Dark Matter Searches in Gravitational Waves

Bird, IC, Munoz, Ali-Haimoud, Kamionkowski, Kovetz, Raccanelli and Riess (JHU) PRL 116.201031,
IC, Kovetz, Ali-Haimoud, Bird, Kamionkowski, Munoz,
Raccanelli PRD 94 084013
Raccanelli, Kovetz, Bird, IC, Munoz PRD 94 023516
Mandic, Bird, IC PRL 117.201102, IC JCAP 06 037 2017
Kovetz, IC, Breysse, Kamionkowski PRD 95 103010

Towards Dark Matter Discovery

Kovetz, IC, Kamionkowski, Silk
arXiv: 1803.00568

Ilias Cholis 04/11/2018
Signals of thermal DM

- Production (accelerators)
- Cosmic rays/indirect detection (PAMELA/Fermi/Planck...)
- Direct detection (DAMA/XENON/CDMS...)

Direct Detection scattering off normal matter, Xe, Ar, Ge, Si:

Dark matter production at colliders

Indirect detection: annihilation into gamma-rays, cosmic rays, neutrinos
What about Gravitational Waves?

Two black holes coalescing

LISA (future searches in space)

VIRGO (Italy)

LIGO (WA)

LIGO (LA)

Signals of thermal DM

- Production (accelerators)
- Cosmic rays/indirect detection (PAMELA/Fermi/WMAP...)
- Direct detection (DAMA/XENON/CDMS...)

Direct Detection scattering off normal matter, Xe, Ar, Ge, Si:

Dark matter production at colliders

LHC

AMS

Fermi

HESS

PAMELA

Planck

LUX

CDMS

Indirect detection: annihilation into gamma-rays, cosmic rays, neutrinos

Searches for Particle Dark Matter
The GW150914 event

- Hanford, Washington (H1)
  - Strain (10^{-21})
  - H1 observed
  - Numerical relativity
  - Reconstructed (wavelet)
  - Reconstructed (template)
  - Residual

- Livingston, Louisiana (L1)
  - L1 observed
  - H1 observed (shifted, inverted)
  - Numerical relativity
  - Reconstructed (wavelet)
  - Reconstructed (template)
  - Residual

- 8 peaks → 4 rotations

- \( m_1 = 36^{+5}_{-4} M_\odot \)
- \( m_2 = 29^{+4}_{-4} M_\odot \)
- \( m_{final} = 62^{+4}_{-4} M_\odot \)
- \( z_s = 0.09^{+0.03}_{-0.04} \)
Different estimates on the coalescence rates come from different astrophysical assumptions
Different estimates on the coalescence rates come from different astrophysical assumptions.

### TABLE II. Rates of BBH mergers based on populations with masses matching the observed events, and astrophysically motivated mass distributions. Rates inferred from the PyCBC and GstLAL analyses independently as well as combined rates are shown. The table shows median values with 90% credible intervals.

<table>
<thead>
<tr>
<th>Mass distribution</th>
<th>PyCBC</th>
<th>GstLAL</th>
<th>Combined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Event based</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GW150914</td>
<td>3.2^{+8.3}_{-2.7}</td>
<td>3.6^{+9.1}_{-3.0}</td>
<td>3.4^{+8.6}_{-2.8}</td>
</tr>
<tr>
<td>LVT151012</td>
<td>9.2^{+30.3}_{-8.5}</td>
<td>9.2^{+31.4}_{-8.5}</td>
<td>9.4^{+30.4}_{-8.7}</td>
</tr>
<tr>
<td>GW151226</td>
<td>35^{+92}_{-29}</td>
<td>37^{+94}_{-31}</td>
<td>37^{+92}_{-31}</td>
</tr>
<tr>
<td>All</td>
<td>53^{+100}_{-40}</td>
<td>56^{+105}_{-42}</td>
<td>55^{+99}_{-41}</td>
</tr>
<tr>
<td>Astrophysical</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Flat in log mass</td>
<td>31^{+43}_{-21}</td>
<td>30^{+43}_{-21}</td>
<td>30^{+43}_{-21}</td>
</tr>
<tr>
<td>Power Law (−2.35)</td>
<td>100^{+136}_{-69}</td>
<td>95^{+138}_{-67}</td>
<td>99^{+138}_{-70}</td>
</tr>
</tbody>
</table>

