Gravitational waves from Massive PBH as Dark Matter and Models of Inflation

based on JGB & Ruiz Morales, arXiv:1702.03901
JGB, M. Peloso & C. Unal, JCAP 12 (2016) 031
S. Clesse & JGB, Phys Dark Univ 10 (2016) 002

Juan García-Bellido
3rd March 2017
Happy 69th Birthday Andrei!
Outline

• Discovery of 3 BBH by aLIGO-O1 started a new era of GW Astronomy
• Propose Massive PBH as the main component of Dark Matter
• Specific signatures of PBH
• Future: Testing the idea with astro-cosmological observations
• Conclusions
Merging Binary BHs @ LIGO

September 14, 2015
CONFIRMED

October 12, 2015
CANDIDATE

December 26, 2015
CONFIRMED

LIGO’s first observing run
September 12, 2015 - January 19, 2016

Black Holes of Known Mass

LIGO

X-Ray Studies

GW150914

GW151226

LVT151012
\[ f_{ISCO} = 4400 \, \text{Hz} \left( \frac{M_{\odot}}{M} \right) \]
## Parameters of aLIGO BH Binaries

<table>
<thead>
<tr>
<th>Detector frame</th>
<th>GW150914</th>
<th>GW151226</th>
<th>LVT151012</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total mass M/M_☉</strong></td>
<td>71.0±4.6</td>
<td>23.6±8.0</td>
<td>45.1±17</td>
</tr>
<tr>
<td>**Chirp mass ( M_c ) /M_☉</td>
<td>30.4±3.3</td>
<td>9.71±0.07</td>
<td>18.1±1.3</td>
</tr>
<tr>
<td>**Primary mass ( m_1 ) /M_☉</td>
<td>40.2±5.2</td>
<td>15.3±3.8</td>
<td>29.2±23</td>
</tr>
<tr>
<td>**Secondary mass ( m_2 ) /M_☉</td>
<td>30.6±5.1</td>
<td>8.3±2.5</td>
<td>15.5±5</td>
</tr>
<tr>
<td>**Final mass ( M_f ) /M_☉</td>
<td>67.8±3.6</td>
<td>22.5±1.4</td>
<td>43.1±4</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source frame</th>
<th>GW150914</th>
<th>GW151226</th>
<th>LVT151012</th>
</tr>
</thead>
<tbody>
<tr>
<td>**Total mass ( M_{\rm source} ) /M_☉</td>
<td>65.5±4.4</td>
<td>21.6±7.4</td>
<td>38.7±15</td>
</tr>
<tr>
<td>**Chirp mass ( M_{\rm chirp} ) /M_☉</td>
<td>28.1±2.1</td>
<td>8.87±0.35</td>
<td>15.1±1.5</td>
</tr>
<tr>
<td>**Primary mass ( m_{1\rm source} ) /M_☉</td>
<td>37.0±4.9</td>
<td>14.0±3.5</td>
<td>24.3±7</td>
</tr>
<tr>
<td>**Secondary mass ( m_{2\rm source} ) /M_☉</td>
<td>28.3±3.9</td>
<td>7.5±2.6</td>
<td>13.4±3</td>
</tr>
<tr>
<td>**Final mass ( M_{\rm source} ) /M_☉</td>
<td>62.5±3.9</td>
<td>20.6±7.6</td>
<td>36.1±15</td>
</tr>
<tr>
<td>**Energy radiated ( E_{\rm rad} / (M_☉c^2) )</td>
<td>2.98±0.40</td>
<td>1.02±0.24</td>
<td>1.48±0.39</td>
</tr>
</tbody>
</table>

| Mass ratio **q** | 0.77±0.20 | 0.54±0.40 | 0.53±0.42 |
| Effective inspiral spin \( \chi_{\rm eff} \) | -0.08±0.17 | 0.21±0.24 | 0.06±0.31 |
| Primary spin magnitude \( a_1 \) | 0.33±0.30 | 0.42±0.37 | 0.31±0.46 |
| Secondary spin magnitude \( a_2 \) | 0.62±0.35 | 0.51±0.42 | 0.49±0.48 |
| Final spin \( \eta \) | 0.68±0.05 | 0.73±0.06 | 0.65±0.09 |

| Luminosity distance \( D_L /\text{Mpc} \) | 400±160 | 450±180 | 1000±540 |
| Source redshift \( z \) | 0.086±0.031 | 0.096±0.035 | 0.198±0.092 |

