Cosmological and Astrophysical Probes of Axions

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I summarize several cosmological and astrophysical probes of axions and axion-like particles. Topics covered include an introduction to the Strong CP problem and axions, axion emission from compact stars and supernovae, the impact of axion dark radiation on the cosmic microwave background (CMB) anisotropies, and the imprint of axion strings on the CMB.

1 Preface

This brief document is a rough transcript of a presentation by the same name that I delivered at the Recontres du Vietnam meeting on August 6, 2023 in Quy Nhon, Vietnam. It is provided here as a record of my contribution to the meeting's proceedings. This document is not intended to serve as a review of axions – it does not fully explore the landscape of ideas that are currently being investigated, it does not provide an entirely comprehensive picture of each topic, and it does not include an exhaustive list of references. Instead, my talk and this article are intended to give a broad brush perspective on recent activities and several key developments in regard to the potential cosmological and astrophysical signatures of axions. Since the the main session of Recontres du Vietnam is attended by researchers with particularly diverse backgrounds, spanning expertise from high-energy experiment to exoplanet astronomy, my talk in Quy Nhon and this article are aimed at a broad audience who are not assumed to have any prior knowledge of (or interest in) axions. If the reader seeks to learn more about the physics of axions, they are encouraged to look into several excellent recent review articles.[1,2,3,4,5] Moreover, due to length restrictions in this article, referencing is sparse; additional references can be found in the reviews.

Let me begin here as I began my presentation in Quy Nhon by thanking the organizers for putting together such a wonderful meeting and for inviting me to be a part of it. The conference was stimulating, the lectures were exceptionally clear and well presented, the venue was stunningly beautiful, and the food was unparalleled. Congratulations on the 30$^{\text{th}}$ anniversary of Recontres du Vietnam, and on the 10$^{\text{th}}$ anniversary of the ICISE! I hope to see many more.

2 Introduction

2.1 Preface

Id like to begin the talk by offering you three things. First I offer my thanks to the organizers for the invitation to join Recontres du Vietnam. Its an honor to give this talk on axions and a pleasure to be here in Quy Nhon. Second I offer my apologies. Due to a mixup which was entirely my fault an incorrect title for my talk appears in the printed program. I wont be talking about dark matter today, but if youre interested in hearing more about the so-called Nightmare Scenario in which dark matter only couples to gravity, please feel free to find me later today. You might wonder why I didnt notice this mixup before the program was printed, and to that, all I can offer are the following excuses. For the past week, Ive been traveling in South and Central Vietnam with my family and some friends that we picked up along the way. So you can imagine how Ive been distracted by natural beauty of this country and its smiling, welcoming people. And while Ive spent the last week on a whirlwind tour of Vietnam, for the next half hour Id like to take you and a similarly speedy tour of the astrophysical and cosmological probes of axions.

2.2 Standard Model

Our tour begins by reflecting upon the known laws of particle physics as they're codified in The Standard Model of the Elementary Particles. Here I want to echo something that Tao Han said on Tuesday: the Standard Model must be heralded as a triumph of science. For the last half century, it has been wildly successful at describing the properties of the known elementary particles as well the forces by which they interact. Nevertheless, the Standard Model presents us also with several puzzles, which were laid out very nicely in David Kaplan's talk on Monday morning. What's important to understand about these puzzles is that they should not be viewed as shortcomings or flaws of the Standard Model, but rather as clues or loose threads which – upon further investigation – will lead us to the discovery of new physics.

2.3 Strong CP Problem

The puzzle that I want to draw your attention to, has to do with the electric dipole moment of the neutron. The neutron is a charge neutral composite particle built from quarks and gluons and held together by the Strong Nuclear Force. The structure and composition of a nucleon is quite complex, involving of course virtual sea quarks and gluons. However, for the following heuristic argument, it suffices to model the neutron as a set of three point charges: an up-type quark with electric charge $+2e/3$ and a pair of down-type quarks with charge $-e/3$. If we ask for the typical electric dipole moment of this system of charges, we can get a rough estimate from dimensional analysis: the constituent particles have charges around e, and their typical separation is around a femtometer implying an EDM on the order of $10^{-13}\, e\,\mathrm{cm}$. However, as we heard yesterday in the talk by Peter Feirlinger the measured neutron EDM is compatible with zero at the level of $10^{-26}\, e\,\mathrm{cm}$.[6] In other words our rough estimate was over 13 orders of magnitude too large!

