Does CMB Distortion Disfavour Intermediate Mass Dark Matter?
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ABSTRACT
We investigate the published constraints on MACHOs in the mass region $10^2 - 10^5 M_\odot$ and their possible contribution to dark matter. We focus on constraints which rely on the accretion of matter which emits X-rays that can lead, after downgrading to microwaves, to distortion of the CMB spectrum and isotropy. The most questionable step in this chain of arguments is the use of overly simplified accretion models. We compare how the same accretion models apply to X-ray observations from supermassive black holes SMBHs, M87 and Sgr A*. The comparison of these two SMBHs with intermediate mass MACHOs suggests that the latter could, after all, provide the constituents of all the dark matter. We discuss the status of other constraints on IM-MACHOs.

Keywords: CMB distortion: MACHOs: X-rays: accretion: wide binaries

1. INTRODUCTION
Our ignorance of the nature of dark matter has led to theoretical suggestions of candidates for dark matter constituents which famously range in mass over one hundred orders of magnitude. These candidates can usefully be divided into two classes: those which can be discovered by terrestrial experiments and those which cannot. In the first class are new elementary particles for which huge resources have been invested in so-far unsuccessful attempts at their detection.

An astrophysical candidate proposed (Chapline 1975), (Frampton et al 2010), (Frampton 2015), (Chapline and Frampton 2016) for the constituent of the cosmological dark matter is the Primordial Intermediate Mass Black Hole (PIMBH) with mass in the range $10^2 - 10^5 M_\odot$. The best observational method positively to detect PIMBHs appears to be by microlensing experiments pointing towards the Magellanic Clouds, following the earlier success of finding lighter mass examples (Alcock et al 2000).

One deep reason to believe that dark matter is astrophysical is that, if we regard the visible universe as an isolated thermodynamic system, its entropy is expected to grow according to the second law of thermodynamics. Although the question of whether or not it is “isolated” may be debated, we believe it is reasonable to assume that the complex dynamics of the early universe obey this statistical law. In comparison, no microscopic dark matter candidate such as a new elementary particle can make a fractionally significant contribution to the entropy of the universe.

2. CMB DISTORTION
The hypothesis made in (Frampton 2015), (Chapline and Frampton 2016) is that $f_{DM} \sim 100\%$ of the dark matter in the Milky Way halo is made up of PIMBHs in the mass range $10^2 - 10^5 M_\odot$. Examining the literature one finds that this hypothesis appears to be strongly disfavoured by the use of Bondi-like accretion models Bondi and Hoyle (1944), Bondi (1952) which lead to limits which have been placed (Ricotti, Ostriker and Mack 2008), (Ali-Haimoud and Kamionkowski 2017), (Carr et al 2020) on the basis of CMB distortion. Are these limits correct and if not, why not?
The CMB spectrum was first measured with high accuracy by the Far Infrared Absolute Spectrophotometer (FIRAS) mounted on the Cosmic Background Explorer (COBE) satellite (Fixsen et al 1996). The result is an extremely accurate black-body spectrum, the most accurate such spectrum ever measured. Also the isotropy of the CMB is measured accurately and found to be uniform to the high level of 1 part in $10^5$, at which point important tiny homogeneities appear which are interpreted as the seeds of structure formation. Any theoretical model is tightly constrained by agreement with the CMB spectrum and isotropy.

Calculation of the limits on MACHOS from lack of CMB distortion was pioneered in (Ricotti, Ostriker and Mack 2008) and makes four steps (1) Calculate the amount of material accreted on to the PIMBHs; (2) Calculate the amount of X-rays emitted by this accreted matter; (3) Calculate the downgrading of these X-rays to microwaves due to Thomson scattering and cosmic expansion; (4) Investigate how much these microwaves distort the CMB spectrum and isotropy. Later in the present article, of these four steps we shall mainly query the validity of step (1).

Starting with the paper (Ricotti, Ostriker and Mack 2008), from its Figure 9 (left) we deduce the limit for the mass range $10^2 - 10^5 M_\odot$ that $f_{DM} < 0.01\%$ which strongly disfavours the prediction $f_{DM} \sim 100\%$. Bondi-like quasi-spherical accretion was more recently used again in (Ali-Haimoud and Kamionkowski 2017), together with a reduction by a couple of orders of magnitude in the radiation efficiency, as an attempt to correct some of the deficiencies in (Ricotti, Ostriker and Mack 2008). However, similarly to (Ricotti, Ostriker and Mack 2008), we deduce from Figure 14 in Ali-Haimoud and Kamionkowski (2017) that for $M > 10^3 M_\odot$ there is a limit $F_{DM} < 0.01\%$, again strongly disfavouring $f_{DM} = 100\%$.

