Discussion
Astrophysical signatures of / bounds on axions

Alessandro Mirizzi  globular clusters, red giants, supernova
Kfir Blum  Supernova
Koichi Hamaguchi  Neutron Star
Axions in the Lab and in the Cosmos
@CERN, July 19, 2019
$\mathcal{O}(10^8) \text{ GeV} < f_a < \mathcal{O}(10^{12}) \text{ GeV}$
Axions in Lab and in the Cosmos
CERN, 14-19/07/2019

ASTROPHYSICAL AXION BOUNDS/HINTS

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ALPs have very small mass
- Emission from stellar plasma not suppressed by threshold effect
- New energy-loss channel
- Back-reaction on stellar properties and evolution

Additional energy loss ("cooling")
- Loss of pressure
- Contraction
- Heating
- Increased nuclear burning
Globular clusters are gravitationally bound associations of typically $10^6$ stars. The low metallicity is one indicator for their great age. All stars in a given cluster are coeval; they differ only in their mass.
The color-magnitude diagram of a globular cluster represents an “isochrone” of a stellar population. Locus of coeval stars with different initial masses.
Axions would reduce the lifetime of stars in HB, while producing negligible change in RGB evolution (Primakoff rate suppressed in degenerate RGB core).

[Salaris et al., astro-ph/0403600] [57 GCs]

$$R = \frac{N_{HB}}{N_{RGB}}$$

Well reproduced, within 30 %, by models of GC without axions.
We found dependence of $R$ on Helium mass fraction $Y$, neglected in previous investigations.

$$R = 6.26Y - 0.41g_{10}^2 - 0.12$$
Taking as benchmark the direct determination of Helium fraction by Izotov et al. (1308.2100) $Y_\text{p}=0.254 \pm 0.003$ we find

$$g_{\alpha \gamma} < 0.66 \times 10^{-10} \text{GeV}^{-1} \quad (95 \% \text{ CL})$$

The strongest bound on $g_{\alpha \gamma}$ is comparable with CAST one.
A particularly useful observable is the brightness of the tip of the RG branch. Additional cooling would give rise to a brighter RGB tip.

RGB: Very dense. Sensitive to $g_{ae}$

[Viaux et al., 1311.1669]
HINTS OF NEW PHYSICS?

Several stellar systems seem to be cooling faster than predicted by the models [Giannotti et al., 1512.08108], perhaps hinting to new physics

Though these hints should be taken carefully, they could show a systematic problem in our understanding of stellar evolution
Stellar cooling shows a mild preference for a small coupling to photons and electrons

Best fit

\[ g_{ae} = 1.6 \times 10^{-13} \]
\[ g_{a\gamma} = 0.12 \times 10^{-10} \text{ GeV}^{-1} \]

\[ g_{ae} = m_e \frac{C_{ae}}{f_a} \quad g_{a\gamma} = \frac{\alpha}{2\pi} \frac{C_{a\gamma}}{f_a} \]

best fit corresponds to:

\[ \frac{C_{ae}}{C_{a\gamma}} \approx 2.7 \times 10^{-2} \]

[Giannotti et al., 1708.02111]
ALP interpretation

Stellar cooling shows a mild preference for a small coupling to photons and electrons

For the DFSZ I (II) model, this means a preference for a small (large) $\tan \beta$

DFSZ I: $\frac{C_e}{3} = \frac{\cos^2 \beta}{3}$; $\frac{C_{\alpha \nu}}{3} = \frac{8}{3} - 1.92$

DFSZ II: $\frac{C_e}{3} = \frac{\sin^2 \beta}{3}$; $\frac{C_{\alpha \nu}}{3} = \frac{2}{3} - 1.92$

Both DFSZ I and II explain fairly well the combined observations

$\chi^2_{\text{min}}/\text{d.o.f.} \approx 1$

EXPERIMENTAL SENSITIVITY

[Armengaud et al., 1904.09155]
Models with two Higgs doublets and flavor-dependent PQ charges
Extant estimates of the progenitor (initial) masses are based on:

- Pre-explosive luminosity
- Properties of the light-curves

Excluding SN 2012ec, the masses estimated from the luminosity curves are $2.9 \pm 0.8\, M_{\odot}$ higher than those derived from the progenitor luminosity!

