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Search for Subsolar Mass Ultracompact Binaries in Advanced LIGO’s Second Observing Run

B. P. Abbott et al.*

(LIGO Scientific Collaboration and the Virgo Collaboration)

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We present a search for subsolar mass ultracompact objects in data obtained during Advanced LIGO’s second observing run. In contrast to a previous search of Advanced LIGO data from the first observing run, this search includes the effects of component spin on the gravitational waveform. We identify no viable gravitational-wave candidates consistent with subsolar mass ultracompact binaries with at least one component between 0.2 \( M_\odot \) and 1.0 \( M_\odot \). We use the null result to constrain the binary merger rate of (0.2 \( M_\odot \), 0.2 \( M_\odot \)) binaries to be less than \( 3.7 \times 10^5 \) \( \text{Gpc}^{-3} \text{yr}^{-1} \) and the binary merger rate of (1.0 \( M_\odot \), 1.0 \( M_\odot \)) binaries to be less than \( 5.2 \times 10^3 \) \( \text{Gpc}^{-3} \text{yr}^{-1} \). Subsolar mass ultracompact objects are not expected to form via known stellar evolution channels, though it has been suggested that primordial density fluctuations or particle dark matter with cooling mechanisms and/or nuclear interactions could form black holes with subsolar masses. Assuming a particular primordial black hole (PBH) formation model, we constrain a population of merging 0.2 \( M_\odot \) black holes to account for less than 16\% of the dark matter density and a population of merging 1.0 \( M_\odot \) black holes to account for less than 2\% of the dark matter density. We discuss how constraints on the merger rate and dark matter fraction may be extended to arbitrary black hole population models that predict subsolar mass binaries.

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Introduction.—Gravitational-wave and multimessenger astronomy progressed remarkably in Advanced LIGO [1] and Advanced Virgo’s [2] second observing run, which included the first observation of gravitational waves from a binary neutron star merger [3] and seven of the ten observed binary black hole mergers [4–7]. These detections, as well as the candidates presented in the gravitational-wave transient catalog [7], have led to a better understanding of the populations of compact binaries detectable by ground based interferometers [8]. These observations, however, represent just a portion of the parameter space that Advanced LIGO and Advanced Virgo currently search [9,10] and are sensitive to [11].

We report on an extension of the parameter space in data obtained during O2 to compact binaries with component masses < 1 \( M_\odot \). To distinguish between other astrophysical compact objects (e.g., white dwarfs) that are not compact enough to form binaries that merge within LIGO’s sensitive frequency band, we label our target population as ultracompact. This is the second search for subsolar mass ultracompact objects in Advanced LIGO data and the fourth since initial LIGO [12–14], as well as the first search to incorporate spin effects into the modeling of the gravitational-wave emission.

There is no widely accepted mechanism for the formation of ultracompact objects with masses well below a solar mass within the standard model of particle physics and the standard \( \Lambda \) cold dark matter (\( \Lambda \)CDM) model of cosmology. Neutron stars are expected to have masses greater than the minimum Chandrasekhar mass [15] minus the gravitational binding energy. Calculations in Ref. [16] and more recently in Ref. [17] found the minimum mass of a neutron star to be 1.15 \( M_\odot \) and 1.17 \( M_\odot \), respectively. These predictions closely agree with the lowest currently measured neutron star mass of 1.17 \( M_\odot \) [18]. Similarly, black holes formed via established astrophysical collapse mechanisms are not expected to have masses below the maximum mass of a nonrotating neutron star, which recent pulsar timing observations [19] suggest is \( \sim 2 \) \( M_\odot \). We note that there is one model that predicts that rapidly rotating collapsing cores could fission and produce a neutron star binary [20,21], though this is not a favored astrophysical mechanism for the production of binary systems.

