`Thank for the invitation`

PIMBHs

AS

DARK MATTER

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Introduction

Astronomical observations have led to a consensus that the energy make-up of the visible universe is approximately 70% dark energy, 25% dark matter and only 5% normal matter.

General discussions of the history and experiments for dark matter are in several books. A nice recent popular book, The Cosmic Cocktail by Freese, is strong on the panoply of unsuccessful WIMP searches. As we shall see, this lack of success might be due to the fact that WIMPs are not really the dark matter constituents.

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 is a supermassive mass black hole (SMBH) with $M = 10^{12}M_{\odot}$ which is an impressive hundred orders of magnitude larger.

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 the Primordial Intermediate Mass Black Hole (PIMBH) with mass in the range

$$20M_{\odot} < M_{PIMBH} < 2,000M_{\odot} \quad (1)$$

corresponding to microlensing light curves of duration between one and ten years for the Blanco 4m telescope with DECam at Cerro Tololo, Northern Chile, pointed towards the Large and Small Magellanic Clouds.

An explanation for the neglect of PIMBHs may be that the literature is confusing.

At least one study claimed entirely to rule out Eq.(1). We shall attempt to clarify the situation which actually still permits the whole range of Eq.(1).

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

Axions

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

$$10^{-12}eV < M < 10^{-3}eV \tag{2}$$

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

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^{\alpha}_{\mu\nu}G^{\mu\nu}_{\alpha} - \frac{1}{2}\sum_i \bar{q}_{i,a}\gamma^{\mu}D^{ab}_{\mu}q_{i,b} \tag{3}$$

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

$$\Delta\mathcal{L}_{QCD} = \frac{\Theta}{64\pi^2} G^{\alpha}_{\mu\nu} \tilde{G}^{\mu\nu}_{\alpha} \qquad (4)$$

where $\tilde{G}_{\mu\nu}$ is the dual of $G_{\mu\nu}$.
When the quark masses are complex, the full phase to be considered is

$$\bar{\Theta} = \Theta + \arg\det ||\mathcal{M}_{quark}|| \qquad (5)$$

The additional term, Eq.(4),violates P and CP, and contributes to the neutron electric dipole moment whose upper limit provides a constraint

$$\bar{\Theta} < 10^{-9} \qquad (6)$$

The axion particle then arises from a technique to resolve Eq.(6).

Over twenty years ago, in 1992, three papers independently pointed out a problem of the invisible axion. The point is that the invisible potential is so fine-tuned that adding gravitational couplings for weak gravitational fields at dimension-five requires tuning of a dimensionless coupling g to be at least as small as $g < 10^{-40}$.

There remains the strong CP problem of Eq.(6). For the moment, Eq.(6) must be regarded as fine tuning. We recall that the ratio of any neutrino mass to the top quark mass in the standard model satisfies

$$\left(\frac{M_\nu}{M_t}\right) < 10^{-12}. \tag{7}$$

I shall say no more about axions. They may exist & make up a fraction of dark matter.

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,

$$\sigma_{WIMP-N} < 10^{-45} cm^2 \tag{8}$$

which is roughly comparable to the characteristic strength of the known weak interaction.

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.

By far the most popular WIMP example came from electroweak supersymmetry where a discrete R symmetry has the value R=+1 for the standard model particles and R=-1 for all the sparticles. Such an R parity is less *ad hoc* being essential to prevent too-fast proton decay. The lightest R=-1 particle is stable and, if not a gravitino which has the problem of too-slow decay in the early universe, it was the neutralino, a linear combination of zino, bino and higgsino. The neutralino provided an attractive candidate.

The big problem with the neutralino is that at the LHC where electroweak supersymmetry not many years ago confidently predicted sparticles (gluinos, etc.) at the weak scale ~ 250 GeV there is no sign of any additional particle with mass up to at least 2000 GeV and above, so electroweak supersymmmetry probably does not exist.

The present run of the LHC is not necessarily doomed if WIMPs and sparticles do not exist. An important question, independent of naturalness but surely related to anomalies, is the understanding of why there are three families of quarks and leptons. For that reason the LHC could discover additional gauge bosons, doubly-charged bileptons $Y^{\pm\pm}$ which are siblings of the singly-charged $W^{\pm}$ of the standard model.

