Check for updates

Looking into dark matter with asteroseismology

Adrián Ayala*

Institute of Astrophysics of Andalusia, Department of Stellar Astrophysics, Granada, Spain

Dark matter remains as an elusive component of modern Cosmology. According to previous research, stellar physics observables can be affected by the presence of hypothetical dark matter particles, which can be produced or accreted into the stars. Stellar pulsations are among the observables affected by dark matter, because the changes of the internal structure of the stars due to dark matter produce variations in the pulsation frequencies. We review the current research in the interplay between astroparticles, precise stellar observations, and accurate asteroseismic models, which can be extremely useful in order to constrain dark matter candidates from asteroseismic observables.

KEYWORDS

dark matter, stellar physics, asteroseismology, solar physics, stellar populations, space missions

1 Introduction

Staying as one of the most puzzling problems in Astrophysics, dark matter has motivated a lot of experiments and theoretical research (Bertone, 2010). The hypothetical existence of dark matter has been supported by the mismatch between our knowledge of Gravity and the dynamics of several systems like galaxy clusters, rotating galaxies, etc. Although this mismatch could be also explained by the Modified Newtonian Dynamics (MOND) hypothesis (Milgrom, 1983), many theoretical models consider that dark matter is composed by exotic weakly interacting particles. This is an appealing possibility, if we attend to some open questions in our description of the Standard Model (Jaeckel and Ringwald, 2010) like, for instance, strong CP violation (Peccei and Quinn, 1977) or some aspects of neutrino physics (Raffelt, 1999), which require invoking new particles, arising from additional terms in the Standard Model (SM) Lagrangian.

In the theoretical frame of Quantum Field Theory, couplings between the new terms of the Lagrangian, accounting for dark matter, and the previous ones can be expected. In particular, these couplings can happen between the new additional terms of the dark matter and the electromagnetic, weak or strong sectors, and they give account of the relatively scarce interactions of dark matter and SM particles. As a consequence of this, it is possible to calculate the rate of decay of dark matter particles into SM ones, or alternatively the rate of production of dark matter from SM components, within several models (Raffelt, 1999). Therefore in principle, experiments and astrophysical observations can constrain the parameter space of many dark matter candidates, on the basis of the phenomenology of the interactions of dark and baryonic matter.

Stellar interiors are suitable environments to expect the production, accretion, and/or annihilation of dark matter (Raffelt and Dearborn, 1987; Córsico et al., 2001; Iocco, 2008; Isern and García-Berro, 2008; Scott et al., 2008; Taoso et al., 2008; Bertone, 2010; Córsico et al., 2012; Vinyoles et al., 2015; Isern et al., 2022), and the star life times are long enough to be affected by continous emission fluxes of dark matter from their interiors. Thus, the observables related to stars and stellar populations can be significantly modified when dark matter is introduced in the stellar models (Scott et al., 2008; Taoso et al., 2008; Casanellas and Lopes, 2011; Ayala et al., 2014). In particular, the observables related to the stellar structure, like the size of the convective and/or radiative regions, could change as a consequence of the energy carried away for the dark matter particles (Martins et al., 2017; Ayala et al., 2020).

As it has been demonstrated (Aerts et al., 2010), the stellar pulsations, studied by Asteroseismology, are critically affected by changes in the stellar structures, like those due to hypothetical dark matter particles. In this review we justify the use and explore the future prospects of Asteroseismology, as a tool to constrain the dark matter. The ongoing and future space missions, and surveys of pulsating stars, open a promising opportunity for Asteroseismology, in order to impose more accurate constraints on several dark matter models, improving the previous asteroseismic bounds derived from main sequence (Cadamuro and Redondo, 2010; Lopes and Silk, 2012; Turck-Chièze and Lopes, 2012; Redondo and Raffelt, 2013; Vinyoles et al., 2015) and evolved stars (Lopes et al., 2019; Ayala et al., 2020), as well as in WDs (Córsico et al., 2019, 2001). In addition, some theoretical predictions about the pulsations of exotic stellar objects, composed of dark matter, could be tested by means of future observations (Panotopoulos and Lopes, 2019; Lopes and Panotopoulos, 2020).

In this paper, we focus on the asteroseismic observables related to the stellar structures and discuss three dark matter candidates: weakly interacting massive particles (WIMPs), asymmetric dark matter (ADM), and weakly interacting slim particles (WISPs) like axions or dark photons. Concerning the latter particles, my collaborators and I have made some valuable contributions, constraining for the first time dark photon properties from the study of the pulsations of the red giant stars. We also recall that the techniques we discuss in this work are general enough to be applied to other particle models, apart from the aforementioned.

This review is organized as follows: in section 2 we explore the role of Asteroseismology in elucidating the internal structure of stars. Section 3 explains the effects of some dark matter candidates on the stellar evolution and structure and the way the asteroseismic observables have been used to constrain these effects. Finally we present a general discussion and prospects of future work in section 4.

2 Asteroseismology and stellar structure

Asteroseismology, the study of stellar pulsations (Christensen-Dalsgaard, 2004; Aerts et al., 2010; Kurtz, 2022), is nowadays a powerful technique. Part of its success is due to space missions devoted to ultra-precise photometry like CoRoT (Baglin et al., 2006), Kepler (Koch et al., 2010) or TESS (Ricker et al., 2015). By means of asteroseismic techniques, stellar parameters are inferred with an uncertainty of up to 2% on the radius, 4% on the mass and 15% on the age for stars showing solar-like oscillations (Silva Aguirre et al., 2017). Moreover, Asteroseismology, enables us to pierce into the stellar interiors, giving a useful information about the extensions of the convective structures inside the stars, which could shade some light on the energy transport mechanism. About this last topic, it is worth mentioning that the period variation of the stellar pulsations have been proposed in order to study the size variation of the internal cavities of the stars, which is related to the convective transport, (Kurtz, 2022). Moreover, the measured change of periods of some white dwarfs has been proposed as a way to look into their radiative cooling mechanisms, constraining also some dark matter properties, like the mass of the axion (Isern and García-Berro, 2008; Isern et al., 2022).

