

Snowmass2021 - Letter of Interest

Gravitational waves from primordial black holes

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
- ☐ (Other) *[Please specify frontier/topical group]*

Contact Information:

Sebastien Clesse (University of Louvain) [sebastien.clesse@uclouvain.be]

Authors: (long author list after the text)

Sebastien Clesse (University of Louvain) [sebastien.clesse@uclouvain.be]
Patrick Brady (University of Wisconsin) [prbrady@uwm.edu],
Vuk Mandic (University of Minnesota) [vuk@umn.edu],
Mario Martinez (Universitat Autònoma de Barcelona) [mmp@ifae.es],
Andrew Miller (University of Louvain) [andrew.miller@uclouvain.be],
Mari Sakellariadou (King's College London) [mairi.sakellariadou@kcl.ac.uk],
Bangalore Sathyaprakash (Pennsylvania State University) [bss25@psu.edu]

Abstract: The current and the third generation of gravitational-wave (GW) detectors will investigate one of the most tantalizing ideas triggered by the first GW detections: that the observed black holes may have a primordial origin and explain all, or part of the Dark Matter (DM) in the Universe. With thousands of detections expected in the next observing runs of LIGO/Virgo/KAGRA, and hundred thousands for third generation instruments like Cosmic Explorer and Einstein Telescope, GWs will be the ideal probe of primordial black hole (PBH) signatures, in order to bring solid but model-dependent answers to these fundamental questions. GW probes include the mass, spin, rate and redshift distributions of black hole mergers, stochastic backgrounds from PBH formation and PBH binaries, GW bursts from close encounters, continuous waves from planetary-mass PBH binaries in our galaxy. The discovery of even a single PBH would revolutionize our understanding of the Universe, shedding light on new Physics at the origin of their formation. PBHs could also solve cosmological and astrophysical puzzles, including the nature of DM and the seeds of supermassive black holes at the center of galaxies.

Motivations. The first gravitational wave (GW) observations [1–10] have revealed some intriguing properties of black hole (BH) mergers, linked to their low spins and their large or asymmetric masses. They are challenging astrophysical models of BH formation [10] and may favor new stellar evolution scenarios [11, 12]. Alternatively, these properties could be explained by a primordial origin, and GW observations have rekindled the suggestions that primordial black holes (PBHs) may exist and constitute from a fraction to all of the dark matter (DM) in the Universe [13–17]. If some of these BHs are primordial, this would have tremendous consequences for Cosmology, High Energy Physics, DM and the physics of the early Universe.

PBHs may have formed in the early Universe due to the gravitational collapse of large inhomogeneities [18–22] produced during inflation [23, 24] or phase transitions [25], from scalar field fragmentation [26–28], vacuum bubbles [29, 30] or the collapse of topological defects like cosmic strings [31, 32]. Their abundance in the Universe could range from a negligible fraction to the totality of DM. The various astrophysical limits (see [33, 34] for reviews and [35, 36] for recent developments) and their uncertainties, depicted on Figure 1, still allow certain mass windows, including the stellar-mass range of interest to ground-based GW detectors. In some models, PBHs form in this range. On top of the effect of the distribution of primordial density fluctuations, the thermal history of the Universe, in particular the quantum chromodynamics (QCD) transition, introduces universal features in the PBH mass function [37–40] and spin distribution of PBHs and their merger remnants [25], which could be used to distinguish the origin of BHs [40]. In [41], various detection strategies based on electromagnetic (EM) probes have been considered in the context of the Astro2020 decadal survey. We focus here on PBH searches using GW observations [42] by ground-based instruments (for PBH perspectives with LISA, see [43–45]) which will be complementary to EM searches.

Searches in GW observations. Advanced LIGO and Virgo, and future ground-based GW observatories, e.g. Cosmic Explorer (CE) [46, 47] and Einstein Telescope (ET) [48–50], will probe the origin of BHs (stellar or primordial) through different methods and observations:

