PhD Proposal:
Axions and neutrinos in astrophysics and cosmology

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Astroparticle physics

Astroparticle physics is an interdisciplinary field merging astrophysics, cosmology and particle physics. It aims at addressing fundamental issues ranging from origin of the universe and the nature of gravity to the understanding of dark matter and dark energy. In recent years this field has witnessed a rapid growth, also in connection to the wealth of new data. In my opinion this research field is very interesting because it opens a plethora of research lines, ranging from fundamental interactions and their cosmological implications to alternatives theories of gravitation.

Astroparticle physics aims to gain insights into longstanding enigmas at the heart of our understanding of the Universe, such as:

- *The extreme Universe*: What can we learn about the cataclysmic events in our Universe by combining all of the messengers (neutrinos, photons, cosmic rays and gravitational waves) that we have at our disposal?
- *The dark Universe*: What is the nature of dark matter and dark energy?
- *Mysterious neutrinos*: What are their intricate properties and what can they tell us?
- *The early Universe*: What can we learn about the Big Bang, for instance from the cosmic microwave background?

Related to these exciting questions, I plan to focus my PhD research activity on:

(a) *Dark matter and axions*

(b) *Axions in astrophysics*

(c) *Supernovae as laboratory for neutrinos and axions*

In the following I will give a brief overview of my research plans.

Dark matter and axions

Dark matter (DM) is a hypothetical form of matter that is thought to account for a quarter of the total Universe energy density. The majority of DM candidates are thought to be some yet undiscovered particles. Its presence is justified by a variety of astrophysical observations, including gravitational effects that cannot be explained unless more matter is present than the baryonic one.

DM is classified as cold or hot according to its velocity. Cold DM (CDM) is composed by non-relativistic particles and hot DM (HDM) by relativistic ones. Cosmological observations exclude a dominant component of HDM. Indeed, relativistic particles would be free-streaming, erasing the formation of cosmological structures at scales smaller than their free-streaming length. Therefore, DM would be mostly “cold”.

Dark matter requires new particles beyond the ones accounted by the Standard Model. In this context strongly motivated candidates for CDM could be Weakly-Interacting-Massive-Particles (WIMPs) ($m \sim O(100\,\mathrm{GeV})$), predicted in different extension of the Standard Model. WIMPs might have been thermally produced in the early Universe and then might constitute the CDM. Since supersymmetric extensions of the Standard Model usually predict new particles with these properties, this apparent coincidence is known as the “WIMP miracle”. However, recent null results from direct-detection experiments and the current absence of signals from supersymmetry at the Large Hadron Collider (LHC) experiment has cast doubt on the WIMP hypothesis.

At this regard, there exist a large number of alternative DM candidates with different masses and cross sections [Fig. (1)]. One of the most interesting candidates are weakly interacting slim particles (WISPs), i. e. hypothetical light and weakly interacting particles such as axions, axion-like particles (ALPs) and dark photons. Axions were postulated long time ago [Pec77a, Pec77b, Wei78, Wil78] to solve a puzzle of Quantum Chromodynamics: the *strong CP problem*. Thus their discovery is very desirable since it would allow one to “kill two birds with the same stone”. Axions can behave as CDM or HDM depending on their production mechanism: thermally produced axions are HDM and their interaction with ordinary matter is stronger than CDM axions, which are produced by non-thermal processes (topological defects decay and misalignment mechanism).

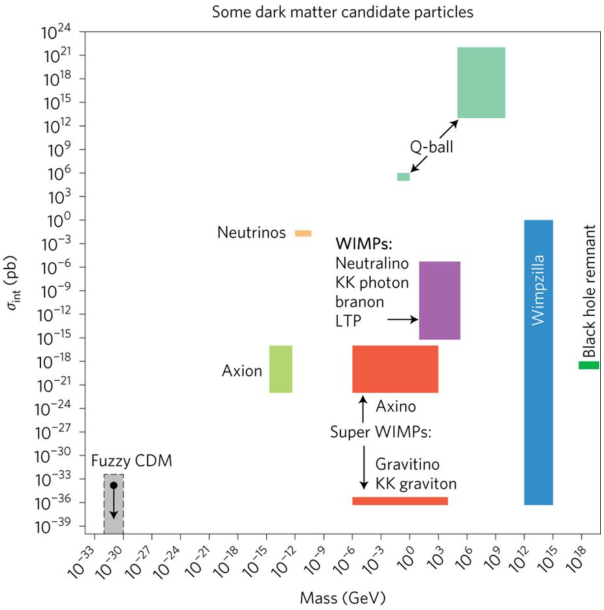

Figure 1: DM candidates.