Driven by different mechanisms of pulsation, from the stochastic to the classical cepheids one (Aerts et al., 2010), pulsating stars are spread throughout the Hertzsprung-Russell diagram, the distribution of pulsating stars on the $L/L_\odot$ vs. T_{eff} plane. The oscillation modes on solar-like and some giant stars form a clear structure where p modes of consecutive radial orders n and the same spherical degree l are separated by an almost constant frequency distance. As it was shown by previous research (Tassoul, 1990, 1980), the frequency pattern of these modes satisfy:

$$\nu_{nl} = \Delta\nu\left(n + \frac{l}{2} + \tilde{\alpha}\right) + \epsilon_{nl}, \tag{1}$$

where $\tilde{\alpha}$ is a constant of order unity and $\Delta\nu$ is a periodic spacing known as the large separation. The large separation is defined as the inverse of the sound travel from the surface of the star to the core and back again, (Aerts et al., 2010)

$$\Delta\nu = \left(2\int_0^R \frac{dr}{c(r)}\right)^{-1}, \tag{2}$$

where $c(r)$ stands for the sound speed. Alternatively, the large separation can be defined by means of the asymptotic formula:

$$\Delta\nu = \nu_{n+1,l} - \nu_{n,l} \tag{3}$$

The term ϵ_{nl} in Eq. 1 gives rise to the small frequency separation, $\delta\nu_l$, defined as

$$\delta\nu_l = \nu_{nl} - \nu_{n-1l+2} \tag{4}$$

Whereas the large separation is sensitive to the radius, and therefore to the stellar mass at the main sequence, the small frequency separation is related to the core condensation and the stellar age (Aerts et al., 2010).

Finally, we defined the ratio of small separation and large separation as r_{02}

$$r_{02} = \frac{\nu_{n,0} - \nu_{n-1,2}}{\nu_{n,1} - \nu_{n-1,1}} \quad (5)$$

The aforementioned quantities can be obtained from the periodograms of pulsating stars and are sensitive to the structure of stellar cores, in such a way that they can be used to constraint dark matter candidates. Among the previous studies which proposed to use the asteroseismic parameters to bound dark matter, we mention:

- Vinyoles et al. (2015), focused on the sound velocity profile, in the case of the Sun.
- Ayala et al. (2020) and Casanellas and Lopes (2013), about the large separation in evolved and solar-like stars, respectively. Casanellas and Lopes (2013) also regard the small separation in solar-like stars.
- Martins et al. (2017), focused on r_{02} parameter in solar-like stars.
- Córsico et al. (2019) and Isern and García-Berro (2008), which focus on the period variation of white dwarfs.

In the next sections we will review the bounds on dark matter from these observables. In particular we point out that changes in the large separation throughout the red giant branch could be produced by additional energy losses, related to a kind of dark matter candidate: dark photons. Besides the large separation, dark photon could also influence the luminosity of the RGB tip and bump phases, as we have proved **in previous studies** (Ayala et al., 2015; Ayala et al., 2020).

3 Dark matter models and stars. Constraints from asteroseismology

The role of stars as particle physics laboratories, or more specifically, as dark matter probes has attained an increasing interest in the last decades (Raffelt, 1999; Casanellas and Lopes, 2011). The main reasons are the possibility of constraining dark matter on the basis of their hypothetical influence on stellar structure and evolution. In addition, dark matter could drive the formation and evolution of stars (Turck-Chièze and Lopes, 2012) and therefore, to have a complete understanding of stars, it is mandatory to elucidate the hypothetical production or annihilation of dark matter, or the energy transported by it, inside stellar interiors.

Regarding the search of dark matter in stellar interiors, the Sun has been more studied than other stars, due to its proximity.

However, with the advent and refinement of space missions and the improvements in photometry, the search of dark matter inside stars has extended to main sequence (Casanellas and Lopes, 2013), red giants (Ayala et al., 2020), and white dwarfs (Isern and García-Berro, 2008; Córsico et al., 2012). The forthcoming missions as HAYDN (Miglio et al., 2021), which aims to provide a large survey of the pulsating stars from both Open and Globular Clusters, or PLATO (Rauer, 2021), devoted to obtain ultra precise light curves of variable stars and planetary transits, will hopefully make possible to analyze more in detail the presence of dark matter in stars.

3.1 Constraints on the dark matter from solar-like and low mass stars

As the closest star, the Sun has been observed with a detail unavailable for other stellar objects. Besides optical, UV, and X-ray observational data, we have information about neutrino fluxes, gravity and acoustic measurements (Turck-Chièze and Lopes, 2012), as well as measurements of the magnetic activity. The study of the solar pulsations is the scope of the discipline called "Helioseismology", which has motivated many observations to obtain precise data of the solar light curves (Domingo et al., 1995; Gabriel et al., 1995; Gabriel et al., 1997).

The Sun, a potential laboratory for discovering new particles, is the first target of IAXO (International Axion Observatory, described in Armengaud et al. (2014)), which is devoted to the detection of axions, a pseudoscalar, low-mass dark matter candidate (Peccei and Quinn, 1977; Wilczek, 1978). According to some models, axions can be produced inside the Sun by means of the Primakoff process (Vinyoles et al., 2015). Besides axions, other hypothetical light dark matter particles called dark or hidden photons (An et al., 2014) could carry away energy from the solar interior (Redondo and Raffelt, 2013).

Vinyoles et al. (2015) propose a global best-fit of solar models, neutrino observations and Helioseismology, in order to constrain axions and dark photons, both emitted from the solar interior. The changes in the sound speed profile can be used to discriminate among several axion and dark photon models at the solar internal regions ($r/R \leq 0.2$). In particular the variations of the sound speed profile depend on the axion coupling to the photon, and are also influenced by the product of dark photon mass and dark photon-photon coupling (or kinetic mixing). From a detailed statistical analysis, considering two different solar compositions, Vinyoles et al. (2015) derive the constraint $g_{a\gamma} < 4.1 \times 10^{-10} \, GeV^{-1}$ for the axion-photon coupling, and $1.8 \times 10^{-12} \, eV$ for the product of dark photon mass and kinetic mixing, both at 3σ confident level.

