Black Dark Matter

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A piece of history

The idea that PBM might be constituents of DM was first discussed by George F. Chaplin "Cosmological effects of primordial black holes" Nature 253 (1975) 5489, 251-252. Assumed scale independent spectrum of cosmological perturbations and thus flat mass spectrum in log interval:

$$\mathbf{dN = N_0(dM/M)}$$

with maximum mass $\mathbf{M_{max} \lesssim 10^{22}}$ g, which hits the allowed mass range.

A. Dolgov, J. Silk (Mar 13, 1992), Baryon isocurvature fluctuations at small scales and baryonic dark matter, PRD 47 (1993) 4244, **first paper with inflation applied to PBH formation, so PBH masses up to $10^6 M_\odot$ can be created, log-normal mass spectrum was predicted.**

Two years later P. Ivanov, P. Naselsky, I. Novikov (May 10, 1994), "Inflation and primordial black holes as dark matter" PRD 50 (1994) 7173.

An avalanche of papers on inflationary formation of PBH nowadays.

Conventional PBH creation mechanism

The idea of primordial black holes (PBHs) i.e. of black holes which could be formed the early universe during the prestellar epoch was put forward and developed by:

Ya.B. Zeldovich and I.D. 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).

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).

According to their idea, the density contrast in the early universe inside the bubble with the 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 own gravitational radius i.e. it became a PBH, which decoupled from the cosmological expansion.

PBH formation, modified mechanism

A different mechanism (AD, J.Silk, 1992) could lead to creation of 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**".

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 Affleck-Dine baryogenesis, **but the central mass, $M_0 \sim 10 M_\odot$, is close to the mass inside horizon at the QCD phase transition.** Such form of the mass spectrum and similar ones, the so called extended spectra, became quite popular presently.

Central mass value

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

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

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 M_0 be bigger.
So the central mass of PBH log-normal mass spectrum is predicted to be close to $10M_{\odot}$ (AD, K.Postnov, JCAP 07 (2020) 063, astro-ph 2004.11669) in good agreement with observations, see figures below.

Chirp mass distribution

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 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, 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 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 2020, accepted; 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

