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Electromagnetic probes of primordial black holes as dark matter

Thematic Areas: ☐ Planetary Systems ☐ Star and Planet Formation
☒ Formation and Evolution of Compact Objects ☒ Cosmology and Fundamental Physics
☐ Stars and Stellar Evolution ☐ Resolved Stellar Populations and their Environments
☐ Galaxy Evolution ☒ Multi-Messenger Astronomy and Astrophysics

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Abstract: The LIGO discoveries have rekindled suggestions that primordial black holes (BHs) *may constitute part to all of the dark matter* (DM) in the Universe. Such suggestions came from 1) the observed merger rate of the BHs, 2) their unusual masses, 3) their low/zero spins, and 4) also from the independently uncovered cosmic infrared background (CIB) fluctuations signal of high amplitude and coherence with unresolved cosmic X-ray background (CXB). Here we summarize the prospects to resolve this important issue with electromagnetic observations using the instruments and tools expected in the 2020's. These prospects appear promising to make significant, and potentially critical, advances. We demonstrate that **in the next decade, new space- and ground-borne electromagnetic instruments, combined with concurrent theoretical efforts, should shed critical light on the long-considered link between primordial BHs and DM.** Specifically the new data and methodologies under this program will involve:

- Probing with high precision the spatial spectrum of source-subtracted CIB with *Euclid* and *WFIRST*, and its coherence with unresolved cosmic X-ray background using *eROSITA* and *Athena*,
- Advanced searches for microlensing of Galactic stars by the intervening Galactic Halo BHs with OGLE, *Gaia*, LSST and *WFIRST*,
- Supernovae (SNe) lensing in the upcoming surveys with *WFIRST*, LSST and also potentially with *Euclid* and *JWST*,
- Advanced theoretical work to understand the details of PBH accretion and evolution and their influence on cosmic microwave background (CMB) anisotropies in light of the next generation CMB experiments,
- Better new samples and theoretical understanding involving stability and properties of ultra faint dwarf galaxies, pulsar timing, and cosmological quasar lensing.

The LIGO discovery of the first gravitational wave (GW) signal from two merging black holes (BHs) [2, 3] rekindled suggestions that primordial BHs (PBHs) [58, 33, 34] constitute most or all of the dark matter (DM). The suggestions were based on the deduced rate of their mergers [37, 18] as well as the properties of the near-IR cosmic infrared background (CIB) uncovered in 2005 [68]. Latest LIGO O1+O2 results find 10 significant BH mergers of high ($\sim$10–50$M_\odot$) masses with low or zero spins [118] consistent with the above proposals, although alternatives have been suggested [16]. At present this intriguing possibility remains to be firmly ruled in - or out.

In the next decade, new space- and ground-borne electromagnetic (EM) instruments, combined with ongoing theoretical efforts, should shed critical light on PBHs. The new data could have groundbreaking implications for DM and our understanding of the physics in the early Universe.