Progenitors appear fainter than expected
Fainter progenitor might point to an additional energy loss channel on top of neutrinos.

Axions may account for the missing contribution to the stellar energy-loss.
Core collapse SN corresponds to the terminal phase of a massive star [$M \gtrsim 8 \, M_\odot$] which becomes unstable at the end of its life. It collapses and ejects its outer mantle in a shock wave driven explosion.

- **ENERGY SCALES:** 99% of the released energy ($\sim 10^{53}$ erg) is emitted by $\nu$ and $\bar{\nu}$ of all flavors, with typical energies $E \sim O(15 \, \text{MeV})$.

- **TIME SCALES:** Neutrino emission lasts $\sim 10 \, \text{s}$

- **EXPECTED:** 1–3 SN/century in our galaxy ($d \approx O(10) \, \text{kpc}$).
LIFE AND DEATH OF A MASSIVE STAR

Onion-like layers of a massive, evolved star just before core collapse.

Collapse

Nuclear density

Core-bounce & shock wave

Shock revival
**Why No Prompt Explosion?**

- **Dissociated Material** \( (n, p, e, \nu) \)
  - 0.1 M\(_{\text{Sun}}\) of iron has a nuclear binding energy \( \approx 1.7 \times 10^{51} \text{ erg} \)
  - Comparable to explosion energy
  - Shock wave forms within the iron core
  - Dissipates its energy by dissociating the remaining layer of iron
NEUTRINOS AND EXPLOSION MECHANISM

Paradigm: Explosions by the convectively supported neutrino-heating mechanism

- "Neutrino-heating mechanism": Neutrinos "revive" stalled shock by energy deposition [Colgate & White, 1966, Wilson, 1982, Bethe & Wilson, 1985]

Figure 5. A Convective Engine
(a) For simplicity, supernovae were often modeled in one dimension. A star was assumed to be spherically symmetric, its radius being the only spatial parameter that mattered. Doing simulations was therefore equivalent to doing physics in a long tube, even though the transfer of heat from one end of a pipe to the other is not very effective. (b) With the advent of multidimensional models, convection could occur. Hot, buoyant material could rise in one part of the star, to be replaced by cooler material falling from some other region. An in-out circuit is established that allows for the efficient and continuous transfer of heat out of the core and into the quasi-static layer. Energy from the gravitational collapse is thus converted into mechanical work as heat is being transferred between hot and cold reservoirs. In this sense, supernovae can be thought of as being powered by a simple convective engine.
Neutrino-Driven Supernovae

- Stalled accretion shock still pushed outward to ~150km as matter piles up on the PNS, then recedes again.
- *Heating* or *gain* region develops some tens of ms after bounce.
- Convective overturn & shock oscillations “SASI” enhance the efficiency of $\nu$-heating, which finally revives the shock.
- **Big challenge:** Show that this works!
Problems: Shock revival by the $\nu$-driven mechanism in 3D

Simplified 3D “light-bulb” model from Hanke et al. (2012):
Turbulent convection in 2D and 3D

First-principle 3D models:

- Often failures or delayed explosions compared to 2D
- Models close to the threshold – not unexpected because we except failures in nature!
- Still no proof that mechanism is robust

Or with simpler schemes: e.g. IDSA+leakage Takiwaki et al. (2014)
THREE PHASES OF NEUTRINO EMISSION

10.8 $M_{\odot}$ progenitor mass
(spherically symmetric with Boltzmann $\nu$ transport)

**Neutronization burst**
- Shock breakout
- De-leptonization of outer core layers

**Accretion**
- Shock stalls $\sim 150$ km
- $\nu$ powered by infalling matter

**Cooling**
- Cooling on $\nu$ diffusion time scale

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**FIGURE**

[Figure adapted from Fischer et al. (Basel group), arXiv: 0908.1871]
Sanduleak –69 202

Large Magellanic Cloud
Distance 50 kpc (160,000 light years)

