Primordial Black Holes Around Us Now, Long Before, and Far away

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Black holes everywhere in space and time

Astronomical data of the last decade strongly indicate that contemporary universe $t_U = 14.5$ Gyr and the young one, $\mathbf{t_U} \sim \mathbf{0.5}$ Gyr are filled with unexpectedly high amount of black holes in all mass ranges:
supermassive black holes (SMBH), $M = 10^{10} - 10^{6})M_\odot$,
intermediate mass black holes (IMBH), $\mathbf{M} = (\mathbf{10^2} - \mathbf{10^5})\mathbf{M}_\odot$,
BHs with $M \sim 10 M_\odot$,
and maybe BHs even with a fraction of $\mathbf{M}_\odot$ mass.
These BHs are observed just next door in our Galaxy, in contemporary far-away galaxies, and in the young universe at $\mathbf{z} = \mathbf{5} - \mathbf{10}$.
They 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; a lot of new data since that time.

Three types of BH: astrophysical, accreting, primordial

I. Astrophysical BHs: created by stellar collapse after star exhausted its nuclear fuel. Expected masses are just above the neutron star masses $3M_\odot$ and normally they are quite close to it.
Instead, the mass spectrum of BH in the Galaxy has maximum at $M \approx 8M_\odot$ with the width: $\sim (1-2)M_\odot$.

II. BH created by matter accretion to excessive density regions.
There is a supermassive BH (SMBH) in any large galaxy with $M \gtrsim 10^9 M_\odot$ in elliptic and lenticular galaxies and $\mathbf{M} \sim (10^6 - 10^7)\mathbf{M}_\odot$ in elliptic galaxies, as Milky Way. However, the known mechanisms of accretion are not efficient enough to create such monsters during the universe age $t_U \approx 15$ Gyr. Very massive seeds are necessary, but their origin is mysterious. Moreover SMBH are found in very small galaxies and one SMBH lives even in almost empty space.
SMBH are also discovered recently in quite young universe with the age about (1 - 0.5) Gyr. Probably SMBH belong to class III, next page.

Three types of BH: astrophysical, accreting, primordial

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

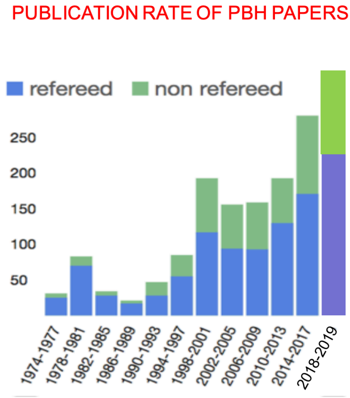
The idea of the primordial black hole (PBH) i.e. of black holes which could be formed the early universe prior to star formation was first put forward by Zeldovich and Novikov: "The Hypothesis of Cores Retarded During Expansion and the Hot Cosmological Model", Astronomicheskij Zhurnal, 43 (1966) 758,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

According to their idea, the density contrast in the early universe inside the bubble with 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 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).

Publication on PBH per year, B. Carr, 2019. Exotics turned into routine.



PBH formation, modified mechanism

A different mechanism (AD, J.Silk, 1993) could create 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.
The suggested scenario of PBH formation pioneered in implementation of inflation to PBH formation. It allows for PBH huge masses, much larger than horizon mass in the very early universe.
A long list of works on inflationary formation nowadays...

PBH formation, modified mechanism

The suggested 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 the central mass, M_0, is equal to the known mass inside horizon at the QCD phase transition.**

Central mass value

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

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

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.

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 M_c is the so called chirp mass:

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

and

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

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 ($\sim \mathbf{30} M_{\odot}$); recently there appeared much more striking problem of BH with $M \sim \mathbf{100} M_{\odot}$. 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 .

1. Such BHs are believed to be created by massive star collapse, though a convincing theory is still lacking.

To form so heavy BHs, the progenitors should have $M > \mathbf{100} M_{\odot}$. and a low metal abundance to avoid too much mass loss during the evolution. Such heavy stars might be present in young star-forming galaxies but they are not observed in the necessary amount. PBHs with the observed by LIGO masses may be easily created with sufficient density.

Gravitational waves from BH binaries

2. Formation of BH binaries. Stellar binaries are formed from common interstellar gas clouds and are quite frequent in galaxies. If BH is created through stellar collapse, a small non-sphericity results in a huge velocity of the BH and the binary is destroyed. BH formation from PopIII stars and subsequent formation of BH binaries with tens of $M_\odot$ is estimated to be small. The problem of the binary formation is simply solved if the observed sources of GWs are the binaries of primordial black holes. They were at rest in the comoving volume, when inside horizon they are gravitationally attracted and may loose energy due to dynamical friction in the early universe. The probability to become gravitationally bound is significant.