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

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

Detection rate per year

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

Chirp mass distribution

Chirp mass distribution

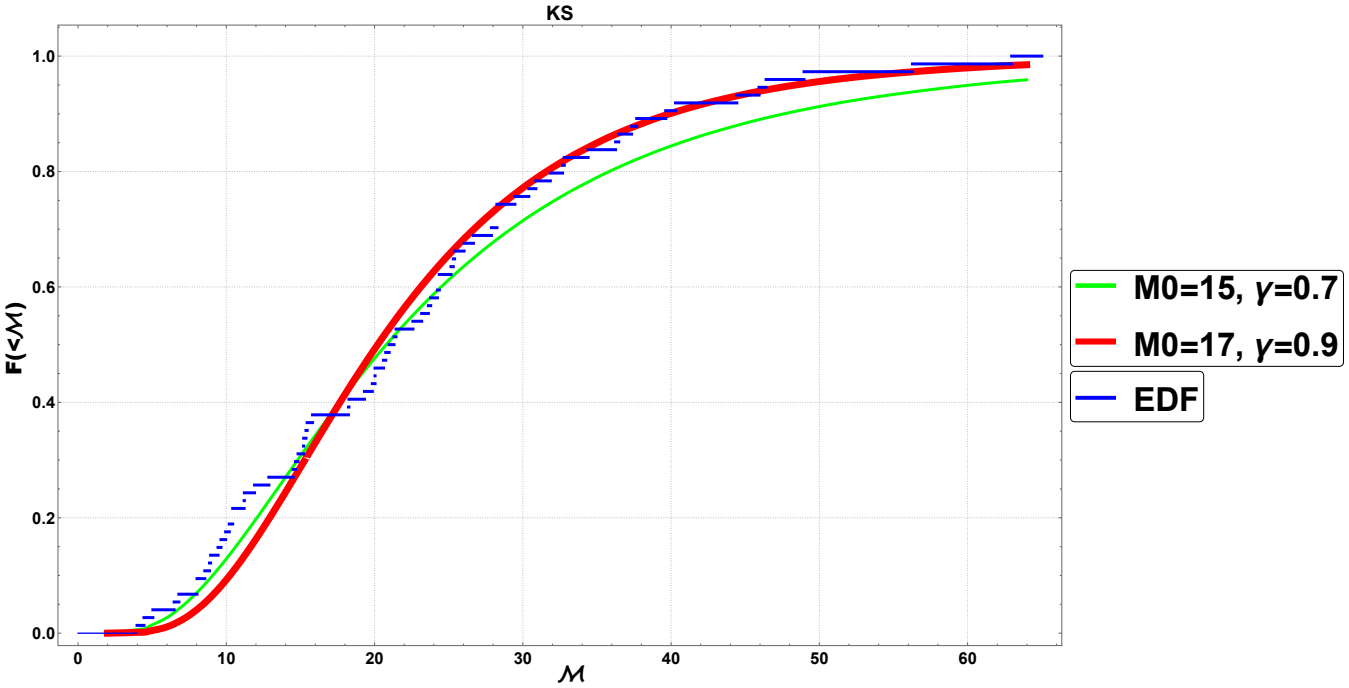


Figure: Model distribution $F_{PBH}(< M)$ with parameters M_0 and γ for two best Kolmogorov-Smirnov tests. EDF= empirical distribution function.

