Black Holes Today, Yesterday, and at the Dawn of the Creation of the Universe

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Outline

Topics of the lectures, (short and long):

1. Black holes (BH), what's that? Different types of BH.
2. How we see "invisible".
3. BH by creation mechanisms.
4. Schwarzschild metric. Particle propagation.
5. BH evaporation. Gray spectrum.
6. Breaking of global symmetries by BH. All particles are unstable.
7. Baryonic, leptonic, and electric asymmetries generated by BH.
8. Schwinger process at Schwarzschild horizon, p turns into e^+.
9. Superluminous propagation near BH. Causality?
10. BH binaries and gravitational waves.
11. Review of new observations incompatible, with conventional wisdom. Miracles in the sky,
12. Model of 1993 which predicted miracles observed now and led to extended mass spectrum of PBH. Claim: DM=PBH, all or a part?

BH, what's that

Ancient point of view: BH are objects with so strong gravitational field that nothing can escape it.
Mitchell (1784): there may be bodies for which the second cosmic velocity is larger than the speed of light.
They do not shine and do not reflect light, i.e. are absolutely dark, invisible.
This is wrong: BH can emit all kind of radiation in the process of their evaporation (nobody has yet seen it).
BH create the most powerful sources of radiation - quasars, point-like objects which shine as thousands of galaxies. Clouds around smaller BHs emit X-rays.

BH, what's that

Four possible types ob BHs are described by 4 exact solutions of the General Relativity Equations:

BH are characterized by 3 and only 3 parameters (hairs): mass M, electric charge Q, and spin a, $\mathbf{0} < a < \mathbf{1}$.

If $m_\gamma \neq \mathbf{0}$, whatever tiny, electric hairs do not exist (Coulomb field disappears).

Schwarzschild (1916) $Q = a = \mathbf{0}$

Reissner-Nordström (1916,1918), $Q \neq \mathbf{0}$

Kerr (1963) $a \neq 0$

Kerr-Newman (1965) $Q \neq \mathbf{0},\ a \neq \mathbf{0}$.

BH, what's that

Types of BH by creation mechanism:

I. Astrophysical: created by stellar collapse, when star exhausted its fuel. Masses expected just above the neutron star masses, $\mathbf{3}M_\odot$, and normally quite close to it. Instead the mass spectrum of BH in the Galaxy has maximum at $M \approx \mathbf{8}M_\odot$ with the width: $\sim (\mathbf{1}-\mathbf{2})M_\odot$. Scientists do not know why.

BH, what's that

II. Accretion of matter to regions with excessive density.

There is a supermassive BH (SMBH) in all (?) large galaxies. Masses are in the range: $M \sim 10^9 M_\odot$ in elliptic and lenticular galaxies and $\mathbf{M} \sim (\mathbf{10^6} - \mathbf{10^7})\mathbf{M}_\odot$ in elliptic galaxies, like Milky Way. Maybe the type of the galaxy is determined by the mass of BH and not vice versa.
However, the known mechanisms of accretion is not efficient enough to create such monsters during the universe age $t_U \approx 15$ Gyr, more than by an order of magnitude
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 0.5 -1 Gyr. Their formation is multifold less probable.
Massive seed are necessary, but their origin is mysterious.

BH, what's that

III. Primordial black holes (PBH) created in pre-stellar epoch in the very early universe.

The canonical picture: the density excess might accidentally happen to be large, $\delta\varrho/\varrho \sim 1$, at the cosmological horizon scale. Then this piece would be inside its gravitational radius i.e. it becomes a BH, and decouple from the cosmological expansion. (Zeldovich and Novikov mechanism, elaborated later by Carr and Hawking). Usually this mechanism created PBH with rather low masses and with sharp almost delta-function mass spectrum.

A different mechanism (AD and J.Silk, 1993) could make PBH with masses exceeding millions solar masses and with extended mass spectrum (log-normal) which became quite popular recently.

BH observations

Before the recent 2-3 years all the methods leading to conclusion of BH existence were INDIRECT. The data indicate that in a small volume a large mass is concentrated. With theory applied, one concludes that there is a BH inside this volume:
1. Star motion around galactic center.
2. Gravitational lensing of stars by invisible objects (MACHOs)
3. Electromagnetic radiation (X rays) from the gravitationally attracted matter heated up to million degrees. That's how supermassive (quasars) and smaller BH radiate.