Stimulated photon emission from axion clumps

Axions with mass $m_a \sim \mu$eV would be produced by non thermal mechanisms as a non-relativistic condensate and they would constitute CDM. Moreover, due to their self-interactions and to the gravitational interactions, they would form compact astrophysical objects. Those objects are collectively called *clumps* and the axion density in those regions is very high ($\rho \sim O(10^{24}\,\mathrm{cm}^{-3})$). It has been shown in literature [Her18b] that in these objects it might occur a stimulated emission of photons from the axions, analogous to an *axion laser*. Indeed, a condensate of axion CDM has an instability that might rapidly mixing axions with photons [Saw18]. This is an intriguing effect that I plan to investigate since it might affect the stability of axion clumps.

Axion mass bound in non-standard cosmologies

Axions with $m_a \sim$ eV would be thermally produced in the early Universe and they would constitute an HDM component in analogy with neutrinos. From analysis of CMB and LSS it is possible to obtain a mass bound on neutrinos and axions. In particular the most stringent bound on axions is $m_a < 0.6\,\mathrm{eV}$ [Fig. (2)]. However, this constraint relies on the axion thermalization based on standard cosmology where is assumed that radiation domination begins

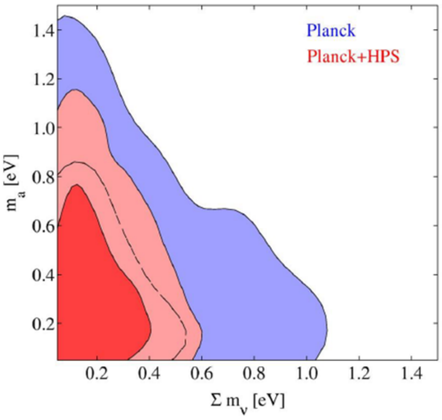

Figure 2: Axion and neutrinos cosmological mass bounds in standard cosmology (Figure taken from [Arc13]).

earlier than the chemical freeze-out of light relics. However, there is no direct evidence for radiation dominated epoch prior to big-bang nucleosynthesis (BBN). The transition to radiation dominated epoch may be more gradual than typically assumed [Gri08]. In such a modified thermal history, the axion relic abundances change because the Hubble expansion rate scales differently with temperature until radiation dominated epoch begins, leading to a different freeze-out temperature. The reheating could end at a temperature as low as 1 MeV, with standard radiation dominated epoch beginning thereafter. This *low-temperature reheating* (LTR) scenario may be modeled simply through the entropy-generating decay of a massive particle into radiation. This decay softens the scaling of temperature with cosmological scale factor, increasing the Hubble parameter and leading to earlier freeze-out for axion relics.

In my work I plan to study axion thermalization in the LRT and determine how the axion mass bound relaxes in this non-standard scenario. In order to study the influence of non-standard thermal histories over axions, I will analyze the spectrum of the Cosmic Microwave Background Radiation (CMBR) and Large Scale Structure (LSS) data. Therefore I plan to learn the methods of cosmological perturbation theory and the computational tools needed to analyze cosmological data.