1. *Subsolar black holes.* Detecting a black hole of mass below the Chandrasekhar mass would almost unambiguously point towards a primordial origin. Subsolar searches have been carried out in the first and second observing runs of LIGO/Virgo [51, 52], assuming component masses between 0.1 and $2M_{\odot}$. They will be continued and extended to BH binaries with a larger primary component mass, which are motivated by a boosted PBH formation at the QCD transition, corresponding to masses between 0.5 and $5M_{\odot}$ [37–40]. CE and ET will reach the sensitivity to detect binaries with a sub-solar black hole at cosmological distances, as seen in Figure 1. They will allow to set unprecedented limits on the abundance of subsolar BHs. Finally, the absence of a GW signal from a kilonova may point to neutron stars (NS) destroyed by sublunar PBHs [53].
2. *BHs in the NS mass range and low mass gap.* The third observing run of LIGO/Virgo has revealed the existence of compact objects in the mass-gap between the highest mass of known NS and the lowest mass of astrophysical BHs [9, 10]. BHs in the mass gap could also form when NS merge [54], contaminating a plausible PBH population. Multi-messenger astronomy could probe the origin of these objects, eventually revealing their primordial origin by searching for an EM counterpart. CE and ET could also detect their final merging phase and thereby distinguish the nature of these objects. The existence of BHs in this range is motivated in PBH models, due to a boosted formation at the QCD transition [39, 40].
3. *Intermediate-mass BHs.* Above $60M_{\odot}$, pair-instability should prevent BHs to form from single stellar explosions. PBHs are not sensitive to this limit and may lead to BH mergers in this range. Accurate spin reconstructions will allow to distinguish them from secondary mergers in dense environments [55]. CE will probe the existence of intermediate-mass black hole binaries up to 10^4M_{\odot} , which will reveal a possible primordial origin of the seeds of the super-massive BHs at the center of galaxies [40, 56].
4. *BH mergers at high redshift.* The third generation of GW detectors like CE and ET will have an astrophysical reach $20 \lesssim z + 1 \lesssim 100$, prior the formation of stars, as shown in Figure 1. Any BH merger detection would therefore almost certainly point to a primordial origin.

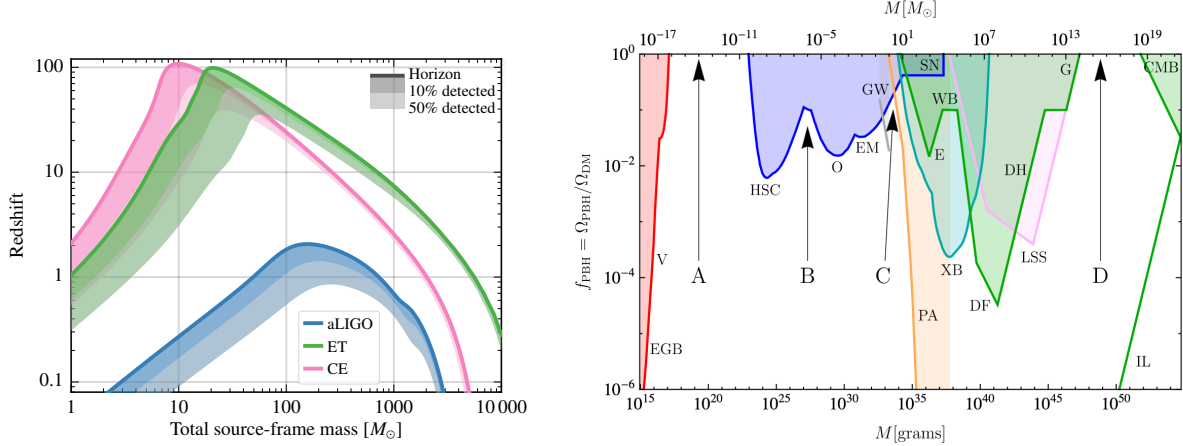


Figure 1: *Left: Astrophysical range in redshift as a function of the total binary mass for Advanced Ligo (aLIGO), ET and CE (figure from [50]). Right: Astrophysical limits on the PBH density with respect to DM, for a monochromatic PBH mass function. The arrows point to the mass windows where PBHs can constitute a substantial part of DM. Figure from [35, 36], where details and references on these limits and their uncertainties can be found.*

5. *Distinguishing PBH vs stellar BHs with statistical methods.* Besides the above-mentioned exceptional BH merger events, Bayesian statistical methods and model selection [57] applied to the rate, mass, spin and redshift distributions will help to distinguish PBHs from the stellar scenarios [40, 45, 58–72]. They can be used to set new limits on PBH models and reveal the existence of different black hole populations. PBH binaries with merging rates large enough to be detected may have formed by tidal capture in clusters [13, 14, 73, 74] and before recombination [59, 75–78] (see however [79] for an opposite claim). Deep learning based techniques will be used to search for low mass or highly-asymmetric PBH binary candidates.

6. *Stochastic backgrounds.* If PBHs contribute to a non-negligible fraction of DM, their binaries generate a detectable stochastic GW background (SGWB) [80–83]. Its spectral shape depends on the PBH mass distribution and binary formation channel and its amplitude can be comparable or higher than other astrophysical sources. The number of sources contributing to the signal may also help to distinguish the SGWB from neutron stars, stellar BH and PBHs. Other SGWBs may come from Hawking radiation [84] or the density fluctuations at the origin of PBH formation [43, 44, 85–93]. At second order in the theory of cosmological perturbations, they source a SGWB. Present and future ground-based detectors will probe PBH masses between 10^{-20} and $10^{-17} M_\odot$ [90, 91] and will provide complementary limits on their abundance.

