Black Holes, Primordial and Other

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Black holes everywhere in space and time

Astronomical data of the last decade strongly indicate that contemporary universe $t_U = \mathbf{14.5}$ Gyr and the young one, $\mathbf{t_U \sim 0.5}$ 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), $\mathbf{M = (10^2 - 10^5) M_\odot}$,
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 close and far-away galaxies, and in the young universe at $\mathbf{z = 5 - 10}$.
They can make all or a weighty fraction of the cosmological dark matter, seed 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: $\sim (1-2)M_\odot$.
The result is rather surprising but reasonable explanations in the frameworks of the standard astrophysics are found.
As we see in what follows (also in the lecture by Postnov) the predicted distribution of PBH has similar form.

BUT, LIGO/Virgo discovered BHs with masses close to 10^2 solar masses. Their astrophysical origin was believed impossible. Nowadays several quite exotic explanations are suggested.

Three types of BH: astrophysical, accreting, primordial

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 in lenticular galaxies and
$\mathbf{M} \sim (\mathbf{10^6} - \mathbf{10^7})\mathbf{M}_\odot$ in spiral galaxies, such 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. There is not only too little time but the supply of matter is extremely meager. SMBH are also discovered recently in quite young universe with the age about (1 - 0.5) Gyr.
Probably SMBH and not only them are primordial..

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, $\delta\varrho/\varrho \sim 1$, then that piece of volume would be inside its gravitational radius i.e. it became a PBH, which woeuld decoupl 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

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: $\boldsymbol{\mu}$, γ, $\boldsymbol{M_0}$:

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

A power law prefactor changes M_0 but log-normal form remains.. The values of γ and μ depend upon unknown high energy parameters of the Affleck-Dine baryogenesis, **but the central mass is predicted to be $M_0 \sim 10 M_\odot$, close to the mass inside horizon at the QCD pt.**

The spectrum is in excellent agreement with the available observations.

PBH formation, modified mechanism

The mechanism of PBH formation is based on the popular model of the SUSY motivated baryogenesis, proposed by Affleck and Dine (AD). This model 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.**

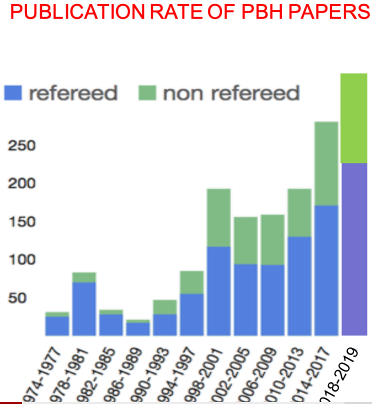
PBH formation, modified mechanism

The emerging universe looks like Swiss cheese, holes being high baryonic density bubbles (HBB) occupying a minor fraction of the total volume, but finally acquiring a dominant part of the total mass of the universe.
Inflationary prehistory allows for creation of huge PBH with masses up to $(\mathbf{10^4 - 10^5}) M_\odot$, 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.
They may be abundant enough to make significant (up to 100%) contribution to the cosmological dark matter.
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.

PBH formation, modified mechanism

Very large PBH masses became possible because the conditions for PBH formations were arranged at inflationary epoch. The idea of inflationary creation was first proposed in our paper with Joe Silk in 1993.
Subsequent paper on a mechanism of inflationary creation of PBH was studied about two years later in P. Ivanov, P. Naselky, I. Novikov. It was based on suggestion by Starobinsky of 1992 on the generation of the perturbation of the inflaton field in a model with double field inflation.
At the present time there is a large lot of inflationary mechanisms of PBH creation with variety of mass spectra; e.g. the very recent paper by Bragllia et al Aug. 2020, based on the double field inflation.
The PBH mass spectra calculated by Ivanov *et al* and in the subsequent works have rather complicated analytical structure and to the best of my knowledge was not applied to the analysis of the observational data.

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



Black Dark Matter

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 $\mathbf{M_{max}} \lesssim \mathbf{10^{22}}$ 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 $\mathbf{10^6 M_\odot}$ can be created,**

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

Bounds on PBHs - B.Carr, F. Kuhnel arXiv:2006.02838, June 2020 for monochromatic mass spectrum of PBH.

All bounds are model dependent and have caveats.