A detection of a subsolar mass object in a merger would therefore be a clear signal of new physics. Indeed, there are several proposals that link subsolar mass compact objects to proposals for the nature of dark matter, which makes up nearly 85\% of the matter in the Universe. One possibility is that black holes with masses accessible to ground based interferometers could have formed deep in the radiation era from the prompt collapse of large primordial overdensities on the scale of the early time Hubble volume [22,23]. The size and abundance of any such PBHs depends on the spectrum of primordial perturbations and on the equation of

*Full author list given at the end of the article.
An alternative inflationary mechanism proposes that vacuum bubbles nucleated during inflation may result in black holes (with masses that can be around a solar mass) after inflation ends [28]. A different class of possibilities, explored more recently, is motivated by ideas for the particle nature of dark matter. For example, dark matter may have a sufficiently complex particle spectrum to support cooling mechanisms that allow dense regions to collapse into black holes at late times, in processes analogous to known astrophysical processes [29]. Alternatively, dark matter may have interactions with nuclear matter that allow it to collect inside of neutron stars and trigger their collapse to black holes [30–36]. The details of when dark matter can collapse a neutron star to form a black hole or another exotic compact object are still under investigation [37], but the postulated black holes will have masses comparable to the progenitor neutron star mass, or perhaps smaller if some matter can be expelled by rapid rotation of the star during collapse.

A detection of a subsolar mass black hole would have far-reaching implications. In the PBH scenario, the mass and abundance of the black holes would constrain a combination of the spectrum of initial density perturbations on very small scales and the equation of state of the Universe at a time when the typical mass inside a Hubble volume was of the order of the black hole mass. For particle dark matter scenarios, the abundance of subsolar mass black holes would provide a direct estimate of the cooling rate for dark matter. The black hole mass would constrain the masses of cosmologically abundant dark matter particles through, for example, the Chandrasekhar relation for fermions [29] or analogous relations for noninteracting bosons [38,39]. In the case in which all black holes are observed to be near but not below the mass of neutron stars, the abundance of such objects would constrain the dark matter-nucleon interaction strength, as well as the dark matter self-interaction strength and mass(es) [36].

This Letter reports on the results of a search for gravitational waves from subsolar mass ultracompact binaries using data from Advanced LIGO’s second observing run. No significant candidates consistent with a subsolar mass binary were identified. The null result places the tightest constraints to date on the merger rate and the abundance of subsolar mass ultracompact binaries. We describe an extension of our merger rate constraints to arbitrary populations and models under the assumption that the horizon distance controls the sensitivity of the search. We once more consider the merger rate constraints in the context of merging PBH populations contributing to the dark matter [14]. We describe how to extend the dark matter fraction parametrization to other models by separating LIGO observables from model dependent quantities. Finally, we conclude with a discussion of the implications of this search.

Search.—We analyze data obtained from November 30, 2016, to August 25, 2017, during Advanced LIGO’s second observing run (O2) [40]. Noise artifacts are linearly subtracted from the data; this includes strong sinusoidal features in both detectors due to injected calibration frequencies and the ac power grid, as well as laser beam jitter in the LIGO-Hanford detector data [41]. We find that 117.53 days of coincident data remain after the application of data quality cuts [42–46]. The Advanced Virgo interferometer completed commissioning and joined Advanced LIGO in August 2017 for 15 days of triple coincident observations [7]; however, we report only on the analysis of data obtained by the LIGO Hanford and LIGO Livingston interferometers.

The search was conducted using publicly available gravitational-wave analysis software [47–53]. The initial stage of the search performed a matched-filter analysis using a discrete bank of template waveforms generated using the TaylorF2 frequency-domain, post-Newtonian inspiral approximant. This waveform was chosen since negligible power is deposited in the merger and ringdown portion of the waveform for low-mass systems [54]. The template bank used for this search was designed to recover binaries with component masses of 0.19 M⊙–2.0 M⊙ and total masses of 0.4 M⊙–4.0 M⊙ in the detector frame with 97% fidelity, as in Ref. [14]. The search presented here, however, additionally includes spin effects in the modeling of the gravitational waveform. The bank is constructed to recover gravitational waves originating from binaries with component spins purely aligned or antialigned with the orbital angular momentum, and with dimensionless spin magnitudes of 0.1 or less. The inclusion of spin effects required denser placement of the waveforms in the template bank; the resulting bank had 992,461 templates, which is nearly twice as large as the nonspinning bank used in Ref. [14].