The conventional scenario is not excluded but less natural.

Gravitational waves from BH binaries

3. The low value of the BH spins in GW150914 and in almost all (except for three) other events. It strongly constrains astrophysical BH formation from close binary systems. Astrophysical BHs are expected to have considerable angular momentum, nevertheless the dynamical formation of double massive low-spin BHs in dense stellar clusters is not excluded, though difficult. On the other hand, PBH practically do not rotate because vorticity perturbations in the early universe are vanishingly small.

However, individual PBH forming a binary initially rotating on elliptic orbit could gain COLLINEAR spins about 0.1 - 0.3, rising with the PBH masses and eccentricity (Postnov, Mitichkin, JCAP 1906 (2019) no.06, 044 arXiv:1904.00570; Postnov, Kuranov, Mitichkin, Physics-Uspekhi vol. 62, No. 11, (2019), arXiv:1907.04218) . This result is in agreement with the GW170729 LIGO event produced by the binary with masses $\mathbf{50}\boldsymbol{M_\odot}$ and $\mathbf{30}\boldsymbol{M_\odot}$ and and GW190521. **To summarize: each of the mentioned problems may be solved in the conventional frameworks but it looks much simpler to assume that the LIGO sources are primordial.**

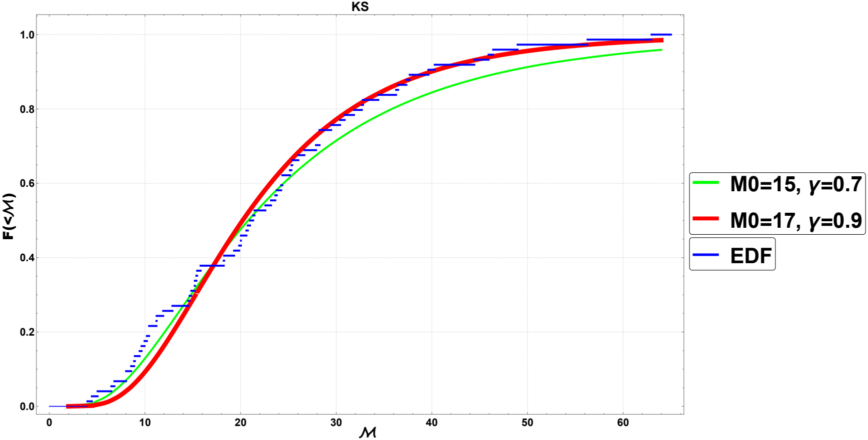
Chirp mass distribution

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.

