This is the pre-published version published in The European Physical Journal Plus,
available online at: http://dx.doi.org/10.1140/epjp/s13360-023-03877-7

The cosmological axion dark matter decay

Man Ho Chan

Department of Science and Environmental Studies, The Education University of Hong Kong, Tai Po, New Territories, Hong Kong, China

Abstract

It has been shown that the axions produced in early universe can account for the cosmological dark matter. Theoretically, axions can decay and their decay rate can be greatly enhanced by stimulated emission of photons. In this article, we present a theoretical framework to describe the decay of the cosmological axion dark matter. We show that, for a certain parameter space of axion mass m_a and the axion-photon coupling constant $g_{a\gamma\gamma}$, the axion decay would be significantly triggered so that no axion dark matter remains. For the popular benchmark models of the cosmological axion dark matter $m_a \sim 10^{-5}$ eV, current observational constraints of the axion-photon coupling constant can ensure that axions are stable enough to be the cosmological dark matter.

Keywords: Dark Matter, Axion

1. Introduction

Although observational data reveal the existence of dark matter, we do not know much about its nature. Some suggest that the existence of weakly interacting massive particles (WIMPs) can account for the cosmological dark matter. The WIMPs can probably interact with ordinary matter or self-annihilate to give high-energy particles. However, recent observations based on the direct-detection experiments [1], and the indirect-detection using gamma rays [2, 3, 4], cosmic rays [5, 6] and radio waves [7, 8, 9, 10, 11] do not have any smoking-gun signals. The particle search in the large hadron collider experiments also show null result of WIMPs [12]. Therefore, the existence of WIMPs has become a big puzzle now.

Email address: chanmh@eduhk.hk (Man Ho Chan)

This is the pre-published version published in The European Physical Journal Plus, available online at: http://dx.doi.org/10.1140/epjp/s13360-023-03877-7

On the other hand, some theoretical proposals have suggested another class of light scalar or pseudo-scalar particles called axions which can account for cosmological dark matter [13, 14, 15, 16]. Not only for the dark matter problem, the existence of axions can help solve the CP-violation problem in particle physics [13]. Therefore, axion is another popular candidate of dark matter. Axions can be produced thermally [17, 18] or produced from oscillation in the QCD era [19, 20, 21]. For the latter production mechanism, the axions produced (the QCD axions) behave like the cosmological cold dark matter. Recent studies following the misalignment mechanism suggest that the axion mass m_a should be of the order $m_a \sim 10^{-5}$ eV [19, 21].

Axions can decay into photons spontaneously. Some detectors are built to search for the signal of axion decay [22, 23]. However, the rate of spontaneous axion decay is very low. The decay rate can be as small as 10^{-40} s^{-1} for $m_a \sim 10^{-5}$ eV [21]. Nevertheless, it has been shown that the existence of background photon field can stimulate the decay and significantly enhance the spontaneous decay rate [21, 24, 25]. Interestingly, the photons given out in the spontaneous decay can contribute to the background photon field and stimulate another axion decay (i.e. the resonant decay). As a result, an exponential growth of photons would be arisen and a significant amount of axions would decay [26, 27]. However, inside a structure, there are some factors which would suppress the resonant decay of axions [28].

In this article, we assume all axions being the cosmological dark matter and formulate a theoretical framework to describe the cosmological axion decay. We find that there are some ranges of axion mass and the axion-photon coupling constant which can significantly trigger the axion decay. Based on the argument if axions are stable enough to be the cosmological dark matter, we derive the constraints of the axion mass m_a and the axion-photon coupling constant $g_{a\gamma\gamma}$ for a wide range of $m_a \sim 10^{-15} - 10^6$ eV.

2. The stimulated axion decay model

The decay constant of spontaneous axion decay is given by [21]

$$\Gamma = \frac{g_{a\gamma\gamma}^2 m_a^3 c^6}{32h} = 8.4 \times 10^{-41} \left(\frac{g_{a\gamma\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}} \right)^2 \left(\frac{m_a c^2}{10^{-5}\ \mathrm{eV}} \right)^3\ \mathrm{s}^{-1}. \qquad (1)$$

Without any stimulation, the rate of change of axion number density is $\dot{n}_a = -\Gamma n_a$. If there exists a background photon field (e.g. the cosmological

This is the pre-published version published in The European Physical Journal Plus,
available online at: http://dx.doi.org/10.1140/epjp/s13360-023-03877-7

microwave background), the photons with the same frequency as those produced by decay $\nu = m_a c^2/2h$ would stimulate the axion decay so that the total decay rate would be greatly enhanced. The rate of change of the axion number density for stimulated decay is given by [21]

$$\frac{dn_a}{dt} = -\Gamma n_a(1+2f), \tag{2}$$

where f is the photon occupation number of the background photon field. Since the cosmological photon background exhibits a blackbody spectrum, the photon occupation number is

$$f = f_b = \frac{1}{e^{m_a c^2/2kT} - 1}, \tag{3}$$

where T is the temperature of the cosmological photon background.