In addition to the search of light dark matter candidates, the Sun has motivated several studies with the aims of constraining massive particles. For example, some authors looked for signatures of WIMPs (Weakly Interacting Massive Particles,

with masses in the range of GeV) in the solar helioseismic data, as these particles could vary the local luminosity and sound speed in the Sun (Turck-Chièze and Lopes, 2012). The reason is, that even though the massive WIMPS can not be produced by thermal processes of the plasma, they can be accreted into the star cores, providing a certain density of dark matter in the vicinity of the star. Thus the massive WIMPs can annihilate with their antiparticles, releasing energy and changing the stellar evolution predicted by models without dark matter (Casanellas and Lopes, 2011).

A number of massive particle models, consider the existence of an asymmetry in the number of dark matter particles and antiparticles of dark matter. They are referred as ADM (Asymmetric Dark Matter) models in the literature (Gudnason et al., 2006; Lopes and Silk, 2012). An important feature of these theoretical treatments is that annihilation of the accreted particles is not so important or even excluded. Therefore the accretion of dark matter contributes more to the energy transport inside the stars than to the existence of an additional source of energy. As in the case of WIMPs models, most theoretical descriptions of ADM consider either the spin-independent or the spin-dependent interactions with baryonic matter.

The ADM models have been constrained successfully using asteroseismic observations and models of low mass stars (Casanellas and Lopes, 2013; Martins et al., 2017). As a consequence of the ADM energy transport in these stars, the models predict that the central temperature decreases, whereas the central density increases. Figure 1 shows these effects for models of KIC 8006161, a star with a mass of $0.92\,M_\odot$, computed
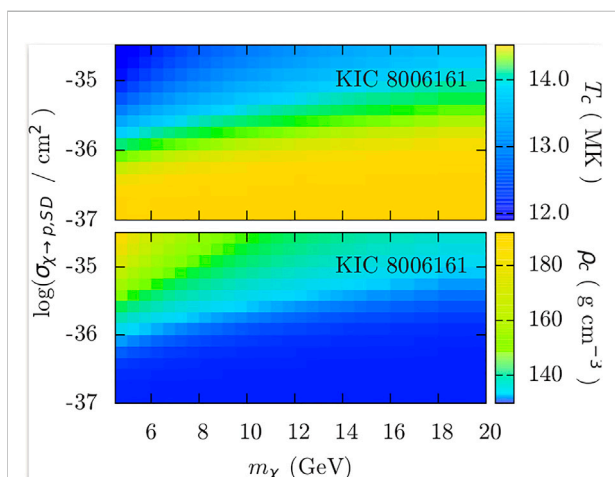
by Casanellas and Lopes (2013). The models were performed considering different values of ADM masses and ADM-baryon cross sections. The authors found that these changes of the central conditions of low mass stars could be used to impose constraints on ADM masses and cross sections, more stringent than the previously derived from the Sun (Taoso et al., 2010).

A key point is that this additional energy transport, due to ADM, can reduce and eventually suppress the convective cores that appear in main-sequence stars in the mass interval $1.1\,M_\odot$ – $1.3\,M_\odot$, as it was also demonstrated by Casanellas and Lopes (2013) (see Figure 2, for the case of the star HD 52265 with a mass of $1.18\,M_\odot$).

The bounds derived on ADM by Casanellas and Lopes (2013) rely on the impact that the ADM energy transport has on the small frequency separation: a decrease of the predicted value of this observable, as it was obtained from the models of HD 52265 and KIC 8006161. They also verified this effect with models of the low-mass star α Cen B ($0.93\,M_\odot$), which they compared with asteroseismic observations of the small separation of this star. On the basis of this analysis, it was
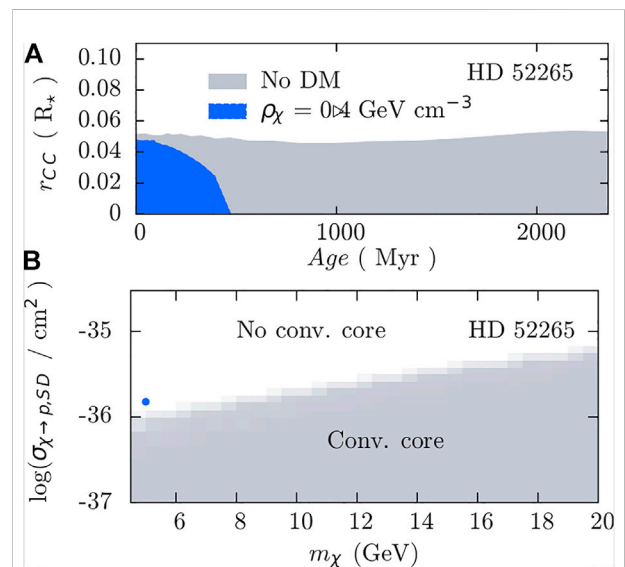

FIGURE 2
Upper **(A)**: convective core radius (r_{cc}) vs. star age, computed for two evolution models of the star HD 52265 ($1.18\,M_\odot$), one of them without dark matter (grey); the other considering the presence of asymmetric dark matter (ADM) with mass m_χ = 5 GeV, cross-section $1.5 \times 10^{-36}\,cm^2$, and a density ρ_x = 0.4 GeV cm^{-3} (blue). Notice that the convective core rapidly disappears at the beginning of the main sequence. Lower **(B)**: HD 52265 models, at its estimated age, considering the action of ADM particles. The vertical axis is the logarithm of the spin-dependent baryon-dark matter cross section (log ($\sigma_{\chi \to p}$)), the horizontal axis is the dark matter particle mass (m_χ). Only some values are compatible with the existence of a convective core (notice the transition between the white and the gray shaded area, defining the separation between the regions where the convective core is excluded or not). The blue point corresponds to the ADM model with the conditions of the upper panel. Taken by Casanellas and Lopes (2013).