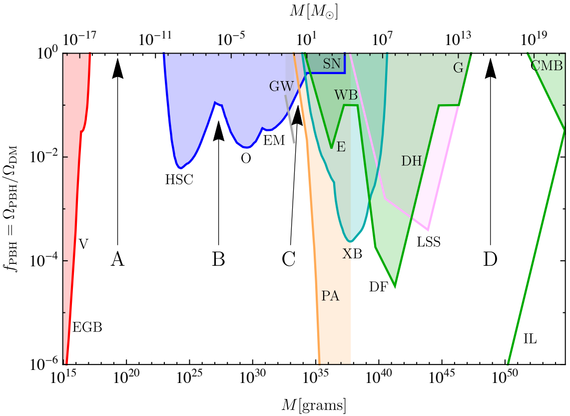
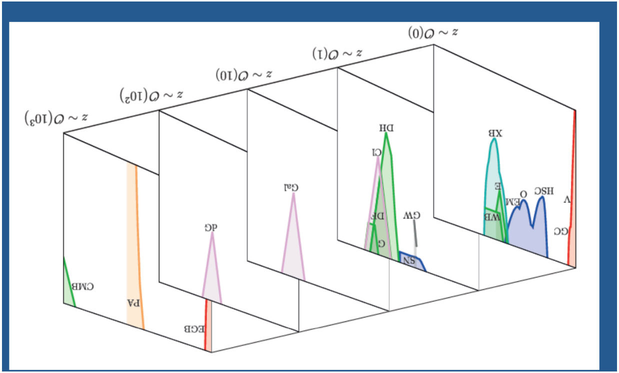


Figure caption

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,



Comparison with the data, 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 $\boldsymbol{M_c}$ 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, 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, $M_0 \approx 10 M_\odot$ and $\gamma = 0.7$, 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.

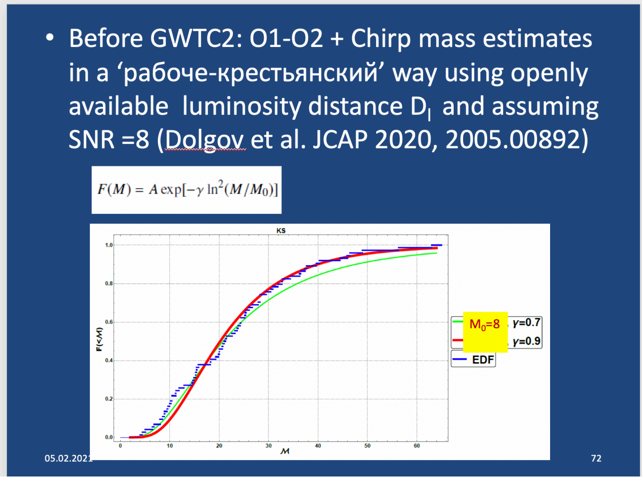
The only known mass spectrum which so well describes the observed chirp mass distribution.

Chirp mass distribution

Chirp mass distribution of coalescing binary PBH
The integrsted relative distirbution is 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.

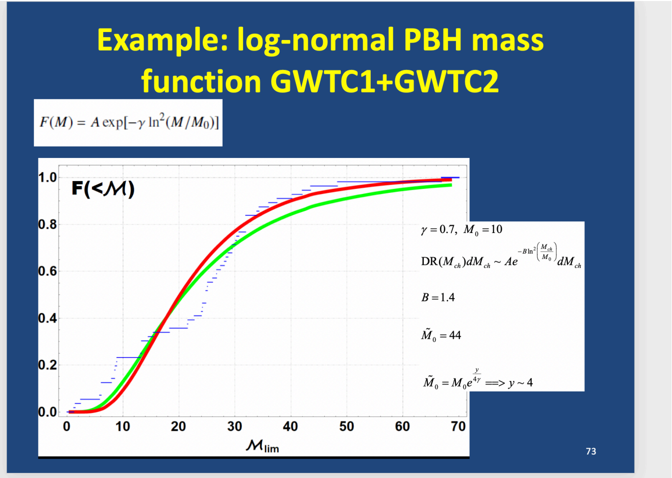
Chirp mass distribution

From K.Postnov lecture, $M_0 \approx 8 M_\odot$, $\gamma = 0.7$, full official data