Source-subtracted cosmic infrared background. The spatial spectrum of CDM-type matter perturbations uniquely specifies the epochs and abundances of first stars era (FSE) objects at $z \gtrsim$15–20. FSE sources produce emissions in the near-IR observer bands $\lambda > 1\mu$m with potentially measurable anisotropies in the near-IR cosmic infrared background (CIB) [69, 41]. Ref. [70] have conducted the first search of this component using, with specifically developed map-making tools [11], deep *Spitzer* data at 3.6–8μm, discovering source-subtracted CIB fluctuations significantly exceeding those from remaining known galaxies [70, 62], thereby indicating new cosmological populations. Follow-up measurements from more *Spitzer* fields identified the CIB fluctuation power excess to $\simeq 1°$ with similar levels across the sky [72, 71, 74, 42]. The shot noise of these fluctuations, $P_{\rm SN} = \int_0^{S_0} S^2 dN$, is still dominated by the known sources below the limiting flux S_0, while the clustering component, by the new sources, appears consistent with the high-z ΛCDM model (Fig. 1,top-left). The clustering CIB component does not yet appear to decrease with lower shot noise implying its origin in faint, possibly high-z, sources of $\lesssim$10–20 nJy [73]. The source-subtracted CIB fluctuations at 3.6 and 4.5 μm appear strongly coherent with soft (0.5-2 keV) unresolved cosmic X-ray background (CXB) [27, 95, 28, 86], which cannot be accounted for by the remaining known populations [63]. The CIB signal thus must arise in populations having a much higher fraction of BHs than known sources. (See review [75].) The standard ΛCDM power spectrum in the regime corresponding to collapsing first halos ($\sim 10^{6-8}M_\odot$) at $z \gtrsim$10–15, follows
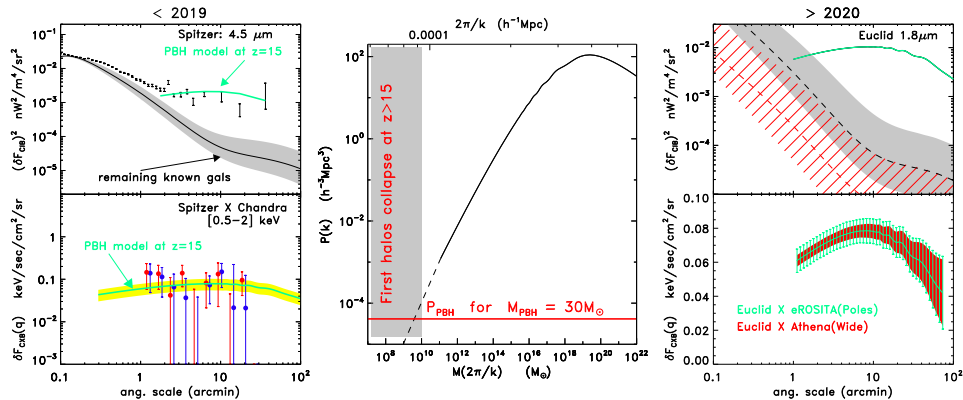

Figure 1: **Left**: Top: source-subtracted CIB anisotropies vs remaining known galaxies [74]. Bottom: reconstructed CXB fluctuation from the CIB sources are consistent with the high-z origin at levels not directly detectable with future planned X-ray missions [76]. **Middle**: ΛCDM power spectrum compared with the Poissonian granulation component from $30M_\odot$ PBHs making up the DM. [from 68]. **Right**: Top: source-subtracted CIB fluctuations at 1.8 μm due to a PBH-like model normalized to *Spitzer* measurements, which will be measured at sub-percent statistical accuracy with *Euclid* compared to that from known galaxy populations remaining in *Euclid*'s Wide (black) and Deep Surveys (red)[adapted from 75]. Bottom: CXB signal from lower left panel recovered using CIB-CXB cross-power with *Euclid* and *eROSITA* (green) and *Athena* (red) X-ray missions [76].

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$P \propto k^{-3}$ limiting their abundance and the resultant CIB. Yet the measured levels of the clustering component of the CIB anisotropies appear higher than simple high-z evolutionary models, in conjunction with the above regime, would predict [64] - i.e. *the CIB clustering component may require more power than $P \propto k^{-3}$*. The excess power is naturally provided by LIGO-type PBHs and was proposed as evidence of this population [68]. If DM is made up of LIGO-type PBHs, the latter would thus introduce an additional granulation component [93] of the amplitude naturally accounting for the observed source-subtracted CIB [68], which would be Poissonian on scales of the first collapsed minihalos ($>10^{6-8}M_\odot$) [6]. The uncovered coherence of the source-subtracted CIB with the (observer frame) soft CXB, a sign of abundant accreting BHs, would then be explained naturally by this extra component. Fig. 1 summarizes the current measurements (left), shows the effects on the signals from LIGO-type PBHs making up DM (middle) and illustrates the future prospects for significantly more refined probes of the signal with *Euclid* and *WFIRST* CIB probes combined with upcoming X-ray missions, *eROSITA* and *Athena* (right).

