Primordial Intermediate Mass Black Holes as Dark Matter

Paul H. Frampton

Dipartimento di Matematica e Fisica "Ennio De Giorgi", Università del Salento and INFN-Lecce, Via Arnesano, 73100 Lecce, Italy.

E-mail: paul.h.frampton@gmail.com

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Abstract. Among particle theory candidates for the dark matter constituents, axions and WIMPs are the most popular. In this talk we discuss these then focus on our preferred astrophysical candidate, the Primordial Intermediate Mass Black Holes in the acronym $DM = PIMBHs$. The earliest experimental confirmation may come from microlensing of the Magellanic Clouds at the LSST 8m telescope in the mid-2020s, or possibly a few years earlier in 2021 from work being pursued, using DECam data from the smaller Blanco 4m telescope, at LLNL.

1. Introduction

Astronomical observations have led to a consensus that the energy make-up of the visible universe is approximately 72% dark energy, 24% dark matter and only 4% normal matter.

General discussions of the history and experiments for dark matter are in several books. A popular book, ”The Cosmic Cocktail” by Katherine Freese, discusses a large number of WIMP searches.

The present ignorance of the dark matter sector is put into perspective by looking at the uncertainty in the values of the constituent mass previously considered. The lightest such candidate is the ultra-light axion with $M = 10^{-22} eV$. The heaviest such candidate for dark matter, suitably defined in terms of the entropy of the universe, is a supermassive black hole (SMBH) with $M = 10^{12} M_\odot$. This is one hundred orders of magnitude, $10^{100}$ or a googol, times more massive than the ultra-light axion.

Our aim is to reduce this uncertainty.
The result of the present analysis will be that the number of orders of magnitude uncertainty in the dark matter constituent mass can be reduced to two. We shall conclude, after extensive discussion, that the most viable candidate for the constituent which dominates dark matter in the Milky Way dark halo is [1, 2, 3] the Primordial Intermediate Mass Black Hole (PIMBH) with mass in the range

$$25M_\odot < M_{PIMBH} < 1,600M_\odot$$

(1)
corresponding to microlensing light curves of duration between one and eight years for the Blanco 4m telescope with DECam at Cerro Tololo, Chile, pointed towards the Large Magellanic Cloud.

An explanation for the relative neglect of PIMBHs, relative to WIMPs, may be that the literature is confusing.

At least one study claimed to rule out the entire mass range from 25$M_\odot$ to 1600$M_\odot$ that we displayed in Eq.(1). We shall attempt to clarify the observational situation which actually still permits the whole range in Eq.(1).

The present talk is, in part, an attempt to redress the imbalance between the relatively few experimental efforts to search for PIMBHs compared to the very extensive variety of WIMP searches.

2. Axions

It is worth reviewing briefly the history of the QCD axion particle now believed, if it exists, to lie in the mass range

$$10^{-12}eV < M < 10^{-3}eV$$

(2)

The lagrangian originally proposed for Quantum Chromodynamics (QCD) was of the simple form, analogous to Quantum Electrodynamics,

$$\mathcal{L}_{QCD} = -\frac{1}{4} G^\alpha_{\mu\nu} G^{\mu\nu}_\alpha - \frac{1}{2} \sum_i \bar{q}_{i,a} \gamma^\mu D^a_\mu q_{i,b}$$

(3)
summed over the six quark flavors.
The simplicity of Eq. (3) was only temporary and became more complicated in 1975 by the discovery of instantons which dictated an additional term

$$\Delta \mathcal{L}_{QCD} = \frac{\Theta}{64\pi^2} G_{\mu\nu}^\alpha \tilde{G}_{\mu\nu}^\alpha$$

where $\tilde{G}_{\mu\nu}$ is the dual of $G_{\mu\nu}$. The additional term, Eq. (4), violates CP and contributes to the neutron electric dipole moment whose upper limit provides a constraint on $\bar{\Theta}$ (simply related to $\Theta$)

$$\bar{\Theta} < 10^{-9}$$

The QCD axion arises from spontaneously breaking a symmetry imposed to set $\bar{\Theta} = 0$. The QCD axion may exist and contribute to dark matter.

