# Snowmass2021 - Letter of Interest

# *Rubin/LSST Black Hole Dark Matter Microlensing*

**Thematic Areas:** (check all that apply ☐/■)

■ (CF1) Dark Matter: Particle Like
☐ (CF2) Dark Matter: Wavelike
■ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
■ (CF7) Cosmic Probes of Fundamental Physics
■ (TF09) Astro-particle physics & cosmology

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**Abstract:** Primordial black holes may be the first density perturbations to collapse during the early universe, and have long been considered a dark matter candidate. While much of the black hole dark matter parameter space has been constrained by existing probes, it is still possible that primordial black holes make up the entirety of dark matter. Accounting for systematics and revisiting constraints in the context of the broad-mass and spatially clustered scenario, as well as the recent LIGO black hole detections, makes black hole dark matter an important candidate to study. The Vera C. Rubin Observatory and associated 10-year Legacy Survey of Space and Time (LSST) can constrain primordial black hole dark matter abundance from $\sim 10^{-12} - 10^{3}\,\mathrm{M}_{\odot}$, as well as constrain their fundamental properties. Just as important, even if primordial black holes do not make up the entirety of dark matter, the measurement of primordial black hole abundance and properties probes small scale primordial density fluctuations between $k = 10^{7} - 10^{19}$ $h$/Mpc, much smaller than those measured by other current and future probes.

Primordial black holes (PBHs) have long been considered as a dark matter (DM) candidate [1], which could form at early times from the direct gravitational collapse of large density perturbations that originated during inflation. The same fluctuations that lay down the seeds of galaxies, if boosted on small scales, can lead to some small areas having a Schwarzschild mass within the horizon, which spontaneously collapse to form black holes [1–5].

Compact object DM is fundamentally different from particle models; PBHs cannot be studied in an accelerator and can only be detected through their gravitational force. PBHs are one possible source of the merging $30M_{\odot}$ black holes recently detected by LIGO [6, 7] and compelling candidates to seed early galaxy formation [8]. These possibilities have rekindled interest in these objects, both as a source of dark matter and in their own right.

While there are many existing constraints on the abundance of PBH DM from a range of astrophysical probes [e.g., the cosmic microwave background, wide-binary stars, and dwarf galaxies, see 8, 9, and references therein], most of these rely on complex astrophysical assumptions resulting in orders of magnitude uncertainty [see, 10, for a summary], with existing constraints continuing to be be loosened as theoretical assumptions are further explored [e.g. 11–13]. Additionally the impact of spatially clustered PBHs on existing constraints is debated [14–16]. Clearly more theory/simulation work is needed to better qualify existing constraints. Even under some of the strictest constraints it is still possible to have all of DM be composed of PBHs, if they have an extended mass spectrum [5] as is predicted by theory [e.g., 5, 17].

The most direct and robust means of constraining PBH DM abundance and properties is through gravitational microlensing – the brightening and associated motion of stars as foreground compact objects pass between the observer and star and distort space-time. The Vera C. Rubin Observatory and 10-year Legacy Survey of Space and Time (LSST), with its regular high precision photometric measurements over the entire visible sky provides one of the best means of measuring the microlensing signal. LSST will detect tens to hundreds of microlensing events per square degree, depending on the Milky Way (MW) stellar density of the field [18], resulting in $> 3 \times 10^4$ total black hole events from stellar end product events alone [19]. If $\sim 40M_{\odot}$ PBHs make up all of dark matter more than double this number of events are expected [Pruett et al. in prep.], enabling dark matter fraction constraints at a precision of $\sim 10^{-3}$ [10]. Furthermore, the all sky coverage of LSST can multiply the PBH DM constraining power versus a MW bulge only microlensing survey [20, 21]. Precursor surveys such as the Optical Gravitational Lensing Experiment (OGLE) and the Zwicky Transient Facility (ZTF) are demonstrating the power of microlensing to detect and constrain the compact object abundance and properties [20, 22].