### Upper bound
- Primary spin magnitude \( a_1 \): 0.62
- Secondary spin magnitude \( a_2 \): 0.93

### Lower bound
- Mass ratio \( q \): 0.62

### Log Bayes factor \( \ln \mathcal{R}_{\nu} \)
- 287.7±0.1
- 59.5±0.1
- 22.8±0.2

### Information criterion DIC
- 32977.2±0.3
- 34296.4±0.2
- 94695.8±0.0
<table>
<thead>
<tr>
<th>Mass distribution</th>
<th>( R/(\text{Gpc}^{-3}\text{yr}^{-1}) )</th>
<th>( \text{PyCBC} )</th>
<th>( \text{GstLAL} )</th>
<th>( \text{Combined} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{Event based} )</td>
<td></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>
<td></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>
<td></td>
</tr>
<tr>
<td>GW151226</td>
<td>( 35^{+92}_{-29} )</td>
<td>( 37^{+94}_{-31} )</td>
<td>( 37^{+92}_{-29} )</td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>( 53^{+100}_{-40} )</td>
<td>( 56^{+105}_{-42} )</td>
<td>( 55^{+99}_{-41} )</td>
<td></td>
</tr>
<tr>
<td>( \text{Astrophysical} )</td>
<td></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>
<td></td>
</tr>
<tr>
<td>Power Law ((-2.35))</td>
<td>( 100^{+136}_{-69} )</td>
<td>( 95^{+138}_{-67} )</td>
<td>( 99^{+138}_{-70} )</td>
<td></td>
</tr>
</tbody>
</table>

**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.
The second Advanced LIGO run began on November 30, 2016 and is currently in progress.

As of January 23rd 2017 approximately 12 days of Hanford-Livingston coincident science data have been collected, with a scheduled break between December 22, 2016 and January 4, 2017.

The average reach of the LIGO network for binary merger events have been around 70 Mpc for 1.4+1.4 Msun, 300 Mpc for 10+10 Msun and 700 Mpc for 30+30 Msun mergers, with relative variations in time of the order of 10%.

So far, 2 new event candidates, identified by online analysis using a loose false-alarm-rate threshold of one per month, have been identified and shared with astronomers who have signed memoranda of understanding with LIGO and Virgo for electromagnetic followup.

A thorough investigation of the data and offline analysis are in progress; results will be shared when available.”
Gravitational Wave Astronomy

• Discovery of binary BHs by AdvLIGO
• VIRGO, KAGRA, INDIGO = GW Astron
• GW150914 = 36 + 29 $M_{\text{sun}}$ BH binary
• GW151226 = 14 + 8 $M_{\text{sun}}$ BH binary
• LVT151012 = 23 + 13 $M_{\text{sun}}$ “candidate”
• Expected 50-100 events/yr/Gpc$^3$
• AdvLIGO+ can map the mass and spin

Massive BH ($1 \, M_{\text{sun}} < M_{\text{BH}} < 150 \, M_{\text{sun}}$)

n.b. $f_{\text{ISCO}} = 4400 \, \text{Hz} \left( M_{\text{sun}} / M_{\text{BH}} \right)$
Massive Primordial Black Holes as DM
Density perturbations and black hole formation in hybrid inflation

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The resulting density inhomogeneities lead to a copious production of black holes.

...quantum fluctuations at the time corresponding to the phase transition between the two inflationary stages can... for certain values of parameters these black holes may constitute the dark matter in the Universe.

these models can be made extremely small, but in general it could be sufficiently large to have important cosmological and astrophysical implications. In particular, for certain values of parameters these black holes may constitute the dark matter in the Universe. It is also possible to have hybrid models with two stages of inflation where the black hole production is not suppressed, but where the typical masses of the black holes are very small. Such models lead to a completely different thermal history of the Universe, where postinflationary reheating occurs via black hole evaporation... PACS number(s): 98.80.Cq
Steven Weinberg

“our problem is not that we take our theories too seriously, but that we don't take them seriously enough”
These PBHs could have acquired large stellar masses today, via merging, the model passes both the constraints from CMB distortions and microlensing. the tail of the PBH mass distribution could be responsible for the seeds of supermassive black holes at the center of galaxies, as well as for ultraluminous x-ray sources.
Moreover, PBH binaries should emit gravitational waves that could be detected by future gravitational wave experiments such as LIGO, DECIGO and eLISA [70,71].

Binaries of PBHs forming a fraction of dark matter should emit gravitational waves; this results in a background of gravitational waves that could be observed by LIGO, DECIGO and eLISA [70–72].
What models of Inflation produce PBH
Potential

$V(\phi)$

Inflection point
$\log P(k)$  Power spectrum

$10^{-5}$

clustering & merging

$\log k$
Concrete realization: A toy model

\[ V(\phi) \]

\[ V(x) = \frac{\lambda v^4}{12} \frac{x^2(6 - 4a x + 3x^2)}{(1 + b x^2)^2} \]

\[ N(\phi) \]
Primordial Spectrum for PBH

$P_R(k)$

$P_R(k)$

$k \ [h\text{-Mpc}]$

JGB, Ruiz Morales (2017)
Mass Spectrum @ MR equality

\[ \beta^\text{form}(M) \equiv \left. \frac{\rho_{PBH}(M)}{\rho_{\text{tot}}} \right|_{t=t_M} \]

\[ \Omega_{PBH}(z_{eq}) = \int_0^{M_{eq}} \beta(M, N_{eq}) \, d\ln M = 0.42 \]
Constraints on Primordial Black Holes
Present Constraints on PBH

Clesse, JGB (2015)
Massive Primordial Black Holes

• These are NOT the (small) PBH with $10^{-24} \, M_\odot < M_{PBH} < 10^{-7} \, M_\odot$ of Carr et al.