FIGURE 1
Theoretically predicted central temperature (upper panel, in MK), and density (lower panel, in g cm^{-3}), of KIC 8006161 ($0.92\,M_\odot$). Notice the variations with respect to the asymmetric dark matter masses (m_χ) and baryon-dark matter spin-dependent cross sections (log ($\sigma_{\chi \to p}$)). Taken from Casanellas and Lopes (2013).

possible to exclude the values of the ADM cross section $\sigma \gtrsim 3 \times 10^{-36}\ cm^2$, for an ADM mass $m_\chi \simeq 5\ GeV$, at 99% confidence level (see Figure 3).

An interesting additional analysis, also focused on the ADM particles within the spin-dependent interaction models, was performed by Martins et al. (2017), a work which also discusses WIMP models with low annihilation. They derive bounds on ADM by means of the r_{02} parameter defined in Eq 5. The choice of r_{02} is motivated by the fact it is weighted towards the stellar core, and therefore r_{02} is more sensitive to the effects of ADM, which are stronger on this region (Martins et al., 2017). The authors used a careful calibration of the Sun, a less massive star, KIC 7871531 (0.85 $M_\odot$), and KIC 8379927 a star more massive than the Sun (1.12 $M_\odot$). An interesting point is that the simulations of energy transport, due to asymmetric dark matter, show that this process is more important in the less massive KIC 7871531 star than in the Sun. This is because of the lower mass and older age of the former, which implies that the energy transport is a larger fraction of the luminosity and that the star has accumulated ADM for longer. On the other hand, for the more massive star KIC 8379927 the energy transport is more efficient, whereas the accretion of ADM is less important than in the Sun and KIC 7871531, due to KIC 8379927 younger age. These outcomes implies different bounds on the ADM from each star. For instance for a mass of the ADM $m_\chi = 5\ GeV$, r_{02} data exclude a cross section $\sigma \gtrsim 6 \times 10^{-36}$ for the Sun; $\sigma \gtrsim 5 \times 10^{-36}$ for KIC 7871531, and $\sigma \gtrsim 4 \times 10^{-36}$ for KIC 8379927.
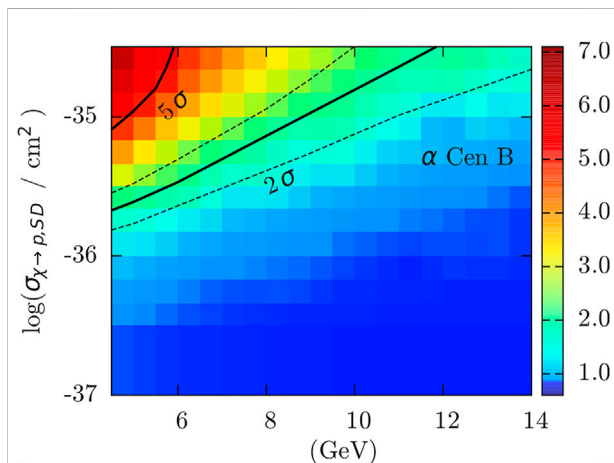
3.2 Constraints on dark matter from evolved stars

In this section we discuss the constraints imposed by Ayala et al. (2020) on dark matter models from red giant branch stars. We focused on the dark photons, which can interact with the electromagnetic sector of the Standard Model, being produced by means of plasmon oscillations in the degenerate cores of red giant stars. These particles could carry away energy from the stellar cores, affecting the luminosities at the RGB bump and tip phases, as we have found before (Ayala et al., 2015).

In a previous work by Khan et al. (2018) the authors looked into the effect of introducing the core overshooting on the pulsation models of RGB stars at the bump, finding an increase of the average large separation. As both processes, core overshooting and dark photon emission, could affect the size of the internal core of the stars, we made the hypothesis that dark photons would increase the large separation too. Therefore, to check this hypothesis, we decided to simulate RGB stars at the bump phase, including the production of dark photons in the models, and to obtain the frequencies of pulsation and the large separation from each simulation. We computed a grid of stellar models with different initial star masses and allowing different values of dark photon masses (m_V) and kinetic mixing (χ). As core overshooting could compete with the effect of dark photons, we also included this in some models of our grid.In order to characterize the frequencies and large separation of a sample of RGB stars at the bump phase, we used a catalogue of seismic data of RGB stars (Albareti et al., 2017) and the previous analysis of Khan et al. (2018). The observational data of the average **large** separation and the corresponding errors are represented by the black line at Figure 4. Our models prediction for large separation are represented by the color and color dashed lines, the latter considering the combined effect of overshooting and dark photon energy losses. We verified the increase of large separation with respect to the increase of the mass and the kinetic mixing of the dark photon, which drive the total amount of energy carried away by this particle (Redondo and Raffelt, 2013; Ayala et al., 2015; Ayala et al., 2020). As both processes, dark photon emission and overshooting, reinforce together on increasing the large separation, we were able to rule out several dark photon models, where even a minimum core overshooting implies a large separation beyond the observational 2σ limits (see Figure 4 and Figure 5). In particular, we excluded the models with mass $900 eV$ and χ values 5×10^{-15}, 7×10^{-15}, and 9×10^{-15}; mass $700 eV$ and χ values of 7×10^{-15}, and 9×10^{-15}; and mass $500 eV$ and χ of 9×10^{-15}.