Recently there has been widespread interest in axion-like particles (ALPs). For dark matter, there is the possibility of ultra-light ALPs with masses as low as $10^{-22}$ eV.

Such ultra-light axions are suggested by moduli and dilatons in string theory and can ameliorate some issues for cold dark matter (CDM), cusps at galactic centres and excess satellite galaxies associated with CDM calculations.

These ultra-light axions play no role in solving the strong CP problem and so ”axion” is an slightly inappropriate name; ultra-light boson is better. Such ultra-light bosons can superradiate and limit the spin of Kerr black holes.

3. WIMPs

By Weakly Interacting Massive Particle (WIMP) is generally meant an unidentified elementary particle with mass in the range, say, between 10 GeV and 1000 GeV and with scattering cross section with nucleons ($N$) satisfying, according to the latest unsuccessful WIMP direct searches,

$$\sigma_{WIMP-N} < 10^{-45} \text{ cm}^2$$

which is roughly comparable to the characteristic strength of the known weak interaction. Actually, Eq. (6) now imposed by WIMP searches is
few orders of magnitude below the expectation from weak interactions. This may be a first sign that something is rotten in the state of Denmark.

The WIMP particle must be electrically neutral and be stable or have an extremely long lifetime. In model-building, the stability may be achieved by an ad hoc discrete symmetry, for example a $Z_2$ symmetry under which all the standard model particles are even and others are odd. If the discrete symmetry is unbroken, the lightest odd state must be stable and therefore a candidate for a dark matter. In general, this appears contrived because the discrete symmetry is not otherwise motivated.

In supersymmetry, such a discrete symmetry appears naturally and gives rise to a wonderful candidate for a WIMP called the neutralino. However, since the LHC data has lent no support to weak-scale supersymmetry, this WIMP has less motivation than it once did.

4. MACHOs

Massive Compact Halo Objects (MACHOs) are commonly defined by the notion of compact objects used in astrophysics as the end products of stellar evolution when most of the nuclear fuel has been expended. They are usually defined to include white dwarfs, neutron stars, black holes, brown dwarfs and unassociated planets, all equally hard to detect because they do not emit any radiation.

This narrow definition implies, however, that MACHOs are composed of normal matter which is too restrictive in the case of black holes. It has been shown that black holes of mass up to $100,000 M_\odot$ (even up to $10^{12} M_\odot$) can be produced primordially, according to a paper published at IPMU-Univ. of Tokyo by F.K.T.Y. in 2010\textsuperscript{[4, 5]}. Unlike the axion and WIMP elementary particles which would have a definite mass, the black holes will have a range of masses. The lightest PBH which has survived for the age of the universe has a lower mass limit

$$M_{PBH} > 10^{-18} M_\odot \sim 10^{36} TeV$$  \hspace{1cm} (7)
already thirty-six orders of magnitude heavier than the heaviest would-be WIMP. This lower limit comes from the lifetime formula derivable from Hawking radiation

\[ \tau_{BH}(M_{BH}) \sim \frac{G^2 M_{BH}^3}{\hbar c^4} \sim 10^{64} \left( \frac{M_{BH}}{M_\odot} \right)^3 \text{years} \]  

Because of observational constraints the dark matter constituents must generally be another twenty orders of magnitude more massive than the lower limit in Eq. (7).

We assert that most dark matter black holes are in the mass range above 25 and up to 1,600 and more times the solar mass. The name primordial intermediate mass black holes (PIMBHs) is appropriate because they lie in mass above stellar-mass black holes and below the supermassive black holes which reside in galactic cores.