Microlensing of the Galactic disk and halo. Gravitational microlensing can probe the mass distribution of stellar remnants and DM in the form of compact objects, the so-called MACHOs [103, 56]. The technique relies on continuous monitoring of millions of stars to search for magnification events caused by gravitational lensing by massive objects crossing near the line of sight. The observations of the Magellanic Clouds over 13 years by the MACHO, EROS and OGLE surveys as well as from other surveys, have claimed that sub-solar-mass MACHOs cannot make more than a few percent of the DM in the Milky Way halo [5, 120, 123, 124, 57, 26]. However, in the LIGO BH mass regime there was still not enough sensitivity to confirm or rule out massive DM lenses. Stellar and Primordial BH lenses can be detected only in a very long and wide photometric sky surveys, e.g., MACHO [17], OGLE [125], MOA [19], *Gaia* [49], VVV [101], ASAS-SN, ZTF, etc. Natural directions for the search are where the source stars are dense, i.e., the Galactic plane, the Magellanic Clouds or M31. While the Galactic bulge poses a real challenge for the LSST due to crowding, the Galactic Disk (GD) fields are much sparser, yet still provide billions of potential sources for lensing. Over its nominal operation LSST should discover hundreds of temporal lensing events due to BHs [112]. Understanding the nature of the lens, however, would still require additional resources. High-resolution spectroscopy of the magnified source (to get the source distance) will still be a challenge at 20-23 mag range. Even more important are the ultra-precise astrometric observations, as the size of the positional displacement directly yields the Einstein ring size, which combined with the long-term photometry, yields the lens mass measurement [87]. Milli-arcsecond angular resolution is currently possible with Gaia space mission, but with limiting magnitude of about V=16 mag [111], while in future WFIRST should provide precise enough astrometric time-series (see Fig. 2). Interferometric measurements in the optical are even more brightness limited [45]. In summary, the recipe for a BH lens discovery via microlensing
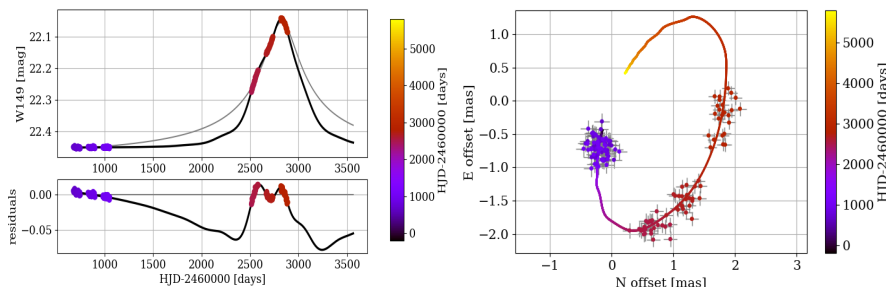

Figure 2: Example of a 9 $M_\odot$ BH microlensing event as observed by WFIRST. Left: photometric observations are marked with red points and the lines denote the standard and parallax models (thin and thick, respectively). Right: astrometric data for the source motion due to microlensing [111]. Color codes the time in days.

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is a long-term monitoring of millions of stars, assisted with spectroscopy, high-angular resolution imaging and, most importantly, detection of astrometric microlensing.