Now the astute observers among you may already have recognized that there are some special configurations for which the EDM can be made small. For example, if the three quarks are arranged in a line, then the contributions from the two down-type quarks cancel and the EDM vanishes. What understanding can we take away from this exercise? Whats important to recognize is that the configuration with small EDM is especially symmetric. Since the Strong Nuclear Force governs the structure of the nuclei, the vanishingly small neutron electric dipole moment indicates that the strong force exhibits a symmetry, which we call CP symmetry.

As I said at the outset, this is a puzzling feature of the Standard Model. Why should the strong force have CP symmetry? To give some additional context, I'll remind you that the Weak

Nuclear Force famously does NOT respect the CP symmetry. And the discovery of this fact in the neutral kaon system by Kronin & Fitch in 1964 led to them receiving the Nobel Prize in 1980. Why then is CP symmetry a property of the Strong Force? In other words, why is this parameter θ so tiny?

2.4 Peccei-Quinn Solution

One proposed solution to the Strong CP Problem was put forward in 1977 by Roberto Peccei and Helen Quinn. It follows from the observation that there is an energy cost for having nonzero θ. If theta is a fixed parameter of the theory, this energy is simply another contribution to the vacuum energy. However, Peccei and Quinn proposed that the parameter theta should be promoted into a field, which can vary throughout space and evolve over time. Since $\theta = 0$ is energetically preferable, the θ field relaxes to zero, thereby providing a dynamical explanation for the symmetric structure of the neutron and its tiny EDM.

2.5 The QCD Axion

Since weve extended the theory to include a new field, a by-product of the Peccei-Quinn Solution is a new particle. Frank Wilczek named this particle "axion" after the detergent, since it "cleaned up" the Strong CP Problem. This is a new spin-0 particle with no electromagnetic charge or color, like the neutral pion or the Higgs. But unlike those Standard Model particles, the QCD axion is expected to have a tiny mass (if you want to have a number in mind, think micro-eV) and its expected to have feeble interactions with both itself and the Standard Model particles. As a side-effect, this implies that the QCD axion should be cosmologically long lived, making it a viable candidate for the cold dark matter.[7]

2.6 Axion-Like Particles

Before I get into a bit more detail about the axions interactions, let me first mention that the QCD Axion has cousins: the axion-like particles, also known as ALPs. In fact, light spin-0 particles with feeble couplings to ordinary matter are fairly generic in extensions of the Standard Model. Light or massless spin-0 particles can arise as Goldstone Bosons in theories with spontaneously broken symmetry, as we heard from Dam Son on Tuesday. Or in theories with additional spacetime dimensions that are compactified, like string theory, the size and shape of the internal dimensions may vary from point to point across the three extended spatial dimensions. In other words, they behave just like scalar fields whose quantum excitations are spin-0 particles.[8,9] Suffice it to say, these days when people talk about "axions" the term often refers to both *The* QCD Axion and Axion-Like Particles collectively, and Ill do the same here.

2.7 Interactions

In order to discuss the astrophysical and cosmological probes of axions, I need to say a few words about how these particles interact with light and matter. When talking about Axion-Like Particles at low energies it is customary to allow for couplings to photons as well as electrons, muons, neutrons, and so on. I'll denote these couplings by g as follows:

$$\mathcal{L}_{\text{axion}} = -\tfrac{1}{2}m_a^2 a^2 - \tfrac{1}{4}g_{a\gamma\gamma} a F_{\mu\nu}\tilde{F}^{\mu\nu} + \tfrac{1}{m_e} g_{aee}\bar{e}\gamma^\mu\gamma_5 e\,\partial_\mu a + \tfrac{1}{m_n} g_{ann}\bar{n}\gamma^\mu\gamma_5 n\,\partial_\mu a + \cdots \quad (1)$$

$$\text{where} \qquad g_{a\gamma\gamma} = C_\gamma \frac{\alpha_{\text{em}}}{2\pi f_a} \quad \text{and} \quad g_{a\psi\psi} = C_\psi \frac{m_\psi}{f_a}\ , \quad (2)$$

and I want to draw you attention to the fact that they're inversely proportional to a new energy scale, denoted by f_a and called the Peccei-Quinn scale. Typically the PQ scale is much higher than the Standard Model electroweak scale, which is why the axion's couplings are so tiny and its interactions so feeble.