The limits provided in (Ricotti, Ostriker and Mack 2008), (Ali-Haimoud and Kamionkowski 2017) and other papers are frequently cited in reviews, see e.g. Figure 10 in (Carr et al 2020), and such an exclusion plot is almost invariably included as one slide in any review talk at a dark matter conference. As a result, the widespread belief is that ($\sim 100\%)DM = PIMBHs$ is ruled out. We shall now proceed seriously to query whether such a conclusion is warranted.

3. OBSERVATIONS OF M87 AND SGR A*

There are a few reasons to question whether the environments of SMBHs such as M87 and Sgr A* are sufficiently similar to those of dark matter PIMBHs that their direct comparison is sensible.

(i) Sgr A* and M87 may have formerly been AGNs (Active Galactic Nuclei) (Macroni et al 2004) when they would likely have radiated more than at present. Such AGN radiation may not have been radially symmetric (Russell et al 2013). The SMBHs have feedback effects which create a duty cycle. For AGNs there is evidence that this duty cycle depends inversely with mass (Shankar, Weinberg and Shen 2010).

(ii) If the SMBHs were formed by mergers of smaller black holes, this could have disrupted their gas environment, although SMBHs could instead be primordial. (iii) The CMB distortion is believed to occur at redshifts $100 < Z < 500$ (Ali-Haimoud and Kamionkowski 2017), (Horowitz 2016) when the universe was denser, facilitating accretion.

(iv) SMBHs have angular momentum, while for PIMBHs the question of their spin is model dependent but in some models (De Luca et al 2019) is expected to be close to zero.

In this section we shall make the assumption, faute de mieux, that the environments of SMBHs and PIMBHs, while certainly somewhat different, are sufficiently similar that their comparison is meaningful.

Observations of X-rays from supermassive black holes (SMBHs) can shed useful light on whether Bondi-like accretion on to a PIMBH is a sensible model. By Bondi-like, we include all models that are spherically symmetric, quasi-spherical or involve radial inflow.

The X-ray observations have included two supermassive black holes (SMBHs), namely M87 with mass $M \simeq 6.5 \times 10^9 M_\odot$ and Sgr A* with mass $M \simeq 4.1 \times 10^6 M_\odot$. The reason these two black holes are the ones most thoroughly studied observationally in X-rays is simply that they are the two biggest black holes on the sky. M87, the 87th in the Messier catalogue of objects and discovered by Messier himself in 1781, is at a distance $16.4 \times 10^3$ pc and subtends $38\mu$as ($\mu$as = microarcsecond). Sgr A* in the Milky Way was discovered more recently at $8.2 \times 10^3$ pc and subtends $52\mu$as.
We shall show that Bondi-like models fail badly for both these supermassive black holes by vastly overestimating, by four orders of magnitude, the rate of accretion. Although these two examples are more massive than PIMBHs ranging up to $10^5 M_\odot$, we are not aware of any reason that if an accretion model fails badly for SMBHs it should start working for PIMBHs.

The accretion rate for M87, calculated from a Bondi-like model is $\dot{M} = 0.2 M_\odot/y$ (Kuo et al 2014). X-ray observations reported in 2014, however, correspond to a far smaller accretion rate $< 10^{-5} M_\odot/y$ (Kuo et al 2014). A similar conclusion was confirmed two years later in 2016 in both (Feng, Wu and Lu 2016) and (Li, Yuan and Xie 2016). We conclude that the accretion rate on to M87 is four orders of magnitude smaller than that predicted in a Bondi-type model of accretion.

The SMBH Sgr A* in the Milky Way is an exceptionally faint SMBH, the faintest SMBH known and visible only due to its proximity. In any other galaxy, Sgr A* would be invisible. In the case of Sgr A*, already in 2000 Quateart and Gruzinov (Quateart and Gruzinov 2000) used a Bondi-type model to predict an accretion rate $\sim 10^{-4} M_\odot/y$ but provided observational evidence that the actual accretion rate $\sim 10^{-8} M_\odot/y$, like M87 showing that the Bondi-type model overestimates the accretion rate by four orders of magnitude. This observational accretion rate on to Sgr A* was confirmed in 2018 (Bower et al 2018).

Let us next revisit the PIMBH limits derived from CMB distortion, with now the new assumption Bondi-type models overestimate accretion rates by four orders of magnitude. It is straightforward to revise the previous limits based on CMB distortion by replacing the published $f_{DM}$ by $f_{DM}^{(revised)} = 10^4 f_{DM}$.