With this study, we demonstrated that near the so-called RGB bump, dark photons production may be an energy sink for the star significative enough to modify the extension of the convective zones, in a way detectable with modern asteroseismic techniques. A follow-up of this study, taking

FIGURE 3
Deviations of the observed and simulated (with ADM) small separation values of α Cen B (0.93 $M_\odot$), in units of σ (color map). The deviations are plotted vs. the logarithm of the spin-dependent cross sections ($\log(\sigma_{\chi \to p})$), and masses in GeV, two parameters of the asymmetric dark matter. The solid black line shows the two σ region. The dashed lines around the solid black one indicate the observational errors. Taken by Casanellas and Lopes (2013).
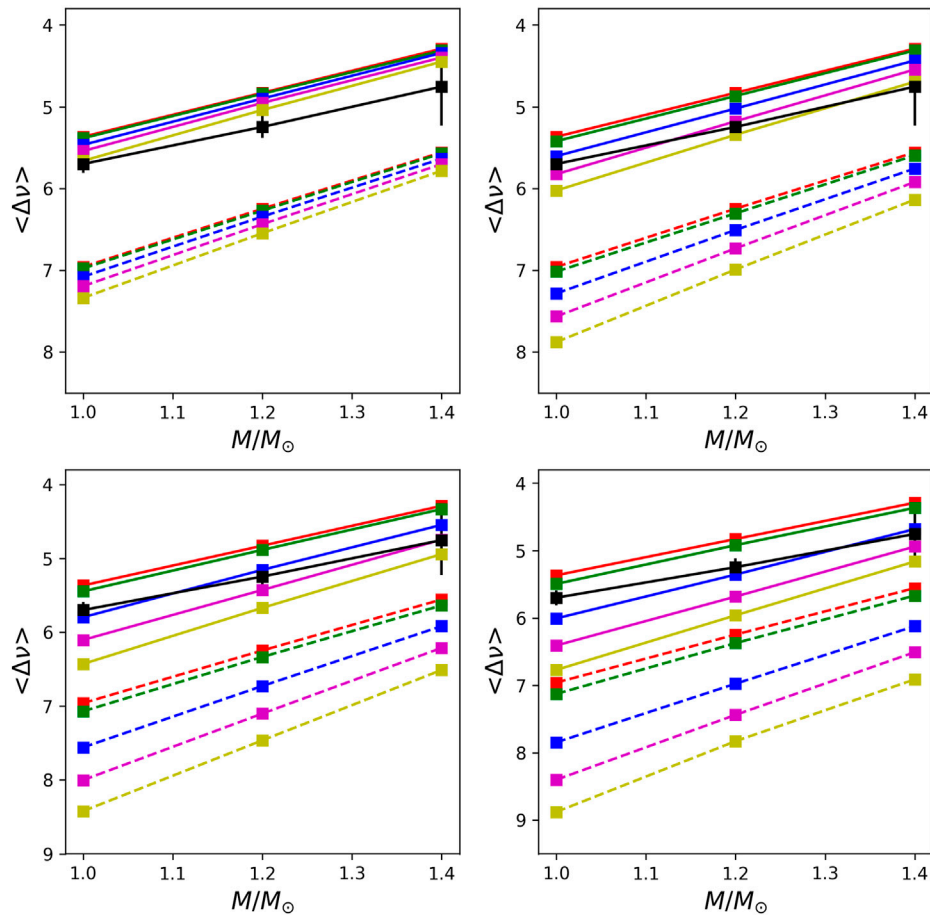
FIGURE 4
Variations of the large separation, $\Delta\nu$, vs. the initial mass $M/M_\odot$ for a set of simulations of RGB stars, introducing the production of dark photon models. Black line correspond to the observations of the large separation. The different panels correspond to m_V (dark photon masses) of 300 eV (upper left panel), 500 eV (upper right), 700 eV (lower left) and 900 eV (lower right). For each panel the solid lines correspond to models with kinetic mixing (χ) values of $\chi = 0$ (red), $\chi = 2 \times 10^{-15}$ (green), $\chi = 5 \times 10^{-15}$ (blue), $\chi = 7 \times 10^{-15}$ (magenta), and $\chi = 9 \times 10^{-15}$ (yellow). Dashed lines correspond to stellar models with χ given by the same color code, but considering a moderate core overshooting, $\alpha_{ov} = 0.025$. Taken from Ayala et al. (2020).

into account the observational uncertainties, and where we expect to derive stronger bounds, is in progress.

3.3 Degenerate stars and new hypothetical objects

In case of the degenerate stars, white dwarfs are a good scenario for axion physics. These objects excite g-mode oscillations with a period well measured by several authors (Córsico et al., 2019; Kepler et al., 2021). According to previous research, the period drift of g-modes of some pulsating white dwarfs, that is, the rate of change of the pulsation period, can not be explained by means of the standard cooling mechanism, which invokes mainly photon and neutrino cooling processes. Therefore an excess in the rate of change of the period exists. This is the case of the

pulsating WD G117-B15A (Figure 6), a ZZ Ceti object Isern et al. (2022); Córsico et al. (2019). For this white dwarf the discrepancy between the standard theory and the observations has been explained with the inclusion in the models of an additional cooling process, due to axion emission (Isern et al., 2022). If an additional axion cooling is included for G117-B15A, the energy, ϵ_{eff} changes, according to Eq 6.

$$\epsilon_{eff} = \epsilon_{nu} - \epsilon_\nu - \epsilon_a \qquad (6)$$

Where ϵ_{nu}, ϵ_ν and ϵ_a stand for the nuclear energy, neutrino and axion rates, respectively. ϵ_{nu} vanishes in general in the case of white dwarfs. Therefore, G117-B15A loses energy by means of the combined emission of neutrinos and axions, the latter with a rate proportional to the square of axion-electron coupling, g_{ae}
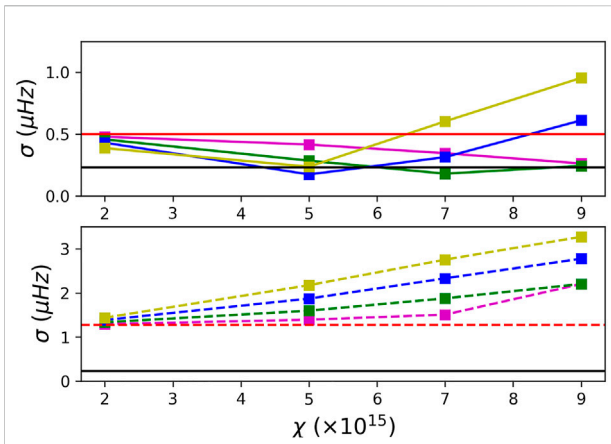
$$\epsilon_a \propto g_{ae}^2 \qquad (7)$$

