Primordial black holes in the era of Planck and LIGO

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Motivations

- We still don’t know what the DM is. Let’s explore every avenue.
- PBHs probe the ultra-small-scale primordial power spectrum.

![Graph showing primordial perturbations](image)

- BBN (Jeong et al. 2014)
- PBHs (Josan et al. 2009)
- CMB spectrum (Chluba et al. 2012)
- UCMHs (Bringmann et al. 2012, model-dependent)

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spectral distortions bounds at the time \[23\], since then the dark matter, as was implied by the stringent CMB detection of a binary-black-hole merger \[5\], Sasaki.

merger rate at the present time. Following the first de-
the chance proximity of PBH pairs, and estimated their form binaries in the early Universe, as a consequence of

We see that LIGO O1 may limit show the result in Fig. 7, alongside other existing bounds of

of PBH binaries forming in present-

We have also estimated the e

magnitude, depending on the mass. This indicates that LIGO could rule out PBHs as the dominant dark mat-

er component, and set stringent upper limits to their abundance.

LIGO could rule out PBHs as the dominant dark mat-

ter but not significantly perturbed between formation and merger (solid line).

If confirmed with numerical

weaker than previous estimates \[43\], but potentially im-

We have deep inside the radiation era and are very tight. We have also estimated the e

correctly estimated the characteristic properties of the first non-linear

effects on the or-

torques and encounters with other PBHs. This robust-

binaries merging today are essentially unscathed by tidal

structures, and as a consequence their e

all

initial angular momentum for a close pair torqued by

computed the distribution of orbital parameters of PBH

provements to the calculation of NSST, and accurately revised and significantly alleviated \[24\] (see also \[33\]).

CMB anisotropies

Thirdly, we have revisited the calculation of Ref. \[8\] (see Ref. \[74\] for caveats and Ref. \[32\] for a discussion of

EROS \[21\] (\(2\) collaborations

risen fluctuations resulting from the granularity of PBH

large.

We have,

also strongly constrains masses PBHs, and general-

only numerical prefactors happen to be

weaker than previous estimates \[43\], but potentially im-

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Our second and most important addition was to check

in PBHs as a function of their mass, derived in this paper (red

and, assuming a narrow PBH mass function. These

potential limits from LIGO O1 run

YAH, Kovetz & Kamionkowski \[1709.06576\]

YAH & Kamionkowski \[1612.05644\]

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Underlying physics for CMB bounds
Carr 1981, Ricotti et al. 2008, YAH & Kamionkowski 2017

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Philosophy: (i) first-principles, low-fudge-number calculation (ii) estimate the minimal physically plausible effect in order to set conservative upper limits
Accretion rate: Bondi-Hoyle-Lyttleton ++

\[
\frac{\dot{M} c^2}{L_{\text{Edd}}} \begin{array}{c}
\text{Compton drag ceases to be efficient} \\
\text{Compton cooling ceases to be efficient} \\
(\Rightarrow \text{more pressure})
\end{array}
\]

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Temperature near horizon

- Photoionization
- Collisional ionization

Compton cooling

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Temperature near horizon

- Photoionization
- Collisional ionization
- Recombination
- Compton cooling

Temperature scale: $T_s$ (K)

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Luminosity per BH (Bremsstrahlung)

\[
\frac{L}{L_{\text{Edd}}} \propto \mathcal{F}(T_S) \left( \frac{\dot{M}c^2}{L_{\text{Edd}}} \right)^2
\]

\[
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\]

- \(10^4 \, M_\odot\)
- \(10^2 \, M_\odot\)
- \(1 \, M_\odot\)

\(\dot{M}\) - mass accretion rate
\(L_{\text{Edd}}\) - Eddington luminosity
\(T_S\) - Stephan-Boltzmann constant
\(c\) - speed of light

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Energy deposition into the plasma

\[ \dot{\rho}_{\text{inj}} = n_{\text{pbh}} L \]
Energy deposition into the plasma

\[ \dot{\rho}_{\text{inj}} = n_{pbh} L \]

Deposition mostly through Compton scattering of \(~0.1-10\) MeV photons

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Change to mean free-electron fraction

\[ \Delta x_e \]


\[ 10^4 M_\odot, f_{pbh} = 10^{-4} \]
\[ 10^3 M_\odot, f_{pbh} = 10^{-2} \]
\[ 10^2 M_\odot, f_{pbh} = 1 \]
Change to CMB anisotropies

\[ \Delta C_\ell \quad \frac{C_\ell}{C_\ell} \quad \text{Computed with modified CLASS} \]

(Blas, Lesgourgues & Tram 2011)

TT

\[ 10^2 M_\odot, f_{\text{pbh}} = 1 \]

\[ 10^4 M_\odot, f_{\text{pbh}} = 10^{-4} \]

EE

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Bounds to be taken at the order-of-magnitude level only.