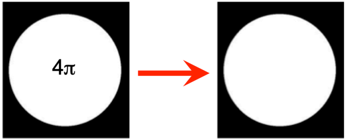
Still some skepticismof minorities was not eliminated, but recently it was strongly swiped by the registration of gravitational waves (LIGO and Virgo) and by a photo of a black hole shadow.

BH observations

The form of the signal created by gravitational waves is best fit to the hypothesis that it is emitted by two coalescing BH with Schwarzschild metric.
Masses of both initial BH and the final one are accurately determined and their spins are measured.
It is the first experimental test of GR for a strong gravitational field. All numerous earlier tests verified General Relativity only in weak field limit.

BH shadow, Shatsky-Novikov

M. Ehterington, 1933: homogeneous and isotropic background after gravitational lensing remains homogeneous and isotropic for any metric theory.



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BH shadow, Shatsky-Novikov

If lensing is made by BH, there is a region from which the light cannot reach the observer, so the picture of the background is modified. This is the so called BH shadow

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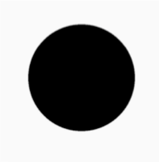
BH shadow, Shatsky-Novikov

If the background radiation is homogeneous and infinitely large then the image would also be homogeneous and infinite while the black hole shadow must be have sharp bounds:



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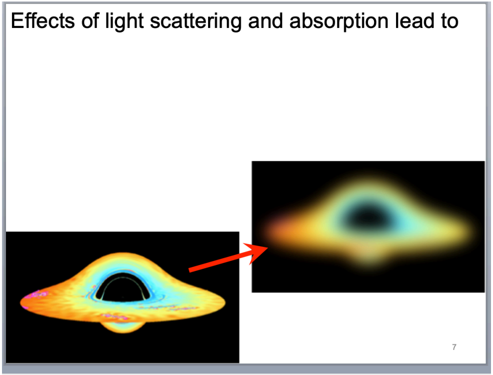
BH shadow, Shatsky-Novikov

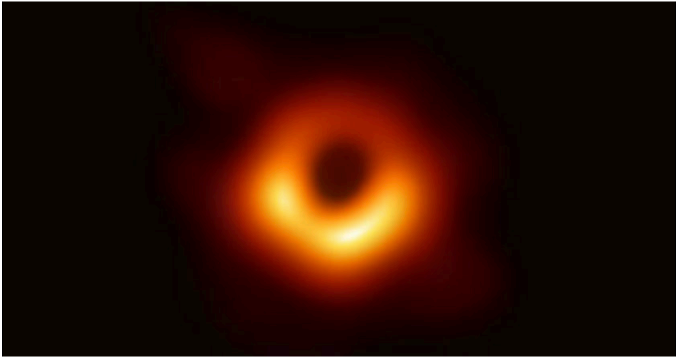


BH snap shot

The Event Horizon Telescope Collaboration et al.
First M87 Event Horizon Telescope Results.
The Shadow of the Supermassive Black Hole.
The Astrophysical Journal Letters. April 10, 2019.
BH mass $(\mathbf{6.5} \pm \mathbf{0.7}) \cdot \mathbf{10^9} M_\odot$,
giant elliptical galaxy M87, distance 16.4 Mpc

BH snap shot

hole shadow.pdf



Schwarzschild metric. Particle propagation.

$$ds^2 = \eta dt^2 - (1/\eta) dr^2 - r^2 d\theta^2 - r^2 sin^2\theta d\phi^2$$

$\eta = 1 - r_g/r$. Gravitational radius: $r_g = 2M/m_{Pl}^2$.
An object falling into a BH never reaches it (by the clock of a distant observer); Zeldovich, Novikov - frozen stars.
Scalar field in Schwarzschild background, $(D^2 + m^2)\psi = 0$:

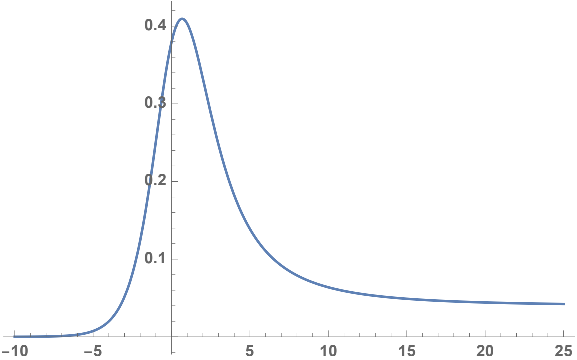
$$U = \left[\eta^{-1}\partial_t^2 - \eta\partial_r^2 - (2\eta r^{-1} + r_g/r^2)\partial_r - \hat{l}^2/r^2 + m^2\right]\psi(\mathbf{r}, t) = 0$$