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 is here posited that black holes of mass up to $100,000 M_{\odot}$ (even up to $10^{12} M_{\odot}$) can be produced primordially as demonstrated in FKTY (2010). Nevertheless for the halo the acronym MACHO still nicely applies to dark matter PIMBHs which are massive, compact, and in the halo.

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

$$M_{PBH} > 10^{-18} M_{\odot} \sim 10^{36} TeV \tag{9}$$

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

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

Because of observational constraints the dark matter constituents must generally be another twenty orders of magnitude more massive than the lower limit in Eq.(9).

We assert that most dark matter black holes are in the mass range between 20 and 2,000 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 about a million solar masses from galactic disk stability for any MACHO residing inside the galaxy.

Wide Binaries

There exist in the Milky Way pairs of stars which are gravitationally bound binaries with a separation more than 0.1pc. 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.

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 some 4 or 5 orders of magnitude and that up to 100% of the dark matter is permitted by arguments about CMB distortion to be in the form of PIMBHs. More recent 2017 versions of this calculation similarly overestimate the accretion by assuming quasi-sphericity.

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 $M < 20M_\odot$ and so should work equally well for $M > 20M_\odot$ provided one can devise a suitable algorithm and computer program to scan enough sources.

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*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.

The longevity of a given lensing event is proportional to the square root of the lensing mass and numerically is given by ($\hat{t}$ is longevity)

$$\hat{t} \simeq 0.2yr \left(\frac{M_{lens}}{M_{\odot}}\right)^{1/2} \tag{11}$$

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

The MACHO Collaboration investigated lensing events with longevities ranging between about two hours and one year. From Eq.(11) this corresponds to MACHO masses between approximately $10^{-6}M_{\odot}$ and $20M_{\odot}$.

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 ten years.

Microlensing experiments involve systematic scans of millions of distant star sources because it requires accurate alignment of the star and the intermediate lensing MACHO. Because the experiments are already highly computer intensive, it makes us more optimistic that the higher longevity events can be successfully analyzed. Study of an event lasting two centuries should not necessitate that long an amount of observation time. It does require suitably ingenious computer programming to track light curves and distinguish them from other variable sources. This experiment is undoubtedly extremely challenging, but there seems no obvious reason it is impracticable.

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 disfavored 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.

ASSERTION: $f_{DM} = 1$ is permitted
for M_{PIMBH} from $20M_{\odot}$ to $2,000M_{\odot}$
with single mass or smooth mass function.

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 or an exaggerated halo environmental baryon density.

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.

The best *existing* telescope, since 1986, has been identified – see next slide.

The future LSST under construction in Northern Chile will take first light in 2022. LSST = Large Synoptic Survey Telescope. It will be 8.4m with a 3200 Megapixel camera.

CHILE

Blanco 4m at Cerro Tololo with DECam having 520 Megapixels.

This telescope was named after the late Victor Blanco the Puerto Rican astronomer who was the CTIO Director.

Microlensing Experiment

George Chapline (theorist) and eight experimentalists. Uses Blanco 4m with DECam at Cerro Tololo in Northern Chile.

Started February 2018 and expects results by the summer of 2020.

The same DECam data are being analysed by a group of astronomers at the University of Salento in Italy, with a similar time frame.

The Reason for Dark Matter

The paper cited in the Introduction: *Searching for Dark Matter Constituents with Many Solar Masses.* MPLA **A31,** 1650093 (2016). `arXiv:1510.00400[hep-ph]` contains two ingredients, one of which is WHAT is the Dark Matter? Answer: PIMBHs. There is a second ingredient addressing WHY is the dark matter? (See Section 6 therein).

The question why there is dark matter seems to us to be equally as important as what is the dark matter, so we have given a more complete discussion about the origin and nature of the dark matter in:

P.H. Frampton,
On the Origin and Nature of Dark Matter.
`arXiv:1804.03516[physics.gen-ph]`

The answer to why is the second law of thermodynamics applied to the entropy of the universe during the first three years when the PIMBHs are formed. There is no comparable reason for the formation of WIMPs or axions.

The entropy from the SMBHs at galactic cores gives $S/k \sim 10^{103}$ and the identification $DM = PIMBHs$ can increase this to $S/k \sim 10^{106}$ depending on the PIMBH mass function.

`Thank you for your attention`