In order to reduce the computational burden, matched filtering was performed only for a subset of Advanced LIGO’s full sensitive band [11]. The choice to only analyze the 45–1024 Hz band led to a detector averaged signal-to-noise ratio (SNR) loss of 8% when compared to the full ∼10–2048 Hz frequency band. This estimated SNR loss is a property of Advanced LIGO’s noise curves and is independent of the templates used in the search; the discrete nature of the template bank causes an additional ≥3% loss in SNR.

Gravitational-wave candidates that were found coincident in both the Hanford and Livingston detectors were ranked using the logarithm of the likelihood ratio, $L$ [47–49]. For a candidate with a likelihood ratio of $L^*$, we assign a false-alarm rate (FAR) of

$$\text{FAR}(\log L^*) = \frac{N}{T} P(\log L \geq \log L^* \mid \text{noise}),$$

where $N$ is the number of observed candidates, $T$ is the total live time of the experiment, and $P(\log L \geq \log L^* \mid \text{noise})$
describes the probability that noise produces a candidate with a ranking statistic at least as high as the candidate’s. The search recovered the previously detected signal GW170817 [3], which was observed along with an electromagnetic counterpart [55]. This signal is consistent with a binary neutron star. No other viable gravitational-wave candidates were identified. The next loudest candidate was identified by a template waveform with a chirp mass of 0.23 $M_\odot$ and a SNR of 9.5. The candidate was consistent with noise and assigned a FAR of 3.25 per year.

**Constraint on binary merger rate.**—As in Ref. [14], we consider nine populations of equal mass, nonspinning binaries that are $\delta$-function distributed in mass, i.e., $m_i \in \{0.2, 0.3, \ldots, 1.0\}$. We injected 913931 fake signals into our data; the injections were randomly oriented and spaced uniformly in distance and isotropically across the sky. The recovered signals provide an estimate of the pipeline’s detection efficiency as a function of source distance for each equal mass population. This in turn allows us to estimate the sensitive volume-time accumulated for each mass bin. We once more use the loudest event statistic formalism [56] to estimate the upper limit on the binary merger rate to 90% confidence,

$$R_i = \frac{2.3}{\langle VT \rangle_i}.$$  

These upper limits are shown for equal mass binaries and as a function of chirp mass in Fig. 1. Although our template bank includes systems with a total mass of up to 4 $M_\odot$, we place bounds on the merger rate of systems only where both components are $\leq 1 M_\odot$. We estimate that detector calibration uncertainties [7,57,58] and Monte Carlo errors lead to an uncertainty in our rate constraint of no more than 20%.

Advanced LIGO and Virgo’s horizon distance scales as

$D_{\text{horizon}} \propto M^{5/6} \sqrt{\int_{f_{\text{min}}}^{f_{\text{max}}} \frac{f^{-7/3}}{S_n(f)} df},$  

where $S_n(f)$ is the noise spectra of the detector and $f_{\text{min}}$ and $f_{\text{max}}$ are 45 and 1024 Hz, respectively [59]. For a null result, we therefore expect $R(M) \propto M^{-15/6}$ provided that the horizon distance controls the sensitivity of the search. The observed power law dependence of the rate constraint on the chirp mass is within $\sim$4% of the expected $M^{-15/6}$ dependence; this is well within the error bound on the rate upper limit and is strong evidence that the chirp mass is the primary parameter that dictates the sensitivity of the search. Therefore our upper limits from equal mass systems also apply to unequal mass systems within the range of mass ratios we have searched over. For verification, we performed a small injection campaign over five days of coincident data with injected component masses distributed between 0.19 $M_\odot$ and 2.0 $M_\odot$ with at least one component $<1.0 M_\odot$. The search sensitivity remained a function of the chirp mass; this implies that the rate constraints found from the equal mass injection sets can therefore be applied to systems with arbitrary mass ratios provided that both component masses lie within 0.20 $M_\odot$ and 1.0 $M_\odot$, where our injection sets were performed.