When talking about Axion-Like Particles we typically treat the axion's mass and these couplings as free parameters, and we vary them independently. However, for the QCD Axion the mass is linked to the coupling through the relation:[10] $m_a \simeq (5.7\,\mu\text{eV})(f_a/10^{12}\,\text{GeV})^{-1}$. This is because the QCD Axion gets its mass by virtue of interacting with QCD. If f_a is larger, the interaction is weaker, and the mass is smaller. So when we look at parameter space plots – e.g., axion mass versus axion-photon coupling – it's customary to draw a diagonal band representing the subset of parameter space where the QCD Axion lives. Away from the band we're (typically) thinking about Axion-Like Particles instead. Well see several plots like this later in the talk.

2.8 Outline

So the key questions that will guide the remainder of our tour are these: Does the QCD Axion or an ALP exist in Nature, and if so, how can we discover this New Physics? Searches for axions can be very broadly classified into three categories. Terrestrial Probes seek to create axions here on Earth or detect axions (such as dark matter) as they're passing by the Earth. Astrophysical Probes seek to observe the influence of axions on the stuff within galaxies: stars, gas, and compact objects like black holes. And Cosmological Probes search for the effect of axions on cosmological relics such as the light element abundances, the cosmic microwave background, or the large scale structure of the universe. So in the remainder of our tour, I want to highlight a few of the most well-studied astrophysical and cosmological probes of axions. This certainly wont by a comprehensive review, but just like any good tour, I hope to hit the main attractions.

3 Astrophysical Probes

3.1 Indirect tests of stellar axion emission

If axions couple to the constituent particles that make up a star such as electron, ions, neutrons, and photons and if the axion mass is below the core temperature of the star typically on the order of keV then the star will emit axions.[11] Various emission channels are available, and which channel dominates depends on the axions couplings and the type of star. It is important to note that axion emission may occur from throughout the stars volume, similar to neutrino emission, whereas photon emission primarily occurs at the stars surface. In this way, axion emission provides an additional avenue for the star to exhaust energy that can be competitive with standard cooling channels. This leads to powerful constraints on the axion parameter space.

For example, if you carry out this calculation for a white dwarf star, youll find that axions would carry away a significant fraction of the stars energy if the axion-electron coupling were too large. As a result, there would be statistically fewer bright white dwarf stars today [12,13]. The good agreement between the observed White Dwarf Luminosity Function and the standard cooling calculation implies an upper limit on the axion-electron coupling at the level of $g_{aee} < 10^{-13}$. In fact, this is the strongest constraint on g_{aee} that's currently available for low-mass axions, and I think it's a nice illustration of the power and utility of astrophysical probes.

For another example, consider a set of young and isolated neutron stars known as the Magnificent Seven. The M7 are distributed throughout our neighborhood of the galaxy at distances that range from 120 to 500 parsecs from Earth. Since their discovery in the mid 1990s, the M7 have been studied extensively leading to robust measurements of their age, luminosity, and composition. The age and luminosity measurements are compatible with a standard cooling history, and thereby put constraints on addition cooling channels such as axion emission.[14] In the context of a QCD Axion, these constraints can be expressed as an upper limit on the axion's mass, and they come in at the level of $10^{-2}\,\text{eV}$. In turn, this implies a lower-limit on the energy scale of the axion's UV embedding, $f_a > 5 \times 10^8\,\text{GeV}$ which is a valuable input for model building.

As a third and final example of axion-induced energy losses, lets consider SN 1987A.[15,16]

This is a Type II (core-collapse) supernova that occurred in the Large Magellanic Cloud, a satellite galaxy of the Milky Way, about 50 kpc away from Earth. A supernova leads to the formation of a proto-neutron star that cools rapidly by neutrino emission. In the case of SN 1987A, three neutrino observatories, including Kamiokande II, observed a 13-second burst of neutrinos a few hours before the visible light reached Earth. The duration of the neutrino burst was consistent with the standard cooling paradigm, thereby constraining additional channels for energy loss. In the context of a QCD Axion,[17] these observations constrain f_a to be larger than about $(2 - 5) \times 10^8$ GeV for $m_a = 1$ MeV, and the limit weakens as m_a approaches 100 MeV.