Axions in astrophysics

Astrophysics provide an important laboratory to probe axions [Raf96]. In particular, the low energies available in stars are well suited for very sensitive

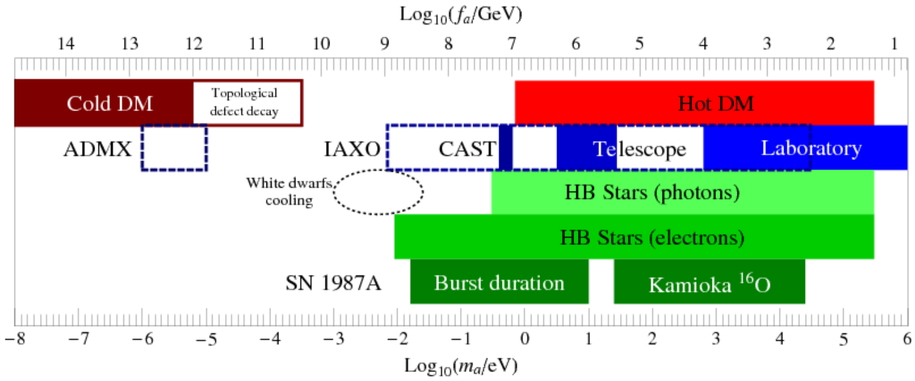

Figure 3: Constraints and searches on QCD axions. The red and brown bounds are given by cosmological considerations on hot and cold dark matter respectively. The blue bounds refer to direct detection experiments. The sensitivity of future experiments is represented in the blue dotted boxes. The light green zones are excluded by the energy loss of horizontal branch stars in globular clusters. The dark green zones are excluded by the analysis of the neutrino signal from SN 1987A.

tests. The basic idea is very simple. Stars are powerful sources for weakly interacting particles such as neutrinos, gravitons, hypothetical axions, and other new particles that can be produced by nuclear reactions or by thermal processes in the stellar interior. Even when this particle flux cannot be directly measured, the properties of stars themselves would change if they lose too much energy into a new channel. This *energy-loss argument* has been widely used to constrain a long list of particle properties. In this context I plan to take a fresh look to these astrophysical bounds [Fig. (3)], updating them by means of the state-of-the-art astrophysical simulations.

Axion-photon oscillations in cosmic magnetic fields

Gamma-ray astrophysics has impressively developed in the last two decades. This trend is continuing nowdays, thanks to the current generation of gamma-ray instruments currently running. The observation of the sky at high-energy scales will provide us with a lot of new data in the next few years. I plan to exploit this exciting opportunity to study the sensitivity of gamma-ray observations to axion-like particles. Remarkably, the coupling of axions with photons in the presence of cosmic magnetic fields may lead to peculiar features in the observed spectra of the very high-energy sources, associated with photon-axion oscillations. I plan to work out accurate solutions of the photon-axion mixing equations considering realistic models of the different galactic and intergalactic magnetic fields, taken from the most recent simulations.

Supernovae as laboratory for neutrinos and axions

Neutrinos

The next Galactic SN will be a lifetime event for particle astrophysics, offering a unique opportunity for a multi-messenger detection of gravitational waves, neutrinos of all flavors, multi-wavelength photons and hypothetical axions. In this context, the role of *astrophysical messengers* played by supernova neutrinos is largely associated with the signatures imprinted on the observable neutrino burst by the flavor conversions occurring deep inside the star. In this regard SNe are unique astrophysical environments where the neutrino density is so high to provide a relevant background for neutrino propagation and flavor evolution, causing nonlinear feedback effects. The resulting *self-induced flavor conversions* would reshuffle the neutrino flavor among different momentum modes [Mir15]. The main effects are driven by collective run-away modes of the self-interacting neutrino gas, that can spontaneously break the initial symmetries of the flavor evolution such as axial symmetry, homogeneity, isotropy and even stationarity. The feedback of the non-linear flavor changes on the SN dynamics, on stellar nucleosynthesis, and on the observable neutrino signal from a SN will be investigated.

Axions

Axions are efficiently produced in a SN and a Galactic SN explosion could produce an observable axion signal. Furthermore, axions constitute an extra SN energy-loss channel, shortening the duration of the neutrino burst. I plan to study the SN axion signal and the influence of axions on the neutrino burst with recent supernova simulations. Moreover, I plan to update the SN axion bound from SN 1987A performing an improved calculation of the axion emissivity from supernovae.

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