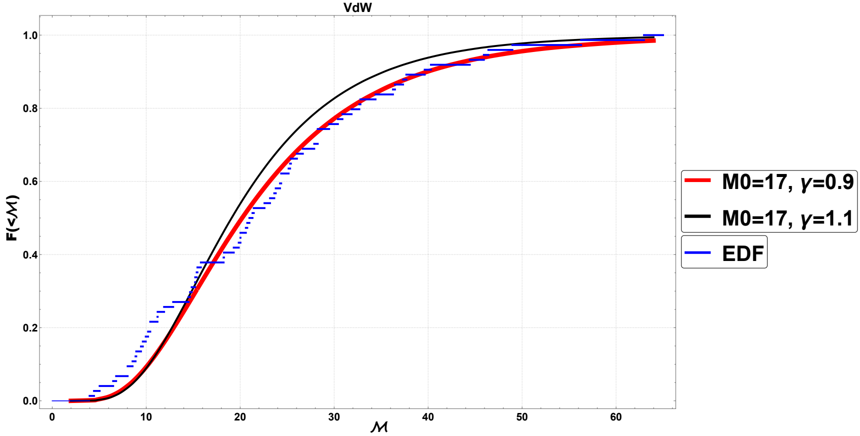
Chirp mass distribution

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



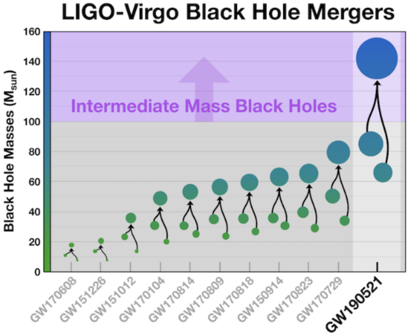
Chirp mass distribution

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



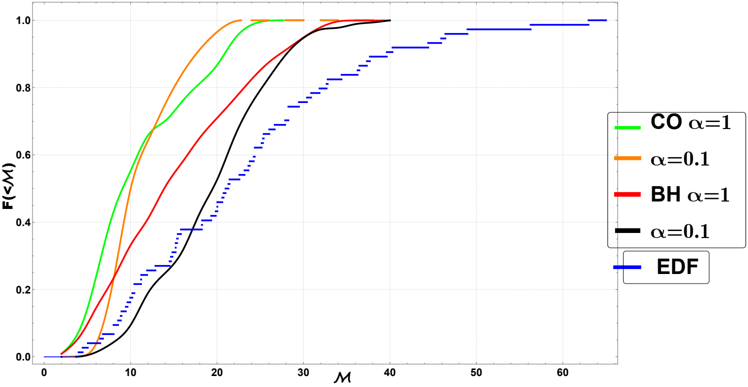
GW190521

Merging of $(65 + 85) M_\odot \to 142 M_\odot$.
With this event the agreement is even better. The spins of the initial BHs may be about 0.3 as predicted by Postnov and Mitichkin.



Chirp mass distribution, astrophysical BHs

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



PBH as DM

It was suggested by Chapline that PBH with masses below the solar mass might be abundant in the present-day universe with the density comparable to the density of dark matter. Neither mechanism of PBH formation was specified. G.F. Chapline, Nature, 253, 251 (1975).
AD and J. Silk: New mechanism of PBH formation with log-normal mass spectrum and masses up to $10^5 M_\odot$ and possibly much higher. Dark matter with extended mass spectrum.
An avalanche of papers on PBH DM much later, reviewed by B. Carr and F. Kuhnel, "Primordial Black Holes as Dark Matter: Recent Developments", arXiv:2006.02838 [astro-ph.CO] June, 2020. Limits on BH for different mass.
NB: Carr, 2019: all limits are model dependent and have caveats.
Eliminating LIGO bounds on PBH dark matter, C. Boehm, et al arXiv:2008.10743 .... reopens the possibility for dark matter in the form of LIGO-mass PBHs.

Bounds on PBHs - B.Carr, F. Kuhnel arXiv:2006.02838, June 2020

for monochromatic mass spectrum

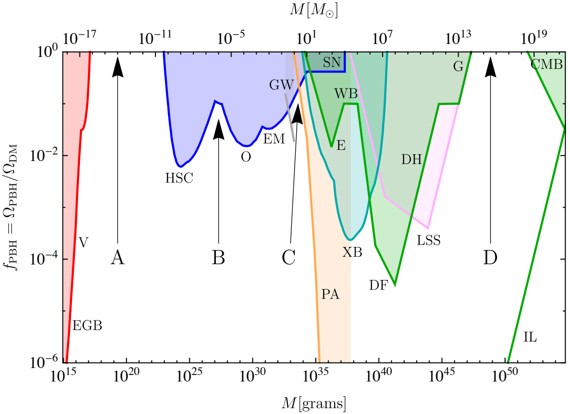


Figure caption

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.

SMBH today, $t_U = 14.6 \cdot 10^9$ year old

Every large galaxy contains a central supermassive BH with mass $\sim (10^6 - 10^7) M_\odot$ in spiral galaxies like Milky Way and larger than $10^9 M_\odot$ in giant elliptical and compact lenticular galaxies, up to the record **60 billions solar masses:TON 618** (C.H. Nelson,Ap.J. 544 (2), L91).

The origin of these BHs is not understood.

Accepted belief is that these BHs are created by matter accretion to a central seed. But, the usual accretion efficiency is insufficient to create them during the Universe life-time, 14.6 Gyr. An estimate of the accretion efficiency in the Galaxy E.M. Murchikova, et al Nature 570, 83 (2019): Building up SMBH SgrA* with the mass $\sim 4 \times 10^6 M_\odot$ residing at the centre of our galaxy. within the $\sim 10^{10}$ year lifetime of our galaxy would require a mean accretion rate of $4 \times 10^{-4} M_\odot$ per year. At present, X-ray observations constrain the rate of hot gas accretion to $\dot{M} \sim 3 \times 10^{-6} M_\odot$ per year and polarization measurements constrain it near the event horizon to $\dot{M}_{hor} \sim 10^{-8} M_\odot/\mathrm{yr}$.

The universe age is short by two orders of magnitude.