3.2 Direct tests of stellar axion emission

So weve been talking about using stellar cooling as an indirect probe of axions, leading to powerful constraints. But if stars are emitting axions, can we also directly detect those axions? A good candidate is our own Sun. It may not be the strongest axion source when compared with larger or hotter stars, but it is certainly is the closest.

A class of experiments called helioscopes seek to detect axions emitted by the Sun. Most notable is the CERN Axion Solar Telescope or CAST, which has been in operation since the early 2000s. CAST uses a decommissioned test magnet designed for the LHC that can produce a field of 9.5 T. When an axion is exposed to a magnetic field, it develops a tiny probability of converting into a photon of the same energy, through a phenomenon known as the Inverse Primakoff Effect. Axions produced in the Sun would have energies comparable to the Suns core temperature, about a keV, which corresponds to X-ray photons at CAST.

CAST has not yet uncovered evidence for axion emission in the Sun, but instead it has yielded some of the strongest constraints. In their 2017 results paper,[18] using data taken from 2003 to 2015, they obtained one of the current tightest upper limits on the strength of the axion-photon coupling across a wide range of axion masses $g_{a\gamma\gamma} < 0.66 \times 10^{-10}\,\text{GeV}^{-1}$. Mostly these observations constrain axion-like particles with large axion-photon coupling, but the limit also scratches the QCD axion band for eV-scale axions.

CASTs successor is the International AXion Observatory (or IAXO). By virtue of several improvements in the design including larger magnetic field volume, X-ray focusing optics, and low-background detectors IAXO expects to improve on CASTs sensitivity by over an order of magnitude. Importantly, this means that IAXOs sensitivity will push further into the QCD Axion band at masses above milli-eV or so.

3.3 X-Ray emission from magnetic white dwarf stars

Now I want to talk about a second strategy for potentially “seeing” the axions emitted by stars. Whereas CAST and IAXO rely on strong magnetic fields in laboratories on Earth in order to convert stellar axions into visible X-ray photons, one could instead try to make use of the immensely strong magnetic field surrounding the axion’s parent star. Stars like our Sun have a magnetic field of only about 1 Gauss, but smaller compact stars have much stronger magnetic fields reaching hundreds of mega-Gauss for white dwarfs and terra-Gauss for neutron stars.

In this scenario, an axion is produced in the star’s core, it converts to an X-ray photon in the star’s magnetosphere, and the signal is an enhanced X-ray spectrum that’s rising at keV energies. Magnetic white dwarf stars make particularly compelling candidates for these kinds of X-ray observations, since the intrinsic emission for an isolated star is negligibly small, and any anomalous X-ray flux could be associated with axion emission.

A couple years ago, collaborators and I took a survey of all the known magnetic white dwarf stars – there are a few hundred of them – and identified the stars that would be most promising for X-ray observations.[19] We submitted an observing proposal to the Chandra X-ray observatory, who were kind enough to spend about 10 hours looking at our top-ranked star. Unfortunately they didn’t see any X-ray emission, but that still proved to be valuable information. We were able to derive new constraints on the coupling of axions to photons and electrons:[20] $g_{aee} g_{a\gamma\gamma} < 1.3 \times 10^{-25}\,\mathrm{GeV}^{-1}$.

3.4 Radio emission from cold axion dark matter

And let me mention one final thing that you can do with compact stars before moving on to other topics. Up to this point we've been thinking about axions that are created by stars. But the Universe may also contain a population of cold axion dark matter, created at the Big Bang. As these axion dark matter particles pass through a star's strong magnetic field, some of them will be converted into photons. Since energy is conserved in the conversion, and axion dark matter is ultra-light, the photons produced in this way would be in the radio frequency band.

The galactic center is a good target for these observations, since it's expected to contain a larger number of both neutron stars and dark matter particles. Using archival data taken by the Green Bank Telescope, a search was performed for this anomalous radio emission, and finding none, these authors derived constraints on the axion's coupling to photons.[21] The constraints from GBT are really impressive, considering that theyre derived from archival data rather than a dedicated search. Future observations with the Square Kilometer Array could potentially extend the sensitivity by several orders of magnitude.