Supernova (SN) lensing in the upcoming surveys. SN lensing by intervening compact objects is a potential powerful probe of the size and mass of BHs and their clusters that could constitute the (majority of) DM [108, 114, 94, 127, 51]. Microlensing affects the distribution of SN residuals: a few events are magnified, thereby appearing brighter than the average, while the bulk is demagnified and hence appears dimmer than average (see Fig. 3). There is no evidence for such an effect in the present SN catalogs, due to their small size, and to systematic effects like host evolution (galaxy, cluster) and environment (dust, etc.) In recent catalogs, (e.g. DES SNe [77, 23]), SN light-curve fitters include models for weak lensing, but not micro-lensing. A large catalog of several thousand SNe will allow us to study all the relevant systematics and, in particular, the skewness of the residuals caused by micro-lensing. With such a catalog, one can begin to address more accurately the SN lensing signal as a function of redshift, unravelling the evolution of clustering of black holes with masses between a few and thousands of solar masses, especially if they constitute the bulk of the dark matter.
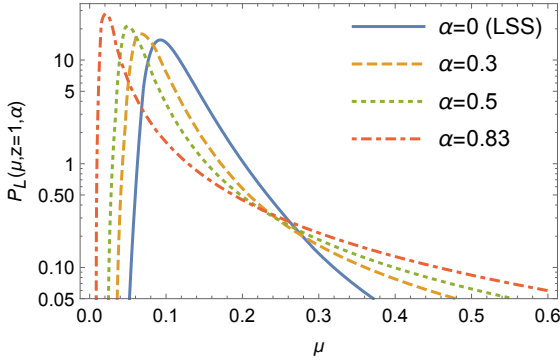

Figure 3: The probability distribution of SN magnification μ at z=1 for different values of the fraction α of DM made of compact objects ($\alpha = 0.83$ corresponds to $f_{\mathrm{PBH}} = 1$ and $\alpha = 0$ to f_{PBH}=0). *In the future we may determine via SN lensing the abundance and concentration of DM lumps made of primordial black holes, and distinguish them from the expected substructure around galaxies in the form of dwarf spheroidals that the standard CDM hierarchical structure formation paradigm predicts.*

Probing PBHs with the CMB. The Cosmic Microwave Background (CMB) is an exquisitely sensitive probe of energy injection in the early Universe. Heat injection at $10^3 \lesssim z \lesssim 2 \times 10^6$ can distort the frequency spectrum of the CMB, while energy injection at $z \lesssim 10^3$ leads to extra ionizations and increases the residual abundance of free electrons. The latter leads to a suppression of small-scale temperature and polarization power, and an enhancement of large-scale polarization fluctuations. PBHs with mass $M \gtrsim M_\odot$ can lead to energy injection through accretion-powered radiation [29, 109]. Due to the large Compton drag by CMB photons, accretion is suppressed at early times, and the largest impact of accreting PBHs is on the recombination history [7, 9] rather than spectral distortion [78, 104]. The most conservative bounds are derived by assuming a modified quasi-spherical Bondi-Hoyle accretion, and a very low radiative efficiency due to free-free radiation of the infalling gas [109, 7]. The physics of BH accretion is rich and, at the present time, remains highly uncertain. The geometry of accretion might be disk-like rather than quasi-spherical, provided the infalling gas has sufficient angular momentum, and enough time to cool to settle into a disk. Should this be the case, the radiative efficiency might be much larger, and CMB anisotropies could be sensitive to much lighter and/or much lower abundances of PBHs [105]. Finally, just like other probes of PBHs, accretion is sensitive to the underlying small-scale density field, as well as the clustering properties of PBHs, which remain poorly understood [36, 6, 14, 44, 21]. The main effort to be pursued on the topic of accreting PBHs and their impact on the CMB is therefore theoretical. In particular, the nature, rate and efficiency of early-Universe

accretion onto PBHs needs to be explored in much greater depth. The problem is well defined, and significant progress can be made in the next decade by combining analytic and numerical studies.