Furthermore, since the photons arising from the axion decay have a specific frequency $\nu = m_a c^2/2h$, these photons can contribute to the photon background field and further stimulate the decay rate. Such phenomenon is called the resonant decay [26, 27]. The photon occupation number due to the contribution of the photons produced by decay is

$$f = f_d = \frac{n_\gamma h^3}{\pi m_a^3 c^3}, \tag{4}$$

where n_γ is the number density of the photons produced by decay. Since $\dot{n}_\gamma = -2\dot{n}_a$, we can write $n_\gamma = 2[n_{a0} - n_a]$, where n_{a0} is the initial number density of axions.

In general, if the contribution of the photons produced by decay is significant, the decay rate would grow exponentially with time so that the factor of the background photon field is insignificant. However, as our universe is expanding, the frequency of the photons would decrease and the resonant decay could be greatly suppressed. In this case, the photon occupation number would be dominated by the background photon field. Therefore, there exist two regimes for our consideration: 1. background photons-dominated regime and 2. resonant-decay regime.

2.1. Background photons-dominated regime

In this regime, the photon occupation number is dominated by the cosmological photon background. The temperature of the photon field is $T =$

This is the pre-published version published in The European Physical Journal Plus,
available online at: http://dx.doi.org/10.1140/epjp/s13360-023-03877-7

2.725 K/a, where a is the cosmic scale factor. By putting Eqs. (1) and (3) into Eq. (2) and considering the axion decay from $a \approx 0$ (at axion production) to $a = 1$ (at present), we have:

$$n_a = n_{a0} \exp\left[-\frac{\Gamma}{H_0}\int_0^1 \frac{(1+2f_b)da}{\sqrt{\Omega_m a^{-1}+\Omega_r a^{-2}+\Omega_\Lambda a^2}}\right], \tag{5}$$

where H_0 is the Hubble constant, Ω_m, Ω_r and Ω_Λ are the cosmological density parameters of matter, radiation and the cosmological constant respectively. Generally speaking, the value of the exponential factor in Eq. (5) $\xi \equiv (\Gamma/H_0)\int_0^1(1+2f_b)da/(\Omega_m a^{-1}+\Omega_r a^{-2}+\Omega_\Lambda a^2)^{1/2}$ depends on m_a (see Fig. 1). The ratio n_a/n_{a0} is very close to 1 when m_a is small while it is close to 0 when m_a is large. The critical m_a of the transition is at $m_a \sim 100$ eV. We define the critical value $g_{a\gamma\gamma}$ when the exponential factor in Eq. (5) is -1 (i.e. $\xi = 1$). Therefore, we can get the critical $g_{a\gamma\gamma}$ as a function of m_a:

$$\frac{g_{a\gamma\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}} = 1.66\times10^{11}\left(\frac{m_a}{10^{-5}\ \mathrm{eV}}\right)^{-3/2}\times\left[\int_0^1 \frac{(1+2f_b)da}{\sqrt{\Omega_m a^{-1}+\Omega_r a^{-2}+\Omega_\Lambda a^2}}\right]^{-1/2}, \tag{6}$$

where we have taken $H_0 = 70$ km/s/Mpc.

Here, the critical $g_{a\gamma\gamma}$ can be regarded as the approximate upper limit of $g_{a\gamma\gamma}$ such that there is no significant decay of axions (i.e. axions are relatively stable throughout the universe expansion). In Fig. 2, we plot the values of critical $g_{a\gamma\gamma}$ against m_a and compare with the existing observational constraints, including the Any Light Particle Search (ALPS) experiment [22], CERN Axion Solar Telescope (CAST) experiment [23], SN1987a supernova data [29] and the stellar model simulation data [30]. In particular, the most stringent constraints are $g_{a\gamma\gamma} < 6.6\times10^{-11}$ GeV^{-1} based on stellar modelling for $m_a < 100$ keV [30] and the CAST detection for $m_a < 0.02$ eV [23]. Our argument of 'no significant axion decay' gives a more stringent constraint on $g_{a\gamma\gamma}$ for $m_a > 400$ eV. In fact, the contribution of the photon occupation number f_b is less than 1% for $m_a \gtrsim 400$ eV. Therefore, considering the effect of stimulated decay due to the cosmic photon background cannot give a more meaningful constraint compared with the existing observational bounds.