FIGURE 5
χ^2 test values (given by σ (μHz)), of the theoretical large separation, when dark photons are introduced in the models, with respect to the RGB observations. The plot shows the variation of σ (μHz) vs. the dark photon kinetic mixing, χ. We consider dark photons and overshooting. The solid lines with squares represent the scenarios without overshooting, whereas the dashed with squares are the models combining dark photons and overshooting. The red solid line in the upper panel corresponds to models without dark photons nor overshooting, whereas the dashed red line in lower panel represents the overshooting models, without dark photons. The colors indicate dark photon masses of 300 eV (magenta), 500 eV (green), 700 eV (blue) and 900 eV (yellow). The observational 2σ errors are indicated by the black solid line.
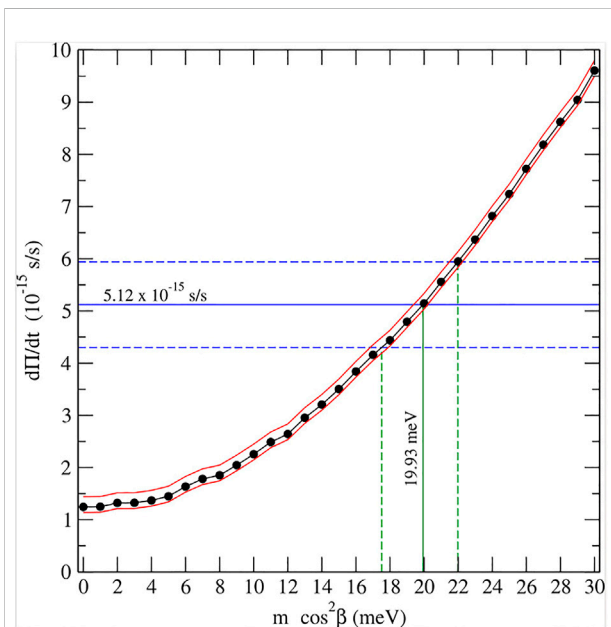

FIGURE 6
Period drift, $d\Pi/dt$ in s/s, vs. $m_a \cos^2\beta$ (in meV) in G117-B15A: a plausible consequence of axion additional cooling (see text for details). Taken from Kepler et al. (2021).

On the other hand, g_{ae} is proportional to the axion mass and the square of the cosine of a certain angle β (Córsico et al., 2019; Isern et al., 2022)

$$g_{ae} = 2.8 \times 10^{-14} m_a \cos^2 \beta \qquad (8)$$

The more massive the axion is the larger is the axion emission, which speeds up the cooling process and increases the rate of change of period of the white dwarf. Using this axion cooling model and the period drift of G117-B15A, Isern et al. (1992) obtained an upper limit for the axion-electron coupling ($g_{ae} \leq 2.4 \times 10^{-13}$), as well as for the product $m_a \cos^2\beta$ ($m_a \cos^2\beta \leq 8.7$ meV). Considering recent measurements of the period change ratio, and excluding the hypothetical effects on the light curve due to magnetic fields or planets, Kepler et al. (2021) give the values $g_{ae} = 5.66 \pm 0.57 \times 10^{-13}$, and $m_a \cos^2\beta = 20 \pm 2$ meV. These are obtained from the theoretical curve of period drift vs. $m_a \cos^2\beta$, computed using a complete asteroseismic model, and the observational value limits, as it is shown in Fig 6.

Concerning the constraints on dark matter from the Asteroseismology of more exotic objects, it is worth mentioning boson or axion stars (Hung-Hsu Chan et al., 2022). These are puzzling theoretical objects, predicted by some light dark-matter models, where Bose-Einstein condensate of axions is supposed to originate self-gravitant axion spheres, called axion stars. The theoretical non-radial pulsation power spectrum, originated by the tidal distorsion of the axion star due to a neutron star companion has been calculated in a recent paper (Panotopoulos and Lopes, 2019). This spectrum is derived assuming well-known asteroseismic model, compatible with the equation of state of the axion star, and should be characteristic of this kind of object. The spectrum is also potentially detectable, if the axion star interacts with the magnetic field of a companion, for instance a neutron star with a strong magnetic field, which enables the conversion of axions into photons.

4 Discussion and future work

The search of dark matter using Asteroseismology will become more important in next decades. Next generation missions, like PLATO (Martins et al., 2017; Rauer, 2021), or HAYDN (Miglio et al., 2021) will increase the volume of available data and will make possible the systematic study of stellar populations like those of the Globular Clusters. This will be a great opportunity to complement the previous constraints on dark matter from these stars, coming from photometry (Viaux et al., 2013; Ayala et al., 2014). Moreover, the increase of precision of the future asteroseismic surveys could find significative differences between the stars close to the halo of the Milky Way and those laying on the galactic plane, which

could confirm or not the influence of dark matter on the internal processes of the halo stars.

The refinement of asteroseismic observations will impact the accurate description of the stellar interiors. The elucidation of the role played by convection in the overall energy transport of the stars, and the determination of the extensions of the convective structures are two goals of Asteroseismology, which, when fully accomplished, will impose bounds on several dark matter models.

In the next years, the increase of precision in the measurements of solar-like and giant stars pulsations will enable to impose constraints on light **particle dark** matter, which can be produced by thermal resonant processes in stars. These constraints will complement the direct and indirect search of WISPs (Weakly Interacting Slim Particles) like axions or dark photons (Jaeckel and Ringwald, 2010). In summary, Asteroseismology besides stellar models will be fundamental for the study of dark matter in the next decades.

Author contributions

I am the first and only author. The preparation of the manuscript and the figures was done by me. I am also responsible of the selection of the contents and the discussion of this review.

Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

References

Aerts, C., Christensen-Dalsgaard, J., and Kurtz, D. W. (2010). *Asteroseismology*.