Chirp mass distribution

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

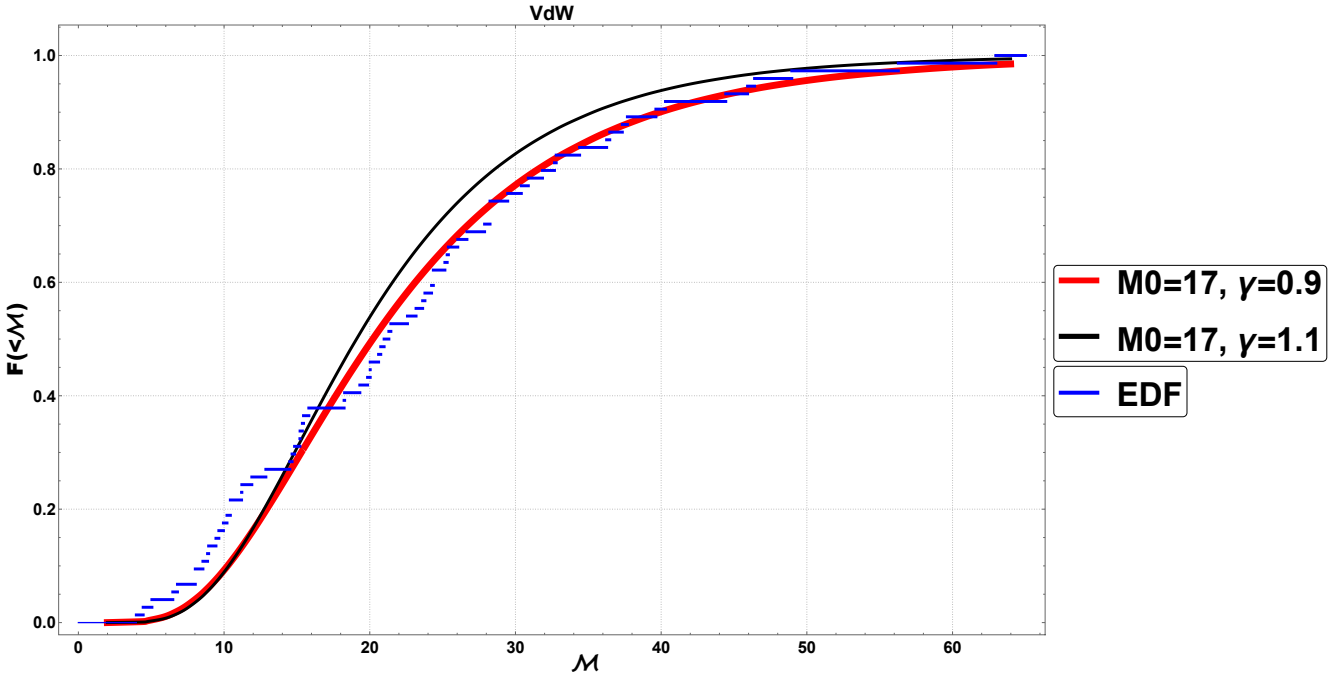