Other constraining EM measurements. Other EM-based datasets would provide further insights into the PBH-DM connection [30, 31, 32]: i) *Dynamical heating of star clusters in ultra-faint dwarf galaxies (UFDG)* [20, 54, 85, 79]. One can constrain the PBH abundance of mass above 10 $M_\odot$ within UFDG. However, the evolution and interpretation of such systems are subject to various selection effects and systematics, e.g. the assumption on the possible existence of a central massive BH, projection effects, etc. A way to rule out sub-solar PBH as DM is to detect an UFDG (or a stable star clusters in a UFDG) with radius $\lesssim$10 pc, which would be unstable due to dynamical heating. Confirming a cut-off radius between 10 and 20 pc with upcoming UFDG observations could be an evidence for the compact nature of DM. ii) *Central DM profile in dwarf galaxies* [38]. The scattering cross-section of solar-mass PBH is about $\sigma_{\mathrm{PBH}}/m_{\mathrm{PBH}} \approx \mathcal{O}(\mathrm{cm}^2/\mathrm{g})$, which could explain the core profiles of dwarf galaxies. iii) *Measurements with pulsar timing arrays* (PTA) should probe the 2nd order Shapiro time delay from a large sample of millisecond pulsars induced by a Stochastic GW Background (SGWB) from LIGO-type BH. This background could be due to second order perturbations at PBH formation [98, 66, 52, 50, 102, 40], or due to early- or late-time inspirals [89, 39, 106]. iv) *Cosmological QSO lensing variability* at various wavelengths and multi-year timescales is sensitive up to few $M_\odot$ BH [59, 90]. Shorter timescale microlensing of QSO/AGN and femto-lensing of GRB probe planetary mass BHs [43, 15]. Other probes include point sources towards the Galactic center [48, 60], wide binaries in the Galactic halo [96], 21cm signal from reionization [61] and strong gravitational lensing of extragalactic fast radio bursts (FRBs), which can produce observable "echoes" of these radio signals [97].

Future prospects and capabilities.

• Probing the source-subtracted CIB fluctuations at high precision, determining its epochs and coherence with unresolved CXB would provide important clues to the origin of its populations and the role of PBHs in their production. The information will come from the LIBRAE (Looking at Infrared Background Radiation with *Euclid*) project within *Euclid* [46]. The *Euclid* mission, with its deep coverage of ∼half the sky in three near-IR bands (Y,J,H) and visible (0.6-0.9μm) in the Wide Survey and a still deeper coverage of additional 40deg^2 in the Deep Survey [81, 82], will result, in this context, in 1) measurement of the CIB power spectrum to sub-percent statistical accuracy and establishing the epochs of its sources by cross-correlating with visible diffuse maps, and then 2) probing the CIB-CXB cross-power at high fidelity [76] with surveys from the concurrent *eROSITA* [91] mission. The later ESA's *Athena* X-ray mission [100] will bring further improvements to the measurement [76] if it surveys ∼100deg^2 to the depth of the currently deepest *Chandra* exposures used in [27, 28, 95, 86]. See Fig.1. Further opportunities will be available with NASA's *WFIRST* [115] mission which, while covering less area that *Euclid*, will go deeper and over a broader near-IR range.

• Microlensing: On-going and continuing long-term wide-field surveys like OGLE, *Gaia* and then primarily LSST will provide hundreds of BH lensing events. However, only with future ultra-precise and sensitive astrometric instruments, like *WFIRST, Euclid, JWST*, ELT or *Gaia*NIR, it will be possible to derive the mass of the lens, hence recognizing BH lenses. These facilities will also detect thousands of quadruply lensed quasars, allowing to detect PBH through microlensing.

• SN lensing: SNeIA are the best cosmological candidates for probing PBHs via lensing. They are predicted to be ∼100 SNeIA/deg^2/yr to z=1 [121], so assembling a sufficient sample of SNIa will require a multi-year coverage of wide areas of the sky with a suitable cadence. Going to higher z would increase their expected number, but would also require deeper exposures. Out to