Turtle coordinate $\xi = r/r_g + \ln(r/r_g - 1)$; if $r \to r_g$, then $\xi \to -\infty$.

$$\mathbf{U} = \eta\left[\frac{\mathbf{l(l+1)r_g^2}}{\mathbf{r^2}} - \mathbf{m^2 r_g^2} - \left(\frac{\mathbf{r_g}}{\mathbf{r}}\right)^3\right]$$

Fourier transformed partial wave amplitudes satisfy:

$$\left[\partial_\xi^2 + E^2 r_g^2 + U\right] R_{l,l_3} = 0$$



Scalar field potential in Schwarzschild background as a function of turtle coordinate. U vanishes at on, i.e. at $\xi \to -\infty$; when $r \to \infty$ then $U \to m$. There is a shallow minimum (not seen) corresponding to Newtonian orbit.

Black hole evaporation

S Hawking, thermal spectrum at horizon:

$$f = [\exp(E/T) \pm 1]^{-1}$$

The only parameter is r_g, so $T \sim 1/r_g$ in fact $T_{BH} = m_{Pl}^2/(8\pi M_{BH})$
Discussion between Gribov and Zeldovich before Hawking discoverey.
Gray spectrum due to gravitational potential(Don Page, 1974?)
The luminosity of evaporating BH:

$$L_{BH} = \frac{\pi^2 g_*}{30} T^4 \times 4\pi r_g^2 = \frac{g_* m_{Pl}^4}{30 \cdot 2^8 \pi M^2}$$

Since the decrease of the BH mass is equal to the luminosity with the opposite sign, $\dot{M} = -L$, we find for the BH life-time

$$\tau_{BH} = \frac{2.5 \cdot 10^3 M^3}{g_* m_{Pl}^4},$$

which is only slightly different from the exact expression with the gray spectrum of the emitted radiation, by the coefficient 3 instead of 2.5.

Black hole evaporation

BH life-time with $M = 5 \cdot 10^{14}$ g is equal to the universe age 10^{10} years. Even if BH was formed by baryons, it evaporate producing equal number of baryons and antibaryons. Breaking of all global symmetries by BHs. Proton decay due to formation of virtual black hole, when 3 quarks happened to be inside gravitational radius of proton.
$\boldsymbol{\tau_p \sim m_{Pl}^4/m_p^5 \sim 10^{45}}$ years (Ya.B. Zeldovich, Phys. Lett. A 59, 254). All particles, except for $e^\pm$ are unstable. If $m_\gamma \neq 0$, then all massive particles without any exception are unstable.
A problem for TeV-gravity. Maybe resolved by conjecture of C.Bambi, AD, K. Freese, Nucl.Phys. B763 (2007) 91: that, just as in classical gravity, sub-Planck mass BHs in quantum gravity can exist with zero local charge (electric or color) and zero angular momentum. BH with mass smaller than the Planck mass must have zero electric charge and angular momentum; otherwise no horizon exists and naked singularity is exposed. Predictions for $\boldsymbol{\mu \rightarrow e}\gamma$, $n - \bar{n}$ oscillations are close to the existing bounds.

Cosmological Charge Asymmetries

A.D. Sakharov, 1967, three principles of baryogenesis:

- Nonconservation of baryonic number.
- Breaking of C and CP symmetries.
- Deviation from thermal equilibrium.

None of them is obligatory.

Spontaneous baryogenesis proceeds most efficiently in thermal equilibrium.

A non-zero amplitude of a complex scalar field mimics C and CP violation but leads to no C or CP violation in particle physics.

Even if baryonic number is conserved, black holes may hide baryons inside and the rest of the universe would be asymmetric. If BH later evaporated, the hidden inside baryons would disappear without any trace.

Cosmological Charge Asymmetries

Baryon asymmetry generated by BH, two possible mechanisms:
1. Excessive baryon production in the process of BH evaporation.
2. Excessive antibaryon capture from primordial plasma.