7. *Continuous waves (CWs) from planetary-mass binaries.* If PBHs have a wide mass distribution down to $10^{-8} M_\odot$ or with a peak on planetary-masses, they would form binaries emitting CWs waves in the frequency range of detectors, years before they merge. The methods originally designed to detect CWs from asymmetrically rotating neutron stars [94] can be adapted to search for subsolar PBHs in our galaxy. The Frequency-Hough method exploits the continuous, quasi-monochromatic nature of inspiraling BHs that are sufficiently far apart such that their orbital frequency can be approximated as linear with a small spin-up. The Generalized Frequency-Hough method drops the assumption of linearity and allows the inspiral signal to have a power-law evolution. Both can detect or set new limits on PBHs in the mass range $[10^{-8} - 10^{-3}] M_\odot$. CE and ET could even detect such binaries in the solar system vicinity.

8. *GW bursts from close encounters.* Another signal from PBHs comes from the GW bursts from hyperbolic encounters in dense halos [95, 96]. The signal frequency can lie in the frequency range of ground-based detectors for stellar-mass BHs, with a duration of order of milliseconds.

Summary. GW offer multiple ways to probe and constrain the existence of PBHs, as well as their formation scenarios. PBHs may be linked to the nature of DM, to the baryogenesis [97, 98], be the seeds of supermassive BHs [56] and galaxies [99], and would provide new ways to test the existence of particles like WIMPs [100]. Observing them would therefore have groundbreaking implications in fundamental physics.

References

- [1] B.P. Abbott et al. Observation of Gravitational Waves from a Binary Black Hole Merger. *Phys. Rev. Lett.*, 116(6):061102, 2016.
- [2] B.P. Abbott et al. Binary Black Hole Mergers in the first Advanced LIGO Observing Run. *Phys. Rev. X*, 6(4):041015, 2016. [Erratum: *Phys.Rev.X* 8, 039903 (2018)].
- [3] B. P. Abbott et al. GW151226: Observation of Gravitational Waves from a 22-Solar-Mass Binary Black Hole Coalescence. *Phys. Rev. Lett.*, 116(24):241103, 2016.
- [4] Benjamin P. Abbott et al. GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2. *Phys. Rev. Lett.*, 118(22):221101, 2017. [Erratum: *Phys.Rev.Lett.* 121, 129901 (2018)].
- [5] B.P. Abbott et al. GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence. *Phys. Rev. Lett.*, 119(14):141101, 2017.
- [6] B.. P.. Abbott et al. GW170608: Observation of a 19-solar-mass Binary Black Hole Coalescence. *Astrophys. J.*, 851(2):L35, 2017.
- [7] B. P. Abbott et al. GWTC-1: A Gravitational-Wave Transient Catalog of Compact Binary Mergers Observed by LIGO and Virgo during the First and Second Observing Runs. *Phys. Rev.*, X9(3):031040, 2019.
- [8] R. Abbott et al. GW190412: Observation of a Binary-Black-Hole Coalescence with Asymmetric Masses. 4 2020.
- [9] B. P. Abbott et al. GW190425: Observation of a Compact Binary Coalescence with Total Mass $\sim 3.4M_{\odot}$. *Astrophys. J. Lett.*, 892:L3, 2020.
- [10] R. Abbott et al. GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object. *Astrophys. J.*, 896(2):L44, 2020.
- [11] Simon Stevenson, Matthew Sampson, Jade Powell, Alejandro Vigna-Gómez, Coenraad J. Neijssel, Dorottya Szécsi, and Ilya Mandel. The impact of pair-instability mass loss on the binary black hole mass distribution. 4 2019.
- [12] A. Olejak, M. Fishbach, K. Belczynski, D.E. Holz, J.-P. Lasota, M.C. Miller, and T. Bulik. The Origin of inequality: isolated formation of a 30+10Msun binary black-hole merger. 4 2020.
- [13] Simeon Bird, Ilias Cholis, Julian B. Muñoz, Yacine Ali-Haïmoud, Marc Kamionkowski, Ely D. Kovetz, Alvise Raccanelli, and Adam G. Riess. Did LIGO detect dark matter? *Phys. Rev. Lett.*, 116(20):201301, 2016.
- [14] Sebastien Clesse and Juan García-Bellido. The clustering of massive Primordial Black Holes as Dark Matter: measuring their mass distribution with Advanced LIGO. *Phys. Dark Univ.*, 15:142–147, 2017.
- [15] Misao Sasaki, Teruaki Suyama, Takahiro Tanaka, and Shuichiro Yokoyama. Primordial Black Hole Scenario for the Gravitational-Wave Event GW150914. *Phys. Rev. Lett.*, 117(6):061101, 2016. [erratum: *Phys. Rev. Lett.* 121,no.5,059901(2018)].