SMBH today, $t_U = 14.6 \cdot 10^9$ year old

Even more puzzling: SMHBs are observed in **very small galaxies** and even in almost EMPTY space, where no material to make a SMBH can be found. A Nearly Naked Supermassive Black Hole J.J. Condon, et al arXiv:1606.04067.

The mass of BH is typically 0.1% of the mass of the stellar bulge of galaxy but some galaxies may have huge BH: e.g. NGC 1277 has the central BH of $\mathbf{1.7 \times 10^{10} M_\odot}$, or $\mathbf{60}$% of its bulge mass. This creates serious problems for the scenario of formation of central supermassive BHs by accretion of matter in the central part of a galaxy.

F. Khan, et al arXiv:1405.6425. Although supermassive black holes correlate well with their host galaxies, there is an emerging view that outliers exist. Henize 2-10, NGC 4889, and NGC1277 are examples of SMBHs at least AN ORDER OF MAGNITUDE MORE MASSIVE than their host galaxy suggests.

An inverted picture is more plausible, when first a supermassive BH was formed and attracted matter seeding the galaxy formation!!!

SMBH today, SMH clumping

Several binaries of SMBH observed:

P. Kharb, et al "A candidate sub-parsec binary black hole in the Seyfert galaxy NGC 7674", d=116 Mpc, $\mathbf{3.63 \times 10^7} M_\odot$. (1709.06258).

C. Rodriguez et al. A compact supermassive binary black hole system. Ap. J. 646, 49 (2006), $d \approx \mathbf{230}$ Mpc.

M.J.Valtonen,"New orbit solutions for the precessing binary black hole model of OJ 287", Ap.J. 659, 1074 (2007), $z \approx \mathbf{0.3}$.

M.J. Graham et al. "A possible close supermassive black-hole binary in a quasar with optical periodicity". Nature 518, 74 (2015), $z \approx \mathbf{0.3}$.

Triple Quasar.

E. Kalfountzou, M.S. Lleo, M. Trichas, SDSS J1056+5516: A Triple AGN or an SMBH Recoil Candidate? [1712.03909].

Discovery of a kiloparsec-scale supermassive black hole system at z=0.256. The system contains three strong emission-line nuclei, which are offset by $< \mathbf{250}$ km/s by 15-18 kpc in projected separation, suggesting that the nuclei belong to the same physical structure.

Universe today, SMBH quartet.

"Quasar quartet embedded in giant nebula reveals rare massive structure in distant universe", J.F. Hennawi et al, Science 15 May 2015, 348 p. 779, Discovery of a a physical association of four quasars at $z \approx 2$. The probability of finding a quadruple quasar is $\sim 10^{-7}$. Our findings imply that the most massive structures in the distant universe have a tremendous supply ($\sim 10^{11}$ solar masses) of cool dense (volume density $\sim 1/\text{cm}^3$) gas, which is in conflict with current cosmological simulations.
Orthodox point of view: merging of two spiral galaxies creating an elliptical galaxy, leaving two or more SMBHs in the center of the merged elliptical. No other way in the traditional approach. However, even one SMBH is hard to create.

Heretic but simpler: primordial SMBH forming binaries in the very early universe and seeding galaxy formation.

14 billion years ago

About 100 QSO with $z > 6$ are known, with billion solar mass SMBH.
Maximum redshift: z=7.54, E. Bañados, et al. "An 800-million-solar-mass black hole in a significantly **neutral** Universe at a redshift of 7.5". Nature. 553 (7689): 473.
Second most-distant quasar (Pōniuā'ena): z=7.52, $M = 1.5 \cdot 10^9 M_\odot$.
J. Yang et al, A Luminous z=7.5 Quasar Hosting a 1.5 Billion Solar Mass Black Hole". arXiv:2006.13452 June 2020. Models indicate it must have formed not later than 100 million years after the Big Bang.
In addition to all that another monster was discovered "An ultraluminous quasar with a twelve billion solar mass black hole at redshift 6.30". Xue-BingWu et al, Nature 518, 512 (2015). The problem with formation of lighter quasars multifold deepens with this new "creature".
Accretion rate: M.A. Latif, M Volonteri, J.H. Wise, [1801.07685] ".. halo has a mass of $\mathbf{3 \times 10^{10}}$ $M_\odot$ at $z = \mathbf{7.5}$; MBH accretes only about 2200 $M_\odot$ during 320 Myr."

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, $z \sim \mathbf{6}$, 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."