The idea of the first mechanism was proposed by S.Hawking (1974, 1975) and Ya.B.Zeldovich (1976) Ya.B.Z. had also elaborated details of the mechanism. Quantitative calculations by A.D. in 1980. Criticism by. Toussaint, Treiman, Wilczek, and Zee (1979) also by Kolb and Turner: since the process of evaporation is thermally equilibrium one, no asymmetry can be generated, is incorrect. The evaporation deviates from the thermal one. due to subsequent interaction of the evaporated particles with gravitational field of BH.

Cosmological Charge Asymmetries

Baryogenesis through primordial black hole evaporation.
Energy density could be dominated by PBH at some early stage.
Heavy particles with $\mathbf{m} \sim \mathbf{10^{10} - 10^{6}}$ GeV are needed.
Thermal evaporation cannot create any charge asymmetry.
However the spectrum is not BLACK but GRAY due to propagation of the produced particles in gravitational field of BH. Moreover, an interaction among the produced particles is essential.
A model: A-meson is created at the horizon and decays as:

$$\mathbf{A} \to \mathbf{H} + \bar{\mathbf{L}} \ \textbf{and} \ \mathbf{A} \to \bar{\mathbf{H}} + \mathbf{L}$$

with different branching ratios.
Back-capture of **H** is larger than that of **L**. Net baryon asymmetry could be created.
If $\varrho_{BH}/\varrho_{tot} = \epsilon$ at the production, then at red-shift $z = 1/\epsilon$ BH would dominate. Their evaporation could provide baryon asymmetry and reheat the universe.

Cosmological Charge Asymmetries

Cosmological electric charge asymmetry.

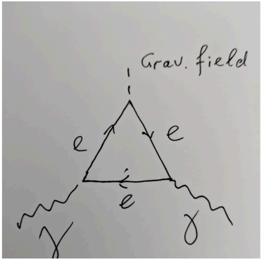
If $\boldsymbol{m_\gamma \neq 0}$, the electric field of a charged BH is zero, see e.g. AD, H. Maeda, T. Tori, hep-ph/0210267, and references therein. Exact solution can be found for charged sphere outside of BH and the Coulomb field is proportional to $Q(1 - r/r_g)$. No continuous limit to $\boldsymbol{m_\gamma = 0}$. Maybe the time of the electric field disappearance is inversely proportional to a power of m_γ. Probably not.

Electric charge can vanish in BH without trace, as baryonic number does,

A problem: one can construct a theory in whcih gauge invariance in QED is broken at high temperature and restores at $T = 0$. At large T electric asymmetry can be generated by hiding electric charge into PBH. What happens after restoration of gauge invariance?

Superluminous propagation near BH

I.T. Drummond, S.J. Hathrell, Phys. Rev., D22 (1980) 343. Radiative correction to light propagation in gravitational field



Superluminous propagation near BH

The photon effective action in vacuum in one loop approximation is described by vacuum polarization diagram in external gravitational field. Gauge invariance of electrodynamics and general covariance of gravity uniquely determine the result in the lowest order in curvature::

$$S = \int d^4x \sqrt{-g} \left(-\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{\alpha C}{m_e^2} R_{\alpha\beta\mu\nu} F_{\mu\nu} F^{\alpha\beta} \right)$$

Here $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field tensor and $R_{\mu\nu\alpha\beta}$ is the Riemann tensor $\alpha = 1/137$ is the fine structure constant, m_e is the mass of electron and the coefficient C, as calculated by Drummond and Hathrell, $C = -1/360\pi$. For our purpose is essential just that $C \neq 0$, even its sign is not important. The action may also contain other terms proportional to the Ricci tensor $R_{\mu\nu}$ or to the curvature scalar R but they both vanish in vacuum and will be neglected in what follows.

Superluminous propagation near BH

The characteristics of the modified Maxwell equations generically would not coincide with the normal light cone. It means that the velocity of the propagation of the front of the signal would be modified.
Photons with different polarization propagate differently: one inside the cone, the other outside. Light in gravitational field goes faster than light.
Breaking of causality (AD and I. Novikov): there exist reference frames where chronology is reversed.
Difference with tachyons, for them group velocity may be larger than unity, but the front of the sygnal goes with the speed of light