DM?
Making a connection with DM

Bird, IC, Munoz, Ali-Haimoud, Kamionkowski, Kovetz, Raccanelli and Riess (JHU) PRL 116.201031

Assuming Dark Matter is composed by Primordial BHs.

There is some allowed parameter space around ~20-70 $M_\odot$

Qüinn et al.
arXiv:0903.1644
MNRAS 2009
Making a connection with DM

Bird, IC, Munoz, Ali-Haimoud, Kamionkowski, Kovetz, Raccanelli and Riess (JHU) PRL 116.201031

Assuming Dark Matter is composed by Primordial BHs.

There is some allowed parameter space around ~20-70 $M_\odot$

For the remainder I will assume that all DM is composed of PBHs and set their mass to 30 $M_\odot$

Limits on spectral distortions of the CMB are efficient above 100 $M_\odot$

Ali-Haimoud & Kamionkowski (1612.05644)

Limits from GC in dwSphs (e.g. Eridanus II) (Tim Brandt arXiv:1605.03662) are robust below 15$M_\odot$.

Limits from micro-lensing of macro-lensed quasars depend on the DM profile and vel. dips. prof.
How fast do two BHs form a binary?

\[ \sigma = 2^{3/7} \pi \left( \frac{85 \pi}{6 \sqrt{2}} \right)^{2/7} R_s^2 \left( \frac{\nu}{c} \right)^{-18/7} \]

How fast do two BHs form a binary?

\[
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\]


Assuming an NFW profile for the PBHs:

\[
\rho_{NFW}(r) = \frac{\rho_0}{(r/R_s) \cdot (1 + r/R_s)^2}
\]

One gets a Rate of PBHs mergers:

\[
\mathcal{R} = 4\pi \int_0^{R_{\text{vir}}} r^2 \frac{1}{2} \left( \frac{\rho_{\text{nfw}}(r)}{M_{\text{pbh}}} \right)^2 \langle \sigma v_{\text{pbh}} \rangle \, dr
\]
After including information regarding the different DM halos properties (concentration, and velocity dispersions) and effects on the smallest DM halos:

\[
\frac{dn}{dM} \sim 10^{-3} Gpc^{-3} yr^{-1}
\]

\[
M_{\text{vir}} (M_\odot / h)
\]

\[
Ludlow concentration
Prada concentration
Press-Schechter m.f.
Jenkins m.f.
\]

S. Bird, IC, J. Munoz et al. (2016)
The halo mass function. The total merger rate per unit LIGO are relatively low we will neglect redshift evolution
volve the merger rate increases significantly as the halo mass is decreased. virialized earlier), so that the merger rate per unit mass higher concentration (since they are more likely to have
PBH merger rate. However, less massive halos have a results. An increase in halo mass produces an increased Eq. (8), for two concentration-mass relations. As can
to the rate of binary BH formation, Eq. (8).

The characteristic time it takes for a binary BH to merge can be obtained from Ref. [29]) is less than a Hubble time. This formation mechanism should not af-
ries that will not be able to harden and merge within a
but they generically lead to the formation of wide bina-
dissipative three-body encounters. The rate of these bi-
we can neglect disruption of the binary by a third PBH
the small size of the binary, and rapid time to merger,
is thus instantaneous on cosmological timescales. Given
hours for
varies as a function of halo velocity dispersion. It can be
Once formed. BH binaries can also form through non-
formed will grow continuously through mergers or accre-
tice, during matter domination, halos which have already
and the evaporation timescale is [33] objects by dynamical relaxation processes. The evapora-
smallest halos will evaporate due to periodic ejection of

does not a
the final result.
Given the exponential fallo
for the concentration-mass relation and halo mass function.

