS cooling, leaving the rest of the star out of the calculation. This scenario could be correct: it is conceivable that DvM simulations would eventually achieve self-consistent explosions a-la SN1987A (see, e.g. [18]). In that case, the supernova axion bound could perhaps be substantiated. However, if the DvM failed in SN1987A, then the stellar envelope would have continued to accrete onto the compact central object. In that case one is left to wonder whether the accretion-induced neutrino luminosity could invalidate the axion bound. In the next section we attend to this question.

III. AXION EMISSION DOES NOT AFFECT ACCRETION-INDUCED NEUTRINO LUMINOSITY.

As we reviewed in the previous section, the early \((t \lesssim 2 \, \text{sec})\) phase of the CCSN neutrino burst is known to be insensitive to axion emission [7]. We therefore focus on the late-time part of the burst. Our observation is that axion emission also does not affect the neutrino luminosity of an optically thin (to neutrinos) accretion disk, that would be compatible with the observed late-time neutrino events.

If the pre-collapse star was rotating, and if the DvM fails to explode the star, then an accretion disk forms on time [13, 30, 34]

\[
t_{\text{disk}} \approx \frac{\sqrt{r_f^3}}{2GM(r_f)} \approx 4 \left(\frac{r_f}{10^9 \, \text{cm}}\right)^{\frac{3}{2}} \left(\frac{2 \, M_\odot}{M(r_f)}\right)^{\frac{1}{2}} \, \text{sec}
\]

at a radius

\[
R_{\text{disk}} \approx \left(\frac{f}{2}\right) r_f \approx 50 \left(\frac{f}{0.01}\right) \left(\frac{r_f}{10^9 \, \text{cm}}\right) \, \text{km}.
\]

Here \( f \) is the ratio of the centrifugal force to the component of the gravitational force perpendicular to the rotation axis, \( r_f \) is the radial coordinate at which \( f \) first becomes appreciable, and \( M(r_f) \) is the mass enclosed within \( r_f \). While stellar rotation is not yet well understood, especially so in the relevant time window just prior to core-collapse [56, 57], the reference values of \( f \) and \( r_f \) in Eqs. (2,3) are in the range considered in [58, 59].

Accretion disks around stellar-mass compact objects were studied in the literature [34–36]. Because the formation of the disk is associated with the failure of the DvM to produce an explosion, Ref. [54] considered this scenario a “failed supernova”. However, if the CITE model operates [30–32], then at least some of these “failed supernovae” may not fail after all. What if such a disk formed in SN1987A [13]? For a progenitor profile relevant for SN1987A, the mass accretion rate of matter falling through the disk is in the ballpark of \( \dot{M} \approx 0.05 \, M_\odot / s \) and can be sustained for many seconds [13, 34–36]. The accretion rate can be used to estimate the accretion luminosity\(^1\),

\[
L_{\nu_e} \approx \frac{GM_{\text{rem}} \dot{M}}{2R_{\text{disk}}} \approx 2.6 \times 10^{51} \left(\frac{M_{\text{rem}}}{2 \, M_\odot}\right) \left(\frac{\dot{M}}{0.05 \, M_\odot / s}\right) \left(\frac{50 \, \text{km}}{R_{\text{disk}}}\right) \, \text{erg s}^{-1}.
\]

For an optically-thin disk, the neutrino spectrum approximately follows a pinched Fermi-Dirac spectrum with

\(^1\) An equal luminosity is also emitted in \( \nu_\mu \).
mean neutrino energy related to the emitting plasma temperature via \( (E_{\nu_e}) \approx 5.07 T \). Numerical simulations with \( R_{\text{disk}} \approx 50 \, \text{km} \), \( M_{\text{env}} \approx (2 - 3) M_{\odot} \), and \( M \sim 0.05 \, M_{\odot} \) find \( T \approx 2.5 \, \text{MeV} \) \cite{13, 34}, for which \( \langle E_{\nu_e} \rangle \approx 12.7 \, \text{MeV} \). These results for \( L_{\nu_e} \) and \( \langle E_{\nu_e} \rangle \) are consistent with the SN1987A late-time data shown in Fig. 1.

Axion emission with values of \( f_a \) within a few orders of magnitude from the standard axion bound \( (f_a \approx 10^{20} \, \text{GeV} \) \cite{27}) does not affect the neutrino emission of the disk. To see this, we model the axion emissivity by \cite{8}

\[
\epsilon_a \approx 4.7 \times 10^{20} \left( \frac{\rho}{10^{14} \, \text{g/cm}^3} \right) \left( \frac{T}{30 \, \text{MeV}} \right)^{3.5} \times \left( \frac{4 \times 10^8 \, \text{GeV}}{f_a} \right)^2 \text{erg g}^{-1} \text{s}^{-1}.
\] (5)

The details of the axion couplings are not very important for the discussion; for concreteness, in Eq. (5) we assumed that the dominant axion emission mechanism is nucleon bremsstrahlung \( NN \rightarrow NNa \) and used \( C_N = 1 \) in the dilute approximation \cite{8}. For comparison, the \( \bar{\nu}_e \) emissivity can be estimated including only nucleon conversion \cite{60},

\[
\epsilon_{\bar{\nu}_e} \approx 2.7 \times 10^{20} \left( \frac{X_n}{0.5} \right) \left( \frac{T}{2.5 \, \text{MeV}} \right)^6 \text{erg g}^{-1} \text{s}^{-1}.
\] (6)

where \( X_n \) is the neutron fraction and we consider the disk to consist of a dissociated plasma of \( n, p, e^\pm \). Using again characteristic values for the density and temperature consistent with simulations \cite{13, 34} we see that the axion emissivity of the disk is negligibly compared to the neutrino emissivity, for values of \( f_a \) within 4 orders of magnitude of the canonical axion bound:

\[
\frac{\epsilon_{\bar{\nu}_e}}{\epsilon_a} \approx 3.4 \times 10^8 \left( \frac{X_n}{0.5} \right) \left( \frac{\rho}{10^9 \, \text{g/cm}^3} \right)^{-1} \left( \frac{T}{2.5 \, \text{MeV}} \right)^{2.5} \times \left( \frac{4 \times 10^8 \, \text{GeV}}{f_a} \right)^2.
\] (7)