Schwinger process at the Schwarzschild horizon,

C. Bambi, AD, A. Petrov JCAP 0909:013,2009. Possible explanation of 0.511 Mev line from the Galactic center. ($e^+e^- \to 2\gamma$, at rest.)
As is known that the difference between the mass of proton and electron results in a difference of their elastic scattering on photons and hence in a difference of their mobilities in interstellar plasma. Thus it leads to predominant capture of protons by celestial bodies, making them electrically charged (Shwarzman mechanism of star charging).
If a light primordial black hole is surrounded by a ionized medium exist in the Galaxy, they could operate as an efficient antimatter factories converting accreting protons into positrons. If the black hole mass is sufficiently small, the electrostatic field at the horizon can exceed the critical value of the vacuum stability, $E_c = \pi m_e^2/e \approx 10^{16}$ V/cm, and electron-positron pair production by Schwinger mechanism becomes efficient. Primordial black holes with the mass in the range $10^{18} - 10^{20}$ g might be abundant (see the third lecture) in the Universe, eating protons and injecting positrons.

Gravitational waves from BH binaries

• Grav. waves from BH binaries, great discovery → great problems (in much wisdom is much grief). GW discovery by LIGO has proven that the sources of GW are most probably PBHs. see e.g. S.Blinnkov, A.D., N.Porayko, K.Postnov, JCAP 1611 (2016) no.11, 036 "Solving puzzles of GW150914 by primordial black holes,"

1. Origin of heavy BHs ($\sim \mathbf{30 M_\odot}$).
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 conventional theory is still lacking.
To form so heavy BHs, the progenitors should have $\boldsymbol{M > 100 M_\odot}$ 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. Primordial BH 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 were 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 $(\mathbf{36+29})M_\odot$ is analyzed and found to be negligible.

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 and may loose energy due to dynamical friction in the early universe. The probabiity to become gravitationally bound is not small

Gravitational waves from BH binaries

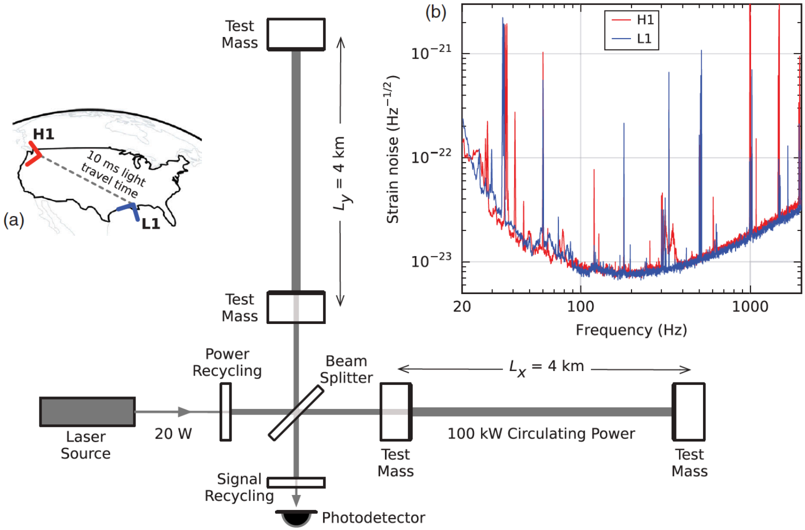
3. The low value of the BH spins in GW150914 and in almost all (except for 2-3) other events. It strongly constrains astrophysical BH formation from close binary systems. Astrophysical BHs are expected to have considerable angular momentum, nevertheless the dynamical formation of double massive low-spin 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, A. Kuranov, N. 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 $\boldsymbol{50 M_\odot}$ and $\boldsymbol{30 M_\odot}$ and and GW151216 (?). Earlier M. Mirbabayi, et al. (1901.05963) and V. De Luca et al. (1903.01179D) much weaker angular momentum gain was obtained.

GW, prehistory and theory

On February 11, LIGO (Laser Interferometer Gravitational wave Observatory) collaborations announced discovery of gravitational waves from a coalescing binary systems of black holes.
The shape of the signal is in perfect agreement with the theory of BH interactions in the strong (Schwarzschild) sefl-fields, so it can be considered as a first direct proof of BH existence. All previous data was about weak fields.
Now there are about 15 more events (!?).
This discovery opens a new era of gravitational waves telescopes which will presumably allow to observe several (many) such catastrophic events per year and with onset of operation of VIRGO (Italy) and KAGRA (The Kamioka Gravitational Wave Detector, Japan) the direction to source can be reliably established and studied by optical and other electromagnetic telescopes. New discoveries are imminent.