Tarantula Nebula

Supernova 1987A
23 February 1987
NEUTRINO SIGNAL OF SUPERNOVA 1987A

Kamiokande-II (Japan)
Water Cherenkov detector
2140 tons
Clock uncertainty ±1 min

Irvine-Michigan-Brookhaven (US)
Water Cherenkov detector
6800 tons
Clock uncertainty ±50 ms

Baksan Scintillator Telescope
(Soviet Union), 200 tons
Random event cluster ~ 0.7/day
Clock uncertainty +2/-54 s

Within clock uncertainties, signals are contemporaneous
Emission of very weakly interacting particles would “steal” energy from the neutrino burst and shorten it.

Assuming that the SN 1987A neutrino burst was not shortened by more than $\sim \frac{1}{2}$ leads to an approximate requirement on a novel energy-loss rate of

$$\varepsilon_x < 10^{19} \text{ erg g}^{-1} \text{ s}^{-1}$$

for $\rho \approx 3 \times 10^{14} \text{ g cm}^{-3}$ and $T \approx 30 \text{ MeV}$
AXION EMISSION FROM A NUCLEAR MEDIUM

$NN \rightarrow NN\alpha$

nucleon-nucleon bremsstrahlung

Bulk nuclear interaction  One pion exchange

Non-degenerate energy-loss rate $\varepsilon_a = g_{aN}^2 \times 10^{39} \text{erg g}^{-1} \text{s}^{-1} \rho_{15} T_{30}^{3.5}$

\[
\begin{align*}
T_{30} &= T / 30 \text{ MeV} \\
\rho_{15} &= \rho / 10^{15} \text{g cm}^{-3} \\
\langle \rho_{15} \rangle &\approx 0.4 \\
\langle T_{30}^{3.5} \rangle &\approx 1.4
\end{align*}
\]

$g_{aN} < 9 \times 10^{-10}$
Free streaming

Volume emission of axions

Trapping
[Burrows, Ressell & Turner, PRD 42:3297,1990]

Axion diffusion from an "axion-sphere"

Possible detection in a water Cherenkov detector via oxygen nuclei excitation
Including corrections to axion emissivity, the bound might be relaxed by factor $\sim 5$

**Caveat:** How robust is the new bound?

We performed a recent re-evaluation of the SN 1987A bound

[Carenza, Giannotti, Fischer, A.M., 1906.11844]
Beyond the OPE approximation

- Non-zero pion mass in the propagator $\rightarrow \sqrt{3m_N T} \sim m_\pi$
- Two-pions exchange $\rightarrow$ Important around $2\text{fm} \sim 1.5m_\pi^{-1}$
- Effective nucleon mass $\rightarrow m^*_N(\rho)$
- Multiple nucleon scatterings $\rightarrow$ Nucleon spin fluctuations
The SN1987A neutrino burst lasted \( \sim \) 10 s, then

\[ L_a < 2 \times 10^{52} \text{ erg s}^{-1} \]

The axion luminosity for our model at \( t = 1 \) s is

\[
L_{a, \text{OPE+MS}} = 4.2 \times 10^{70} g_a^2 \left( C_n^2 + 0.35 C_p^2 + 0.02 C_n C_p \right) \text{ erg s}^{-1}
\]

\[
L_{a, \text{corr.+MS}} = 1.6 \times 10^{70} g_a^2 \left( C_n^2 + 0.36 C_p^2 + 0.04 C_n C_p \right) \text{ erg s}^{-1}
\]
Bounds on axion couplings and mass for KVSZ model in our SN model at $t_{pb} = 1$ s

<table>
<thead>
<tr>
<th>$C_{ap} = -0.47 ; C_{an} = 0$</th>
<th>$g_{ap} \times 10^{-10}$</th>
<th>$m_a$ (meV)</th>
<th>$f_a \times 10^8$ (GeV)</th>
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Figure 11. Constraints on the QCD axion mass and axion decay constant for various supernova temperature and density profiles. The “canonical” bound from the PDG [35, 115] is shown with a solid gray line, while the bound labelled “counts” comes from [123]. Our bounds close the gap between these constraints, known as the “hadronic axion window”.
Archidiacono, Hannestad, Mirizzi, Raffelt & Wong, arXiv:1307.0615