Gravitational microlensing campaigns with LSST have already been advocated by the broader community [10, 23, 24] and recommended by the LSST Science Advisory Committee [25]. So the necessary data for this science is likely to be available, however there is still no dedicated scientific funding support mechanism.

LSST holds the potential to probe PBH DM over fifteen orders of magnitude in mass ($\sim 10^{-12} - 10^3\,\mathrm{M}_{\odot}$). At the low mass end there exists a large region of parameter space were black holes can make up the totality of DM. Low-mass primordial black holes produce lensing events with characteristically short timescales. Observations with the Subaru Hyper Suprime Cam, which currently provide the strongest constraints in this region [26], were limited by a readout time of $\sim 30$ seconds, not fast enough to effectively explore the range $M_{\mathrm{PBH}} \lesssim 10^{-11}M_{\odot}$ [27]. LSST will allow for 2 second readout times[10], significantly improving the capability of observing short duration transient events and extending the mass constraints to $\lesssim 10^{-12}M_{\odot}$, as well as significantly improving existing constraints.

At the high-mass-end (e.g., at the LIGO mass scale of 10's of $M_{\odot}$ and up to $\sim 10^3M_{\odot}$) BH microlensing events can last on the order of hundreds of days to years. Thus the 10-year duration of LSST is important to extending existing constraints at the high-mass-end. Furthermore, the multi-band photometry of LSST is important to disambiguate microlensing events from other long-time-scale transients (e.g., SN), since the microlensing signal is achromatic unlike most other astrophysical transients. One particularly powerful feature for long-duration microlensing events results from the change in the geometric configuration of the source-lens-observer system as the Earth orbits the Sun, which results in a parallax perturbation to the photometric and astrometric microlensing signals. This can be used to dramatically improve the constraints on individual black hole properties [28, 29]

While LSST will find and measure $> 3 \times 10^4$ total events [19], the lensing mass-distance and blending degeneracies can significantly degrade the precision of individual black hole mass estimates [29]. However, these degeneracies can be broken with complementary higher resolution observations such as those provided by ground-based adaptive optics (AO) telescopes [28] or space-based telescopes [29, 30]. These telescopes have too narrow a field of view to efficiently discover the relatively rare PBH microlensing events, which is why LSST is key to this investigation.

Ongoing theoretical work and simulations will complete the necessary set of requirements by enabling an accurate estimate of the expected abundance of black holes in microlensing surveys as a function of the fraction of dark matter composed of PBHs. Additionally they have identified a new method of efficiently, and with high purity, identifying black holes within microlensing surveys [31]. This work is still in its early stages though, and systematics need to be more fully characterized in order to not dominate the precise constraints possible with LSST.

As outlined in [10] and summarized here, measurement of the abundance and properties of PBHs enable us to probe primordial density fluctuations at scales much smaller ($k = 10^7 - 10^{19}$ $h$/Mpc) than current methods are able to probe [2, 3, 32]. This is the case even of PBHs only make up a fraction of dark matter. PBHs are the only known method of probing these small scales [33–35]. All other currently conceived evidence of these snall scales has been lost at late-times due to non-linear gravitational evolution. PBH abundance and properties provides a window into the universe at observationally unexplored energy scales ($10^{15}\mathrm{GeV}$ and above). Support for PBH theoretical/simulation work is key to realizing the powerful potential of PBHs to understand dark matter an the early universe.

## Recommendations for Snowmass 2021

LSST is scheduled to begin a decade of science operation in 2023; however, dark matter research with LSST is not yet funded. Recognizing new opportunities created by LSST to constrain PBH dark matter models over $\sim$15 decades in mass, we make the following recommendations to facilitate this science case:

- Support individual PIs and collaborative teams to analyze LSST data for primordial black hole dark matter science.
- Support associated BH and PBH theoretical research to better understand the expected abundance of black hole microlensing events and systematics with cosmic surveys, as well as PBH connections to primordial physics.
- Ensure that the LSST survey strategy enables the necessary data to constrain the PBH abundance and properties [10, 23, 24].
- Continue to support joint LSST, Roman Space Telescope, and Euclid processing efforts.

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