Early galaxies, 14 billion years ago, overstock

Galaxy at $z \approx 9.6$ created earlier than ~ 0.5 Gyr, W. Zheng, *et al*
Galaxy at $z \approx 11$ formed earlier than the universe age was $t_U \sim 0.4$ Gyr, D. Coe *et al* Astrophys. J. 762 (2013) 32.
Not so young but extremely luminous galaxy Chao-Wei Tsai, P.R.M. Eisenhardt *et al*, arXiv:1410.1751, $L = 3 \cdot 10^{14} L_\odot$; $t_U \sim 1.3$ Gyr.
The galactic seeds, or embryonic black holes, might be bigger than thought possible. The BH was already billions of $M_\odot$, when our universe was only a tenth of its present age. "Another way to grow this big is to have gone on a sustained binge, consuming food faster than typically thought possible. Low spin is needed!
According to D. Waters, et al, MNRAS 461 (2016), L51 density of galaxies at $z \approx 11$ is 10^{-6} Mpc^{-3}, an order of magnitude higher than estimated from the data at lower z.
Origin of these galaxies is unclear. Inverted picture of galaxy formation can solve the problem: primordial SMBHs seeded galaxies but not vice versa, and not only in young universe but also today.

Young universe. QSO alias SMBH

To conclude on QSO/SMBH:
The quasars are supposed to be supermassive black holes and their formation in such short time by conventional mechanisms looks problematic. Such black holes, when the Universe was less than one billion years old, present substantial challenges to theories of the formation and growth of black holes and the coevolution of black holes and galaxies. Even the formation of SMBH in contemporary universe during 14 Gyr is hard to explain.
It is difficult to understand how $10^9 M_\odot$ black holes (to say nothing about $\mathbf{10^{10}} M_\odot$) appeared so quickly after the big bang without invoking non-standard accretion physics and the formation of massive seeds, both of which are not seen in the local Universe.

Intermediate Summary

Model predictions, postdictions and claims.

• All or at least almost all black holes in the universe are primordial.

• Primordial BHs make all or dominant part of dark matter (DM).

• PBHs formed according to this scenario explain the peculiar features of the sources of GWs observed by LIGO/Virgo.

• The existence of supermassive black holes observed in all large and some small galaxies and even in almost empty environment is naturally explained. Conventional models are short by two orders of magnitude.

• Inverted picture of galaxy formation, when supermassive BH seeds are first formed and later accrete matter forming galaxies, looks more natural.

Other problems today and 14 billion years ago.

• MACHOS: invisible stellar type objects with $\mathbf{M \sim 0.5 M_\odot}$ observed through gravitational microlensing.

• IMBH unexpected but quite abundant, thousands of them.

• Peculiar stars" too old, too fast, with strange chemistry.

• Globular clusters seeding by $\mathbf{(10^3 - 10^4)} M_\odot$ BHs, and dwarfs by $\mathbf{(10^4 - 10^5)} M_\odot$ BHs. AD, K.Postnov, JCAP 04 (2017) 036.

• Overpopulation of the young, $\mathbf{z \sim 10}$ universe with early created gamma-bursters and supernovae, early bright galaxies, evolved chemistry including huge amount of dust.

Conclusion

- 1. Natural baryogenesis model leads to abundant fomation of PBHs and compact stellar-like objects in the early universe after QCD phase transition, $t \gtrsim 10^{-5}$ sec.
- 2. Log-normal mass spectrum of these objects.
- 3. PBHs formed at this scenario can explain the peculiar features of the sources of GWs observed by LIGO.
- 4. The considered mechanism solves the numerous mysteries of $z \sim 10$ universe: abundant population of supermassive black holes, early created gamma-bursters and supernovae, early bright galaxies, and evolved chemistry including dust.
- 5. There is persuasive data in favor of the inverted picture of galaxy formation, when first a supermassive BH seeds are formed and later they accrete matter forming galaxies.

Concluskion

• 6. An existence of supermassive black holes observed in all large and some small galaxies and even in almost empty environment is naturally explained.

• 7. "Older than t_U" stars may exist; the large age is mimicked by the unusual initial chemistry.

• 8. Explanation of origin of BHs with 2000 $M_\odot$ in the core of globular cluster and the observed density of GCs.

• 9. A large number of the recently observed IMBH was predicted.

• 10. A large fraction of dark matter or 100% can be made of PBHs.

• 11. Clouds of matter with high baryon-to-photon ratio.

• 12. A possible by-product: plenty of (compact) anti-stars, even in the Galaxy, not yet excluded by observations (C. Bambi, S. Blinnikov, AD., K.Postnov).

Extreme point of view:

• Black holes in the universe are mostly primordial (PBH).