Let us discuss three methods (there may be more) which could be used to search for dark matter PIMBHs. While so doing we shall clarify what limits, if any, can be deduced from present observational knowledge.

Before proceeding, it is appropriate first to mention the important Xu-Ostriker upper bound of $10^5 M_\odot$ from galactic disk stability for any MACHO residing inside the Milky Way galaxy.

4.1. Wide Binaries

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

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, IMBHs. The history of employing this ingenious technique is regretfully checkered. In 2004 a fatally strong constraint was claimed by an Ohio State University group in a paper entitled "End of the MACHO Era" so that, for researchers who have time to read only titles and abstracts, stellar and higher mass constituents of dark matter appeared to be totally excluded.
Five years later in 2009, however, another group this time from Cambridge University reanalyzed 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 important binaries in the earlier sample had been misidentified.

Because of this checkered history, it seems wisest to proceed with caution but to recognize that wide binaries represent a potentially useful source both of constraints on, and the possible discovery of, dark matter IMBHs.

4.2. Distortion of the CMB

This approach hinges on the phenomenon of accretion of gas onto the PIMBHs. The X-rays emitted by such accretion of gas are downgraded in frequency by cosmic expansion and by Thomson scattering becoming microwaves which distort the CMB, both with regard to its spectrum and to its anisotropy.

One impressive-seeming calculation by Ricotti, Ostriker and Mack (ROM) in 2008 of this effect employed a specific model for the accretion, the Bondi model, and carried through the computation all the way up to a point of comparison with data from FIRAS on CMB spectral distortions, where FIRAS was a sensitive device attached to the COBE satellite.

Unfortunately the Bondi model was invented for a static object and assumes spherically symmetric purely s-wave accretion with radial inflow. Studies of the SMBH in the giant galaxy M87 have shown since 2014 that higher angular momenta strongly dominate, not surprising as the SMBH possesses a gigantic spin angular momentum in natural units.

The results from M87 suggest the upper limits on MACHOs imposed by ROM were too severe by orders of magnitude and that up to 100% of the dark matter is permitted to be in the form of PIMBHs. In 2016, Ostriker privately withdrew the ROM limit as being "far too severe". A more recent 2017 modified version of this calculation (Ali-Haïmoud and Kamionkowski), apparently unaware of ROM’s withdrawal, similarly overestimates the accretion by assuming quasi-sphericity and arrives at far too strong bounds on PIMBHs.
4.3. Microlensing

Microlensing is the most direct experimental method and has the big advantage that it has successfully found examples of MACHOs. The MACHO Collaboration used a method which had been proposed by Paczynski where the amplification of a distant source by an intermediate gravitational lens is observed. The MACHO Collaboration discovered several striking microlensing events whose light curves are exhibited in its 2000 paper. The method certainly worked well for $M < 10M_\odot$ and so should work equally well for $M > 25M_\odot$.

The longevity of a given lensing event is proportional to the square root of the lensing mass and, in an admittedly crude approximation, is given by ($\hat{t}$ is duration)

$$\hat{t} \approx 0.2\text{yr} \left(\frac{M_{\text{lens}}}{M_\odot}\right)^{1/2}$$

(9)

where a transit velocity 200 km/s is assumed for the lensing object.

The MACHO Collaboration investigated lensing events with durations ranging between about two hours and 200 days. From Eq.(9) this corresponds to MACHO masses between approximately $10^{-6}M_\odot$ and $10M_\odot$.

The total number and masses of objects discovered by the MACHO Collaboration could not account for all the dark matter known to exist in the Milky Way. At most 10% could be explained. To our knowledge, the experiment ran out of money and was essentially abandoned in about the year 2000. But perhaps the MACHO Collaboration and its funding agency were too easily discouraged.

What is being suggested is that the other 90% of the dark matter in the Milky Way is in the form of MACHOs which are more massive than those detected by the MACHO Collaboration, and which almost certainly could be detected by a straightforward extension of their techniques. In particular, the expected microlensing events have a duration ranging from one to eight years.

