Mass Spectrum of Primordial Black Holes

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Universe is full of PBH now and it was such long ago

Rising sensitivity of telescopes reveals more and more dense population of the universe by black holes in all mass ranges:
supermassive black holes (SMBH), $M = (10^{10} - 10^6) M_\odot$,
intermediate mass black holes (IMBH), $\mathbf{M} = (10^2 - 10^5)\mathbf{M}_\odot$,
BHs of several tens of $M_\odot$,
and maybe BHs even with a fraction of the solar mass.
SMBHs are also observed in quite a young universe: $\mathbf{z = 5 - 10}$, i.e.when the universe was ten-fold younger. Non observation of less massive BH does not mean that they are absent there, they are simply non-visible at such distances.
These BHs make all or a weighty fraction of the cosmological dark matter, seeded galaxy formation, and create binaries emitting gravitational waves observed at LIGO/Virgo interferometers.
Most probably all those BHs are primordial (PBH).

Review: AD, Phys. Usp. 61 (2018) 2, 115-132; big lot of new data appeared since that time, during the last two years..

Primordial black holes

Primordial black holes (PBH) created in pre-stellar epoch

The idea of the primordial black hole (PBH) i.e. of black holes which could be formed the early universe prior to star formation was first put forward by Zeldovich and Novikov: "The Hypothesis of Cores Retarded During Expansion and the Hot Cosmological Model", Astronomicheskij Zhurnal, 43 (1966) 758, Soviet Astronomy, AJ.10(4):602603;(1967).

According to their idea, the density contrast in the early universe inside the bubble with radius equal to the cosmological horizon might accidentally happen to be large, $\delta\varrho/\varrho \approx 1$, then that piece of volume would be inside its gravitational radius i.e. it became a PBH, which decoupled from the cosmological expansion.

Elaborated later in S. Hawking, "Gravitationally collapsed objects of very low mass", Mon. Not. Roy. Astron. Soc. **152**, 75 (1971).

B. J. Carr and S. W. Hawking, "Black holes in the early Universe," Mon. Not. Roy. Astron. Soc. **168**, 399 (1974).

PBH formation, modified mechanism

An essentially different mechanism (AD, J.Silk, 1993) could lead to PBHs with masses exceeding millions solar masses with **log-normal mass spectrum** was proposed and developed in:

- A.Dolgov and J.Silk, PRD 47 (1993) 4244 "Baryon isocurvature fluctuations at small scaler and baryonic **dark matter**".
- A.Dolgov, M. Kawasaki, N. Kevlishvili, Nucl. Phys. B807 (2009) 229, "Inhomogeneous baryogenesis, cosmic antimatter, and **dark matter"**.

Such form of the mass spectrum and similar ones, the so called extended spectra, became quite popular nowadays.
This scenario of PBH formation pioneered in implementation of **inflation** to PBH formation. It allows for huge masses of PBH, much larger than the horizon mass in the very early universe.
A long succession of works on inflationary formation of PBH can be found in the literature now but with quite complicated mass spectra.

PBH formation, modified mechanism

The modified mechanism of PBH formation is based on the popular scenario of the SUSY motivated baryogenesis, proposed by Affleck and Dine (AD). This scenario could lead to the cosmological baryon asymmetry of order unity, much larger than the observed one $\beta \approx 10^{-9}$.
The new PBH creation mechanism could be realized if β reached large values only in cosmologically small but possibly astronomically large bubbles, while in the bulk of the universe it has normal value.
$\beta \approx 6 \cdot 10^{-10}$. This may be achieved by introduction of the **general renormalizable coupling of the AD baryonic scalar field with inflaton.**
The fundament of PBH creation is set on at inflation by making large isocurvature fluctuations at relatively small scales, with practically vanishing density perturbations. **The huge perturbations in baryonic number transformed into density perturbations at the QCD p.t. when massless quarks turned into heavy baryons.**

PBH formation, modified mechanism

The emerging universe looks like a piece of Swiss cheese, where holes are high baryonic density bubbles (HBB) occupying a minor fraction of the universe volume.

Inflationary prehistory allows for creation of huge PBH with masses up to $(10^4 - 10^5) M_\odot$, or even higher depending on the model. Log-normal mass spectrum is predicted with only 3 parameters: μ, γ, M_0

$$\frac{dN}{dM} = \mu^2 \exp\left[-\gamma \ln^2(M/M_0)\right].$$

The values of γ and μ depend upon unknown high energy parameters of the AD baryogenesis, **but since density perturbations are generated at the QCD phase transition, the central mass, M_0, is equal to the mass inside cosmological horizon at that moment**