• Primordial BHs make all or dominant part of dark matter (DM).

The end of the talk but not the end of the story

Universe today, MACHOs

• MACHOs: discovered through gravitational microlensing by Macho and Eros groups. They are invisible (very weakly luminous or even non-luminous) objects with masses about a half of the solar mass in the Galactic halo, in the center of the Galaxy, and recently in the Andromeda (M31) galaxy. Their density is significantly greater than the density expected from the known low luminosity stars and the BH of similar mass.
f = mass ratio of MACHOS to DM.
Macho group: $\mathbf{0.08 < f < 0.50}$ (95% CL) for $\mathbf{0.15 M_\odot < M < 0.9 M_\odot}$;
EROS: $\mathbf{f < 0.2}$, $\mathbf{0.15 M_\odot < M < 0.9 M_\odot}$;
EROS2: $\mathbf{f < 0.1}$, $\mathbf{10^{-6} M_\odot < M < M_\odot}$;
AGAPE: $\mathbf{0.2 < f < 0.9}$,
for $\mathbf{0.15 M_\odot < M < 0.9 M_\odot}$;
EROS-2 and OGLE: $\mathbf{f < 0.1}$ for $\mathbf{M \sim 10^{-2} M_\odot}$ and
$\mathbf{f < 0.2}$ for $\mathbf{\sim 0.5 M_\odot}$.
MACHOs surely exist but who are they is not known.

?

Globular clusters and dwarf galaxies

Only one or two massive BH are observed in Globular clusters.
Definite evidence of BH with $M \approx 2000 M_\odot$ was found in the core of the globular cluster 47 Tucanae.
Origin in standard model is unknown.

Our prediction (AD, K.Postnov): if the parameters of the mass distribution of PBHs are chosen to fit the LIGO data and the density of SMBH, then the number of PBH with masses $(2-3) \times 10^3 M_\odot$ is about $10^4 - 10^5$ per one SMPBH with mass $> 10^4 M_\odot$. This allows all large galaxies to host their own SMBH, sometimes even two!.
This predicted density of IMBHs is sufficient to seed the formation of all globular clusters and dwarf galaxies.

PBH creation mechanism

The mechanism of massive PBH formation with wide mass spectrum:

- 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".

Heretic predictions of 1993 are turning into the accepted faith, since they became supported by the recent astronomical data.
Massive PBHs allow to cure emerging inconsistencies of the standard cosmology and astrophysics with unexpectedly huge number of newly discovered massive BH
Dark matter made out of PBHs became a viable option.
Unusual stellar type compact objects could also be created.
The mechanism leads to Swiss cheese universe "upside down": small bubbles with high $\beta \equiv N_B/N_\gamma \sim 1$ and the under-dense low B background mostly turned into PBH and compact stellar-like objects.

PBH creation mechanism

The model predicts an abundant formation of heavy PBHs with log-normal mass spectrum:

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

with 3 constant parameters: μ, γ, M_0. The value of M_0 should be about $\mathbf{10M_\odot}$.

Can be generalized to multi-maximum spectrum.

For high BH masses, $M_{BH} \gtrsim 10^4 M_\odot$ may be noticeably distorted due to subsequent accretion.

This form is a result result of quantum diffusion of baryonic scalar field during inflation (Starobinsky diffusion equation). Probably log-normal spectrum is a general consequence of diffusion.

Now in many works such spectrum is postulated without justification.

PBH 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:

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

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

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

where $\chi = |\chi| \exp(i\theta)$ and $m = |m|e^{\alpha}$.
If $\alpha \neq \mathbf{0}$, C and CP are broken.
In GUT SUSY baryonic number is naturally non-conserved - non-invariance of $U(\chi)$ w.r.t. phase rotation.

PBH 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}.

PBH 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 $B \neq 0$.
New input: Affleck-Dine field χ with coupling to inflaton Φ

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

An interaction between two scalar fields is Φ and χ must exist. This coupling is a general renormalizable one. The only mild tuning is that Φ reached and passed Φ_1 during inflation. Duration of inflation after that is a free parameter.
When the window to the flat direction is open, near $\Phi = \Phi_1$, the field χ slowly diffuses to large value, according to quantum diffusion

PBH 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 variation of the asymmetry in number densities of massless quarks and antiquarks. Density perturbations are generated rather late after the QCD phase transition when quarks turn into massive baryons.

The emerging universe may be full of black holes occupying a minor fraction of the universe volume, where the total amount of baryons may be larger than that in the rest of the world.