The Advanced LIGO and Virgo rate upper limit can be expanded as

$$R(M_1, M_2) = \int_{M_1}^{M_2} R(M) \times \psi(M) dM,$$  

where $R$ is the rate density as a function of chirp mass and $\psi(M)$ denotes the black hole population distribution in chirp mass. We ignore the effects of redshift due to the small detector range for subsolar mass binaries. Setting $\psi(M) = \delta(M)$ then reveals the form of the LIGO constraining rate density, $R(M)$, which is shown in Fig. 1. For a given model, $\psi(M)$, $R(M_1, M_2)$ provides the LIGO rate constraint on that model for chirp masses between $M_1$ and $M_2$. The resulting rate constraints allow direct comparison of subsolar mass ultracompact object models with LIGO observations.

**General constraints on subsolar mass black hole dark matter.**—We convert our limits on the merger rate of subsolar mass ultracompact objects into a constraint on the abundance of PBHs using our fiducial formation model [60] first developed in Refs. [23,61] and used previously in
LIGO analyses [12,14]. We consider a population of equal mass PBHs that is created deep in the radiation era. We model the binary formation via three-body interactions, though others have considered the full field of tidal interactions [62]. By equating the model’s predicted merger rate with the merger rate upper limit provided by Advanced LIGO and Virgo, we can numerically solve for the upper limit on the PBH abundance. These constraints are shown in Fig. 2 [63].

This interpretation is highly model dependent; the mass distribution, binary fraction, and binary formation mechanisms all have a large effect on the expected present day merger rate and consequently the bounds on the PBH composition of the dark matter. The Advanced LIGO and Virgo observables can be separated from the model dependent terms:

\[
f_{\text{CO}} = \frac{\rho_{\text{lim}}}{\rho_{\text{CDM}}} \times \frac{1}{f_{\text{obs}}} = \frac{\mathcal{R}(M_{\text{tot}}) T_{\text{obs}} M_{\text{tot}}}{M_{\text{PBH}}} \times \frac{1}{f_{\text{obs}}},
\]

where \(T_{\text{obs}}\) is the duration of the observation (in the analysis presented here, 117.53 days). Here we use \(f_{\text{CO}}\) to refer to the dark matter fraction in ultracompact objects instead of \(f_{\text{PBH}}\) to emphasize that this is generally applicable to other compact object models that could contribute to the dark matter [29], and not just PBHs. The first term, \(\rho_{\text{lim}}/\rho_{\text{CDM}}\), represents the upper limit on the fraction of the dark matter contained in presently merging subsolar mass ultracompact binaries. In the second term, \(f_{\text{obs}}\) describes the fraction of subsolar mass ultracompact objects that are observable by Advanced LIGO and Virgo for a particular model. This is set by the binary fraction and the probability density of binaries merging at present day. Note that the merger rate density must be converted from a function of chirp mass to total mass; this can be done by mapping to total mass for each mass ratio on an equal chirp mass curve.

Equation (5) applies to any dark matter model that predicts the formation of dark compact objects. The abundance of those dark compact objects can then be expressed as a fraction of the dark matter density.

**Conclusion.**—We presented the second Advanced LIGO and Advanced Virgo search for subsolar mass ultracompact objects. No unambiguous subsolar mass gravitational-wave candidates were identified. The null result allowed us to place tight constraints on the abundance of subsolar mass ultracompact binaries.

This work represents an expansion of previous initial and Advanced LIGO and Advanced Virgo subsolar mass searches. First, we broadened the searched parameter space to increase sensitivity to systems with non-negligible component spins. Second, we presented a method to extend our constraints on the binary merger rate to arbitrarily distributed populations that contain subsolar mass ultracompact objects. Combined with the existing rate limits, this may already be enough to begin constraining collapsed particulate dark matter models [29] or the cross section of nuclear interactions [30–34,36]. Finally, we provided a method to separate Advanced LIGO and Advanced Virgo observables from model dependent terms in our interpretation of the limits on PBH dark matter.

Ground based interferometer searches for subsolar mass ultracompact objects will continue to inform cosmological and particle physics scenarios. Advanced LIGO and Advanced Virgo began a yearlong observing run in early 2019, with improved sensitivities [70]. Advanced Virgo will have more coincident time with the Advanced LIGO detectors over its next observing run, which will improve network sensitivity and aid in further constraining the above scenarios.