Albareti, F. D., Prieto, C. A., Almeida, A., Anders, F., Anderson, S., Andrews, B. H., et al. (2017). The 13th data release of the sloan digital sky survey: First spectroscopic data from the sdss-iv survey mapping nearby galaxies at Apache point observatory. *Astrophysical J. Suppl. Ser.* 233, 25.

An, H., Pospelov, M., Pradler, J., and Ritz, A. (2014). *Direct detection constraints on dark photon dark matter. ArXiv e-prints*.

Armengaud, E., Avignone, F. T., Betz, M., Brax, P., Brun, P., Cantatore, G., et al. (2014). Conceptual design of the international axion observatory (IAXO). *J. Instrum.* 9, T05002. doi:10.1088/1748-0221/9/05/T05002

Ayala, A., Domínguez, I., Giannotti, M., Mirizzi, A., and Straniero, O. (2014). Revisiting the bound on axion-photon coupling from globular clusters. *Phys. Rev. Lett.* 113, 191302. doi:10.1103/PhysRevLett.113.191302

Ayala, A., Lopes, I., García Hernández, A., Suárez, J. C., and Muñoz Elorza, Í. (2020). Constraining dark photon properties with Asteroseismology. *Mon. Not. R. Astron. Soc.* 491, 409–416. doi:10.1093/mnras/stz3002

Ayala, A., Straniero, O., Giannotti, M., Mirizzi, A., and Dominguez, I. (2015). "Effects of hidden photons during the red giant branch (RGB) phase," in 11th Patras Workshop on Axions, WIMPs and WISPs, 189–192. doi:10.3204/DESY-PROC-2015-02/ayala_adrian

Baglin, A., Michel, E., and Auvergne, M.COROT Team (2006). "The seismology programme of the CoRoT space mission," in *Proceedings of SOHO 18/GONG 2006/ HELAS I, beyond the spherical Sun. Vol. 624 of ESA special publication*, 34.

Bertone, G. (2010). "Dark matter and stars," in *Particle dark matter : Observations, models and searches*. Editor G. Bertone, 586.

Cadamuro, D., and Redondo, J. (2010). *Hidden photons from the Sun. ArXiv e-prints*.

Casanellas, J., and Lopes, I. (2013). First asteroseismic limits on the. *Astrophys. J.* 765, L21. doi:10.1088/2041-8205/765/1/L21

Casanellas, J., and Lopes, I. (2011). Signatures of dark matter burning in nuclear star clusters. *Astrophys. J.* 733, L51. doi:10.1088/2041-8205/733/2/L51

Christensen-Dalsgaard, J. (2004). Physics of solar-like oscillations. *Sol. Phys.* 220, 137–168. doi:10.1023/B:SOLA.0000031392.43227.7d

Córsico, A. H., Althaus, L. G., Miller Bertolami, M. M., and Kepler, S. O. (2019). Pulsating white dwarfs: New insights. *Astron. Astrophys. Rev.* 27, 7. doi:10.1007/s00159-019-0118-4

Córsico, A. H., Althaus, L. G., Romero, A. D., Mukadam, A. S., García-Berro, E., Isern, J., et al. (2012). An independent limit on the axion mass from the variable white dwarf star R548. *J. Cosmol. Astropart. Phys.* 2012, 010. doi:10.1088/1475-7516/2012/12/010

Córsico, A. H., Benvenuto, O. G., Althaus, L. G., Isern, J., and García-Berro, E. (2001). The potential of the variable DA white dwarf G117-B15A as a tool for fundamental physics. *New Astron.* 6, 197–213. doi:10.1016/S1384-1076(01)00055-0

Domingo, V., Fleck, B., and Poland, A. I. (1995). The SOHO mission: An overview. *Sol. Phys.* 162, 1–37. doi:10.1007/BF00733425

Gabriel, A. H., Charra, J., Grec, G., Robillot, J. M., Roca Cortés, T., Turck-Chièze, S., et al. (1997). Performance and early results from the GOLF instrument flown on the SOHO mission. *Sol. Phys.* 175, 207–226. doi:10.1023/A:1004911408285

Gabriel, A. H., Grec, G., Charra, J., Robillot, J. M., Roca Cortés, T., Turck-Chièze, S., et al. (1995). Global oscillations at low frequency from the SOHO mission (GOLF). *Sol. Phys.* 162, 61–99. doi:10.1007/BF00733427

Gudnason, S. B., Kouvaris, C., and Sannino, F. (2006). Towards working technicolor: Effective theories and dark matter. *Phys. Rev. D.* 73, 115003. doi:10.1103/PhysRevD.73.115003

Hung-Hsu Chan, J., Sibiryakov, S., and Xue, W. (2022). *Condensation and evaporation of boson stars. arXiv e-prints, arXiv:2207.04057*.

Iocco, F. (2008). Dark matter capture and annihilation on the first stars: Preliminary estimates. *Astrophys. J.* 677, L1–L4. doi:10.1086/587959

Isern, J., and García-Berro, E. (2008). White dwarfs as physics laboratories: The axion case. *PATRAS* 79, 545.

Isern, J., Hernanz, M., and Garcia-Berro, E. (1992). Axion cooling of white dwarfs. *Astrophys. J.* 392, L23. doi:10.1086/186416

Isern, J., Torres, S., and Rebassa-Mansergas, A. (2022). White dwarfs as physics laboratories: Lights and shadows. *Front. Astron. Space Sci.* 9, 6. doi:10.3389/fspas.2022.815517

Jaeckel, J., and Ringwald, A. (2010). The low-energy frontier of particle physics. *Annu. Rev. Nucl. Part. Sci.* 60, 405–437. doi:10.1146/annurev.nucl.012809.104433

Kepler, S. O., Winget, D. E., Vanderbosch, Z. P., Castanheira, B. G., Hermes, J. J., Bell, K. J., et al. (2021). The pulsating white dwarf G117-B15A: Still the most stable optical clock known. *Astrophys. J.* 906, 7. doi:10.3847/1538-4357/abc626

Khan, S., Hall, O. J., Miglio, A., Davies, G. R., Mosser, B., Girardi, L., et al. (2018). The red-giant branch bump revisited: Constraints on envelope overshooting in a wide range of masses and metallicities. *Astrophys. J.* 859, 156. doi:10.3847/1538-4357/aabf90

Koch, D., Borucki, W., Jenkins, J., Basri, G., Batalha, N. M., Brown, T. M., et al. (2010). "The kepler mission and early results," in 38th COSPAR Scientific Assembly. vol. 38 of COSPAR Meeting.