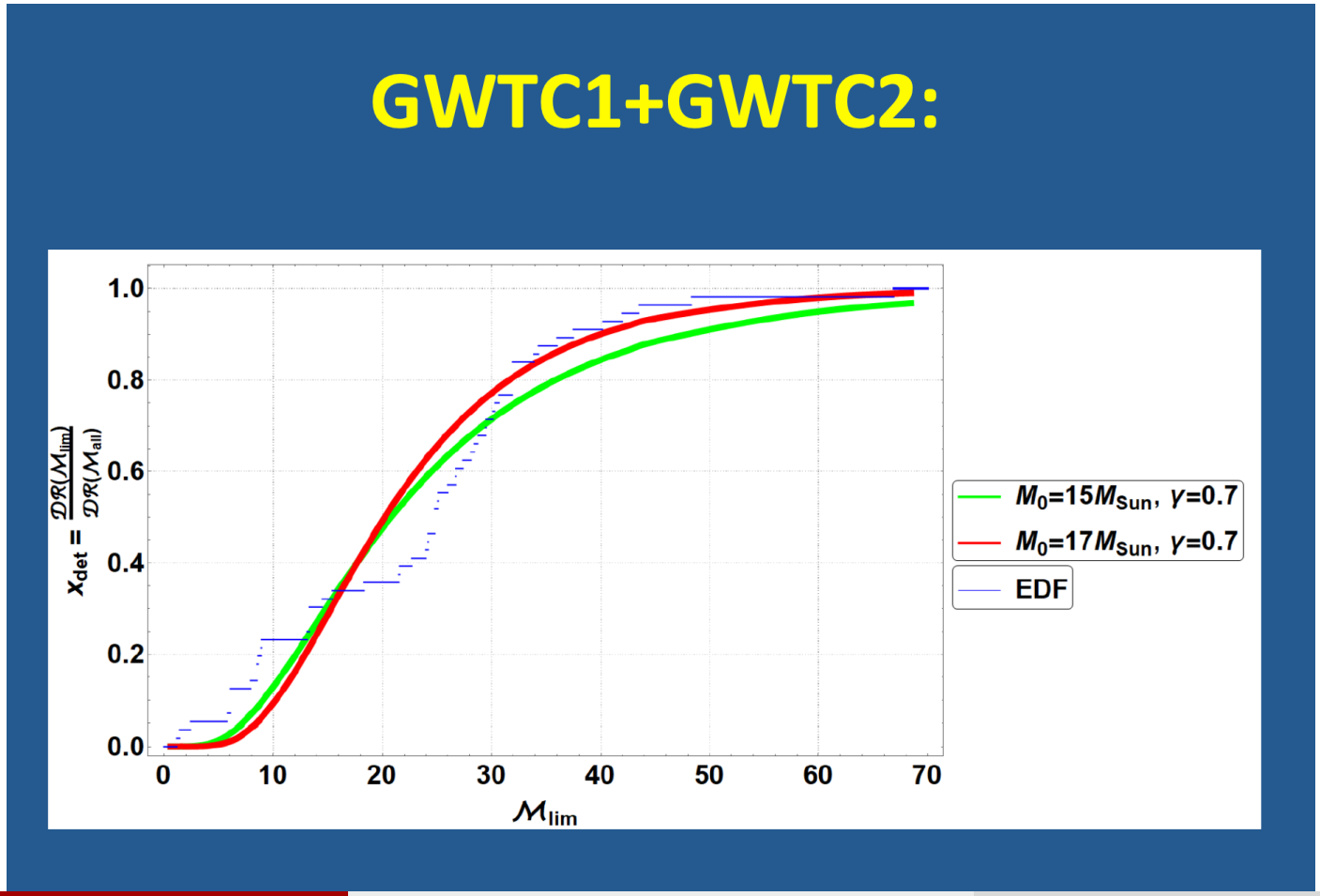


Figure: Model distribution $F_{PBH}(< M)$ with parameters M_0 and γ for two best Van der Waerden tests.

