Have we detected Primordial Black Holes at LIGO-Virgo?

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Inflation

N = \ln \frac{a}{a_{\text{end}}}

Horizon crossing

1/(aH)

1/k comoving scale

CMB

PBH

BBN

QCD

PBH

EW

QCD

LSS

Inflation

Radiation

Matter

\Lambda
Gravitational Collapse

Gravity wins

Radiation wins
Gravitational Collapse of PBH

\[ \log P(k)^{1/2} \]

\[ \zeta_c \approx 0.5 \]

\[ M_{PBH} \approx 30M_\odot e^{2(N-36)} \]
Inflationary predictions

- Wide mass distribution
- Clusters of PBH: $N_{cl} \sim 100-1000$, comoving size $\sim 1\text{mpc}$

uniform single-mass is already ruled out

clustered wide-mass is still viable
PBH constraints

\[ f_{\text{PBH}} = \frac{\Omega_{\text{PBH}}}{\Omega_{\text{DM}}} \]

JGB & Clesse (2017)

“wide-mass”
Thermal history of the universe

Carr, Clesse, JGB, Kühnel (2019)
Thermal history of the universe

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Predictions for PBH mass spectrum

\[ f_{\text{PBH}}(M) \equiv \frac{1}{\rho_{\text{DM}}} \frac{d \rho_{\text{PBH}}(M)}{d \ln M} \]

\[ = \beta(M) \sqrt{\frac{M_{\text{eq}}}{M}} \frac{2(\Omega_{\text{CDM}} + \Omega_b)}{\Omega_{\text{CDM}}} \]

\[ n_s = 0.96 \]

\[ n_s = 0.97 \]

\[ n_s = 0.98 \]

\[ W^\pm, Z^0 \]

\[ \rho, \bar{\rho} \]

\[ \beta(M) \approx \text{erfc} \left[ \frac{\delta_c(w[T(M)])}{\delta_H(M)} \right] \]

\[ \pi^\pm, \pi^0 \]

\[ e^+, e^- \]

Carr, Clesse, JGB, Kühnel (2019)
Microlensing Events

Gravitational lenses (e.g., brown dwarfs)

Earth

Distance \sim 55 \text{kpc}

\[ r_E^2 = 4GM_D d \]

\[ d = \frac{d_1 d_2}{d_1 + d_2} \]

\[ A = \frac{2 + u^2}{u \sqrt{4 + u^2}} \]

\[ u = \frac{r}{r_E} \]

amplification

\[ Dt = \frac{r_E}{v} = \frac{\sqrt{4GM_D d}}{v} \]

average \( \frac{1}{2} \) crossing

- \( M_D = 100 \text{M}_\odot \) \( \Rightarrow \) \( Dt = 4 \) years
- \( M_D = 10 \text{M}_\odot \) \( \Rightarrow \) \( Dt = 1.23 \) years
- \( M_D = 1 \text{M}_\odot \) \( \Rightarrow \) \( Dt = 5 \) months
- \( M_D = 0.1 \text{M}_\odot \) \( \Rightarrow \) \( Dt = 1.5 \) months
- \( M_D = 0.01 \text{M}_\odot \) \( \Rightarrow \) \( Dt = 2 \) weeks
OGLE photometry from 2001-2008 and microlensing model

Mass, Distance

(degenerated estimate)

Wyrzykowski (2016)

M = 9.8 M_⊙

1.8 kpc

OGLE3-UL-PAR-02 - candidate BH

OGLE photometry

M = 9.8 M_⊙

1.8 kpc

Mass, Distance

(degenerated estimate)
OGLE-GAIA microlensing events

Carr, Clesse, JGB, Kühnel (2019)

Wyrzykowski, Mandel (2019)
Predictions for PBH mass spectrum

Carr, Clesse, JGB (2019)

\( f_{\text{PBH}} \) vs. \( M (M_\odot) \)

LVC

O1+O2

O3
PBH are \(\sim\) spinless

\[ L \sim Mr^2 \omega \]

Primordial BH

Mass

Stellar BH
Rate of merger events @ LIGO-Virgo Run O1+O2 (observed)

Carr, Clesse, JGB, Kühnel (2019)
Rate of merger events @ LIGO-Virgo Run O3 (predicted)

Carr, Cleisse, JGB, Kühnel (2019)