Rely on very simplified modeling of complex physics, but ought to be conservative. e.g., disk accretion would imply higher luminosity hence stronger possible bounds.

![Graph showing constraints on accreting PBH as DM.](image)

**Poulin et al. 2017**

- Spherical accretion
- Disk accretion with \( v_{\text{eff}} = c_s,\infty \)
- Disk accretion with \( v_{\text{eff}} = \sqrt{c_s,\infty(v_E^2)^{1/2}} \)
- Other constraints:
  - Micro-lensing
  - Radio
  - Dynamical heating of star cluster

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Did LIGO detect dark matter?
Bird et al. 2016. Clesse & Garcia-Bellido 2017

• If 2 PBHs pass sufficiently close to one another, can lose enough energy through GW emission to become bound.

\[ \sigma \sim \left( \frac{GM\bullet}{c^2} \right)^2 (v/c)^{-18/7} \]

(Quinlan & Shapiro 1989)

see homework 8 of NYU GR class

• With ~ reasonable assumptions about halo properties, merger rate ~ 1/Gpc^3/yr, comparable to LIGO-inferred merger rate.

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Does LIGO rule out PBH-dark matter?

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As they fall towards one another, torqued by other PBHs result in a non-zero (but small) angular momentum.

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Inspiral through GW radiation, some merge at the present time.

Basic idea: Nakamura et al. 1997

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Merger rate

• Compute probability distribution for initial $a$ and $j \equiv \sqrt{1 - e^2}$
Merger rate

- Compute probability distribution for initial $a$ and $j \equiv \sqrt{1 - e^2}$
- Time to merge for $j << 1$ (Peters 1964):
  \[ t = \frac{3}{170} \frac{a^4}{M^3} j^7 \]
Merger rate

- Compute probability distribution for initial $a$ and $j \equiv \sqrt{1 - e^2}$
- Time to merge for $j \ll 1$ (Peters 1964): $t = \frac{3}{170} \frac{a^4}{M^3 j^7}$

$$\frac{d^2 P}{d a d j} \to \frac{d P}{d t}$$

merger rate/volume: $\frac{d N_{\text{merge}}}{d t} = \frac{1}{2} n_{\text{pbh}} \frac{d P}{d t}$
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\[
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\]

merger rate/volume:

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spectral distortions bounds at the time [23], since then the dark matter, as was implied by the stringent CMB the case where PBHs are a very subdominant fraction of ized it to an arbitrary PBH abundance. They focused on protection of a binary-black-hole merger [5], Sasaki merger rate at the present time. Following the first de-
the chance proximity of PBH pairs, and estimated their form binaries in the early Universe, as a consequence of 
maximum PBH fraction for which the merger rate is be-
abundance.

LIGO could rule out PBHs as the dominant dark mat-
show the result in Fig. 7, alongside other existing bounds 
not linear in 
low the LIGO upper limits. Note, that the merger rate is 
exceeds the estimated upper limits, by 3 to 4 orders of 
formation and merger. We see that the latter 
binaries merging today are essentially unscathed by tidal 
structures, and as a consequence their e 

Thirdly, we have revisited the calculation of Ref. [8] 
potential limits 

In this paper, we have, first of all, made several im-

improvements to the calculation of NSST, and accurately 
revised and significantly alleviated [24] (see also [33]).

micro-lensing

ultra-faint dwarfs

cmb anisotropies

potential limits from LIGO O1 run

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Characterestic initial properties for binaries merging today

\[ j \equiv \sqrt{1 - e^2} \]

\[ \Rightarrow \text{do highly-eccentric binaries that form at } z \sim 10^4 - 10^5 \text{ evolve only through GW radiation until the present time?} \]
• Gravitational interactions with other PBHs and rest of dark matter

Using **analytic estimates** of the properties of the first structures, we found that torques due dark matter (PBHs or WIMPs) **do not significantly affect PBH binaries**. **To be checked numerically.**
• Gravitational interactions with other PBHs and rest of dark matter

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• Exchange of energy and angular momentum with accreting baryons

Most uncertain piece. Estimated that torques could be marginally relevant.
Does LIGO rule out PBH-dark matter? It *might*, but more checks are needed.

\[ M_{\text{pbh}} = 30M_\odot \]

\[ f_{\text{pbh}} = 0.1 \]
spectral distortions bounds at the time [23], since then the dark matter, as was implied by the stringent CMB.

The case where PBHs are a very subdominant fraction of the large.

We see that LIGO O1 may limit the maximum PBH fraction for which the merger rate is below the estimated upper limits. Note, that the merger rate is largely not linear in the LIGO upper limits. This indicates that the latter exceeds the estimated upper limits, by 3 to 4 orders of magnitude, depending on the mass. This is shown in Fig. 7, alongside other existing bounds.

The diagram superimposes the upper limits from LIGO given in Table I along with the PBH binary merger rate if they make up all of the dark matter, and provided PBH binaries are not significantly perturbed between formation and merger (solid line).