- [16] A. Kashlinsky. LIGO Gravitational Wave Detection, Primordial Black Holes, and the Near-IR Cosmic Infrared Background Anisotropies. , 823(2):L25, June 2016.
- [17] S. Blinnikov, A. Dolgov, N.K. Porayko, and K. Postnov. Solving puzzles of GW150914 by primordial black holes. *JCAP*, 11:036, 2016.
- [18] Ya. B. Zel’dovich and I. D. Novikov. The Hypothesis of Cores Retarded during Expansion and the Hot Cosmological Model. , 43:758, January 1966.
- [19] Stephen Hawking. Gravitationally collapsed objects of very low mass. *Mon. Not. Roy. astron. Soc.*, 152:75, 1971.
- [20] Bernard J. Carr and S. W. Hawking. Black holes in the early Universe. *Mon. Not. R. astron. Soc.*, 168:399–415, 1974.
- [21] George F. Chapline. Cosmological effects of primordial black holes. *Nature (London)*, 253:251–+, January 1975.
- [22] A.G. Polnarev and M.Yu. Khlopov. COSMOLOGY, PRIMORDIAL BLACK HOLES, AND SUPERMASSIVE PARTICLES. *Sov. Phys. Usp.*, 28:213–232, 1985.
- [23] Alexandre Dolgov and Joseph Silk. Baryon isocurvature fluctuations at small scales and baryonic dark matter. *Phys. Rev.*, D47:4244–4255, 1993.
- [24] P. Ivanov, P. Naselsky, and I. Novikov. Inflation and primordial black holes as dark matter. *Phys. Rev. D*, 50:7173–7178, 1994.
- [25] Eugenio Bianchi, Anuradha Gupta, Hal M. Haggard, and B. S. Sathyaprakash. Quantum gravity and black hole spin in gravitational wave observations: a test of the Bekenstein-Hawking entropy. 2018.
- [26] Eric Cotner and Alexander Kusenko. Primordial black holes from supersymmetry in the early universe. *Phys. Rev. Lett.*, 119(3):031103, 2017.
- [27] Eric Cotner and Alexander Kusenko. Primordial black holes from scalar field evolution in the early universe. *Phys. Rev. D*, 96(10):103002, 2017.
- [28] Eric Cotner, Alexander Kusenko, and Volodymyr Takhistov. Primordial Black Holes from Inflaton Fragmentation into Oscillons. *Phys. Rev. D*, 98(8):083513, 2018.
- [29] Heling Deng and Alexander Vilenkin. Primordial black hole formation by vacuum bubbles. *JCAP*, 12:044, 2017.
- [30] Alexander Kusenko, Misao Sasaki, Sunao Sugiyama, Masahiro Takada, Volodymyr Takhistov, and Edoardo Vitagliano. Exploring Primordial Black Holes from Multiverse with Optical Telescopes. 1 2020.
- [31] Alexander Polnarev and Robert Zembowicz. Formation of Primordial Black Holes by Cosmic Strings. *Phys. Rev. D*, 43:1106–1109, 1991.
- [32] Alexander C. Jenkins and Mairi Sakellariadou. Primordial black holes from cusp collapse on cosmic strings. 6 2020.
- [33] Bernard Carr, Florian Kuhnel, and Marit Sandstad. Primordial Black Holes as Dark Matter. *Phys. Rev. D*, 94(8):083504, 2016.