• These are MASSIVE black holes with $10^{-2} \, M_\odot < M_{PBH} < 10^5 \, M_\odot$ which cluster and merge and could resolve some of the most acute problems of ΛCDM paradigm.

• ΛCDM N-body simulations never reach the $100 \, M_\odot$ particle resolution, so for them PBH is as good as PDM.
Mass distribution of BH

$\log n$

$\log M$

$SBH$

$PBH$

$IMBH$

$SMBH$

$1 M_\odot$

$50 M_\odot$

$10^3 M_\odot$

$10^9 M_\odot$
Mass-\(\sigma\) relation BH at G.C.

Kruijssen et al. (2013)
Microlensing

Gravitational lenses (e.g., brown dwarfs)

Milky Way

Earth

Distance ~ 55kpc

Large Magellanic Cloud
achromatic

\[ A_{\text{max}} = 6.86 \]
\[ \tau = 33.9 \]

symmetric

\[ A_{\text{max}} = 7.20 \pm 0.09 \]

achromatic

\[ \frac{A_{\text{red}}}{A_{\text{blue}}} = 1.00 \pm 0.05 \]

unique

\[ t = 34.8 \pm 0.2 \text{ days} \]

\[ \Rightarrow M_D \approx 0.1 M_\odot \]
\[ A = \frac{2 + u^2}{u\sqrt{4 + u^2}} \quad u = \frac{r}{r_E} \quad \text{amplification} \]

\[ \overline{\Delta t} = \frac{r_E}{v} = \frac{\sqrt{4GM_D d}}{v} \quad \text{average} \quad \frac{1}{2} \quad \text{crossing} \]

\[ M_D = 100 \: M_\odot \implies \overline{\Delta t} = 4 \: \text{years} \]

\[ M_D = 10 \: M_\odot \implies \overline{\Delta t} = 1.23 \: \text{years} \]

\[ M_D = 1 \: M_\odot \implies \overline{\Delta t} = 5 \: \text{months} \]

\[ M_D = 0.1 \: M_\odot \implies \overline{\Delta t} = 1.5 \: \text{months} \]

\[ M_D = 10^{-2} \: M_\odot \implies \overline{\Delta t} = 2 \: \text{weeks} \]

\[ M_D = 10^{-4} \: M_\odot \implies \overline{\Delta t} = 1.5 \: \text{day} \]
Missing satellite & Too-big-to-fail Problems $\Lambda$CDM
Rutherford model

PBH
Gravitational slingshot effect

Close encounters of a star with MPBH @ 100 km/s relative motion is enough to expel the star from the stellar cluster.

\[ \rho v^2 = 2U + (1 - m/M)\rho v_1 (1 + m/M) \]

It may explain large M/L ratios of dSph by ejection of stars in the cluster, \( v > v_{\text{esc}} \).
Missing Satellites
DES Dwarf spheroidals
Eridanus II dwarf spheroidal
Astrometric Anomalies @ GAIA
Average distance between PBH

\[ M_{\text{halo\,MW}}(< 50\,\text{kpc}) = 5.4 \times 10^{11} M_\odot \]

\[ \bar{\lambda}_{BH} \equiv (\bar{n}_{BH})^{-1/3} = 38 \, \text{pc} \left( \frac{M}{50 M_\odot} \right)^{1/3} \]

100,000 stars per black hole of 50 M_\odot in our (solar) neighbourhood
Anomalous accelerations

The acceleration on any given star is due to the surrounding masses. A uniform DM field does not induce an extra force on ★. The ★ only feels the presence of other ★s

\[ a_i = \frac{GM_{BH}}{b^2} + \sum_j \frac{Gm_j}{r_{ij}^2} \hat{u}_{ij} \]

\[ \Delta a = \frac{GM_{BH}}{b^2} = 1 \times 10^{-15} \text{ m s}^{-2} \left( \frac{M}{50 M_{\odot}} \right) \left( \frac{20 \text{ pc}}{b} \right)^2 \]
Anomalous velocities & positions

The relative velocity change of a ★ due to PBH, for a 220 km/s relative motion is

\[
\frac{\Delta v}{v} = 3 \times 10^{-4} \left( \frac{M}{50 M_\odot} \right) \left( \frac{0.1 \text{pc}}{b} \right)^2
\]