To compute the expected LIGO event rate, we con-
Fig. 1 shows the contribution to the merger rate,

To guide the eye, the dot-dashed line
concentration-mass relation from Ref. [27], and the dashed

FIG. 1. The PBH merger rate per halo as a function of

The halo mass function

S. Bird, IC, J. Munoz et al. (2016)
By 2019 the sensitivity will have increased to $z \sim 1$

We expect 100s of events from PBHs (if they compose 100% of DM) by 2025.

All will be in a narrow mass range around 30 solar masses.

No other EM or neutrino signals. (typical though given that BH-BH give GW only)

Following the DM distribution (need better angular resolution though).

Basic Uncertainties in the rate calculation:
DM profile (factor of $\sim 3$)
Mass-Concentration relationship (factor of $\sim 3$)
Sub-halo contribution (previous slide) and discreteness of smallest halos.

Also work from:
S. Class and J. Garcia-Bellido (Phys. Dark Univ. 15 2017) for many mergers leading to generations of PBHs,
H. Nishikawa et al. 2017 on the enhancement from possible DM spikes.
Primordial black hole scenario for the gravitational wave event GW150914

Misao Sasaki\textsuperscript{a}, Teruaki Suyama\textsuperscript{b}, Takahiro Tanaka\textsuperscript{c}, and Shuichiro Yokoyama\textsuperscript{d}

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\textsuperscript{b} Research Center for the Early Universe (RESCEU), Graduate School of Science, The University of Tokyo, Tokyo 113-0033, Japan
\textsuperscript{c} Department of Physics, Kyoto University, Kyoto 606-8502, Japan
\textsuperscript{d} Department of Physics, Rikkyo University, Tokyo 171-8501, Japan

Abstract

We point out that the gravitational wave event GW150914 observed by the LIGO detectors can be explained by the coalescence of primordial black holes (PBHs). It is found that the expected PBH merger rate would exceed the rate estimated by the LIGO scientific collaboration and Virgo collaboration if PBHs were the dominant component of dark matter, while it can be made compatible if PBHs constitute a fraction of dark matter. Intriguingly, the abundance of PBHs required to explain the suggested lower bound on the event rate, $> 2$ events/year/Gpc$^3$, roughly coincides with the existing upper limit set by the non-detection of the CMB spectral distortion. This implies that the proposed PBH scenario may be tested in the not-too-distant future.
All PBH form binaries form early on (~ matter radiation equality or earlier):

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{plot.png}
\caption{Characteristic decoupling redshift of PBH binaries.}
\label{fig:decoupling}
\end{figure}
~All PBH form binaries form early on (~ matter radiation equality or earlier):

FIG. 5. PBH binary merger rate, as a function of PBH fraction $f_{\text{pbh}}$ and mass $m = M/M_\odot$. 

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**FIG. 5. PBH binary merger rate, as a function of PBH fraction $f_{\text{pbh}}$ and mass $m = M/M_\odot$.**

**Large Uncertainties pertaining to the i) formation of the first DM halos and how they affect the binaries and ii) impact of gas accreted into the BH binaries (especially circum-binary disks)**

**FIG. 7. Potential upper bounds on the fraction of dark matter in PBHs as a function of their mass, derived in this paper (red arrows), and assuming a narrow PBH mass function. These bounds need to be confirmed by numerical simulations. For**
How to differentiate DM BH binaries from regular astrophysical BH-BH binaries with future observations.
I) Orbital properties of DM PBH binaries

When these binaries form they have **high initial eccentricities and small peri-center distances**:

\[
M_{\text{vir}} = 10^{12} \left( \frac{M}{h} \right) \quad M_{\text{vir}} = 10^{9} \left( \frac{M}{h} \right) \quad M_{\text{vir}} = 10^{6} \left( \frac{M}{h} \right)
\]