- [34] B.J. Carr, Kazunori Kohri, Yuuiti Sendouda, and Jun'ichi Yokoyama. New cosmological constraints on primordial black holes. *Phys. Rev. D*, 81:104019, 2010.
- [35] Bernard Carr, Kazunori Kohri, Yuuiti Sendouda, and Jun'ichi Yokoyama. Constraints on Primordial Black Holes. 2 2020.
- [36] Bernard Carr and Florian Kuhnel. Primordial Black Holes as Dark Matter: Recent Developments. *Ann. Rev. Nucl. Part. Sci.*, pages 170:14.1–14.40, 6 2020.
- [37] Jens C. Niemeyer and K. Jedamzik. Near-Critical Gravitational Collapse and the Initial Mass Function of Primordial Black Holes. *Phys. Rev. Lett.*, 80:5481–5484, 1998.
- [38] Karsten Jedamzik. Primordial black hole formation during the QCD epoch. *Phys. Rev.*, D55:R5871–5875, 1997.
- [39] Christian T. Byrnes, Mark Hindmarsh, Sam Young, and Michael R. S. Hawkins. Primordial black holes with an accurate QCD equation of state. *JCAP*, 1808(08):041, 2018.
- [40] Bernard Carr, Sebastien Clesse, Juan García-Bellido, and Florian Kuhnel. Cosmic Conundra Explained by Thermal History and Primordial Black Holes. 6 2019.
- [41] A. Kashlinsky et al. Electromagnetic probes of primordial black holes as dark matter. 3 2019.
- [42] Misao Sasaki, Teruaki Suyama, Takahiro Tanaka, and Shuichiro Yokoyama. Primordial black holes—perspectives in gravitational wave astronomy. *Class. Quant. Grav.*, 35(6):063001, 2018.
- [43] N. Bartolo, V. De Luca, G. Franciolini, A. Lewis, M. Peloso, and A. Riotto. Primordial Black Hole Dark Matter: LISA Serendipity. *Phys. Rev. Lett.*, 122(21):211301, 2019.
- [44] N. Bartolo, V. De Luca, G. Franciolini, M. Peloso, D. Racco, and A. Riotto. Testing primordial black holes as dark matter with LISA. *Phys. Rev. D*, 99(10):103521, 2019.
- [45] Caner Unal. Imprints of Primordial Non-Gaussianity on Gravitational Wave Spectrum. *Phys. Rev. D*, 99(4):041301, 2019.
- [46] Benjamin P Abbott et al. Exploring the Sensitivity of Next Generation Gravitational Wave Detectors. *Class. Quant. Grav.*, 34(4):044001, 2017.
- [47] David Reitze et al. Cosmic Explorer: The U.S. Contribution to Gravitational-Wave Astronomy beyond LIGO. *Bull. Am. Astron. Soc.*, 51:035, 7 2019.
- [48] M. Punturo et al. The third generation of gravitational wave observatories and their science reach. *Class. Quant. Grav.*, 27:084007, 2010.
- [49] S. Hild et al. Sensitivity Studies for Third-Generation Gravitational Wave Observatories. *Class. Quant. Grav.*, 28:094013, 2011.
- [50] Michele Maggiore et al. Science Case for the Einstein Telescope. *JCAP*, 03:050, 2020.
- [51] B.P. Abbott et al. Search for Subsolar-Mass Ultracompact Binaries in Advanced LIGO's First Observing Run. *Phys. Rev. Lett.*, 121(23):231103, 2018.
- [52] B.P. Abbott et al. Search for Subsolar Mass Ultracompact Binaries in Advanced LIGO's Second Observing Run. *Phys. Rev. Lett.*, 123(16):161102, 2019.

- [53] George M. Fuller, Alexander Kusenko, and Volodymyr Takhistov. Primordial Black Holes and r -Process Nucleosynthesis. *Phys. Rev. Lett.*, 119(6):061101, 2017.
- [54] Anuradha Gupta, Davide Gerosa, K. G. Arun, Emanuele Berti, Will M. Farr, and B. S. Sathyaprakash. Black holes in the low mass gap: Implications for gravitational wave observations. *Phys. Rev.*, D101(10):103036, 2020.
- [55] R. Farmer, M. Renzo, S.E. de Mink, P. Marchant, and S. Justham. Mind the gap: The location of the lower edge of the pair instability supernovae black hole mass gap. 10 2019.
- [56] Sébastien Clesse and Juan García-Bellido. Massive Primordial Black Holes from Hybrid Inflation as Dark Matter and the seeds of Galaxies. *Phys. Rev.*, D92(2):023524, 2015.
- [57] B.P. Abbott et al. Binary Black Hole Population Properties Inferred from the First and Second Observing Runs of Advanced LIGO and Advanced Virgo. *Astrophys. J. Lett.*, 882(2):L24, 2019.
- [58] Bence Kocsis, Teruaki Suyama, Takahiro Tanaka, and Shuichiro Yokoyama. Hidden universality in the merger rate distribution in the primordial black hole scenario. *Astrophys. J.*, 854(1):41, 2018.
- [59] Yacine Ali-Haïmoud, Ely D. Kovetz, and Marc Kamionkowski. Merger rate of primordial black-hole binaries. *Phys. Rev. D*, 96(12):123523, 2017.
- [60] Sebastien Clesse and Juan García-Bellido. Seven Hints for Primordial Black Hole Dark Matter. *Phys. Dark Univ.*, 22:137–146, 2018.
- [61] Nicolas Fernandez and Stefano Profumo. Unraveling the origin of black holes from effective spin measurements with LIGO-Virgo. *JCAP*, 08:022, 2019.
- [62] V. De Luca, V. Desjacques, G. Franciolini, A. Malhotra, and A. Riotto. The initial spin probability distribution of primordial black holes. *JCAP*, 05:018, 2019.
- [63] Andrew D. Gow, Christian T. Byrnes, Alex Hall, and John A. Peacock. Primordial black hole merger rates: distributions for multiple LIGO observables. *JCAP*, 2001:031, 2020.
- [64] Karsten Jedamzik. Evidence for primordial black hole dark matter from LIGO/Virgo merger rates. 7 2020.
- [65] Karsten Jedamzik. Primordial Black Hole Dark Matter and the LIGO/Virgo observations. 2020.
- [66] S. Bhagwat, V. De Luca, G. Franciolini, P. Pani, and A. Riotto. The Importance of Priors on LIGO-Virgo Parameter Estimation: the Case of Primordial Black Holes. 8 2020.
- [67] V. De Luca, G. Franciolini, P. Pani, and A. Riotto. Primordial Black Holes Confront LIGO/Virgo data: Current situation. *JCAP*, 06:044, 2020.
- [68] V. De Luca, G. Franciolini, P. Pani, and A. Riotto. Constraints on Primordial Black Holes: the Importance of Accretion. *Phys. Rev. D*, 102(4):043505, 2020.
- [69] V. De Luca, G. Franciolini, P. Pani, and A. Riotto. The Evolution of Primordial Black Holes and their Final Observable Spins. *JCAP*, 04:052, 2020.
- [70] Alexander Dolgov and Konstantin Postnov. Why the mean mass of primordial black hole distribution is close to $10M_{\odot}$. *JCAP*, 07:063, 2020.