Kurtz, D. (2022). *Asteroseismology across the HR diagram. arXiv e-prints*, arXiv:2201.11629.

Lopes, I., and Panotopoulos, G. (2020). Radial oscillations of boson stars made of ultralight repulsive dark matter. *Nucl. Phys. B* 961, 115266. doi:10.1016/j.nuclphysb.2020.115266

Lopes, I., and Silk, J. (2012). Solar constraints on asymmetric dark matter. *Astrophys. J.* 757, 130. doi:10.1088/0004-637X/757/2/130

Lopes, J., Lopes, I., and Silk, J. (2019). Asteroseismology of red clump stars as a probe of the dark matter content of the galaxy central region. *Astrophys. J.* 880, L25. doi:10.3847/2041-8213/ab2fdd

Martins, A., Lopes, I., and Casanellas, J. (2017). Asteroseismic constraints on asymmetric dark matter: Light particles with an effective spin-dependent coupling. *Phys. Rev. D.* 95, 023507. doi:10.1103/PhysRevD.95.023507

Miglio, A., Girardi, L., Grundahl, F., Mosser, B., Bastian, N., Bragaglia, A., et al. (2021). Haydn. *Exp. Astron.* 51, 963–1001. doi:10.1007/s10686-021-09711-1

Milgrom, M. (1983). A modification of the Newtonian dynamics as a possible alternative to the hidden mass hypothesis. *Astrophys. J.* 270, 365–370. doi:10.1086/161130

Panotopoulos, G., and Lopes, I. (2019). Acoustic modes of pulsating axion stars: Nonradial oscillations. *Int. J. Mod. Phys. D.* 28, 1950111. doi:10.1142/S0218271819501116

Peccei, R. D., and Quinn, H. R. (1977). Constraints imposed by CP conservation in the presence of pseudoparticles. *Phys. Rev. D.* 16, 1791–1797. doi:10.1103/PhysRevD.16.1791

Raffelt, G. G., and Dearborn, D. S. P. (1987). Bounds on hadronic axions from stellar evolution. *Phys. Rev. D.* 36, 2211–2225. doi:10.1103/PhysRevD.36.2211

Raffelt, G. G. (1999). "Stars as particle-physics laboratories," in *The Eighth mexican school on particles and fields. Vol. 490 of American Institute of physics conference series.* Editors J. C. D'Olivo, G. López Castro, and M. Mondragón, 125–162. doi:10.1063/1.1301384

Rauer, H. (2021). "PLATO science objectives and PLATO Mission Consortium," in Plato Mission Conference 2021. Presentations and posters of the online PLATO Mission Conference 2021, 104. doi:10.5281/zenodo.5585341

Redondo, J., and Raffelt, G. (2013). Solar constraints on hidden photons revisited. *J. Cosmol. Astropart. Phys.* 1308, 034. doi:10.1088/1475-7516/2013/08/034

Ricker, G. R., Winn, J. N., Vanderspek, R., Latham, D. W., Bakos, G. Á., Bean, J. L., et al. (2015). Transiting exoplanet survey satellite. *J. Astron. Telesc. Instrum. Syst.* 1, 014003. doi:10.1117/1.JATIS.1.1.014003

Scott, P., Fairbairn, M., and Edsjo, J. (2008). "Impacts of WIMP dark matter upon stellar evolution: Main-sequence stars," in Identification of Dark Matter 2008, Stockholm, Sweden, 73.

Silva Aguirre, V., Lund, M. N., Antia, H. M., Ball, W. H., Basu, S., Christensen-Dalsgaard, J., et al. (2017). Standing on the shoulders of dwarfs: The kepler asteroseismic LEGACY sample. II.Radii, masses, and ages. *Astrophys. J.* 835, 173. doi:10.3847/1538-4357/835/2/173

Taoso, M., Bertone, G., Meynet, G., and Ekström, S. (2008). "WIMPs annihilations in Pop III stars," in Identification of Dark Matter 2008, Stockholm, Sweden, 76.

Taoso, M., Iocco, F., Meynet, G., Bertone, G., and Eggenberger, P. (2010). Effect of low mass dark matter particles on the sun. *Phys. Rev. D.* 82, 083509. doi:10.1103/PhysRevD.82.083509

Tassoul, M. (1980). Asymptotic approximations for stellar nonradial pulsations. *Astrophys. J. Suppl. Ser.* 43, 469–490. doi:10.1086/190678

Tassoul, M. (1990). Second-order asymptotic approximations for stellar nonradial acoustic modes. *Astrophys. J.* 358, 313. doi:10.1086/168988

Turck-Chièze, S., and Lopes, I. (2012). Solar-stellar astrophysics and dark matter. *Res. Astron. Astrophys.* 12, 1107–1138. doi:10.1088/1674-4527/12/8/011

Viaux, N., Catelan, M., Stetson, P. B., Raffelt, G. G., Redondo, J., Valcarce, A. A. R., et al. (2013). Neutrino and axion bounds from the globular cluster M5 (NGC 5904). *Phys. Rev. Lett.* 111, 231301. doi:10.1103/PhysRevLett.111.231301

Vinyoles, N., Serenelli, A., Villante, F. L., Basu, S., Redondo, J., and Isern, J. (2015). New axion and hidden photon constraints from a solar data global fit. *J. Cosmol. Astropart. Phys.* 10, 015. doi:10.1088/1475-7516/2015/10/015

Wilczek, F. (1978). Problem of strong P and T invariance in the presence of instantons. *Phys. Rev. Lett.* 40, 279–282. doi:10.1103/PhysRevLett.40.279