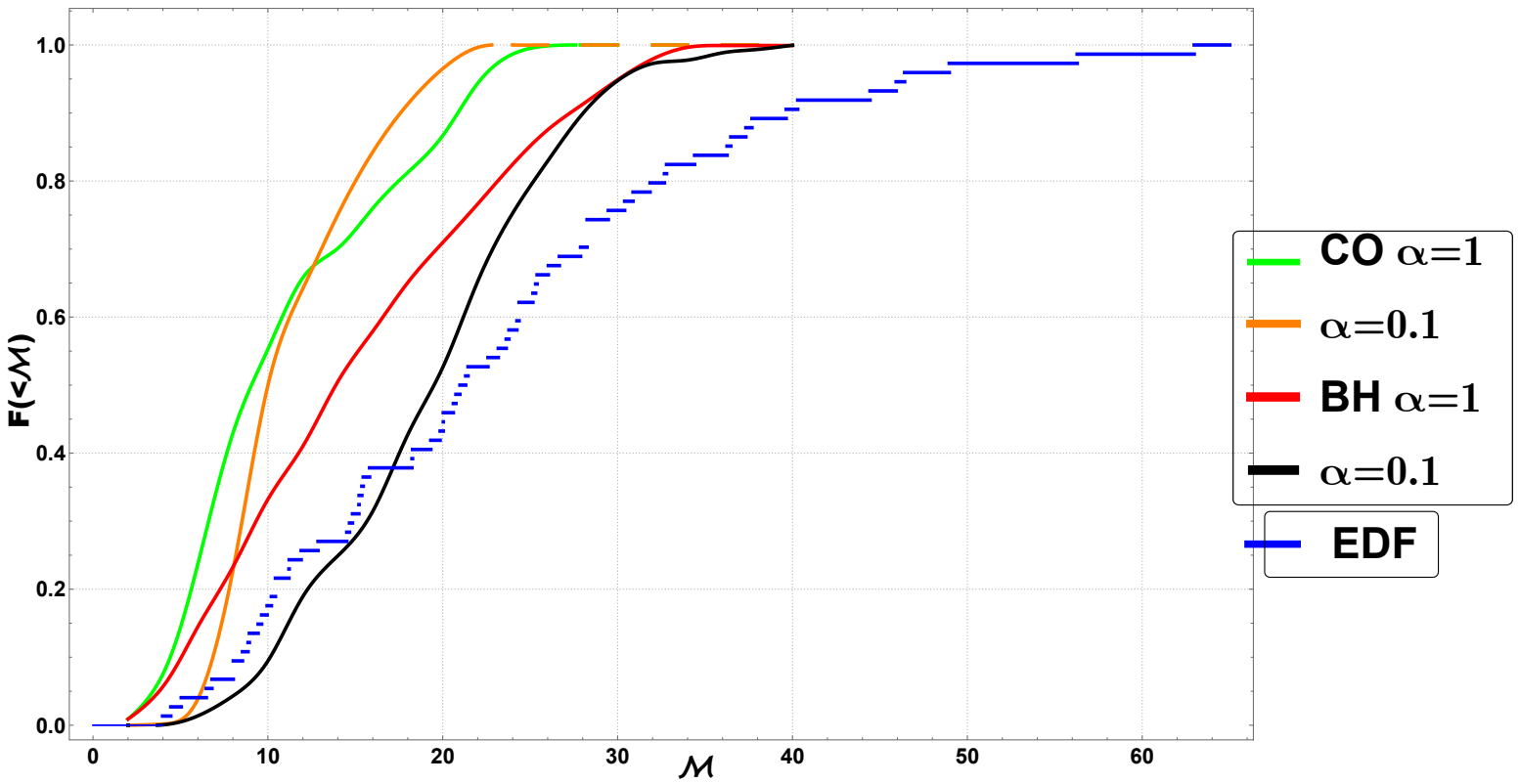
Chirp mass distribution

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.