PDF of initial eccentricity \(e_0\) for PBH binaries

PDF of pericenter distance at formation for PBH binaries

\[
(1 - e_0)^{\text{peak}} \simeq 2.6 \xi \eta^{2/7} \left( \frac{w}{c} \right)^{10/7} \quad \xi \simeq 1, \eta = 1/4 \quad \text{for equal BH masses}
\]

\[
w \simeq 2/20/200 \text{ km/s}
\]

IC, Kovetz, Ali-Haimoud, Bird, Kamionkowski, Munoz and Raccanelli
PRD 94 084013
Which in turn have dramatically different timescales until merger:

\[
\tau_m = \frac{3}{85} \frac{a_0^4}{m_{tot}^3 \eta} (1 - e_0)^{7/2}
\]

By the time of LIGO observation fully circularized.
**An outlier!**

**simplified noise (LIGO final design)**

- Binary BHs, $m_1=m_2=30\,M_\odot$
- Strain Amplitude $h_c$ for $\alpha=0.67$, $z=0.09$, $e=0$

**IC, Kovetz, Ali-Haimoud et al. PRD 2016**

- Inspiral (last 1 sec)
- Merger (9 ms)
simplified noise (LIGO final design)

An outlier! See many more modes of grav. waves.

IC, Kovetz, Ali-Haimoud et al. PRD 2016
With LIGO we expect O(1) events while with the Einstein Telescope we expect O(10) events with multiple modes detected from PBH binaries.

Other astrophysical mechanisms for Binary BHs have typical time-scales of evolution that is ~Myrs-Gyrs.
II) Combining space and ground-based observations

With Future LISA we will also be able to trace back some PBH systems to earlier stages (days-years before the merger event) and thus observe the binaries at even higher eccentricities. That is true for all progenitor models.
III) The stochastic GW background

There are many more too distant or not powerful enough to be resolved above the threshold. These create a “stochastic” grav. wave background.

\[ \Omega_{GW} = \frac{f}{\rho_c} \frac{d \rho_{GW}}{df} \quad \text{← energy density between } f \text{ and } f + df \]

Measuring the stock. back will probe the GW sources and it is a measurable quantity within the next 5-10 years.
Rates on the BH-BH mergers
(some room a PBH component to be seen in the Stoch. Background)

Mandic, Bird, IC (PRL 117.201102) & Cholis (JCAP 06 037 2017)

With Einstein Telescope will be able to probe the PBHs.
IV) Far future direction: Cross-Correlations with Galaxies
IV) Far future direction: Cross-Correlations with Galaxies

If the GW signal comes from BHs originating by standard astrophysical sources e.g. BH in globular clusters, then the binary systems should preferentially reside in galaxies where most of the stars are. So GW and star forming galaxy (SFG) maps would be highly correlated.

If the GW signal comes from PBHs that constitute the DM then their distribution will be more uniform on the sky.

Forecasted Cross-correlation amplitude of of Galaxies with BH-BH mergers. PBH binaries have a smaller bias $b$ (~0.5) compared to stellar BHs (since the PBH rate is dominated by the smallest DM halos)
V) Understanding the Black Holes Mass Function

Early 2017

- Conv. theor. $P_{\text{BH}}(M_1)$
- Measured BHs
- MW BHs (X-rays)
- LG BHs (X-rays)
- Cosm. BHs (GWs)
Understanding the Black Holes mass-function can lead to understanding the progenitors of the Binary BH systems.
A future possible indication for PBH: Mass-Spectrum of BH-BH binaries

Kovetz, IC, Breysse, Kamionkowski PRD 2017

Binned Mass distribution of BBHs: Astrophysical

aLIGO BBH: ~ 2700
aLIGO PBH: ~ 280
aLIGO TOT: ~ 3000
With aLIGO design sensitivity

2D Binned Mass Distribution of BBH Mergers: $\beta = 0$

PBH & LIGO Best Sen.