- [71] A.D. Dolgov, A.G. Kuranov, N.A. Mitichkin, S. Porey, K.A. Postnov, O.S. Sazhina, and I.V. Simkin. On mass distribution of coalescing black holes. 5 2020.
- [72] K.M. Belotsky, A.D. Dmitriev, E.A. Esipova, V.A. Gani, A.V. Grobov, M. Yu. Khlopov, A.A. Kirillov, S.G. Rubin, and I.V. Svadkovsky. Signatures of primordial black hole dark matter. *Mod. Phys. Lett. A*, 29(37):1440005, 2014.
- [73] Valeriya Korol, Ilya Mandel, M. Coleman Miller, Ross P. Church, and Melvyn B. Davies. Merger rates in primordial black hole clusters without initial binaries. *Mon. Not. Roy. Astron. Soc.*, 496(1):994–1000, 2020.
- [74] Konstantin M. Belotsky, Vyacheslav I. Dokuchaev, Yury N. Eroshenko, Ekaterina A. Esipova, Maxim Yu. Khlopov, Leonid A. Khromykh, Alexander A. Kirillov, Valeriy V. Nikulin, Sergey G. Rubin, and Igor V. Svadkovsky. Clusters of primordial black holes. *Eur. Phys. J. C*, 79(3):246, 2019.
- [75] Takashi Nakamura, Misao Sasaki, Takahiro Tanaka, and Kip S. Thorne. Gravitational waves from coalescing black hole MACHO binaries. *Astrophys. J. Lett.*, 487:L139–L142.
- [76] Martti Raidal, Ville Vaskonen, and Hardi Veermäe. Gravitational Waves from Primordial Black Hole Mergers. *JCAP*, 09:037.
- [77] Martti Raidal, Christian Spethmann, Ville Vaskonen, and Hardi Veermäe. Formation and Evolution of Primordial Black Hole Binaries in the Early Universe. 2018.
- [78] Sam Young and Christian T. Byrnes. Initial clustering and the primordial black hole merger rate. *JCAP*, 03:004, 2020.
- [79] Celine Boehm, Archil Kobakhidze, Ciaran A.J. O’Hare, Zachary S.C. Picker, and Mairi Sakellariadou. Eliminating the LIGO bounds on primordial black hole dark matter. 8 2020.
- [80] Vuk Mandic, Simeon Bird, and Ilias Cholis. Stochastic Gravitational-Wave Background due to Primordial Binary Black Hole Mergers. *Phys. Rev. Lett.*, 117(20):201102, 2016.
- [81] Sebastien Clesse and Juan García-Bellido. Detecting the gravitational wave background from primordial black hole dark matter. *Phys. Dark Univ.*, 18:105–114, 2017.
- [82] Sai Wang, Yi-Fan Wang, Qing-Guo Huang, and Tjonnie G. F. Li. Constraints on the Primordial Black Hole Abundance from the First Advanced LIGO Observation Run Using the Stochastic Gravitational-Wave Background. *Phys. Rev. Lett.*, 120(19):191102, 2018.
- [83] Sai Wang, Takahiro Terada, and Kazunori Kohri. Prospective constraints on the primordial black hole abundance from the stochastic gravitational-wave backgrounds produced by coalescing events and curvature perturbations. *Phys. Rev. D*, 99(10):103531, 2019. [Erratum: *Phys.Rev.D* 101, 069901 (2020)].
- [84] Alexandre Arbey and Jérémy Auffinger. BlackHawk: A public code for calculating the Hawking evaporation spectra of any black hole distribution. *Eur. Phys. J. C*, 79(8):693, 2019.
- [85] Kishore N. Ananda, Chris Clarkson, and David Wands. The Cosmological gravitational wave background from primordial density perturbations. *Phys. Rev. D*, 75:123518, 2007.
- [86] Daniel Baumann, Paul J. Steinhardt, Keitaro Takahashi, and Kiyotomo Ichiki. Gravitational Wave Spectrum Induced by Primordial Scalar Perturbations. *Phys. Rev. D*, 76:084019, 2007.