Back to DM

Constraints on PBHs - B.Carr, F. Kuhnel "Primordial Black Holes as Dark Matter: Recent Developments", arXiv:2006.02838, June 2020

For monochromatic mass spectrum of PBHs (caution, model-dependent).

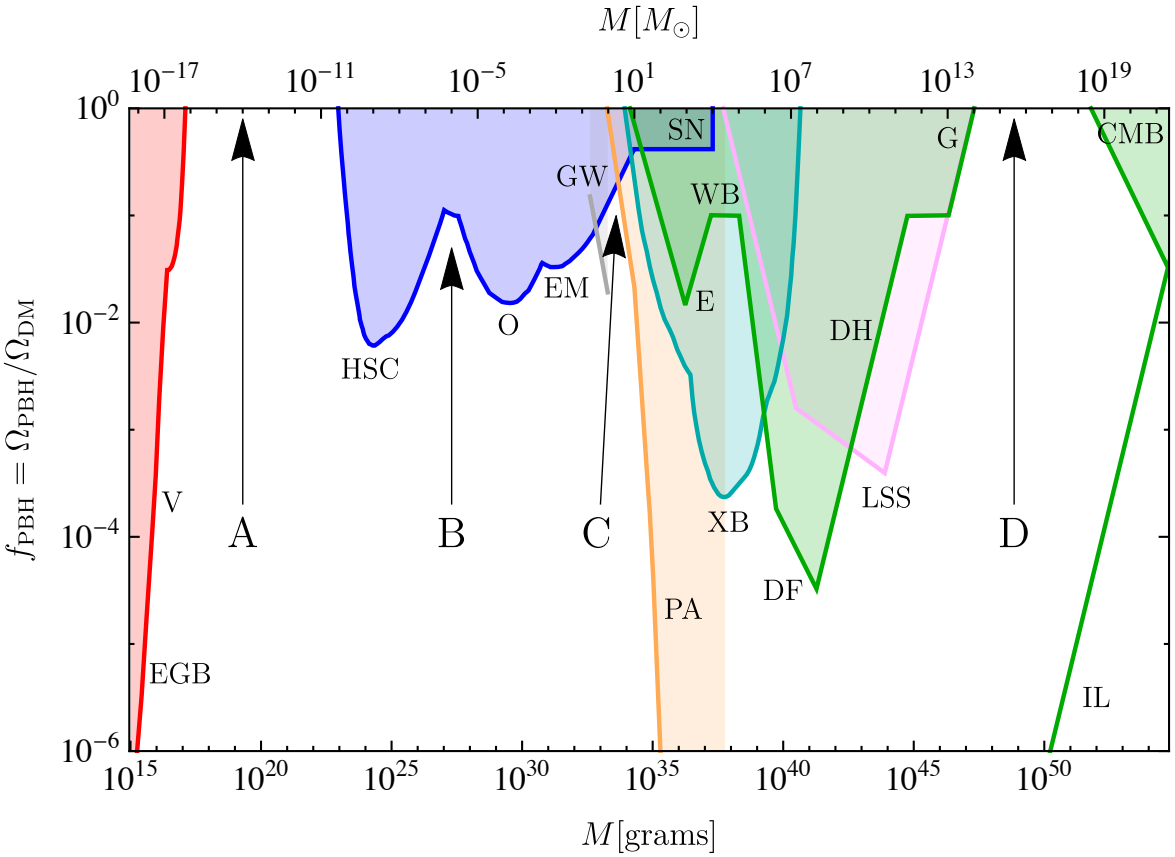
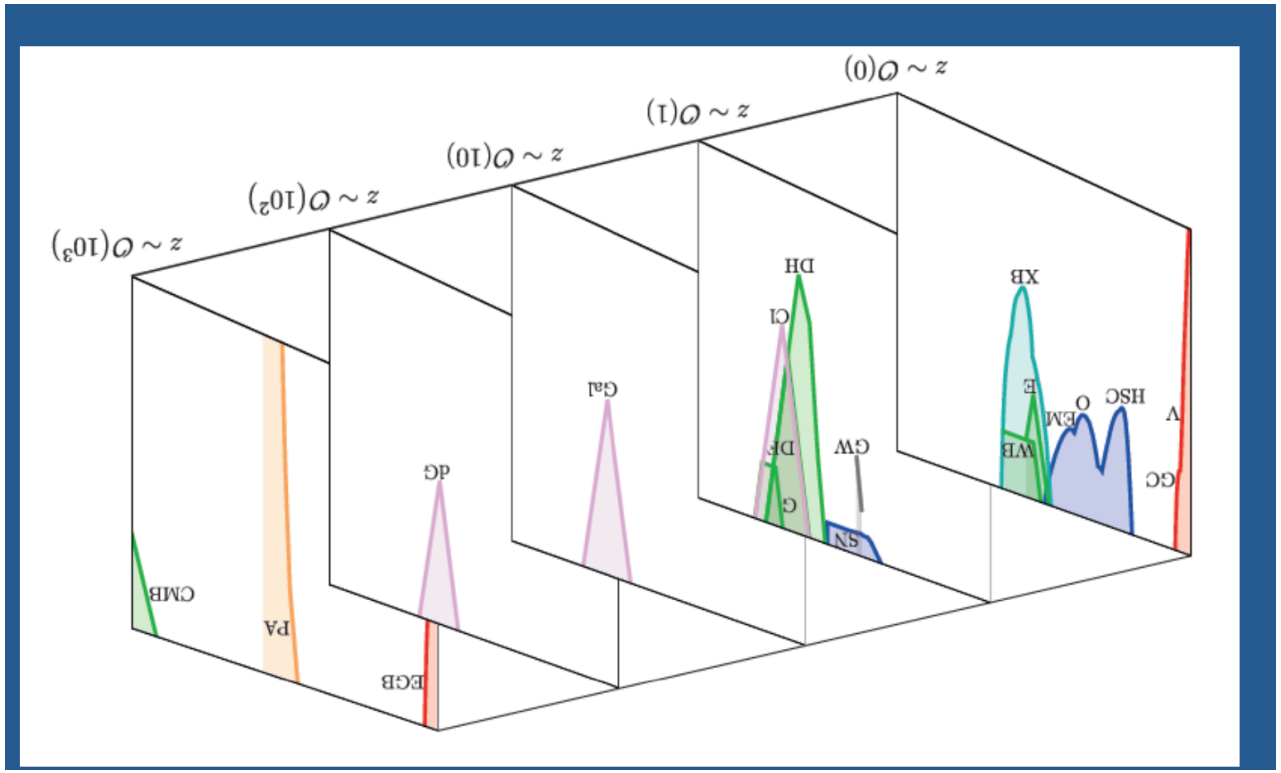