4 Cosmological Probes

4.1 Axion dark radiation

Lets start by considering the influence of axions on the Cosmic Microwave Background (CMB) radiation. We heard from Yvonne Wong and John Kovac on Tuesday that measurements of the CMBs temperature and polarization anisotropies have reached sub-percent level precision. And that these observations inform our understanding of the structure, composition, and evolution of the Universe.

In particular, CMB measurements constrain the abundance of an invisible dark radiation. Recall from Yvonne & John's talks that the parameter $\Delta N_{\mathrm{eff}} = \rho_{\mathrm{dark\ rad}} / \rho_{\mathrm{one}\ \nu}$ measures roughly the energy density in the dark radiation as compared to the energy carried by a single flavor of relic neutrinos. The Planck satellite has already constrained this quantity to be less than about 0.3 [22], and the future CMB-S4 survey aims to push the sensitivity down by another decade.[23]

If axions have a large enough coupling to matter, they would have thermalized with the primordial plasma in the Early Universe and some population of relativistic axions would survive today as a component of Dark Radiation. The amount of dark radiation depends on the number of relativistic degrees of freedom in the plasma at the time when the axions decoupled.[24,25] But even if all of the Standard Model particles were present, we still expect ΔN_{eff} at the level of about 0.027. This is a small value but tantalizingly within reach, and it provides a target for the CMB S4 program. A measurement of nonzero ΔN_{eff} in the next decade could be evidence of axions in the Universe today and provide insight into their couplings with visible matter.

4.2 Decaying axion-like particles

You might think that we could evade the CMB constraints on axion dark radiation if the axions were to decay before recombination. In fact, axions should decay through their coupling to photons, albeit very slowly for the masses and couplings that weve considered thus far. Heavier axions with masses near the MeV scale would decay more quickly. However, these decays would occur near the epoch of nucleosynthesis, and thereby disrupt the excellent agreement between the observed abundances of the light elements and the standard predictions of BBN.[26] In this way, the interplay of axions with another cosmological relic namely the light elements – furnishes constraints on the couplings of axions to matter and radiation.

4.3 CMB polarization probing axion strings

Coming back to the CMB, the last thing I want to talk about is how observations of CMB polarization can be used to test for the presence of axions in the Universe today.[27] When polarized light propagates through a region of space where the axion field is varying, the light's plane of polarization is rotated by an angle that's proportional to the axion-photon coupling and the change in the axion field.[28] $\alpha = g_{a\gamma\gamma}\pi f_a \approx 0.2°C_\gamma$. This is a form of circular birefringence, similar to what's seen in many crystals, except that here it's induced by the axion field.

One reason why the axion field might be varying throughout space is if the Universe contains a network of cosmic axion strings. Axion strings have been an exceptionally hot topic in recent years. Interest has been driven in part by the ability to use large-scale computing facilities to simulate the complex dynamics of axion strings networks on cosmological scales. If we suppose that axion strings are present in the Universe today, then when we look at the CMB we're looking at it through the network of axion strings. And these strings can leave a detectable imprint on the CMB through axion-induced birefringence.[28]

You might be wondering how we can detect birefringence without knowing the polarization orientation at the surface of last scattering. The short answer is that it's statistical: birefringence converts E-mode polarization patterns into B-mode polarization patterns. So a frequency-independent correlation between E and B is a signal of birefringence.

Each of the major CMB telescopes reports a measurement of anisotropic birefringence. Currently all of these measurements are compatible with zero. So they can be used to place constraints on the presence of an Axion String Network in the Universe today. Its exciting that these constraints are already proving valuable.[?,29,30] For instance SPTpol constrains the product of the electromagnetic anomaly coefficient and the number of cosmic strings to be less than about 4. Since simulations suggest that the number of strings per Hubble volume is typically $O(10-30)$, this restricts the magnitude of the EM anomaly coefficient to be less than $O(1)$. Thats already providing valuable information about the UV embedding of the Peccei-Quinn solution, since in these models the anomaly coefficient is typically an $O(1)$ rational number. The situation will only improve with additional data from Simons Observatory and CMB S4.

5 Conclusion

So that concludes our tour. The Universe is a vast and varied place, and I hope you've gotten a glimpse of the vibrant community of particle physicists, astrophysicists, and cosmologists who are working hard to search for axions in all of the Universe's extreme environments.

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