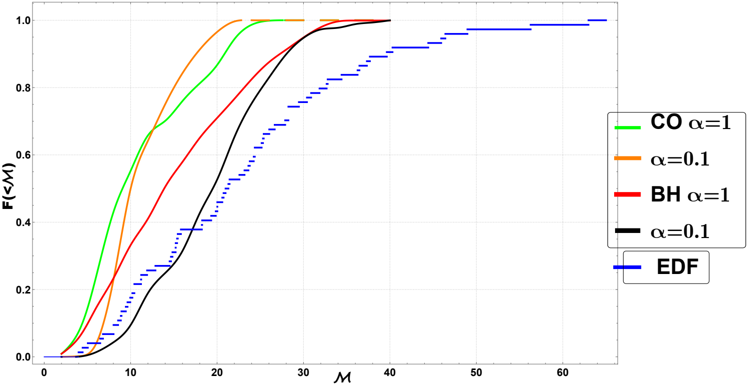
Chirp mass distribution

From K. Postnov lecture, $M_0 = 10M_\odot$, $\gamma = 0.7$



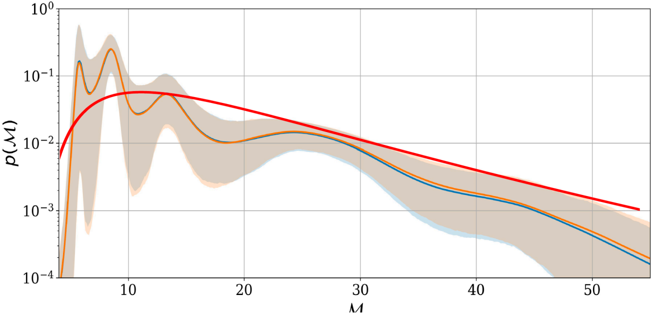
Chirp mass distribution, astrophysical BHs

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



Differential distribution

Recent: V. Tiwari 16 Dec. 2020, arXive 2012.01839 - differential spectrum, two populations; higher mass are log-normal, from Postnov, $M_0 = 9M_\odot$ $\gamma = \mathbf{0.7}$.



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 .

Gravitational waves from BH binaries

Surprising features

Masses higher $60 M_\odot$ 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.

Gravitational waves and PBH

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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. **Impossible last event of $M_{BH} \approx 10^2 M_\odot$.**

To form so heavy BHs, the progenitors should have $\boldsymbol{M} > \mathbf{100}\boldsymbol{M_\odot}$. 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 and PBH

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 and PBH

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 $\mathbf{50}M_\odot$ and $\mathbf{30}M_\odot$ 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.**

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, $t_U = \mathbf{14.6 \cdot 10^9}$ 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 $\mathbf{1.7 \times 10^{10}} \boldsymbol{M_\odot}$, 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, SMBH 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 $\sim 1/\mathrm{cm}^3$) 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.

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: $0.08 < f < 0.50$ (95% CL) for $0.15 M_\odot < M < 0.9 M_\odot$;

EROS: $f < 0.2$, $0.15 M_\odot < M < 0.9 M_\odot$;

EROS2: $f < 0.1$, $10^{-6} M_\odot < M < M_\odot$;

AGAPE: $0.2 < f < 0.9$,

for $0.15 M_\odot < M < 0.9 M_\odot$;

EROS-2 and OGLE: $f < 0.1$ for $M \sim 10^{-2} M_\odot$ and

$f < 0.2$ for $\sim 0.5 M_\odot$.

MACHOs surely exist but what are they is not known. The data are contradictory. Maybe MACHOs are clustered and are observed only in some directions.

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

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 $(\mathbf{3.2 \pm 0.6}) \times \mathbf{10^4} M_\odot$. 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.

Globular clusters and dwarf galaxies

Only one or two massive BH are observed in Globular clusters.
Definite evidence of BH with $M \approx \mathbf{2000} M_\odot$ 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 $(\mathbf{2}-\mathbf{3}) \times \mathbf{10^3} M_\odot$ is about $\mathbf{10^4} - \mathbf{10^5}$ per one SMPBH with mass $> \mathbf{10^4} M_\odot$. 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.

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

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 $\mathbf{3 \times 10^{10}}$ $\boldsymbol{M_\odot}$ at $\boldsymbol{z = 7.5}$; MBH accretes only about 2200 $\boldsymbol{M_\odot}$ 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."