Very Massive Events: probe astrophysical alternatives

Kovetz, IC, Breysse, Kamionkowski PRD 2017
An Astrophysical Alternative: The Centers of Globular Clusters

Six Observed Globular Clusters of the Milky Way:

Kovetz, IC, Kamionkowski, Silk arXiv:1803.00568
If GCs are the birthplaces of merging BHs—> GWs, then for a ~10% of these systems we expect to have a runaway process.

Kovetz, IC, Kamionkowski, Silk, arXiv: 1803.00568
IC, Kovetz, Kamionkowski in prep 2018

**Slowest:**

**Most Fast:**
Binned 1D Mass distribution of BBHs: Astrophysical + IMBH

Kovetz, IC, Kamionkowski, Silk arXiv:1803.00568
Multi-Messenger Approach
I) The gravitational lens is not a smooth field but is composed of many smaller discrete lenses.

II) The chance of getting lensed is \( \sim 10\% \) (for \( z \sim 1 \)). Most rays will find no lens \( \rightarrow \) No magnification.
Constraints on PBHs From Lensing of Type Ia SN

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Some will pass by a PBH lens and have significant magnification.
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Some will pass by a PBH lens and have significant magnification.

Change in the **magnification PDF** from SNe Type Ia. We have 100s of observations, thus can derive limits.

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**Figure 1:**

- **Maximum near empty beam**
- **Magnification tail** \( \propto \Delta \mu^{-3} \)

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- SNe lensing (this work)
- EROS
- Planck (phot.)
- Planck (coll.)
- Reichardt

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**Zumalacarregui & Seljak arXiv:1712.02240**
Other ideas on how to constrain PBH DM:

- Microlensing near caustic crossings

Venumadhav, Dai, Miralda-Escude (arXiv:1707.00003)

Radio and X-ray emission from gas accretion in the Galactic Center

D. Gaggero, G. Bertone, F. Calore et al. PRL 2017

FIG. 2. Example of the distribution of 30 $M_\odot$ PBHs detectable by VLA in the ROI, for one Monte Carlo realization. The colored background depicts the column gas density. The size of the black points is proportional to the PBH velocity in the range 0.3 – 3 km/s (for detectable PBHs).

Munoz, Kovetz, Dai, Kamionkowski PRL 2016
FIG. 4. Sketch displaying the expected limits for future GW experiments as well as the stochastic GW background for various astrophysical and cosmological processes. The mauve band corresponds to the expectations for the PBH-DM model considered in this paper, where PBH are regrouped in dense sub-halos, for merging rates consistent with the ones inferred by AdvLIGO, and for PBH masses in the range $10^{2} < m_{PBH} < 100 M_{\odot}$. For comparison, the green band represents the region covered by the model of Bird et al. [4] extrapolated to lower frequencies. Our model allows to consider a broad mass spectrum and larger merging rates and as a result, the amplitude of the stochastic GW background can reach the level of detectability of SKA and LISA.

obtained using the GWPlotter tool [42], http://rhcole.com/apps/GWplotter/

Clesse & Garcia-Bellido (Phys. Dark Univ. 18 2017)
The future of GWs

The LIGO-VIRGO network

Factors are largely common between two similar detectors, so the time difference between the two detectors is relatively uncorrelated with these nuisance parameters.

The triangulation approach underestimates how well a source can be localized, since it does not include all the relevant information. Its predictions can be improved by introducing the requirement of phase consistency between detectors. Triangulation always performs poorly for a two-detector network, but, with the inclusion of phase coherence, can provide an estimate for the average performance of a three-detector network.

Source localization using only timing for a two-site network yields an annulus on the sky; see Figure 4. Additional information such as signal amplitude, spin, and precession effects resolve this to only parts of the annulus, but even then sources will only be localized to regions of hundreds to thousands of square degrees.