2.2. Resonant-decay regime

In the resonant decay regime, the photons arising from the axion decay would contribute to the photon field to facilitate the decay. Once the background photons have started to stimulate the axion decay, the number of

This is the pre-published version published in The European Physical Journal Plus,
available online at: http://dx.doi.org/10.1140/epjp/s13360-023-03877-7

photons produced by decay would grow exponentially. This would quickly achieve $f_d \gg f_b$. To model this phenomenon, we can approximate Eq. (2) by

$$\frac{dn_a}{dt} \approx -\Gamma n_a[1 + 4K(n_{a0} - n_a)], \tag{7}$$

where $K = h^3/\pi m_a^3 c^3$. The analytic solution of Eq. (7) is

$$n_a = \frac{n_{a0}(1 + 4Kn_{a0})e^{-(4Kn_{a0}+1)\Gamma t}}{1 + 4Kn_{a0}e^{-(4Kn_{a0}+1)\Gamma t}}. \tag{8}$$

Note that if the axions being the cosmological dark matter, we have $n_{a0} \propto \Omega_m a^{-3}/m_a \propto a^{-3}$. This is consistent with the QCD axion model [20]. The Hubble expansion factor for the axion dark matter has been implicitly considered in the scaling of a. Besides, in the radiation dominated era, the time after the Big Bang is $t = (2H_0\sqrt{\Omega_r})^{-1}a^2 \propto a^2$. Therefore, the factor in the exponential function $(2Kn_{a0} + 1)\Gamma t$ is proportional to a^{-1}. This suggests that the resonant decay is more significant when a is small (i.e. in early universe). We will mainly consider the decay in the radiation dominated era.

Roughly speaking, according to Eq. (8), n_a would become very small when t is very large. However, our universe is expanding so that the frequency of the photons produced by decay would decrease at the same time. Therefore, the photons cannot stimulate further decay if their frequency decreases significantly. Nevertheless, the density fluctuation in the early universe would generate a certain momentum fluctuation of axions. This provides a small possible photon decay frequency width $\Delta\nu$ in the spontaneous axion decay. Therefore, if the frequency decrease due to the cosmic expansion is smaller than the photon decay frequency width, a significant resonant decay is still possible.

Theoretically, the fractional change of the photon frequency $\Delta\nu/\nu$ is directly proportional to the fractional change of the cosmic scale factor $\Delta a/a$. On the other hand, the photon decay width $\Delta\nu/\nu$ is directly proportional to the cosmic radiation temperature fluctuation $\Delta T/T$ originated from the gravitational potential perturbation. Observations give $\Delta T \approx 18\mu$K [31], which means $\Delta T/T \approx 6.6 \times 10^{-6}$. Therefore, we have

$$\Delta t = 2t\left(\frac{\Delta a}{a}\right) \sim 2t\left|\frac{\delta T}{T}\right|. \tag{9}$$

Some benchmark models suggest that axions were produced at $T \sim 200$ MeV via QCD non-perturbative effects [20], which is $t \sim 3.4 \times 10^{-5}$ s after

This is the pre-published version published in The European Physical Journal Plus,
available online at: http://dx.doi.org/10.1140/epjp/s13360-023-03877-7

the Big Bang. The initial axion number density would be $n_{a0} \sim 9.5 \times 10^{43}(m_a/10^{-5}\ \mathrm{eV})^{-1}\ \mathrm{cm}^{-3}$. Using Eq. (9), the allowed time duration for the resonant decay after the production of axions is about $\Delta t \sim 4 \times 10^{-10}$ s.