Detector



H1
10 ms light travel time
L1
(a)
Test Mass
Test Mass
L_y = 4 km
Power Recycling
Beam Splitter
L_x = 4 km
Laser Source
20 W
Test Mass
100 kW Circulating Power
Test Mass
Signal Recycling
Photodetector
(b)
H1
L1
10^{-21}
10^{-22}
10^{-23}
Strain noise (Hz$^{-1/2}$)
20
100
1000
Frequency (Hz)

Results, PRL, 116, 061102, 12/02/2016

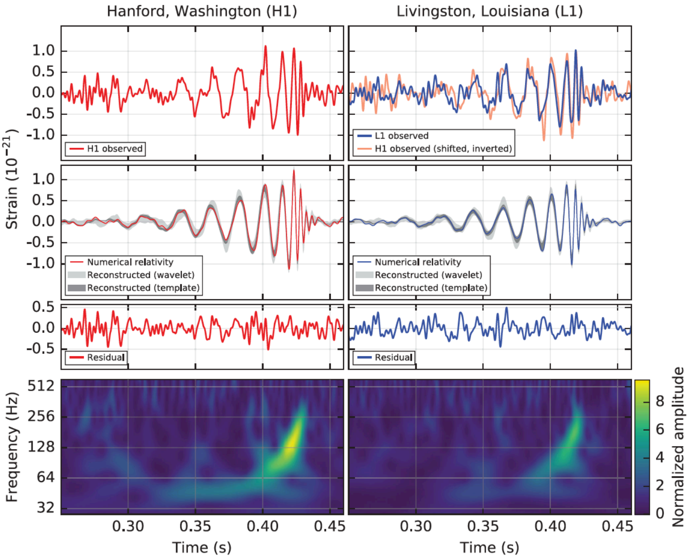
TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame; to convert to the detector frame multiply by $(1+z)$ [90]. The source redshift assumes standard cosmology [91].

Primary black hole mass	$36^{+5}_{-4} M_\odot$
Secondary black hole mass	$29^{+4}_{-4} M_\odot$
Final black hole mass	$62^{+4}_{-4} M_\odot$
Final black hole spin	$0.67^{+0.05}_{-0.07}$
Luminosity distance	410^{+160}_{-180} Mpc
Source redshift z	$0.09^{+0.03}_{-0.04}$

The mass and spin of the final BH, and the total energy radiated in gravitational waves are estimated by the fits to numerical simulations of binary black hole mergers.

The estimated total energy radiated in gravitational waves is $\mathbf{(3.0 \pm 0.5)} M_\odot$ and a peak of gravitational-wave luminosity is $\mathbf{3.0^{+0.5}_{-0.4} \times 10^{56}}$ erg/sec equivalent to $200 M_\odot$/sec, more than whole radiation power of the visible universe.

Rotational energy (outside the BH) is about $\mathbf{0.3} M_\odot$ - may be in principle extracted.


Hanford, Washington (H1)
Livingston, Louisiana (L1)
Strain (10^{-21})
H1 observed
L1 observed
H1 observed (shifted, inverted)
Numerical relativity
Reconstructed (wavelet)
Reconstructed (template)
Residual
Frequency (Hz)
Normalized amplitude
Time (s)
1.0
0.5
0.0
-0.5
-1.0
512
256
128
64
32
0.30
0.35
0.40
0.45
0
2
4
6
8

A possible model of PBH formation explaining the properties of the observed GW sources, was proposed in our papers.
AD and J. Silk (1963) and AD, Kawasaki, Kevlishvili (2006): primordial black holes, "arranged" by supersymmetric baryogenesis and created after the QCD phase transition in the very early universe:

Features:

1. Early creation of heavy BH's.
2. Easy formation of heavy binaries through dynamical friction.
3. Zero spins of PBH's

Two rotating gravitationally bound massive bodies are known to emit gravitational waves. If the back reaction is neglected, the radius of the orbit and the rotation frequency are 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_c is the so called chirp mass:

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

and

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

Order of magnitude estimates.

Gravitational radius: $r_g = 2M/m_{Pl}^2$.

For the Sun: $r_g \approx 3$ km.

Virial theorem: $V^2 = \frac{M}{m_{Pl}^2 R} = \frac{r_g}{2R}$,

and period $T = \frac{2\pi R}{V} = \frac{(2R)^{3/2}\pi}{r_g^{1/2}}$.

For $M = 30 M_\odot$ and $R = r_g$:

$$T \sim 0.003 \mathrm{sec},$$

exactly the observed range.