One more argument against sufficiently efficient accretion is neutrality of medium around QSO because the necessary accretion rate should strongly ionize medium. E. Bañados E *et al* 2018 An 800-million-solar-mass black hole in a significantly neutral Universe at a redshift of 7.5 *Nature* **553** 473 (*Preprint* astro-ph.GA/1712.01860)

A few months ago a remarkable statement was presented in Andika, I.T. *et al* 2020 Probing the Nature of High Redshift Weak Emission Line Quasars: A Young Quasar with a Starburst Host Galaxy, astro-ph.GA/2009.07784v1 It was argued that quasars at $z \approx 6$ remained active only during $10^3 - 10^4$ years. This observation implies that we see only a minor fraction of SMBH, not more than 10^{-4}. It is hardly possible to create so many SMBHs by the conventional accretion mechanism in about 500 million years.

PBHs are necessary.

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 $\mathbf{10^{10}} \boldsymbol{M_\odot}$) 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.

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 of quantum diffusion of baryonic scalar field during inflation (Starobinsky diffusion equation generalized to complex scalar field). Probably log-normal spectrum is a general consequence of diffusion.

Now in many works such spectrum is postulated without justification.

Creation Mechanism

SUSY motivated baryogenesis, Affleck and Dine (AD). SUSY predicts existence of scalars with $\mathbf{B \neq 0}$. 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.

Scalar field diffusion in DS

The equation governing the evolution of the quantum fluctuations of a real scalar field was derived in A. A. Starobinsky, Phys. Lett. B117, 175 (1982). It can be generalized to complex field χ in potential $U(\chi)$ in (quasi) De Sitter space-time with the Hubble parameter H

$$\frac{\partial \mathcal{P}}{\partial t} = \frac{H^3}{8\pi^2} \sum_{k=1,2} \frac{\partial^2 \mathcal{P}}{\partial \chi_k^2} + \frac{1}{3H} \sum_{k=1,2} \frac{\partial}{\partial \chi_k} \left[\mathcal{P} \frac{\partial U}{\partial \chi_k} \right]$$

where $\chi_{1,2}$ are the real and imaginary parts of field, $\chi = \chi_1 + i\chi_2$. From it the known results follow in strictly massless case or $m \ll H$

$$\langle \chi^2 \rangle = H^3 t / 4\pi^2$$

till it reaches the limiting value (Bunch, Davies ?):

$$\langle \chi^2 \rangle = \frac{3H^4}{8\pi^2 m^2}$$

Scalar field diffusion in DS

However, infrared regularization is poorly defined and the method based on rigorous equation of motion for $\langle\chi^2\rangle$, according to AD and Pelliccia Nucl.Phys.B 807 (2009) 229-250. e-Print: 0806.2986 [hep-ph], gives the same result for $m \neq 0$:

$$\langle\chi^2\rangle = \frac{3H^4}{8\pi^2 m^2}$$

but if $m = 0$:

$$\langle\chi^2\rangle = -H^3 t / 4\pi^2$$

notice the opposite sign.
What can we do ?!

Creation Mechanism

As a result of quantum diffusion χ would be away from origin after inflation and, when inflation is over, starts to evolve down to equilibrium point, $\chi = 0$, according to eqn. of 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 - determines M_{max} of PBH.

PBH creation mechanism

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

CP would be broken, if the relative phase of λ_1 and m is non-zero, otherwise one can "phase rotate" χ and come to real coefficients. Coupling to fermions may break CP.

Direction of χ rotation determines if baryonic or antibaryonic PBH are created.

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 $B \neq 0$.

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.

Equations. of motion

Classical evolution of homogeneous fields Φ and χ is determined by the equations:

$$\ddot{\Phi} + 3H\Phi + m_\Phi^2\Phi + \lambda_\Phi\Phi^3 + 2\lambda_1|\chi|^2(\Phi - \Phi_1) = 0,$$

$$\ddot{\chi} + 3H\dot{\chi} + \lambda_1(\Phi - \Phi_1)^2\chi + \lambda_2|\chi|^2\chi\left(2\ln\frac{|\chi|^2}{\sigma^2} + 1\right) + 2m^{*2}\chi^* = 0,$$

which we solved numerically, but qualitative behavior of the solutions can be understood from the following simple considerations. We start from inflationary stage when the cosmological energy density is dominated by the inflaton field. We assume that the product $\lambda_1|\chi|^2$ is sufficiently small, so the χ-dependent term is not essential. In this regime the evolution of Φ is simply a slow roll in the corresponding potential till the Hubble parameter remains large in comparison with the potential slope

