UNIVERSITÀ DEGLI STUDI DI BARI
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# Report on the second year of PhD activity

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## Introduction

I will present in the following my accomplished and ongoing research projects as well as the attended schools and conferences and the list of my talks.

### Schools attended:

- Winter School on Multi-Messenger Astrophysics, Asiago (Italy), 14 - 23 Jan. 2020

### Conferences:

- Workshop "Axion cosmology," Munich (Germany), 17-28 Feb. 2020
- New Frontiers in Theoretical Physics - Convegno nazionale di fisica teorica, e-conference, 27-29 May 2020
- DESY Virtual Theory Forum, e-conference, 22-25 Sep. 2020
- IBS-ICTP Workshop on Axion-Like Particles, e-conference, 21-23 Oct. 2020

### Scientific collaborations:

- Scientific collaboration with O. Straniero
  Osservatorio Astronomico dell'Abruzzo, Teramo (Italy), Dec. 2019

### Talks:

- "*Improved axion emissivity from a supernova and the SN1987A bound*"
  Department of Physics, Bari (Italy), 17 Dec. 2019
- "*Stellar bounds on axions and ALPs*"
  Munich Institute for Astro- and Particle Physics (MIAPP), Munich (Germany), 26 Feb. 2020
- "*Constraints on the coupling with photons of heavy axion-like-particles from Globular Clusters*"
  online talk for the IAXO, MADMAX and ALPS collaborations, 28 May 2020
- "*Reconciling hints on axion-like-particles from high-energy gamma rays with stellar bounds*"
  online talk for the Virtual Axion Institute, hosted by Kai Schmitz and Valerie Domcke, 1 Sep. 2020
- "*Bounds on axion-like particles from the diffuse supernova flux*"
  online talk for the DESY Virtual Theory Forum 2020, 22 Sep. 2020

# Research projects

## Axions from supernovae

### Improved axion emissivity from a supernova via nucleon-nucleon bremsstrahlung - Erratum

**In collaboration with: T. Fischer, M. Giannotti, G. Guo, G. Martínez-Pinedo and A. Mirizzi**

SNe are cosmic laboratories which offer a unique chance to probe axions. Indeed, axions can be produced efficiently in the stellar core leading to an energy-loss that, if excessive, would shorten the duration of the associated SN neutrino burst. At this regard, the neutrino data from SN 1987A has been used to constrain the axion emissivity. The most efficient production mechanism for axions in a SN core is the nucleon-nucleon (NN) bremsstrahlung. This process has been often modelled in literature at the level of one-pion-exchange (OPE) interaction. Starting from this naive recipe, I revised the calculation of the SN axion emissivity including systematically different effects, namely a non-vanishing mass for the exchanged pion, the contribution from the two-pions exchange, effective in-medium nucleon masses and multiple nucleon scatterings [1]. I found that the axion emissivity is significantly reduced (by about an order of magnitude) with respect to the naive OPE approximation. This result has lead to a relaxation by a factor 3 of the SN bound on the axion mass with respect to the OPE result.

### Enhanced Supernova Axion Emission and its Implications

**In collaboration with B. Fore, M. Giannotti, A. Mirizzi and S. Reddy**

I am currently continuing my work in this direction, studying other axion production channels in SNe, in particular the pion-axion conversion [2]. The role of thermal pions in the axion production was first discussed more than two decades ago in a schematic way, but never reconsidered after that. A recent study demonstrated that strong interactions enhance the abundance of negatively charged pions in a SN core. Motivated by this result, and by the large suppression of the bremsstrahlung rate found in [1], I have revisited the calculation of the axion emissivity due to the reaction $\pi^- p \to na$ to asses its impact. I found that it is about $2-5$ times larger than NN bremsstrahlung. Moreover, the axion spectrum is also found be much harder. Together, the larger rates and higher axion energies imply a much stronger bound on the mass of the QCD axion, and larger expected counts in terrestial detectors for axions from a Galactic SN. For the relevance of this result and its conseqences, this paper has been submitted to Physical Review Letters.

## Heavy axion-like particles and core-collapse supernovae: constraints and impact on the explosion mechanism

**In collaboration with: G. Lucente, T. Fischer, M. Giannotti and A. Mirizzi**

Furthermore, I considered the case of axions coupled with photons. In the case of very light axions, the main channel for axion emissivity in SNe is the Primakoff process, i.e. the conversions of thermal photons into axions in the fluctuating electric or magnetic fields generated by the stellar plasma. However, for massive axions ($m_a > 50\,\mathrm{MeV}$) the dominating production process is the fusion of two thermal photons into an axion, the so called photon coalescence, a process overlooked in previous estimates of the SN axion flux [3]. Taking into account this process I obtained updated bounds on the axion-photon coupling $g_{a\gamma}$ for heavy axions. Finally, I investigated the possible impact of radiative decays of heavy axions on the energy deposition in a SN.