‡ We have read that such gravitational lensing was later found to have been calculated in unpublished 1912 notes by Einstein who did not publish perhaps because at that time he considered its experimental measurement impracticable.
Microlensing experiments involve systematic scans of millions of distant star sources because it requires accurate alignment of the star and the intermediate lensing MACHO. The experiments are highly computer intensive, and requires a sophisticated data pipeline.

The experiment is undoubtedly extremely challenging, but there seems no obvious reason it is impracticable. Certain new hurdles have already been discovered (e.g. ”crowding”) but there is reason to think that by 2021 a definitive paper might be published by the LLNL group.

4.4. Interim discussion

Axions may not exist for theoretical reasons discovered in 1992. Electroweak supersymmetry probably does not exist for the experimental reason of its non-discovery at the LHC. The idea that dark matter experiences weak interactions (WIMPs) came historically from the appearance of an appealing DM constituent, the neutralino, in the theory of electroweak supersymmetry for which there is no experimental evidence.

The only interaction which we know for certain to be experienced by dark matter is gravity and the simplest assumption is that gravity is the only force coupled to dark matter. Why should the dark matter experience the weak interaction when it does not experience the strong and electromagnetic interactions?

All terrestrial experiments searching for dark matter by either direct detection or production may be doomed to failure.

We began with four candidates for dark matter constituent: (1) axions; (2) WIMPs; (3) baryonic MACHOs; (4) PIMBHs. We disfavoured the first two by arguments made within the context of particle phenomenology. We eliminated the third by the upper limit on baryons imposed by robust BBN calculations.

Contrary to claims made in the dark matter literature $f_{DM} = 1$ is not excluded for $25M_{\odot} < M_{PIMBH} < 10^5M_{\odot}$. Exclusion plots in the literature which disagree with this assertion make unreliable assumptions
on accretion, such as a Bondi model with spherical symmetry and radial inflow.

We assert that PIMBHs can constitute almost all dark matter while maintaining consistency with the BBN calculations.

Our proposal is that the Milky Way contains between ten million and ten billion massive black holes each with between a hundred and a hundred thousand times the solar mass. Assuming the halo is a sphere of radius a hundred thousand light years the typical separation is between one hundred and one thousand light years which is also the most probable distance of the nearest PIMBH to the Earth. At first sight, it may be surprising that such a huge number of PIMBHs – the plums in a “PIMBH plum pudding” – (c.f. Thomson 1904) could remain undetected. 2015 was 111 years after Thomson and the halo 31 powers of ten bigger than the atom. However, the mean separation of the plums is at least a hundred light years and the plum size is smaller than the Sun.

Of the detection methods discussed, extended microlensing observations seem the most promising and an experiment to detect higher longevity microlensing events is being actively pursued. The wide-field telescope must be in the Southern Hemisphere to use the Magellanic Clouds (LMC and SMC) for sources.

5. Microlensing Experiments

The most appropriate telescope for studying the MCs, active since 1986, is the Blanco 4m at Cerro Tololo with its DECam having 520 Megapixels. This telescope was named after the late Victor Blanco, the Puerto Rican astronomer who was the CTIO Director. A bigger and more powerful telescope will be the LSST (= Large Synoptic Survey Telescope) under construction in Northern Chile which will take first light in 2022. It will be 8.4m with a 3200 Megapixel camera, clearly superior to the Blanco 4m. Since, however, we require two-year duration light curves to discover 100$M_{\odot}$ lenses, the earliest that LSST could discover convincing evidence for DM=PIMBHs would be in 2024 or later.