From Eq. (8), we can see that the resonant decay is significant when the factor $4Kn_{a0}e^{-(4n_{a0}K+1)\Gamma\Delta t}$ is of the order 1. Therefore, we can get the analytical relation of the critical $g_{a\gamma\gamma}$ for different m_a in the resonant-decay regime:

$$\begin{aligned} \frac{g_{a\gamma\gamma}}{10^{-10}\ \mathrm{GeV}^{-1}} &\sim 11.6\left(\frac{m_a}{10^{-5}\ \mathrm{eV}}\right)^{1/2} \\ &\quad \times \left[109 - 4\ln\left(\frac{m_a}{10^{-5}\ \mathrm{eV}}\right)\right]^{1/2}. \end{aligned} \tag{10}$$

In Fig. 2, we plot the critical $g_{a\gamma\gamma}$ against m_a and compare with the existing constraints. Generally speaking, for a large range of m_a, the constraints of $g_{a\gamma\gamma}$ based on the resonant decay argument is less stringent than the existing observational constraints. Nevertheless, for $m_a < 10^{-12}$ eV, this constraint becomes more stringent than the existing constraints. In fact, the critical $g_{a\gamma\gamma}$ depends on the moment of axion production. The relation in Eq. (10) has assumed axion produced at temperature $T = 200$ MeV. Roughly speaking, the critical $g_{a\gamma\gamma}$ is proportional to the production temperature T. If axions were produced at a lower temperature, the values of the critical $g_{a\gamma\gamma}$ would be smaller.

3. Discussion and conclusion

In this article, we examine the stimulated decay and the resonant decay of axions in the cosmological context if axions are cosmological dark matter. The effect of the stimulated decay and the resonant decay would be significant in the large m_a regime and the small m_a regime respectively. The decay argument can give more stringent constraints for $m_a > 400$ eV and $m_a < 10^{-12}$ eV only. For the benchmark model of axion dark matter with $m_a \sim 10^{-5}$ eV, current observational constraints ensure that most of the axions remain stable.

Note that our entire discussion is in the cosmological context. However, when structures form, the resonant decay might be more significant. It is because the gravitational well in different structures would give a larger velocity dispersion for axion dark matter. This would also give a larger fractional decaying frequency width $\Delta\nu/\nu$ in the spontaneous decay. As a result, the

This is the pre-published version published in The European Physical Journal Plus, available online at: http://dx.doi.org/10.1140/epjp/s13360-023-03877-7

suppression of the resonant decay due to the cosmic expansion would be less significant. A recent study has examined the specific conditions for the resonant decay in a gravitational well [28]. These conditions might be able to prevent any exponential decay of axions in a structure. However, in some specific structures, the resonant decay can provide a possible explanation of some galaxies lacking dark matter, like NGC 1052-DF2 and NGC 1052-DF4 [32, 33]. The key issue would be the velocity dispersion of dark matter in the structures. Further simulations and observations are required to test this hypothesis.

Although we have shown that axion decay is not significant for the benchmark cosmological axion dark matter models, the signatures of axion decay might still be detectable by observations. The stimulated decay due to background photons or a small-scale resonant decay might be able to trigger detectable signals. Some recent studies have examined the possibility [24, 34] and we anticipate that future telescopes with higher sensitivity (e.g SKA) can detect the alleged axion decay signals.

4. Acknowledgements

We thank the anonymous referee for useful comments. The work described in this paper was partially supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region, China (Project No. EdUHK 18300922).

5. Data availability statement

The data underlying this article will be shared on reasonable request to the corresponding author.

References

[1] E. Aprile *et al.*, Phys. Rev. Lett. 121, 111302 (2018).

[2] M. Ackermann *et al.* [Fermi-LAT Collaboration], Phys. Rev. Lett. 115, 231301 (2015).

[3] M. H. Chan, C. H. Leung, Sci. Rep. 7, 14895 (2017).

[4] K. N. Abazajian, S. Horiuchi, M. Kaplinghat, R. E. Keeley & O. Macias, Phys. Rev. D 102, 043102 (2020).

This is the pre-published version published in The European Physical Journal Plus,
available online at: http://dx.doi.org/10.1140/epjp/s13360-023-03877-7