$z \sim 2.5$ one finds the rate of ~ 500 SNeIA/deg^2/yr, but with peak AB~ 26.5 in J,H bands [110]. At $z \gtrsim 5$ SNIa are expected to be very rare for standard formation modes [116, 92, 53]. The *WFIRST* dedicated 6-month SN survey appears optimal, and a large catalog of several thousand SNe will be attained. The LSST Survey cadence is well-suited for detection of transients that may turn out to be SNe and the SNe magnification will be monitored very precisely from the expected yield of $\sim 3 \times 10^5$ SNIa/yr. *JWST* can contribute to this effort with observations at proper cadence covering wide areas of the sky, but the current GTO programs are expected to yield several hundred SNIa to $z \simeq 5$. On *Euclid* the DESIRE (Dark Energy Supernova Infra-Red Experiment) was proposed as a dedicated 6-month NIR rolling search predicted to measure distances to 1,700 high-redshift SNe Ia out to $z \simeq 1.5$ [13].

• The relevant CMB work in the coming decade will necessarily be mostly theoretical. Limits will moreover become more robust as more detailed understanding of the accretion process is achieved. So far CMB studies of PBHs have been limited to the CMB angular power spectrum. It is possible that higher-order statistics (such as the bispectrum) can also be used to constrain PBHs. New high-sensitivity, high-angular-resolution CMB-polarization missions, CMB Stage-IV [1] and AdvACTPol [119], should significantly improve over *Planck* for measuring cosmological parameters. A detailed study of the sensitivity of upcoming CMB-anisotropy measurements to accreting PBHs, paralleling that of [55] for annihilating DM particles, needs to be completed.

• UFDGs: Between hundreds and thousands of UFDG could be detected by wide and deep-field surveys with *Euclid*, LSST, *WFIRST* and *JWST*. Wide surveys will have a limiting magnitude lower than the one reached by VST-Atlas (VLT) and HCS-SSP deep field surveys. With a limiting magnitude $r \simeq 31$, *JWST* will detect the faintest and smallest objects, like UFDG with half-light radius $r_{1/2} \lesssim 10$ pc and star clusters within larger UFDG that would detected by wide surveys.

• Pulsar timing and FRB lensing: The 5-year observations from the International Pulsar Timing Array (IPTA) [122], regrouping NANOGrav [12], the Parkes Pulsar Timing Array [88] and the European Pulsar Timing Array [84] have a projected sensitivity to the GW density at nanohertz frequencies of $\Omega_{GW}h^2 \sim 10^{-10}$ [80]. With the PTA of the SKA, this sensitivity could be reduced down to $\Omega_{GW}h^2 \sim 10^{-15}$ [83, 126]. IPTA or SKA should detect the SGWB from (Gaussian) curvature fluctuations leading to stellar-mass PBH formation [65, 24]. Upcoming FRB lensing observations from CHIME [35] can significantly constrain the DM fraction in $\gtrsim 10 M_\odot$ PBHs.

• In addition to the above EM investigations two inputs in this regard from the GW frontier could be critical. The golden observation that would almost surely be a sign of a PBH would be the detection of a BH merger progenitor lighter than the Chandrasekhar mass. Searching for sub-solar mass BH is additionally motivated theoretically, because they would have formed at the QCD transition, when the sound speed reduction naturally boosts PBH formation [67, 25] so they may be more abundant than heavier BHs. In the future, it is therefore important i) to pursue the analysis of LIGO runs [4], ii) to extend it to non-equal mass binaries (and to spinning black holes), iii) to compute more accurately the expected merger rates for different binary formation mechanisms [99, 113, 8, 107], clustering models [22, 44, 14] and PBH mass functions, in the sub-solar mass range. Additionally in the absence of PBH contributions to DM, the standard ΛCDM matter density fluctuations precludes stars forming at very early epochs, $z \gtrsim 15$–20. Finding BH mergers at progressively higher $z \gtrsim 15$, where no stars are expected in the absence of PBHs, will be a strong indicator of PBHs. The three proposed experimental configurations, Cosmic Explorer [47], *LISA* [10] and Einstein Telescope [117], that can probe GWs from BH merges at such epochs, will be important for probing the PBH-DM link.

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