An example of a two-detector BNS localization is shown in Figure 5. The posterior probability distribution is primarily distributed along a ring, but this ring is broken, such that there are clear maxima.

For three detectors, the time delays restrict the source to two sky regions which are mirror images with respect to the plane passing through the three sites. It is often possible to eliminate one of these regions by requiring consistent amplitudes in all detectors. For signals just above the detection threshold, this typically yields regions with areas of several tens to hundreds of square degrees. Additionally, for BNSs, it is often possible to obtain a reasonable estimate of the distance to the source, which can be used to further aid electromagnetic observations.

If there is significant difference in sensitivity between detectors, the source is less well localized and we may be left with the majority of the annulus on the sky determined by the two most sensitive.

We do not intend to produce timing-only sky maps, but timing triangulation can be useful for order-of-magnitude estimates of sky-localization accuracy averaged across the population of signals.
Observational Outlook: Experiment Timeline

Experiment | 2015 | 2020 | 2025 | 2030 | beyond
---|---|---|---|---|---
aLIGO (O1+) |   |   |   |   |   
aLIGO (design) |   |   |   |   |   
ET |   |   |   |   |   
DECIGO |   |   |   |   |   
(e)LISA |   |   |   |   |   
BBO |   |   |   |   |   

And the next decades

Voyager & Cosmic Explorer
Conclusions

- Taking the first detection of GWs we can make a connection to a long standing problem, the nature of dark matter (assuming it is BHs produced at the Early Universe).

- The rate that these BHs merge currently is of the same order of magnitude as the one observed (it could have been many orders of magnitude off).

- These can be very short-lived systems (shorter than this presentation). Thus with properties very unique and Testable! in the next ~decade.

- One can also search for a signal in the mass-spectrum of observed BHs in the next ten years and even derive limits on PBHs from GWs.

- We can also search for a signal in the overall GW emission, testable with the next generation of detectors (2030s).

- Make a connection with other observables as is the distributions of galaxies (2030s++).

- Ask more general questions regarding what are the sources of the GWs and what can we learn in terms of these astrophysical systems.

- A GREAT NEW PROBE TO STUDY THE COSMOS : A NEW INDIRECT DM PROBE.
Thank you!
Constraining MACHO Dark Matter: FRB Lensing
(Muñoz, EDK, Dai, Kamionkowski, PRL 117 (2016))
The observables?

Illustration: J. Muñoz

Flux ratio \( \frac{F_1}{F_2} = g(y) \) \( \rightarrow \) \( y < y_{\text{max}} \) (both images need be detectable)

Time delay \( \Delta t = 4M_L f(y) \sim 1 \text{ ms} \times \frac{M_L}{30 M_\odot} \) \( \rightarrow \Delta t_{\text{int}} \) \( y > y_{\text{min}}(M_L, z_s) \)
Constraining MACHO Dark Matter: FRB Lensing
(Muñoz, EDK, Dai, Kamionkowski, PRL 117 (2016))

CHIME experiment: expected rate of $O(10^4)$ FRBs per year

$$N_{\text{lensed}} = \tau N_{\text{FRB}} \quad \tau \sim 1\% \quad N_{\text{lensed}} = 10 - 100 \text{ yr}^{-1}$$

A null detection will close the “window”:

![Graph showing expected rate of FRBs per year and the window closing with time.]
Other ideas on how to constrain PBH DM:

Microlensing near caustic crossings

Radio and X-ray emission from gas accretion in the Galactic Center

FIG. 2. Example of the distribution of 30 $M_\odot$ PBHs detectable by VLA in the ROI, for one Monte Carlo realization. The colored background depicts the column gas density. The size of the black points is proportional to the PBH velocity in the range $0.3 - 3$ km/s (for detectable PBHs).

D. Gaggero, G. Bertone, F. Calore et al. PRL 2017