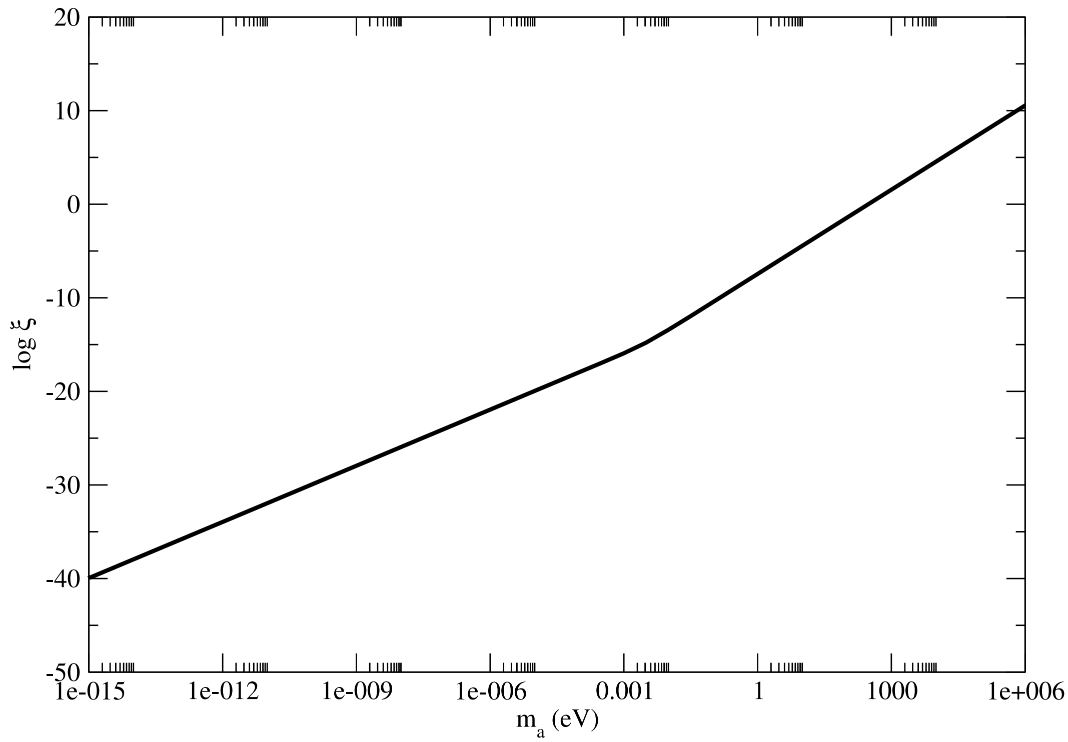

Figure 1: The solid line represents the logarithm of the exponential factor $\xi = (\Gamma/H_0)\int_0^1 (1+2f_b)da/(\Omega_m a^{-1} + \Omega_r a^{-2} + \Omega_\Lambda a^2)^{1/2}$ as a function of m_a. Here, we have assumed $g_{a\gamma\gamma} = 10^{-10}$ GeV^{-1}, $\Omega_m = 0.3$, $\Omega_r = 8.5 \times 10^{-5}$ and $\Omega_\Lambda = 0.7$.

This is the pre-published version published in The European Physical Journal Plus,
available online at: http://dx.doi.org/10.1140/epjp/s13360-023-03877-7