Central mass value

Mass inside horizon at RD stage, $r_{hor} = 2t$: $M_{hor} = m_{Pl}^2 t$ and if $\delta\varrho/\varrho = 1$, then $M_{BH} = M_{hor}$ and the gravitational radius is

$$r_g = \frac{2M}{m_{Pl}^2} = 2r_{hor}.$$

If PBHs were formed at the QCD phase transition at $T \sim 100$ MeV, then $t = 4 \cdot 10^{-5} \left(100\,\mathrm{MeV}/T\right)^2$ sec and

$$M_{hor} = 8M_\odot \cdot \left(\frac{100\,\mathrm{MeV}}{T}\right)^2.$$

According to lattice calculations $T_{QCD} = 100 - 150$ MeV but if quark chemical potential is large, T_{QCD} may be smaller and $\boldsymbol{M_0}$ be bigger.
So the central mass of PBH log-normal mass spectrum is predicted to be close to $\mathbf{10}\boldsymbol{M_\odot}$ (AD, K.Postnov, JCAP 07 (2020) 063, astro-ph 2004.11669) in good agreement with observations, see figures below.

Another way around: if the mass of perturbation is $\mathbf{M} < \mathbf{M_{hor}}$ it would be inside its horizon for huge density contrast

$$\frac{\delta\varrho}{\varrho} \geq \left(\frac{M_{hor}}{M}\right)^2$$

For formationBH at QCD p.t. with $M = M_\odot$ one needs

$$\frac{\delta\varrho}{\varrho} \geq 10^2$$

Gravitational waves from BH binaries. Chirp mass

Two rotating gravitationally bound massive bodies are known to emit gravitational waves. In quasi-stationary inspiral regime, the radius of the orbit and the rotation frequency are approximately constant and the GW frequency is twice the rotation frequency. The luminosity of the GW radiation is:

$$L = \frac{32}{5}\, m_{Pl}^2 \left(\frac{M_c\, \omega_{orb}}{m_{Pl}^2} \right)^{10/3},$$

where M_1, M_2 are the masses of two bodies in the binary system and $\boldsymbol{M_c}$ is the so called chirp mass:

$$M_c = \frac{(M_1\, M_2)^{3/5}}{(M_1 + M_2)^{1/5}},$$

and

$$\omega_{orb}^2 = \frac{M_1 + M_2}{m_{Pl}^2 R^3}.$$

Chirp mass distribution

A.D. Dolgov, A.G. Kuranov, N.A. Mitichkin, S. Porey, K.A. Postnov, O.S. Sazhina, and I.V. Simkine On mass distribution of coalescing black holes, JCAP, 014P, 0520 (2020) e-Print: 2005.00892 [astro-ph.CO], May, 2020.
The available data on the chirp mass distribution of the black holes in the coalescing binaries in O1-O3 LIGO/Virgo runs are analyzed and compared with theoretical expectations based on the hypothesis that these black holes are primordial with log-normal mass spectrum. The inferred best-fit mass spectrum parameters, $M_0 = 17 M_\odot$ and $\gamma = 0.9$, fall within the theoretically expected range and shows excellent agreement with observations. On the opposite, binary black hole models based on massive binary star evolution require additional adjustments to reproduce the observed chirp mass distribution.

The only known to us mass spectrum which so well describes the chirp mass distribution

Chirp mass distribution

Chirp mass distribution of coalescing binary PBH

A.D. Dolgov, A.G. Kuranov, N.A. Mitichkin, S. Porey, K.A. Postnov, O.S. Sazhina, I.V. Simkine "On mass distribution of coalescing black holes. JCAP, 014P,0520 (2020); arXive:2005.00892.

Independent of the (model-dependent) absolute value of the binary PBH merging rate. Depends on the PBH mass function and (less significantly) on the detector sensitivity.

Before the recent release GWTC2: O1-O2, the chirp mass estimates have been done in a "poor man" way using openly available luminosity distance Dl and assuming signal-to-noise ratio, SNR =8.

Perfect agreement with log-normal mass spectrum, strong indication to the primordial origin of the coalescing BH.

Chirp mass distribution

From recent talk by K. Postnov, seminar Shternberg Astronomical inst.

$$f(t)dt \propto \int_0^\infty \int_0^\infty \int_0^\infty \left(\frac{t}{\tilde{t}}\right)^{3/37} \frac{dt}{t} F(M_1)F(M_2)F(M_3)dM_1 dM_2 dM_3$$

$$\mathcal{R} = n_{BH} f(t)$$

Merging rate per volume per year

$$\mathcal{DR}(\mathcal{M}) = \int_0^{z(D_h(\mathcal{M}))} \frac{\mathcal{R}}{1+z'} \frac{dV}{dz'} dz'$$

Detection rate per year

$$D_h(\mathcal{M}) = 122\mathrm{Mpc} \left(\frac{\mathcal{M}}{1.2\ M_\odot}\right)^{5/6}$$

$$F_{\mathrm{PBH}}(<\mathcal{M}) = \int_0^{\mathcal{M}} P_{\mathrm{PBH}}(\mathcal{M})d\mathcal{M} = \frac{\int_0^{\mathcal{M}} \mathcal{DR}(\mathcal{M})d\mathcal{M}}{\int_0^{\infty} \mathcal{DR}(\mathcal{M})d\mathcal{M}}$$