We show these limits in Fig. 6, alongside the PBH binary merger rate if they make all of the dark matter, and general uncertainties, limits from wide Galactic binaries [22], ultra-faint dwarfs [25], and CMB anisotropies [24].

Our second and most important addition was to check the chance proximity of PBH pairs, and estimated their form binaries in the early Universe, as a consequence of the tidal field and encounters with other PBHs. This robustness stems from the fact that these binaries typically form large structures, and as a consequence their eccentricities are small. PBH binaries merging today are essentially unscathed by tidal torques and encounters with other PBHs.

To estimate these potential limits, we solve for the characteristic properties of the first non-linear structures, and as a consequence their e distribution needs to be confirmed by numerical simulations. For a close pair torqued by the tidal field, we have computed the exact probability distribution of the orbital parameters of PBH binaries forming in the early Universe. Specifically, we have computed the distribution of orbital parameters of PBH binaries merging today are essentially unscathed by tidal torques and encounters with other PBHs.

We have revisited the calculation of Ref. [8], and also strongly constrains masses in that mass range. We see that LIGO O1 may limit the dark matter, as was implied by the stringent CMB.

We have accounted for the tidal field and encounters with other PBHs, and have computed the exact probability distribution of the orbital parameters of PBH binaries. We found that PBH binaries merging today are essentially unscathed by tidal torques and encounters with other PBHs. This robustness stems from the fact that these binaries typically form large structures, and as a consequence their eccentricities are small. PBH binaries merging today are essentially unscathed by tidal torques and encounters with other PBHs.

We have also estimated the eccentricities of density perturbations on small scales, and have accounted for the tidal field and encounters with other PBHs. This robustness stems from the fact that these binaries typically form large structures, and as a consequence their eccentricities are small.

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Conclusions

- PBHs are an interesting DM candidate, with a rich phenomenology.
- Difficult to robustly constrain, due to complex astrophysics
- *Planck* excludes PBHs above 100 $M_{\text{sun}}$ to be the dominant DM
- LIGO’s existing data may set the most stringent limits to PBHs of \(~1\text{-}1000\ M_{\text{sun}}\)
- Estimates need to be improved: account for clustering and extended mass function; numerical checks of viability of binaries.

References: arXiv:1612.05644, 1709.06576
Temperature profile

adiabatic

collisional ionization

extends Shapiro (1973)

$T\propto \frac{1}{r^{2/3}}$

$T_S$

$T_{\text{ion}}$

$T_\infty = T_{\text{cmb}}$

Compton cooling

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Temperature profile

\[ T \]

\[ T_S \]

\[ \propto \frac{1}{r^{2/3}} \]

\[ m_e c^2 \]

\[ T_{\text{ion}} \]

adiabatic

collisional ionization region

\[ \propto \frac{1}{r} \]

\[ T_\infty = T_{\text{cmb}} \]

Compton cooling

extends Shapiro (1973)

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Baryon-dark matter relative velocity

Baryons and dark matter have large-scale relative motions (see e.g. Tseliakhovich & Hirata 2010 for effect on small-scale structure)

- before recombination \( v_{\text{rel}} \approx 30 \text{ km/s} \approx 5 \, c_s \)
- after recombination: baryons become cold like DM. \( v_{\text{rel}} \propto 1/a \)

Ricotti et al. 2008 assumed \( v_{\text{rel}} \approx 4 \text{ km/s} \lesssim c_s \)
Baryon-dark matter relative velocity

Simple fudge (à la Bondi-Hoyle): \( c_s \rightarrow (c_s^2 + v_{\text{rel}}^2)^{1/2} \)

in the simple Bondi case: \( L \propto \dot{M}^2 \propto \frac{1}{(c_s^2 + v_{\text{rel}}^2)^{3/2}} \), \( \langle L \rangle \propto \left\langle \frac{1}{(c_s^2 + v_{\text{rel}}^2)^3} \right\rangle \approx \frac{1}{c_s^3 \langle v_{\text{rel}}^2 \rangle^{3/2}}, \quad \langle v_{\text{rel}}^2 \rangle \gg c_s^2 \)

\[ \frac{\langle L \rangle}{L(v_{\text{rel}} = 0)} \sim 10^{-2} \]

See also Horowitz 2016, Aloni, Blum & Flauger 2017
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\[
\langle L \rangle \propto \left\langle \frac{1}{(c_s^2 + v_{rel}^2)^3} \right\rangle \approx \frac{1}{c_s^3 \langle v_{rel}^2 \rangle^{3/2}} , \quad \langle v_{rel}^2 \rangle \gg c_s^2
\]

\[
\frac{\langle L \rangle}{L(v_{rel} = 0)} \sim 10^{-2}
\]

See also Horowitz 2016, Aloni, Blum & Flauger 2017

Notes: (1) detailed suppression is not highly relevant; average luminosity is...