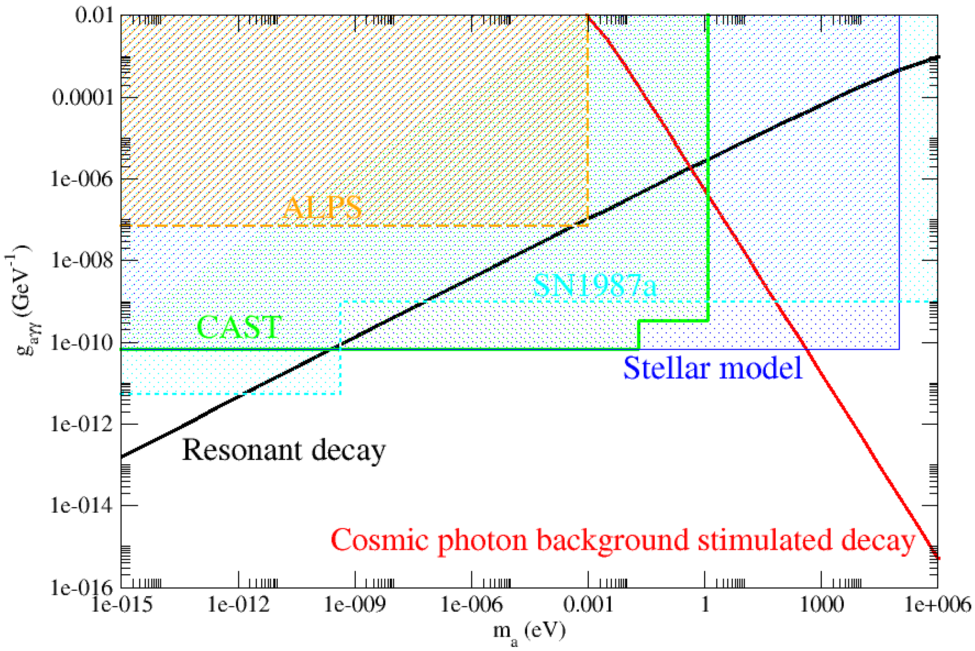

Figure 2: The shaded areas represent the ruled out regions of the parameter space based on the Any Light Particle Search (ALPS) experiment (orange) [22], CERN Axion Solar Telescope (CAST) experiment (green) [23], SN1987a supernova data (cyan) [29] and the stellar model simulation data (blue) [30]. The black and red solid lines indicate the values of the critical $g_{a\gamma\gamma}$ as a function of m_a based on the resonant decay and the cosmic photon background stimulated decay respectively. Here, the critical $g_{a\gamma\gamma}$ can be regarded as the upper limits of $g_{a\gamma\gamma}$ for different m_a.

This is the pre-published version published in The European Physical Journal Plus,
available online at: http://dx.doi.org/10.1140/epjp/s13360-023-03877-7

[5] G. Ambrosi *et al.*, Nature 552, 63 (2017).

[6] M. Aguilar *et al.*, Phys. Rev. Lett. 122, 041102 (2019).

[7] A. E. Egorov & E. Pierpaoli, Phys. Rev. D 88, 023504 (2013).

[8] T. Bringmann, M. Vollmann & C. Weniger, Phys. Rev. D 90, 123001 (2014).

[9] M. H. Chan, L. Cui, J. Liu & C. S. Leung, Astrophys. J. 872, 177 (2019).

[10] M. H. Chan & C. M. Lee, Phys. Rev. D 102, 063017 (2020).

[11] M. H. Chan, Galaxies 9, 11 (2021).

[12] D. Abecrcrombie *et al.*, Phys. Dark Uni. 27, 100371 (2020).

[13] R. D. Peccei & H. R. Quinn, Phys. Rev. Lett. 38, 1440 (1977).

[14] S. Weinberg, Phys. Rev. Lett. 40, 223 (1978).

[15] J. Preskill, M. B. Wise & F. Wilczek, Phys. Lett. B 120, 127 (1983).

[16] L. F. Abbott & P. Sikivie, Phys. Lett. B 120, 133 (1983).

[17] D. Grin, G. Covone, J.-P. Kneib, M. Kamionkowski, A. Blain & E. Jullo, Phys. Rev. D 75, 105018 (2007).

[18] A. Salvio, A. Strumia & W. Xue, J. Cosmol. Astropart. Phys. 01, 011 (2014).

[19] P. W. Graham, I. G. Irastorza, S. K. Lamoreaux, A. Lindner & K. A. van Bibber, Ann. Rev. Nuc. Part. Sci. 65, 485 (2015).

[20] D. J. E. Marsh, Phys. Rep. 643, 1 (2016).

[21] R. A. Battye, B. Garbrecht, J. I. McDonald, F. Pace & S. Srinivasan, Phys. Rev. D 102, 023504 (2020).

[22] K. Ehret *et al.*, Phys. Lett. B 689, 149 (2010).

[23] V. Anastassopoulos *et al.*, Nature Phys. 13, 584 (2017).

[24] A. Caputo, C. P. Garay & S. J. Witte, Phys. Rev. D 98, 083024 (2018).

This is the pre-published version published in The European Physical Journal Plus,
available online at: http://dx.doi.org/10.1140/epjp/s13360-023-03877-7

[25] A. Caputo, M. Regis, M. Taoso & S. J. Witte, J. Cosmol. Astropart. Phys. 03, 027 (2019).

[26] A. Arza, Eur. Phys. J. C 79, 250 (2019).

[27] D. Blas & S. J. Witte, Phys. Rev. D 102, 103018 (2020).

[28] A. Arza, T. Schwetz & E. Todarello, J. Cosmol. Astropart. Phys. 10, 013 (2020).

[29] E. Massó & R. Toldrà, Phys. Rev. D 52, 1755 (1995).

[30] A. Ayala, I. Domínguez, M. Giannotti, A. Mirizzi & O. Straniero, Phys. Rev. Lett. 113, 191302 (2014).

[31] E. L. Wright, Measuring and modeling the universe, from the Carnegie Observatories Centennial Symposia (Cambridge: Cambridge University Press, 2004).

[32] P. van Dokkum *et al.*, Nature 555, 629 (2018).

[33] P. van Dokkum, S. Danieli, R. Abraham, C. Conroy & A. J. Romanowsky, Astrophys. J. 874, L5 (2019).

[34] M. H. Chan, Sci. Rep. 11, 20087 (2021).