Chirp mass distribution

Chirp mass distribution

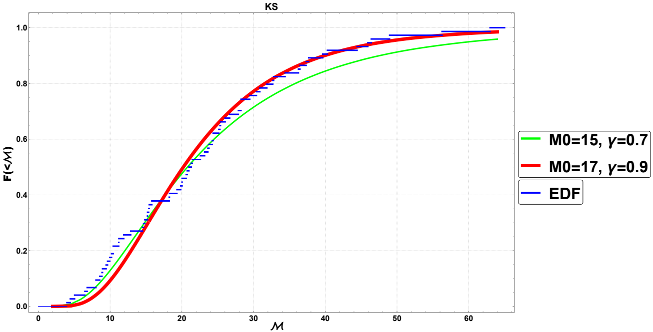


Figure: Model distribution $F_{PBH}(< M)$ with parameters M_0 and γ for two best Kolmogorov-Smirnov tests. EDF= empirical distribution function.

Chirp mass distribution

Model distribution $F_{PBH}(< M)$ with parameters M_0 and γ for two best Van der Waerden tests.

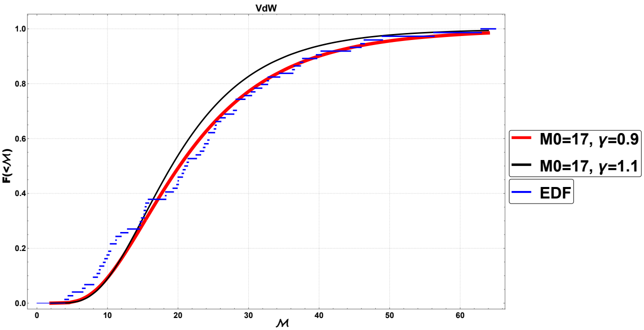
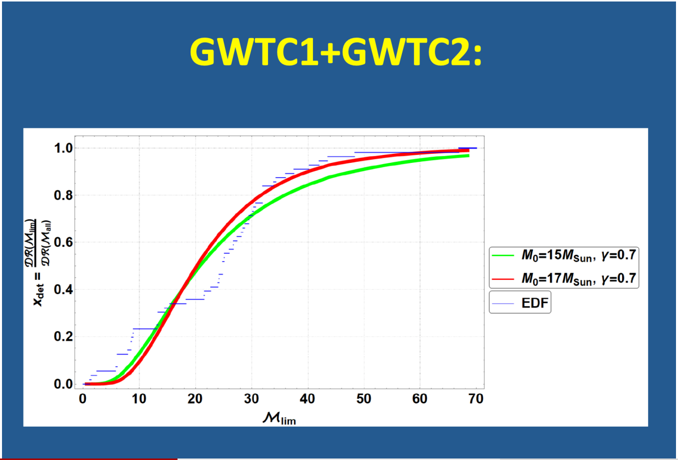


Figure: Model distribution $F_{PBH}(< M)$ with parameters M_0 and γ for two best Van der Waerden tests.

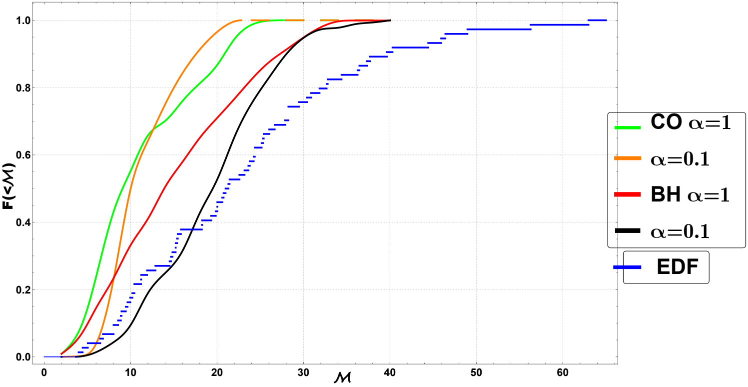
Chirp mass distribution

Cumulative distribution, $F(< M)$, based on the recently released data; only slightly changed values of $\mathbf{M_0}$ and γ.



Chirp mass distribution, astrophysical BHs

Cumulative distributions $F(< M)$ for several **astrophysical** models of binary BH coalescences.



CONCLUSION

- Chirp mass distribution of coalescing binary BH observed by LIGO/Virgo O1-O3 (GWTC-1 and GWTC-2) can be perfectly fitted by PBH binaries with log-normal mass spectrum centered on $\sim 15M_\odot$
- Central mass of coalescing PBHs M_0 as inferred from LIGO/Virgo data is suggestively close to $\sim 10M_\odot$ – the mass inside the cosmological horizon at QCD p.t. in the early Universe
- Chirp mass distribution of coalescing binary PBHs is independent of the (unknown) fraction of PBH in CDM

THE END