PBH creation mechanism

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

- PBHs with log-normal mass spectrum.
- Compact stellar-like objects, similar e.g. to 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 a torrent of new abundant BHs, has been observed presumably primordial. In any single case an alternative interpretation might be possible but the overall picture is very much in favor of massive PRIMORDIAL BHs.

Young universe: chemistry, dust, supernovae, γ-bursters

The medium around the observed early quasars contains considerable amount of "metals" (elements heavier than He). According to the standard picture, only elements up to ^{4}He and traces of Li, Be, B were formed by BBN, while heavier elements were created by stellar nucleosynthesis and dispersed in the interstellar space by supernova explosions. Hence, an evident but not necessarily true conclusion was that prior to or simultaneously with the QSO formation a rapid star formation should take place. These stars should evolve to a large number of supernovae enriching interstellar space by metals through their explosions. Demands very long time.

Another possibility is a non-standard BBN in bubbles with very high baryonic density, leading to formation of heavy elements.

Young universe: chemistry, dust, supernovae, γ-bursters

The universe at $z > \mathbf{6}$ is quite dusty, D.L. Clements et al "Dusty Galaxies at the Highest Redshifts", 1505.01841.
The highest redshift such object, HFLS3, lies at z=6.34 and numerous other sources have been found.

L. Mattsson, "The sudden appearance of dust in the early Universe",1505.04758: Dusty galaxies show up at redshifts corresponding to a Universe which is only about 500 Myr old.
Abundant dust is observed in several early galaxies, e.g. in HFLS3 at $z = \mathbf{6.34}$ and in A1689-zD1 at $z = \mathbf{7.55}$.

Catalogue of the observed dusty sources indicates that their number is an order of magnitude larger than predicted by the canonical theory.

Young universe: chemistry, dust, supernovae, γ-bursters

To make dust a long succession of processes is necessary: first, supernovae explode to deliver heavy elements into space (metals), then metals cool and form molecules, and lastly molecules make dust which could form macroscopic pieces of matter, turning subsequently into early rocky planets.

We all are dust from SN explosions, at much later time but there also could be life in the early universe. Several hundred million years is enough for that.

Observations of high redshift gamma ray bursters (GBR) also indicate a high abundance of supernova at large redshifts. The highest redshift of the observed GBR is 9.4 and there are a few more GBRs with smaller but still high redshifts.

The necessary star formation rate for explanation of these early GBRs is at odds with the canonical star formation theory.

Universe today: IMBH, $M = (10^3 - 10^5) M_\odot$

• Intermediate mass black holes (MBH) $M = (10^3 - 10^5) M_\odot$

Nobody expected them in noticeable amount and now they came out as if from cornucopia (cornu copiae).

Intermediate mass BHs: $M \sim 10^3 M_\odot$, in globular clusters and $M \sim 10^4 - 10^5$ in dwarf galaxies.

10 IMBH, 3 years ago, $M = 3 \times 10^4 - 2 \times 10^5 M_\odot$
and 40 found recently $10^7 < M < 3 \cdot 10^9$ [Chandra, 1802.01567].

More and more: I.V. Chilingarian, et al. A Population of Bona Fide Intermediate Mass Black Holes Identified as Low Luminosity Active Galactic Nuclei arXiv:1805.01467, identified a sample of 305 IMBH candidates with $3 \times 10^4 < M_{\rm BH} < 2 \times 10^5 M_\odot$,

He-Yang Liu, et al, A Uniformly Selected Sample of Low-Mass Black Holes in Seyfert 1 Galaxies. arXiv:1803.04330, A new sample of 204 low-mass black holes (LMBHs) in active galactic nuclei is presented with black hole masses in the range of $(1 - 20) \times 10^5 M_\odot$.

Universe today, IMBH

"Indication of Another Intermediate-mass Black Hole in the Galactic Center"' S. Takekawa, et al.,arXiv:1812.10733 [astro-ph.GA]
We report the discovery of molecular gas streams orbiting around an invisible massive object in the central region of our Galaxy, based on the high-resolution molecular line observations with the Atacama Large Millimeter/submillimeter Array (ALMA). The morphology and kinematics of these streams can be reproduced well through two Keplerian orbits around a single point mass of $(\mathbf{3.2} \pm \mathbf{0.6}) \times \mathbf{10^4} M_\odot$. Our results provide new circumstantial evidences for a wandering intermediate-mass black hole in the Galactic center (tramp in the galaxy), suggesting also that high-velocity compact clouds can be probes of quiescent black holes abound in our Galaxy.
As an alternative: it could be nucleus of a globular cluster with stars stripped away by dense stellar population in the galactic center.