- [87] Keisuke Inomata, Masahiro Kawasaki, Kyohei Mukaida, Yuichiro Tada, and Tsutomu T. Yanagida. Inflationary primordial black holes for the LIGO gravitational wave events and pulsar timing array experiments. *Phys. Rev. D*, 95(12):123510, 2017.
- [88] Tomohiro Nakama, Joseph Silk, and Marc Kamionkowski. Stochastic gravitational waves associated with the formation of primordial black holes. *Phys. Rev. D*, 95(4):043511, 2017.
- [89] Haoran Di and Yungui Gong. Primordial black holes and second order gravitational waves from ultra-slow-roll inflation. *JCAP*, 07:007, 2018.
- [90] Sebastien Clesse, Juan García-Bellido, and Stefano Orani. Detecting the Stochastic Gravitational Wave Background from Primordial Black Hole Formation. 12 2018.
- [91] Keisuke Inomata and Tomohiro Nakama. Gravitational waves induced by scalar perturbations as probes of the small-scale primordial spectrum. *Phys. Rev. D*, 99(4):043511, 2019.
- [92] N. Bartolo, D. Bertacca, V. De Luca, G. Franciolini, S. Matarrese, M. Peloso, A. Ricciardone, A. Riotto, and G. Tasinato. Gravitational wave anisotropies from primordial black holes. *JCAP*, 02:028, 2020.
- [93] Caner Unal, Ely D. Kovetz, and Subodh P. Patil. Multi-messenger Probes of Massive Black Holes from Enhanced Primordial Fluctuations. 8 2020.
- [94] R. Abbott et al. Gravitational-wave constraints on the equatorial ellipticity of millisecond pulsars. 7 2020.
- [95] Juan Garcia-Bellido and Savvas Nesseris. Gravitational wave bursts from Primordial Black Hole hyperbolic encounters. *Phys. Dark Univ.*, 18:123–126, 2017.
- [96] Juan García-Bellido and Savvas Nesseris. Gravitational wave energy emission and detection rates of Primordial Black Hole hyperbolic encounters. *Phys. Dark Univ.*, 21:61–69, 2018.
- [97] Juan García-Bellido, Bernard Carr, and Sebastien Clesse. A common origin for baryons and dark matter. 4 2019.
- [98] A.D. Dolgov, M. Kawasaki, and N. Kevlishvili. Inhomogeneous baryogenesis, cosmic antimatter, and dark matter. *Nucl. Phys. B*, 807:229–250, 2009.
- [99] Bernard Carr and Joseph Silk. Primordial Black Holes as Generators of Cosmic Structures. *Mon. Not. Roy. Astron. Soc.*, 478(3):3756–3775, 2018.
- [100] Julian Adamek, Christian T. Byrnes, Mateja Gosenca, and Shaun Hotchkiss. WIMPs and stellar-mass primordial black holes are incompatible. *Phys. Rev. D*, 100(2):023506, 2019.

Additional Authors:

Alexandre Arbey (University of Lyon) [alexandre.arbey@ens-lyon.fr]

Jérémy Auffinger (University of Lyon) [j.auffinger@ipnl.in2p3.fr]

Nicola Bellomo (University of Barcelona) [nicola.bellomo@icc.ub.edu]