Parameters

Since we want inflation to continue when Φ passes Φ_1, we need $\Phi_1 > m_{Pl}$; $\Phi_1 = (2-3)m_{Pl}$ is sufficient for creation of astronomically large B-bubbles. The inflaton mass should be bounded by $10^{-7}m_{Pl} \lesssim m_\Phi \lesssim 10^{-6}m_{Pl}$ to avoid too large density perturbations, $\delta\varrho/\varrho < 10^{-5}$. The coupling constant λ_Φ must be in the interval $10^{-14} \lesssim \lambda_\Phi \lesssim 10^{-12}$ by the same reason to suppress the density perturbations which at horizon crossing are, roughly speaking, equal to $\delta\varrho/\varrho \sim 10^2\sqrt{\lambda_\Phi}$. The coupling of χ to the inflaton, λ_1, is bounded by $\lambda_1 < 10^{-6}$, because otherwise the one loop correction to the inflaton potential induced by this coupling would give rise to unacceptably large $\lambda_\Phi \sim \lambda_1^2/4\pi^2$. Interesting results are obtained with $\lambda_1 \sim 10^{-10}$. Such a small value of the inflaton coupling to χ naturally fits the idea of very weak coupling of the inflaton to the usual matter. We choose the χ-self-coupling constant λ_2 to be near 10^{-2} to obtain cosmologically interesting consequences.

Important feature

If the life-time of χ noticeably exceeds the life-time of the inflaton, the asymmetry may be much larger than unity, because the energy density of the decay products of the inflaton into relativistic particles would be strongly red-shifted with respect to non-relativistic longer-lived χ-bosons.

Evolution of χ and baryon asymmetry

The baryon asymmetry β depends upon the ratio of the energy density of χ, $\varrho_\chi \sim m^2|\chi|^2$, at the moment of χ decay to the background cosmological energy density. If χ decayed when the background relativistic matter was strongly red-shifted, the energy density inside the bubble would be dominated by the energy density of χ and the ratio of the baryonic charge density to the entropy density inside the bubbles would be about

$$\beta_B \sim \frac{m|\chi|^2}{(m^2|\chi|^2)^{3/4}} = \left(\frac{|\chi|}{m}\right)^{1/2}$$

This value may be much larger than unity.

Evolution of χ

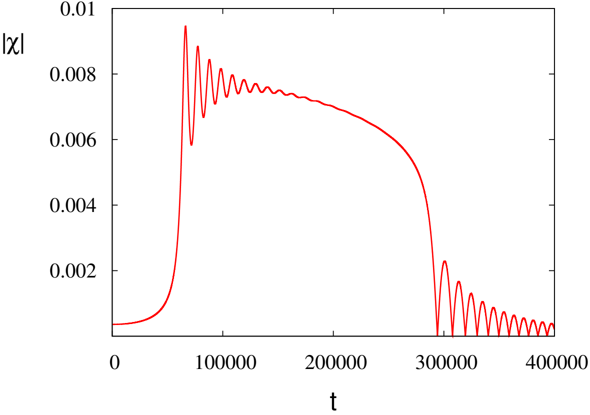

Figure: Evolution of $|\chi|$ in time. The field rolls down toward the deeper minimum, oscillates there following the evolution of the minimum, rolls back to the origin and starts to rotate around it.

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.

Conclusion

Log-normal spectrum is "experimentally" proven

Almost all observed black holes (BH) in the early ($z \sim 10$) and contemporary universe are primordial. Among them:

- MACHOS $0.5 M_\odot$,
- solar mass BH, around $8 M_\odot$; some astrophysical but some PBH ,
- sources of the LIGO gravitational waves, tens of $M_\odot$,
- intermediate mass BH (IMBH) $(10^3 - 10^5) M_\odot$,
- supermassive BH (SMBH) $(10^6 - 10^{10}) M_\odot$.

All these claims are strongly supported by the astronomical data, especially by those of a few recent years. Other versions look much less natural.

Conclusion

Some more to add:

BHs seed galaxy formation but not vice versa.

The universe and even Galaxy may be full of antimatter. (by-product of 1993 A.D and J. Silk).

• DM consisting of PBH up to 100% remains a viable possibility.

• Dark matter made of antimatter is an exciting new possibiity.

• 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.

THE END or to be continued???