Universe today, too old stars

• Old stars in the Milky Way:

Employing thorium and uranium in comparison with each other and with several stable elements the age of metal-poor, halo star BD+17^o 3248 was estimated as $\mathbf{13.8 \pm 4}$ Gyr. J.J. Cowan, et al Ap.J. 572 (2002) 861

The age of inner halo of the Galaxy $\mathbf{11.4 \pm 0.7}$ Gyr, J. Kalirai, "The Age of the Milky Way Inner Halo" Nature 486 (2012) 90, arXiv:1205.6802.

The age of a star in the galactic halo, HE 1523-0901, was estimated to be about 13.2 Gyr. First time many different chronometers, such as the U/Th, U/Ir, Th/Eu and Th/Os ratios to measure the star age have been employed. "Discovery of HE 1523-0901: A Strongly r-Process Enhanced Metal-Poor Star with Detected Uranium", A. Frebe, N. Christlieb, J.E. Norris, C. Thom Astrophys.J. 660 (2007) L117; astro-ph/0703414.

Universe today, too old stars

Metal deficient high velocity subgiant in the solar neighborhood HD 140283 has the age $\mathbf{14.46 \pm 0.31}$ Gyr.
H. E. Bond, et al, Astrophys. J. Lett. 765, L12 (2013), arXiv:1302.3180.
The central value exceeds the universe age by two standard deviations, if $H = 67.3$ and $t_U = 13.8$; and if $H = 74$, then $t_U = 12.5$, more than 10 σ.

Our model predicts unusual initial chemical content of the stars, so they may look older than they are.

X. Dumusque, *et al* "The Kepler-10 Planetary System Revisited by HARPS-N: A Hot Rocky World and a Solid Neptune-Mass Planet". arXiv:1405.7881; Ap J., 789, 154, (2014).
Very old planet, $\mathbf{10.6^{+1.5}_{-1.3}}$ Gyr. (Age of the Earth: 4.54 Gyr.)
A SN explosion must must precede formation of this planet.

Universe today, high velocity stars

Very recent observations: high velocity and "wrong" chemical content stars. We report the discovery of a high proper motion, low-mass white dwarf (LP 40-365) that travels at a velocity greater than the Galactic escape velocity and whose peculiar atmosphere is dominated by intermediate-mass elements. S. Vennes et al, Science, 2017, Vol. 357, p. 680; arXiv:1708.05568. Origin mysterious. Could it be compact primordial star?

Other high velocity stars in the Galaxy.
"Old, Metal-Poor Extreme Velocity Stars in the Solar Neighborhood", Kohei Hattori et al., arXiv:1805.03194,.
Gaia DR2 in 6D: Searching for the fastest stars in the Galaxy, T. Marchetti, et al., arXiv:1804.10607.
They can be accelerated by a population of IMBH in Globular clusters, if there is sufficient number of IMBHs.

Universe today, strange stars

D.P. Bennett, A. Udalski, I.A. Bond, et al, "A Planetary Microlensing Event with an Unusually RED Source Star", arXiv:1806.06106

We find host star and planet masses of $M_{\rm host} = 0.15^{+0.27}_{-0.10} M_\odot$ and $m_p = 18^{+34}_{-12} M_\oplus$.
The life-time of main sequence star with the solar chemical content is larger than t_U already for $M < 0.8 M_\odot$.
The origin is puzzling. May it be primordial helium star?
"A class of partly burnt runaway stellar remnants from peculiar thermonuclear supernovae", arXiv:1902.05061, R. Raddi et al.
Discovery of three chemically peculiar runaway stars, survivors of thermonuclear explosions - according to the authors. "With masses and radii ranging between 0.20-0.28 $M_\odot$ and 0.16-0.60 $R_\odot$, respectively, we speculate these inflated white dwarfs are the partly burnt remnants of either peculiar Type SNIa or electron-capture supernovae".

Universe today, mass spectrum of BHs in the Galaxy

- Mass spectrum of astrophysical (?) BH

It was found that the BH masses are concentrated in the narrow range $(\mathbf{7.8 \pm 1.2}) M_{\odot}$ (1006.2834).
This result agrees with another paper where a peak around $\mathbf{8} M_{\odot}$, a paucity of sources with masses below $\mathbf{5} M_{\odot}$, and a sharp drop-off above $\mathbf{10} M_{\odot}$ are observed, arXiv:1205.1805.
These features are not easily explained in the standard model of BH formation by stellar collapse.