An ongoing MC microlensing project which includes George Chapline (theorist) and eight experimentalists (which include the group’s PI Will
Dawson) is based at LLNL. Their data taking started over two years ago in February 2018. Their interesting work has revealed a technical issue which could have been, but was not, anticipated. The issue is stellar merging which arises, relative to the celebrated experiment done in the 20th century by Alcock, et al. (The MACHO Collaboration)[6], for two main reasons. We recall that Alcock, et al. looked at MACHOs only with mass below \(20M_\odot\) while the LSST will look for lenses with significantly higher masses. First, the Einstein radius increases with the lens mass \(\propto M^{1/2}\); second, the longer exposure as the light curve duration increases (also \(\propto M^{1/2}\)) probes more deeply and records lower magnitude stars. Both effects increase the number of stars and hence exacerbate stellar merging.

Resolution of the issue should be possible using the techniques of CFP (=Crowded Field Photometry), a mature area of research which goes back over thirty years[7]. The experimental situation may thus be summarised as the expectation that the LSST will settle this speculation about dark matter by the mid-2020s but they could be scooped by years if the LLNL group can successfully employ CFP to resolve stellar merging, conceivably as early as 2021.

6. The Reason Dark Matter Exists

The papers cited in the Introduction [1, 2, 3] address the question of what are the constituents of Dark Matter, and the suggested answer to that question is they are our titular Primordial Intermediate Mass Black Holes.

The question why dark matter exists at all seems to us to be equally as important as what the dark matter is, so we have given a more complete discussion about the origin and nature of the dark matter in [8]. The answer lies the second law of thermodynamics applied to the entropy of the universe during the time when the PIMBHs are formed. There is no comparable reason for the formation of WIMPs or axions.

The entropy from the SMBHs known to exist at galactic cores gives a contribution to the dimensionless entropy \(S/k\) of the universe which is roughly \(S/k \sim 10^{103}\) or one thousand googols. The identification \(DM = PIMBHs\) can increase this already large number by as much as another factor of a thousand to \(S/k \sim 10^{106}\), or one million googols, depending on
the PIMBH mass function. The second law of thermodynamics applied to
the cosmic entropy in the early universe is, we believe, why dark matter
was originally formed, and still exists at present, in the form of Primordial
Intermediate Mass Black Holes.

We eagerly await the verdict of Nature on our speculation, expected to
be revealed at the LSST in the mid-2020s, and conceivably much earlier
by the important and interesting work presently being done at Lawrence
Livermore National Laboratory, in California.

7. References

[1] G.F. Chapline, 
*Cosmological Effects of Primordial Black Holes.*
Nature 253, 251 (1975).

[2] P.H. Frampton,
*Searching for Dark Matter Constituents with Many Solar Masses.*
Mod. Phys. Lett. A31, 1650093 (2016).
[arXiv:1510.00400[hep-ph]]

[3] G.F. Chapline and P.H. Frampton,
*Intermediate Mass MACHOs: a New Direction for Dark Matter Searches.*
JCAP 11, 042 (2016).
[arXiv:1608.04297[gr-qc]]

[4] P.H. Frampton, M. Kawasaki, F. Takahashi and T. Yanagida,
*Primordial Black Holes as All Dark Matter.*
JCAP 04:023 (2010).
[arXiv:1001.2308[hep-ph]]

[5] P.H. Frampton and T.W. Kephart,
*The Analysis of Anomalies in Higher Space-Time Dimensions.*
Phys. Rev. D28, 1010 (1983).

[6] C. Alcock, *et al.* (The MACHO Collaboration),
*The MACHO Project: Microlensing Results from 5.7 Years of LMC Observations.*
Astrophys. J. 542, 281 (2000).
[arXiv:astro-ph/0001272]

[7] P.B. Stetson,
*DAOPHOT: A Computer Program for Crowded-Field Stellar Photometry.*
Pubs.Astro.Soc.Pac. 99, 191 (1987).

[8] P.H. Frampton,
*On the Origin and Nature of Dark Matter.*
Int. J. Mod. Phys. A33, 1830030 (2018).
[arXiv:1804.03516[physics.gen-ph]]