In Figure 9(left) of (Ricotti, Ostriker and Mack 2008) the revised $f_{DM}^{(revised)}$ is consistent with $f_{DM}^{(revised)} \simeq 100\%$ and with a private communication (Ostriker 2016) from the senior author of (Ricotti, Ostriker and Mack 2008). In Figure 14 of (Ali-Haîmoud and Kamionkowski 2017) the revised $f_{DM}^{(revised)}$ is also consistent with $f_{DM}^{(revised)} \simeq 100\%$.

It is beyond the scope of this article to provide a better model for accretion than the Bondi-type models. It seems probable that the accretion on to PIMBHs is not approximately quasi-spherical or with radial inflow.

4. WIDE BINARIES

There exist in the Milky Way pairs of stars which are gravitationally bound binaries with a separation more than 0.1pc, even more than 1.0pc. These wide binaries retain their original orbital parameters unless compelled to change them by gravitational influences, for example, due to nearby PIMBHs.

Because of their very low binding energy, wide binaries are particularly sensitive to gravitational perturbations and can be used to place an upper limit on, or to detect, PIMBHs. The history of employing this ingenious technique is regrettfully checkered. In 2004 a fatally strong constraint was claimed by an Ohio State University group (Yoo, Chaname and Gould 2004) in a paper entitled “The End of the MACHO Era”.

Five years later in 2009, however, another group this time from Cambridge University (Quinn et al 2009) re-analysed the available data on wide binaries and reached a quite different conclusion. They questioned whether any rigorous constraint on MACHOs could yet be claimed, especially as one of the most important binaries in the earlier sample had been misidentified.

Confirming wide binaries is challenging, as they are quite rare and hard to distinguish from merely chance associations. Obtaining accurate orbital parameters is also difficult when only a small fraction of one orbit can be observed.

Only three studies of wide binaries have yet appeared in the literature, the two in 2004 and 2009 and one more recent in 2014. This further study of wide binaries (Monroy-Rodriguez and Allen 2014) also attempted to place limits on MACHOs, starting from a longer list of $\sim 100$ candidate binaries. Upon closer inspection, the majority were called into question. It is mildly surprising that in the last seven years, no fourth independent analysis has appeared.
Unlike microlensing which has positive signals (Alcock et al 2000), wide binary analysis is a null experiment where no MACHO-binary interaction has been recorded and this fact tends to physicists remaining skeptical of any limits claimed. Concerning the third and still most recent 2014 analysis (Monroy-Rodriguez and Allen 2014), one of the authors of the second 2009 analysis (Quinn et al 2009) has remarked (Belakurov 2021) that he will remain skeptical until their orbits are re-calculated using Gaia data.

In conclusion about wide binaries, these constraints may possibly be shown on exclusion plots but only with the warning that they are not accepted as robust because of the several uncertainties.

5. X-RAY AND RADIO SOURCES

In one stand-alone paper (Gaggero et al 2017), a study was made of the X-ray and radio emission from the Galactic Ridge region of the Milky Way within 2 kpc of the galactic center which, if $10^9 M_\odot$ PBHs make up all the dark matter, should contain $\sim 10^9$ PBHs. This paper claims that PBHs cannot make up all the dark matter, by a statistical discrepancy of $5\sigma$. However, they use a Bondi-type model of accretion in their Eq.(1) with a multiplicative factor $\lambda = 0.02$. If, as suggested in our text, this is changed to $\lambda = 10^{-4}$ the bounds are relaxed by a factor 200 whereupon study of their Fig. 1 reveals that the PBHs could then comprise all the dark matter without any such discrepancy.

The same paper (Gaggero et al 2017) considers radio emission from an assumed jet associated with each of the black holes. They arrive then at a staggering $40\sigma$ discrepancy in $1.4GHz$ radio waves compared to the VLA catalog. However, this huge discrepancy arises only because of an assumption about jets and could be regarded as much an argument against such jets as against PBH dark matter.

6. SUPERNOVA MICROLENSING

In (Zumalacarregui and Seljak 2018), the absence of microlensing which could provide magnification of SNe 1A supernovas was converted into an upper bound on MACHOs. These authors claimed that only $< 35\%$ of the total matter content could be MACHOs, compared to the required dark matter which is 84%.

In their analysis, they focus on a parameter $\alpha$ defined by $\alpha = \Omega_{PBH}/\Omega_m$ and fix $\Omega_m$ by using a value extracted from CMB and BAO measurements. They require a lens size less than the Einstein radius which implies that $M_{PBH} > 0.01 M_\odot$.

Two samples of SNe data are examined to arrive at independent values for $\alpha$ which would need to be $\alpha \sim 0.84$ for the case that PBHs constitute all the dark matter. One sample is from the Joint Likelihood Analysis (JLA) in reference (Betoule et al 2014), the other is from Union data in reference (Suzuki et al 2012).