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[39] Data from Advanced LIGO’s second observing run are available from the Gravitational Wave Open Science Center with and without noise sources linearly subtracted: https://www.gw-openscience.org.
[58] The waveform model used to generate our template bank, TaylorF2, truncates the waveform at an upper frequency \( f_{\text{ISCO}} \), which corresponds to radiation from the innermost stable circular orbit of a black hole binary with mass \( M_{\text{total}} \). This frequency is above \( f_{\text{max}} \) for all nonspinning waveforms in our template bank and thus does not impact \( D_{\text{horizon}} \).
The normalization of the PBH distribution used in our fiducial model [60] differs by a factor of 2 from the normalization in Ref. [23]. As such, our fiducial model (used here and in Ref. [14]) predicts a more conservative PBH merger rate and leads to less constraining limits on $f_{\text{PBH}}$ than would be attained using the model of Ref. [23].


LIGO Scientific Collaboration and the Virgo Collaboration

S. Shandera89

1LIGO, California Institute of Technology, Pasadena, California 91125, USA
2Louisiana State University, Baton Rouge, Louisiana 70803, USA
3Inter-University Centre for Astronomy and Astrophysics, Pune 411007, India
4Istituto Nazionale di Fisica Nucleare, Sezione di Pisa, I-56127 Pisa, Italy
5INFN, Sezione di Napoli, Complesso Universitario di Monte Sant’Angelo, I-80126 Napoli, Italy
6OzGrav, School of Physics and Astronomy, Monash University, Clayton 3800, Victoria, Australia
7LIGO Livingston Observatory, Livingston, Louisiana 70754, USA
8OzGrav, Australian National University, Canberra, Australian Capital Territory 0200, Australia
9Max Planck Institute for Gravitational Physics (Albert Einstein Institute), D-39166 Hannover, Germany
10Leibniz Universität Hannover, D-30167 Hannover, Germany
11Theoretisch-Physikalisches Institut, Friedrich-Schiller-Universität Jena, D-07743 Jena, Germany
12University of Cambridge, Cambridge CB2 1TN, United Kingdom
13University of Birmingham, Birmingham B15 2TT, United Kingdom
14LIGO, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA
15Instituto Nacional de Pesquisas Espaciais, 12227-010 São José dos Campos, São Paulo, Brazil
16Gran Sasso Science Institute (GSSI), I-67100 L’Aquila, Italy
17INFN, Laboratori Nazionali del Gran Sasso, I-67100 Assergi, Italy
18International Centre for Theoretical Sciences, Tata Institute of Fundamental Research, Bengaluru 560089, India
19NCSA, University of Illinois at Urbana–Champaign, Urbana, Illinois 61801, USA
20Università di Pisa, I-56127 Pisa, Italy
21INFN, Sezione di Pisa, I-56127 Pisa, Italy
22Departamento de Astronomía y Astrofísica, Universidad de València, E-46100 Burjassot, València, Spain
23Laboratoire des Matériaux Avancés (LMA), CNRS/IN2P3, F-69622 Villeurbanne, France
24University of Wisconsin–Milwaukee, Milwaukee, Wisconsin 53201, USA
25SUPA, University of Strathclyde, Glasgow G1 1XQ, United Kingdom
26APC, AstroParticule et Cosmologie, Université Paris Diderot, CNRS/IN2P3, CEAdrfu, Observatoire de Paris, Sorbonne Paris Cité, F-75205 Paris Cedex 13, France
27California State University Fullerton, Fullerton, California 92831, USA
28LAL, Université Paris–Sud, CNRS/IN2P3, Université Paris–Saclay, F-91898 Orsay, France