The relative displacement of a ★ at 1 kpc

\[
\frac{\Delta x}{x} = 0.56 \text{ marcsec} \left( \frac{M}{50 M_\odot} \right) \left( \frac{0.1 \text{pc}}{b} \right)^2
\]
Fluctuations
CIB & X-ray Background
Diffuse Gamma-ray Background
Fermi-LAT Point Sources = PBH?
Chandra
Deep Field
South
Chandra Deep Field South (2017)
Grav. Waves detections @ aLIGO
The clustering of massive Primordial Black Holes as Dark Matter: measuring their mass distribution with Advanced LIGO

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(Dated: March 17, 2016)

The recent detection by Advanced LIGO of gravitational waves (GW) from the merging of a binary black hole system sets new limits on the merging rates of massive primordial black holes (PBH) that could be a significant fraction or even the totality of the dark matter in the Universe. aLIGO opens the way to the determination of the distribution and clustering of such massive PBH. If PBH clusters have a similar density to the one observed in ultra-faint dwarf galaxies, we find merging rates comparable to aLIGO expectations. Massive PBH dark matter predicts the existence of thousands of those dwarf galaxies where star formation is unlikely because of gas accretion onto PBH, which would possibly provide a solution to the missing satellite and too-big-to-fail problems. Finally, we study the possibility of using aLIGO and future GW antennas to measure the abundance and mass distribution of PBH in the range $5 - 200 \, M_\odot$ to 10\% accuracy.

PACS numbers: 98.80.Cq
FIG. 2. Merging rate as a function of the width $\sigma_{\text{PBH}}$ of the PBH density spectrum, for different values of the central mass of the distribution $\mu_{\text{PBH}} = 10/30/60 M_\odot$ (respectively dotted, solid and dashed lines), and of the enhancement factor $E_{\text{factor}} = 10^7/10^8/10^9/10^{10}$ (respectively blue, red, green and brown lines). The colored band corresponds to the bounds inferred by aLIGO.
Merger rate of MPBH in our model

\[ \sigma_{\text{PBH}} = 0.1, \mu_{\text{PBH}} = 30, \delta_{\text{PBH}} = 10^{10} \]

total rate \( \tau = 17 \, \text{yr}^{-1} \, \text{Gpc}^{-3} \)

\[ \sigma_{\text{PBH}} = 0.3, \mu_{\text{PBH}} = 30, \delta_{\text{PBH}} = 10^{10} \]

total rate \( \tau = 10 \, \text{yr}^{-1} \, \text{Gpc}^{-3} \)

\[ \sigma_{\text{PBH}} = 0.7, \mu_{\text{PBH}} = 300, \delta_{\text{PBH}} = 10^{11} \]

total rate \( \tau = 6 \, \text{yr}^{-1} \, \text{Gpc}^{-3} \)

color scale representing \( \log(\tau \, \text{yr} \, \text{Gpc}^3) \)
Stochastic Background from MPBH

\[
h_0^2 \Omega_{GW} = 2.2 \times 10^{-9} \left( \frac{f}{H_Z} \right)^{2/3} \left( \frac{M_c}{100^{10} M_\odot} \right)^{5/3}
\]
Stochastic Background from MPBH

\[ PDF(M) = \frac{1}{\sqrt{2\pi} \sigma^2} \exp \left( -\frac{\log^2(M/\mu)}{2\sigma^2} \right) \]

\[ \tau_{\text{merge}} = 50 \text{ yr}^{-1} \text{Gpc}^{-3} \]
Primordial Black Holes as Dark Matter
Sensitivity of future GW antennas

\[ h_c(f) = 1.36 \times 10^{-23} \left( \frac{f}{\text{Hz}} \right)^{-2/3} \]

Clesse, JGB  arXiv:1610.08479
Discussion
Signatures of MPBH as DM

- Seeds of galaxies at high-z
- Reionization starts early (Kashlinsky)
- Larger galaxies form earlier than $\Lambda$CDM
- Massive BH at centers QSO @ $z>6$
- Growth of structure on small scales
- Ultra Luminous X-ray Transients
- MPBH in Andromeda (Chandra)
- GW from inspiraling BH (LIGO)
- Substructure and too-big-to-fail probl.
- Total integrated mass = $\Omega_M$
Conclusions

• Massive Primordial Black Holes are the perfect candidates for collisionless CDM, in excellent agreement with CMB and LSS observations.
• MPBHs could also resolve some of the most acute problems of $\Lambda$CDM paradigm, like early structure formation and substructure problems.
• MPBHs open a new window into the Early Universe, $\sim 20$-40 e-folds before end inflation.
• There are many ways to test this idea in the near future from CMB, LSS, X-rays and GW.
• LISA could detect the stochastic background from MPBH merging since recombination.