In Zumalacarregui and Seljak (2018), the constraints are found to be, at 95% confidence level, that $\alpha < 0.352$ and $\alpha < 0.372$ respectively for JLA and Union. These translate into exclusion of all dark matter being MACHOs with $> 0.01 M_\odot$ by $4.79\sigma$ for JLA and by $4.54\sigma$ for Union.

However, this claim in (Zumalacarregui and Seljak 2018) has been subsequently disputed in (Garcia-Bellido, Clesse and Fleury 2018) for several reasons, as follows.

Firstly, in (Zumalacarregui and Seljak 2018) the value of $\Omega_m$ was held fixed while $\alpha$ was varied whereas the two are highly correlated. For example, the value of $\Omega_m$ set by the supernova data alone is quite different so the chosen prior on $\Omega_m$ strongly overconstrained the result for $\alpha$.

Secondly, the characteristic size for the supernova is bigger than assumed in (Zumalacarregui and Seljak 2018) and when this is taken into account the constraint is weakened by an order of magnitude.
Thirdly and lastly, using a more realistic broad lognormal mass distribution rather than a monochromatic one, the constraints become even further diluted.

Taking all these considerations into account, the authors of (Garcia-Bellido, Clesse and Fleury 2018) conclude that the supernova data are consistent with 100% of the dark matter being made from PBHs.

In conclusion about supernova microlensing, these constraints should be shown on exclusion plots only with a warning that they are not yet universally accepted.

7. ULTRA FAINT DWARF GALAXIES (UFDGS)

UFDGs have a high ratio of total dynamical mass to stellar mass so that they contain an unusually high fraction of dark matter. An extreme case is Eridanus II with 99.7% dark matter. If dark matter is 100% PBHs, heavier on average than the stars, then two-body collisions between PBHs and stars will give kinetic energy to the stars and heat them up, tending to increase the size of the galaxies. Observations of UFDGs can be used to put limits on such theories of dark matter.

In the paper (Stegmann et al 2020) a study of UFDGs is made and places strong constraints on the range of masses of PIMBHs which are allowed to comprise all the dark matter. A sample of 17 UFDGs is used, and various versions of mass function e.g. monochromatic or lognormal.

From the survival of the stellar cluster Eridanis II, and the entire stellar populations of UFDGs, no solution is found for any mass function of PBHs. In all cases, the PBHs warm up the stellar systems to be too large to agree with observations.

There is a number of possible shortcomings of the detailed analysis in (Stegmann et al 2020) which should be borne in mind:

(i). The stellar observables in the lightest UFDGs have low statistics.

(ii). Some UFDGs may be baryon dominated rather than dark matter dominated.

(iii). In (Stegmann et al 2020), only the case DM = 100% PBHs is studied. If the DM has a significant collisionless component, the analysis is invalid.

(iv). The rôle of gas, or a possible central IMBH, is ignored.

(v). It was assumed that UFDGs are spherical and in dynamical equilibrium.

Finally, the analysis in (Stegmann et al 2020) discusses the range \((1 − 100)M_\odot\) for the PBHs. Intermediate mass PBHs in the range \((100 − 100,000)M_\odot\) are not expected to play other than the central role in UFDGs, for stability reasons analogous to the disk stability (Xu and Ostriker 1994) in full-sized galaxies.

8. CONCLUSIONS

If we take into account all proposed constraints on the allowed fraction \(f_{DM}\) of dark matter which is allowed as a function of mass in the intermediate mass range \(100M_\odot \leq M_{PBH} \leq 10^5M_\odot\), and discard all constraints which are in any way questionable or model-dependent, our considered opinion is that \(0 \leq f_{DM} \leq 1\) is allowed throughout this entire mass range. See Figure 1. We do accept that, within the Milky Way, PBHs with \(M_{PBH} > 10^6M_\odot\) are excluded by the consideration of disk stability (Xu and Ostriker 1994).

As we have discussed, a handful of well-cited papers in the astronomy literature imply that CMB distortion very strongly constrains intermediate mass dark matter, so their answer to our title question is a categoric yes.
However, by making a comparison with data from X-ray observations of two supermassive black holes, and making the strong but defensible assumption that their accretion dynamics are sufficiently similar to those of intermediate mass, we have cast doubt on this conclusion. Hence we believe the answer to our title question may be no, and that intermediate mass black holes can make a significant contribution to the dark matter.

For completeness we have discussed also published constraints arising from (i) wide binaries; (ii) X-ray and radio sources; (iii) supernova microlensing; (iv) ultra-faint dwarf galaxies. Although excellent pieces of work, all of which merit further study, in their present form we do not feel it necessary to change our opinion about the freedom still allowed by all of the present data.

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