Figure caption

Constraints on $f(M)$ for a **monochromatic** mass function, from evaporations (red), lensing (blue), gravitational waves (GW) (gray), dynamical effects (green), accretion (light blue), CMB distortions (orange) and large-scale structure (purple). Evaporation limits from the extragalactic gamma-ray background (EGB), the Voyager positron flux (V) and annihilation-line radiation from the Galactic centre (GC). Lensing limits from microlensing of supernovae (SN) and of stars in M31 by Subaru (HSC), the Magellanic Clouds by EROS and MACHO (EM) and the Galactic bulge by OGLE (O). Dynamical limits from wide binaries (WB), star clusters in Eridanus II (E), halo dynamical friction (DF), galaxy tidal distortions (G), heating of stars in the Galactic disk (DH) and the CMB dipole (CMB). Large scale structure constraints(LSS). Accretion limits from X-ray binaries (XB) and Planck measurements of CMB distortions (PA). The incredulity limits (IL) correspond to one PBH per relevant environment (galaxy, cluster, Universe). There are four mass windows (A, B, C, D) in which PBHs could have an appreciable density.

Bounds arXiv:2006.02838 as a function of z,



Gravitational waves from BH binaries

• GW discovery by LIGO strongly indicate that the sources of GW are PBHs. see e.g. S.Blinnkov, A.D., N.Porayko, K.Postnov, JCAP 1611 (2016), 036 "Solving puzzles of GW150914 by primordial black holes,"

1. Origin of heavy BHs ($\sim \mathbf{30}\boldsymbol{M_\odot}$); recently there appeared much more striking problem of BH with $\boldsymbol{M} \sim \mathbf{100}\boldsymbol{M_\odot}$. See however, J. Ziegler, K. Freese, arXiv:2010.00254: DM annihilation inside stars
2. Formation of BH binaries from the original stellar binaries.
3. Low spins of the coalescing BHs .

Gravitational waves from BH binaries

Surprising features

Masses higher $60M_\odot$ are in GW190521.

Effective spins are consistent with zero, but there are indication of misaligned spins in a few sources.

Highly unequal masses in GW190412 $(30+8)M_\odot$.

All agree with coalescence of PBHs.

PBH formation, modified mechanism

The 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 $\beta \approx 10^{-9}$.
This 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 Swiss cheese, holes being high baryonic density bubbles (HBB) occupying a minor fraction of the total volume, but finely acquiring a dominant part of the total mass of the universe.
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. Initially tiny HBBs are stretched out by inflation far beyond horizon in the very early universe. As a result astronomically significant bubbles with very high isocurvature perturbations had been created. Reentering inside horizon and starting from the QCD phase transition these isocurvature perturbations turned into density perturbations and finally to PBHs.
HBBs, not large enough to end their lives as PBH might turn into peculiar stars: too old (even formally older than the universe), stars with unusual chemistry, too fast stars. All them are observed in the Galaxy.
Even antimatter stars can be created, not yet observed, but still allowed. The may be abundant enough to make significant (up to 100%) contribution to dark matter.

Creation Mechanism

SUSY motivated baryogenesis, Affleck and Dine (AD). SUSY predicts existence of scalars with $\mathbf{B} \neq \mathbf{0}$. Such bosons may condense along flat directions of the quartic potential:

$$U_\lambda(\chi) = \lambda|\chi|^4 \left(1 - \cos 4\theta\right)$$

and of the mass term, $m^2\chi^2 + m^{*\,2}\chi^{*\,2}$:

$$U_m(\chi) = m^2|\chi|^2[1 - \cos\left(2\theta + 2\alpha\right)]\,,$$

where $\chi = |\chi| \exp\left(i\theta\right)$ and $m = |m|e^{\alpha}$.

If $\alpha \neq 0$, C and CP are broken.

In GUT SUSY baryonic number is naturally non-conserved - non-invariance of $U(\chi)$ w.r.t. phase rotation.

Creation Mechanism

Initially (after inflation) χ is away from origin and, when inflation is over, starts to evolve down to equilibrium point, $\chi = 0$, according to Newtonian mechanics:

$$\ddot{\chi} + 3H\dot{\chi} + U'(\chi) = 0.$$

Baryonic charge of χ:

$$B_\chi = \dot{\theta}|\chi|^2$$

is analogous to mechanical angular momentum. χ decays transferred baryonic charge to that of quarks in B-conserving process.

AD baryogenesis could lead to baryon asymmetry of order of unity, much larger than the observed 10^{-9}.

Creation Mechanism

If $m \neq 0$, the angular momentum, B, is generated by a different direction of the quartic and quadratic valleys at low χ. If CP-odd phase α is small but non-vanishing, both baryonic and antibaryonic domains might be formed with possible dominance of one of them. Matter and antimatter domains may exist but globally $B \neq 0$.

Affleck-Dine field χ with CW potential coupled to inflaton Φ (AD and Silk; AD, Kawasaki, Kevlishvili):

$$U = g|\chi|^2(\Phi - \Phi_1)^2 + \lambda|\chi|^4 \ln\left(\frac{|\chi|^2}{\sigma^2}\right)$$
$$+\lambda_1(\chi^4 + h.c.) + (m^2\chi^2 + h.c.).$$

Coupling to inflaton is the general renormalizable one.
When the window to the flat direction is open, near $\Phi = \Phi_1$, the field χ slowly diffuses to large value.