What makes the disk insensitive to axions is not just the smallness of \( \epsilon_a \) compared to \( \epsilon_{\bar{\nu}_e} \), shown by Eq. (7). Even in the high density core of a PNS, with \( \rho \sim 10^{14} \, \text{g/cm}^3 \) and \( T \sim 30 \, \text{MeV} \), the axion emissivity is small compared to the neutrino emissivity. Rather, the key point is that the accretion disk emission region is characterised by relatively low density, \( \rho \sim 10^9 \, \text{g/cm}^3 \), and consequently it is optically-thin to neutrinos: the mean free path of \( \bar{\nu}_e \) is \( l \sim 3 \times 10^8 \left( 10^9 \, \text{g/cm}^3/\rho \right) (10 \, \text{MeV}/E_{\nu_e})^2 \) km, to be compared to a characteristic disk scale of \( R_{\text{disk}} \lesssim 100 \, \text{km} \).

Therefore, the power generated in neutrinos via Eq. (6) flows directly out of the star to form the asymptotic luminosity of Eq. (4), being the dominant cooling mechanism of the plasma in the disk. In contrast, a PNS at \( \rho \sim 10^{14} \, \text{g/cm}^3 \) is deeply optically-thick to neutrinos, cannot cool by neutrino volume emission, and can thus be affected by the volume emission of free-streaming axions even for \( \epsilon_a < \epsilon_{\nu} \).

IV. DISCUSSION AND CONCLUSIONS

The explosion mechanism of core-collapse supernovae (CCSNe) in general, and SN1987A in particular, is still unknown. Nevertheless, the SN1987A neutrino burst had traditionally been used to place constraints on new light particles, such as axions, that free-stream out of the CCSN core.

As reviewed in Sec. II simulations used in the literature to substantiate the axion bound excised, by hand, the envelope of the star above the central proto-neutron star (PNS), such that the only source of neutrinos in these simulations was, by construction, a bare cooling PNS. But a cooling PNS is not the only source of neutrinos in a CCSN. If the delayed neutrino mechanism (D\(\nu\)M) fails, and if the pre-collapse star was rotating, then an accretion disk forms on a time scale of seconds at a typical radius of a few 10’s of km above a stellar-mass compact object (neutron star or black hole). Such accretion disk would be a natural feature of collapse-induced thermonuclear explosion (CITE). We noted in Sec. III that the accretion disk can explain the late-time \((t \gtrsim 5 \, \text{sec})\) neutrino events of SN1987A (for a dedicated analysis, see \cite{13}), and that axions do not cool the disk and do not affect its neutrino output if the disk is optically-thin to neutrinos, as it naturally is.

Even if one takes for granted the D\(\nu\)M as the explosion mechanism of SN1987A, simulations of the D\(\nu\)M in 2D show accretion-induced neutrino luminosity that continues even while the star is exploding \cite{45, 46}, in contrast to results in 1D. This means that a proper evaluation of the axion bound may require 3D simulations extending to \( t \approx 10 \, \text{sec} \). Without such simulations it may be difficult to ascertain that the \( t \approx 10 \, \text{sec} \) neutrino events did not come from residual accretion.

We believe that these considerations cast doubt on the SN1987A cooling bound on axions. Experimental searches (e.g. IAXO \cite{10}) would do good to keep an open eye for axions in the parameter space nominally excluded by the canonical supernova bound. Interestingly, if an axion really does exist with parameters in the “excluded” range, then there should be a diffuse supernova axion background \cite{61}.

Our discussion of the bound pertains to the neutrino burst duration argument of \cite{7}. An independent argument that bypasses our criticism for some particle physics models was proposed in \cite{62}, which noted that dark photons free-streaming from the PNS could con-

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2 See the snapshot at \( t = 5.5 \, \text{sec} \) in Fig. 5 in \cite{13}, and the snapshot at \( t = 7.598 \, \text{sec} \) in Fig. 6 in \cite{34}.
vert into Standard Model photons or $e^\pm$ pairs outside of the star, leading to tension with gamma-ray limits. Another independent argument [63] notes that new particles must not transfer too much of the internal energy of the core ($\gtrsim 10^{53}$ erg) into the kinetic energy of the ejecta ($E_{\text{kin}} \sim 10^{51}$ erg [64]). This is an interesting new consideration, and it may indeed be more robust to the uncertainties of the explosion mechanism compared with the neutrino burst duration argument. One point to note, which may weaken the constraints derived in [62, 63], is that the time available for the PNS to inject the new particles could be limited by black hole formation at $t_{\text{BH}} \lesssim 3$ sec or so [13], compared to the injection time of order 10 seconds assumed in [62, 63].

Finally, while we focused on axions for concreteness, we expect that the situation is similar with regards to other feebly-interacting new particles such as Majorons [65, 66], dark photons [11], sterile neutrinos [12], KK gravitons [67] and other examples [51].

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