Future EUCLID survey would be sensitive to $m_a \sim 0.2$ eV

[Archidiacono et al., 1502.03325]

Alessandro Mirizzi
NBIA
Copenhagen, 21/06/2019
Hadronic axion window closed by cooling argument

Free-streaming

$\frac{L_a}{L_{v,\text{tot}}}$ vs. $g_{an}=g_{ap}$

- OPE
- Complete

Trapping

$10^{-10}$ $10^{-9}$ $10^{-8}$ $10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$

$10^{-10}$ $10^{-9}$ $10^{-8}$ $10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$
Is there a supernova bound on axions?

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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 ($\tau \gtrsim 5$ 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.
ALTERNATIVES TO NEUTRINO-DRIVEN EXPLOSIONS

In supernovae with energies higher than \( \sim 2.5 \times 10^{51} \) erg up to the “hypernova” regime, where the explosions can reach several \( 10^{52} \) erg for progenitor stars above \( \sim 20 M_\odot \), rapid rotation and the efficient amplification of magnetic fields are likely to play a crucial role. These explosions are probably driven by magnetohydrodynamic effects around highly magnetized, fast-spinning neutron stars (possibly associated with the observed “magnetars”) or around rapidly rotating black holes that accrete infalling stellar gas with high rates from a surrounding torus threaded by strong magnetic fields (see Janka 2012 for a review).

Though recent multidimensional models seem to strengthen the case, the paradigm of the neutrino-driven mechanism is far from being convincingly established or even proven. It should not remain unmentioned, that it is still questioned by some because of the remaining problems of self-consistent models to yield robust explosions and to explain the observed energies of typical supernovae by neutrino-energy deposition. While these problems may disappear once 3D models become more mature, one should certainly remain open-minded as long as there is a lack of solid empirical evidence for the neutrino mechanism. However, the suggested alternatives, e.g. the “jittering-jet mechanism” (46, 47) and “collapse-induced thermonuclear explosions” (48), are based on ad-hoc assumptions in tension with the presently established understanding of stellar evolution and supernova dynamics. The involvement of speculative ingredients and the missing self-consistency are neither satisfactory nor convincing and place such suggestions on a level of sophistication far below the current state of the neutrino-driven mechanism.

Moreover, convincing alternatives to the neutrino-heating mechanism, which could elucidate the processes that initiate and power most core-collapse SNe, do not exist. Considering thermonuclear burning in the stellar carbon shell during gravitational collapse as the main energy source of the SN blast wave (Kushnir & Katz (2015)) demands a radical change of the chemical structure of progenitor stars in conflict with the results of stellar evolution calculations. This approach to overrule the common notion of stellar evolution appears as an unnecessary and overmotivated act of desperation. Similarly unsatisfactory
MAIN CRITICISMS

- Thermonuclear explosion model is not compatible with present knowledge of stellar evolution. Requires helium from the helium shell efficiently mixed in the stellar carbon layer. Needs to assume that the star rotates rapidly.

- Majority of collapsing stars will form very massive neutron stars or BHs. Unlikely to be in agreement with the mass distribution of observed neutron stars and black holes.

- Exploding SN1987A and other CCSNe by the thermonuclear burning of helium mixed in the carbon shell would not be compatible with the chemical composition seen in the supernova ejecta. Emitted nickel and titanium form either during explosive silicon burning or during the freeze-out of matter from nuclear statistical equilibrium (i.e. from the cooling of neutrino-heated ejecta). This cannot be explained in thermonuclear scenario.
Every experimental measurement and every astrophysical or cosmological argument has its own systematic uncertainties and its own recognized or un-recognized loop holes. Therefore, to corner axions it is certainly important to use as many independent interaction channels and as many different approaches as possible.
FIG. 1. Axion-photon coupling $|g_{a\gamma}|$ for the astrophobic models in Tab. II as a function of $m_a$. The DFSZ-I,II (respectively with $E/N = 8/3, 2/3$) and KSVZ benchmarks are also shown for comparison.