Creation Mechanism

If the window to flat direction, when $\Phi \approx \Phi_1$ is open only during a short period, cosmologically small but possibly astronomically large bubbles with high β could be created, occupying a small fraction of the universe, while the rest of the universe has normal $\beta \approx 6 \cdot 10^{-10}$, created by small χ. Phase transition of 3/2 order.

The mechanism of massive PBH formation quite different from all others. The fundament of PBH creation is build at inflation by making large isocurvature fluctuations at relatively small scales, with practically vanishing density perturbations.

Initial isocurvature perturbations are in chemical content of massless quarks. Density perturbations are generated rather late after the QCD phase transition.

Creation Mechanism

The outcome, depending on $\beta = n_B/n_\gamma$.

- PBHs with log-normal mass spectrum.
- Compact stellar-like objects, as e.g. cores of red giants.
- Disperse hydrogen and helium clouds with (much) higher than average n_B density.
- β may be negative leading to compact antistars which could survive annihilation with the homogeneous baryonic background.

A modification of inflaton interaction with scalar baryons as e.g.

$$U \sim |\chi|^2(\Phi - \Phi_1)^2((\Phi - \Phi_2)^2$$

gives rise to a superposition of two log-normal spectra or multi-log.

Recently there arose a torrent of new abundant BHs, presumably primordial. In any single case an alternative interpretation might be possible but the overall picture is very much in favor of massive PBHs.

Dark antimatter

C. Bambi, A.D. Dolgov "Antimatter in the Milky Way", Nucl.Phys.B 784 (2007) 132-150 e-Print: astro-ph/0702350 [astro-ph];
A.D. Dolgov, S.I. Blinnikov, "Stars and Black Holes from the very Early Universe" Phys.Rev.D 89 (2014) 2, 021301 e-Print: 1309.3395 [astro-ph];
S.I. Blinnikov, A.D. Dolgov, K. A. Postnov, "Antimatter and antistars in the universe and in the Galaxy", PRD 92, 023516, 2015, 1409.5736;
Very recently: J.S. Sidhu, R.J. Scherrer, G. Starkman, "Antimatter as Macroscopic Dark Matter" arXiv:2006.01200.
Antimatter macroscopic dark matter (macros) refers to a generic class of antimatter dark matter candidates that interact with ordinary matter primarily through annihilation with large cross-sections. A combination of terrestrial, astrophysical, and cosmological observations constrain a portion of the anti-macro parameter space. However, a large region of the parameter space remains unconstrained, most notably for nuclear-dense objects.

14 billion years ago

Anna-Christina Eilers 'The Formation and Growth of Supermassive Black Holes" Aspen Colloquium June 23, 2020
Recent discovery of an unexpected population of very young quasars, $z \sim 6$, indicating lifetimes of only 10,000 years, which is several orders of magnitude shorter than expected. Very short time of activity, which means that the real number of SMBH is much higher than observed.

Eilers, private communication: "Primordial black holes are definitely an interesting potential solution, however, whether they can actually explain the black hole growth in very short times, depends on how massive these initial primordial black holes would be. To my knowledge, these primordial black holes are expected to be around $10^5 - 10^6$ solar masses, which is still not enough time, to grow a billion solar mass black hole in 10^6 years. The primordial black holes would need to be of the order of 10^8 to almost 10^9 solar masses in size, before accretion onto them starts happening."

Conclusion

- DM consisting of PBH up to 100% remains a viable possibility.
- **Log-normal mass spectrum of PBH is observationally established.**
- Dark matter made of antimatter is an exciting new possibiity.

Some extra:

- All or almost all black holes in the universe are primordial, including SMBH and IMBH now and at $\mathbf{z \sim 10}$.
- PBHs explains the peculiar features of the sources of GWs observed by LIGO/Virgo.
- Inverted picture of galaxy formation, when supermassive BH seeds are first formed and later accrete matter forming galaxies, is a good alternative to the canonical one.

HAPPY(?) END