Emanuele Berti (Johns Hopkins University) [berti@jhu.edu]
 Simeon Bird (UCR) [sbird@ucr.edu]
 Giacomo Bruno (University of Louvain) [Giacomo.Bruno@uclouvain.be],
 Christian T. Byrnes (University of Sussex) [ctb22@sussex.ac.uk]
 Francesca Calore (CNRS, LAPTh) [calore@lapth.cnrs.fr]
 Bernard Carr (Queen Mary University of London) [B.J.Carr@qmul.ac.uk]
 Jens Chluba (University of Manchester) [jens.chluba@manchester.ac.uk]
 Agnieszka M. Cieplak (University of California, Berkeley) [acieplak@berkeley.edu]
 Geoffrey Compère (Université Libre de Bruxelles) [gcompere@ulb.ac.be]
 Ioannis Dalianis (National Technical University of Athens) [dalianis@mail.ntua.gr]
 Anne-Christine Davis (University of Cambridge) [ad107@cam.ac.uk]
 William Dawson (Lawrence Livermore National Laboratory) [dawson29@llnl.gov]
 Valerio De Luca (University of Geneva) [Valerio.DeLuca@unige.ch]
 Antoine Depasse (Université Catholique de Louvain) [antoine.depasse@uclouvain.be]
 Alexander Dolgov (Novosibirsk University, ITEP, U. of Ferrara) [dolgov@fe.infn.it],
 Gabriele Franciolini (University of Geneva) [Gabriele.Franciolini@unige.ch]
 Katherine Freese (University of Texas, Austin)
 Juan García-Bellido (Universidad Autónoma de Madrid) [juan.garciabellido@uam.es]
 Archisman Ghosh (Ghent University) [archisman.ghosh@ugent.be],
 Shrobana Ghosh (Cardiff University) [ghoshs9@cardiff.ac.uk],
 Andi Hektor (NICPB, Tallinn) [andi.hektor@cern.ch],
 Thomas Hertog (KU Leuven) [thomas.hertog@kuleuven.be],
 Gert Hütsi (NICPB, Tallinn) [gert.hutsi@to.ee],
 Keisuke Inomata (The University of Tokyo) [inomata@icrr.u-tokyo.ac.jp],
 Cristian Joana (University of Louvain) [cristian.joana@uclouvain.be]
 Kristjan Kannike (NICPB, Tallinn) [kristjan.kannike@cern.ch],
 Maxim Khlopov (APC Laboratory, France; MEPHI and SFEDU, Russia) [khlopov@apc.univ-paris7.fr]
 Kazunori Kohri (KEK, Sokendai and Kavli IPMU, Japan) [kohri@post.kek.jp]
 Ely D. Kovetz (Ben-Gurion University, Israel) [kovetz@bgu.ac.il]
 Florian Kühnel (LMU Munich, Germany) [florian.kuehnel@physik.uni-muenchen.de]
 Alberto Mariotti (Vrije Universiteit Brussel) [alberto.mariotti@vub.be]
 Luca Marzola (KBFI, Tallinn) [luca.marzola@cern.ch]
 Lucio Mayer (University of Zürich) [lmayer@physik.uzh.ch],
 Suvodip Mukherjee (University of Amsterdam) [s.mukherjee@uva.nl]
 Ilia Musco (IGFAE, University of Santiago de Compostela) [iliamusco@gmail.com]
 Germano Nardini (University of Stavanger) [germano.nardini@uis.no]
 Savvas Nesseris (Instituto de Fisica Teorica UAM-CSIC) [savvas.nesseris@csic.es]
 Cristiano Palomba (INFN Roma) [cristiano.palomba@roma1.infn.it]
 Paolo Pani (Sapienza University of Rome) [paolo.pani@uniroma1.it]
 Subodh P. Patil (Leiden University) [patil@lorentz.leidenuniv.nl]
 Marco Peloso (University of Padua) [marco.peloso@pd.infn.it]
 Khun Sang Phukon (Nikhef & University of Amsterdam) [k.s.phukon@nikhef.nl],
 Konstantin Postnov (Sternberg Astronomical Institute) [kpostnov@gmail.com],
 Stefano Profumo (University of California, Santa Cruz) [profumo@ucsc.edu]
 Martti Raidal (NICPB, Tallinn, Estonia) [martti.raidai@cern.ch]
 Antonio Riotto (University of Geneva) [Antonio.Riotto@unige.ch]
 Ester Ruiz Morales (Universidad Politécnica de Madrid) [ester.ruiz.morales@upm.es]
 Marco Scalisi (KU Leuven) [marco.scalisi@kuleuven.be]

Alexander Sevrin (Vrije Universiteit Brussel) [Alexandre.Sevrin@vub.be]
Alexander Kashlinsky (Goddard Space Flight Center) [alexander.kashlinsky@nasa.gov]
Joseph Silk (IAP/JHU) [silk@iap.fr]
Volodymyr Takhistov (UCLA) [vtakhist@physics.ucla.edu]
Gianmassimo Tasinato (Swansea University) [g.tasinato2208@gmail.com]
George Tringas (National Technical University of Athens) [georgiostringas@mail.ntua.gr]
Caner Unal (CEICO, Institute of Physics of the Czech Academy of Sciences) [unalx005@umn.edu]
Ville Vaskonen (King's College London) [ville.vaskonen@kcl.ac.uk]
Hardi Veermäe (NICPB, Tallinn, Estonia) [hardi.veermäe@cern.ch]
Vincent Vennin (APC Paris) [vincent.vennin@apc.in2p3.fr]
David Wands (University of Portsmouth) [david.wands@port.ac.uk]
Scott Watson (Syracuse University) [gswatson@syr.edu]
Misao Sasaki (Kavli IPMU, University of Tokyo)[misao.sasaki@ipmu.jp]
Shuichiro Yokoyama (KMI, Nagoya University)[shu@kmi.nagoya-u.ac.jp]
Lukasz Wyrzykowski (Astronomical Observatory, University of Warsaw, Poland) [lw@astrouw.edu.pl]
Yue Zhao (University of Utah) [zhaoyue@physics.utah.edu]
Miguel Zumalacarregui (Max Planck Institute for Gravitational Physics) [miguel.zumalacarregui@aei.mpg.de]