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86. The University of Mississippi, University, Mississippi 38677, USA
87. Missouri University of Science and Technology, Rolla, Missouri 65409, USA
88. Museo Storico della Fisica e Centro Studi e Ricerche “Enrico Fermi,” I-00184 Roma, Italy
89. The Pennsylvania State University, University Park, Pennsylvania 16802, USA
90. National Tsing Hua University, Hsinchu City, 30013 Taiwan, Republic of China
91. Charles Sturt University, Wagga Wagga, New South Wales 2678, Australia
92. Canadian Institute for Theoretical Astrophysics, University of Toronto, Toronto, Ontario M5S 3H8, Canada
93. University of Chicago, Chicago, Illinois 60637, USA
94. The Chinese University of Hong Kong, Shatin, New Territories, Hong Kong
95. Dipartimento di Ingegneria Industriale (DHIN), Università di Salerno, I-84084 Fisciano, Salerno, Italy
96. Seoul National University, Seoul 08826, Korea
97. Pusan National University, Busan 46241, Korea
98. Carleton College, Northfield, Minnesota 55057, USA
99. INAF, Osservatorio Astronomico di Padova, I-35122 Padova, Italy
100. Dipartimento di Fisica, Università degli Studi di Genova, I-16146 Genova, Italy
101. OzGrav, University of Melbourne, Parkville, Victoria 3010, Australia
102. Universitat de les Illes Balears, IAC3—IJEEC, E-07122 Palma de Mallorca, Spain
103. Université Libre de Bruxelles, Brussels 1050, Belgium
104. Sonoma State University, Rohnert Park, California 94928, USA
105. Departamento de Matemáticas, Universitat de València, E-46100 Burjassot, València, Spain
106. Columbia University, New York, New York 10027, USA
107. Cardiff University, Cardiff CF24 3AA, United Kingdom
108. University of Rhode Island, Kingston, Rhode Island 02881, USA
109. The University of Texas Rio Grande Valley, Brownsville, Texas 78520, USA
110. Bellevue College, Bellevue, Washington 98007, USA
111. MTA-ELTE Astrophysics Research Group, Institute of Physics, Eötvös University, Budapest 1117, Hungary
112. Institute for Plasma Research, Bhat, Gandhinagar 382428, India
113. The University of Shefield, Sheffield S10 2TN, United Kingdom
114. IGFAE, Campus Sur, Universidade de Santiago de Compostela, Santiago de Compostela 15782, Spain
115. Dipartimento di Scienze Matematiche, Fisiche e Informatiche, Università di Parma, I-43124 Parma, Italy
116. INFN, Sezione di Milano Bicocca, Gruppo Collegato di Parma, I-43124 Parma, Italy
117. Dipartimento di Ingegneria, Università del Sannio, I-82100 Benevento, Italy
118. Università di Trento, Dipartimento di Fisica, I-38123 Povo, Trento, Italy
119. INFN, Trento Institute for Fundamental Physics and Applications, I-38123 Povo, Trento, Italy
120. Università di Roma “La Sapienza,” I-00185 Roma, Italy
121. Colorado State University, Fort Collins, Colorado 80523, USA
122. Kenyon College, Gambier, Ohio 43022, USA
123. Christopher Newport University, Newport News, Virginia 23606, USA
124. CNR-SPIN, c/o Università di Salerno, I-84084 Fisciano, Salerno, Italy
125. Scuola di Ingegneria, Università della Basilicata, I-85100 Potenza, Italy
126. National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan
127. Observatori Astronòmic, Universitat de València, E-46980 Paterna, València, Spain
128. INFN Sezione di Torino, I-10125 Torino, Italy
129. School of Mathematics, University of Edinburgh, Edinburgh EH9 3FD, United Kingdom
130. Institute of Advanced Research, Gandhinagar 382426, India
131. Indian Institute of Technology Bombay, Powai, Mumbai 400 076, India
132. University of Szeged, Dóm tér 9, Szeged 6720, Hungary
133. SUPA, University of the West of Scotland, Paisley PA1 2BE, United Kingdom
134. California State University, Los Angeles, 5151 State University Drive, Los Angeles, California 90032, USA
135. Universität Hamburg, D-22761 Hamburg, Germany
136. Tata Institute of Fundamental Research, Mumbai 400005, India
137. INAF, Osservatorio Astronomico di Capodimonte, I-80131 Napoli, Italy
138. University of Michigan, Ann Arbor, Michigan 48109, USA
139. Washington State University, Pullman, Washington 99164, USA
140. American University, Washington, D.C. 20016, USA
141. University of Portsmouth, Portsmouth PO1 3FX, United Kingdom
142. University of California, Berkeley, California 94720, USA
143. GRAPPA, Anton Pannekoek Institute for Astronomy and Institute for High-Energy Physics, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, Netherlands
144. Delta Institute for Theoretical Physics, Science Park 904, 1090 GL Amsterdam, Netherlands