## Bounds on axion-like particles from the diffuse supernova flux

**In collaboration with: F. Calore, M. Giannotti, J. Jaeckel and A. Mirizzi**

In Ref. [4], I pointed out that the cumulative emission of axions from all past core-collapse SNe would lead to a diffuse flux with energies $O(50)\,\mathrm{MeV}$, which we called Diffuse SN Axion-Like Particle Background (DSNALPB). I used this flux to constrain the axion couplings. Indeed, for low-mass axions ($m_a < 10^{-7}\,\mathrm{eV}$) the DSNALPB can be converted into $\gamma-$rays in the Galactic magnetic field. This allowed me to set a new bound on the photon-axion coupling, using recent measurements of the diffuse $\gamma-$ray flux observed by the Fermi-LAT telescope. Thanks to the study of SN axions and of related observables, I acquired significant expertise in the field of weakly interacting particles produced from nuclear media and hot plasmas; modelling the Galactic magnetic field and numerically solving the axion-photon mixing equations in a realistic Galactic magnetic field model.

# Axions from low-mass stars

## Constraints on the coupling with photons of heavy axion-like-particles from Globular Clusters

**In collaboration with: O. Straniero, B. Döbrich, M. Giannotti, G. Lucente and A. Mirizzi**

Globular cluster stars are another powerful laboratory to probe axions. In this context, it is known that axion emissivity via Primakoff process would reduce the lifetime of Helium Burning stars allowing to place a bound on $g_{a\gamma}$. This argument has been recently applied to the case of low-mass axions. I extendend this study to the case of massive axions ($10\,\text{keV} < m_a < 500\,\text{keV}$) where mass effects would suppress the emissivity [5]. In order to asses a bound I have included the axion emissivity in state-of-the-art stellar evolution codes and compared my results with observational data of HB stars in globular clusters. My result is complementary to the constraints from SN 1987A and beam-dump experiments. The combination of the different bounds leaves open a small triangularly shaped region in the parameter space. This is informally known as the axion "cosmological triangle" since it can be excluded only using standard cosmological arguments and might be explored in upcoming accelerator experiments. The results in [5] are cited by the Particle Data Group.

## Reconciling hints on axion-like-particles from high-energy gamma rays with stellar bounds

**In collaboration with: G. A. Pallathadka, F. Calore, M. Giannotti, D. Horns, J. Majumdar, A. Mirizzi, A. Ringwald, A. Sokolov and F. Stief**

I also studied the axion emissivity from the Sun. In particular, in [6] I discussed possibile environmental effects that might suppress the solar axion emissivity, possibly reconciling the limits from CAST experiments with recent claims about an axion signal in Very High Energy $\gamma-$ray data from galactic pulsars.

## Production of axion-like particles from photon conversions in large-scale solar magnetic fields

**In collaboration with: E. Guarini, J. Galan, M. Giannotti and A. Mirizzi**

Furthermore, in [7] I characterized the low-energy solar axion flux coming from conversions of thermal photons in large-scale solar magnetic fields. This process was neglected in previous studies. These new axion production channels could create an extra flux of solar X-rays. In fact axions can be converted into photons in the solar corona magnetic field. This interesting possibility will be studied in details in a future publication.

# Axions in cosmology

## Dynamical evolution of axion condensates under stimulated decays into photons

**In collaboration with: A. Mirizzi and G. Sigl**

I am also interested in the impact of axions in the Early Universe, as dark matter. Indeed, depending on their mass, axions can play the role of both cold DM (with $m_a \sim \mu\,\mathrm{eV}$) and hot DM (with $m_a \sim \mathrm{eV}$). In particular, cold DM axions would behave as a condensate, and might form compact objects like clumps. In this regard, my research started with the study of axions stimulated decay into photons in clumps [8]. Photons produced in this way contribute to the diffuse radio background, which provides a way to place a bound on these photon decays. This research guideline is still unexplored and dedicated studies can have an important interplay with the first recent simulations of Axion Minicluster Halos.

## Relaxing cosmological mass bounds for hot dark matter axions in low-reheating scenarios

**In collaboration with: M. Lattanzi and A. Mirizzi**

At higher masses, eV scale axions would behave as hot-dark matter analogously to neutrinos. In this case mass bounds can be placed from cosmological observations on large scale structures and on cosmic microwave background. In this context, I am studying how these bounds change in non-standard cosmological scenarios, e.g. with low-temperature reheating epoch [9]. For this research project I characterized the axion decoupling in the Early Universe to study the effects of the axion background on cosmological structure formation and on the cosmic microwave background.

## Future plans

Much remains to be explored in the context of axion astrophysics due to the forthcoming data with several new experiments planned in next few years, in particular in relation to X-ray and $\gamma-$ray astronomy. In addition, I plan to extend my researches to other weakly-interacting particles. An example are dark-photons, which have a phenomenology similar to axions. I also plan to extend my interest towards neutrino astrophysics and cosmology. In particular, a fascinating topic is related to the non-linear oscillations of active and sterile neutrinos in dense media.The main application of this effect is for SN physics and Big-Bang Nucleosynthesis. Neutrinos from astrophysical sources provide unique probes to study the flavor mixing phenomena in a strong coupling regime, inaccessible in other cosmic sources or laboratory experiments.

# Bibliography


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