This solution is valid in the adiabatic (inspiral) regime when radius drops and frequency rises due to the energy loss induced by the GW emission. The adiabaticity condition, $\dot{R} \ll \omega_{orb} R$, can be rewritten as $\dot{\omega}_{orb} \ll \omega_{orb}^2$, which can be translated into the lower bound on the radius of the orbit:

$$R \gg r_g^{(eff)} = \frac{M_1 + M_2}{m_{Pl}^2},$$

this is the Newtonian approximation.
For $R \sim r_g$:

$$\omega_{orb} \sim m_{Pl}^2/M \sim 10^3/\text{sec},$$

looks reasonable. But energy taken by GW is

$$E_{tot} \sim L/\omega_{orb} = M,$$

slightly too much, but with an accurate account of numerical coefficients, the result would be quite close to the measured value.

When $R \sim r_g$ only numerical solution of nonlinear and non-spherically symmetric GR equations is possible,

which impressively agrees with the data, after fitting the parameters: M_1, M_2, spins, and distance to BHs.

More about LIGO interferomener.

Let us calculate the number of photons reaching photodetector.

Accumulated circulated power 100 kW.

$1W = 10^7$ erg/sec, 1 erg $= 10^{12}$ eV, because $1g = 10^{24}$ GeV $= 10^{21}$ erg.

If $E_\gamma = 1$ eV, then 100 kW/sec corresponds to $N_\gamma = 10^{24}$/sec.

1 eV photons have $\lambda \sim 10^{-5}$ cm. During 1 msec the number of photons would be $\sim 10^{21}$.

The length displacement is measured with precision 10^{-16} cm. For $\delta L = 10^{-16}$ cm the length difference would be $\Delta L = 70\delta L$, because photons run 70 times, so $\Delta\phi = \Delta L/\lambda = 10^{-9}$ and the number of photons reaching the detector in 1 msec would be 10^3. The sensitivity is limited by noise (Braginsky, Rudenko),

About noise see M. Maggiore, "Gravitational Waves" Oxfors Univ. Press.

Some elementary formalities about GWs.

GR equations:

$$R_{\mu\nu} - (1/2) g_{\mu\nu} R = 8\pi G_N T_{\mu\nu}.$$

Weak GWs in vacuum (in almost flat background):

$$g_{\mu\nu} = g^{(0)}_{\mu\nu} + h_{\mu\nu}$$

Gauge freedom: $\tilde{x}^\mu = x^\mu + \xi^\mu$, allows:

$$\partial_\mu \psi^\mu_\nu = 0, \text{ where } \psi^\mu_\nu = h^\mu_\nu - \delta^\mu_\nu h^\alpha_\alpha / 2.$$

Hence in vacuum

$$R_{\mu\nu} = \frac{1}{2} \Box \psi_{\mu\nu} \equiv \frac{1}{2} \left(\frac{\partial^2}{\partial t^2} - \Delta \right) \psi_{\mu\nu} = 0.$$

More freedom: gauge transformation with $\Box\xi^\mu = 0$ permits to impose $h = 0$ and so:

$$\Box h_{\mu\nu} = 0.$$

Plane wave $h = h(x - t)$. With a proper choice of ξ^μ only two components of $h_{\mu\nu}$ remain non-vanishing:
h_{23} and $h_{22} = -h_{33}$ – transverse waves.
Analogy with electromagnetic wave, massless particles with any non-zero spin have only 2 helicity states. Emission of GWs.

$$\Box\psi_{\mu\nu} = 8\pi G_N T_{\mu\nu},$$

where for weak fields $\partial_\mu T^\mu_\nu = 0$.
Retarded potential solution:

$$h_{\mu\nu} = 4G_N \int \frac{d^3x}{R} T_{\mu\nu}(t - R).$$

For slowly moving bodies:

$$h_{\mu\nu} = \frac{4G_N}{R_0} \int d^3x\, T_{\mu\nu}(t - R_0).$$

Next, use the conservation laws:

$$\partial_i T^{ij} - \partial_0 T^{0j} = 0,$$
$$\partial_0 T^{0j} - \partial_0 T^{00} = 0$$

multiply them by x^k or by $x^k x^j$ and integrate over space. Thus we find e.g.

$$\partial_0 \int d^3x T^{i0} x^k = \int d^3x h^{kj}.$$

Ultimately we obtain:

$$\int d^3x T^{kj} = \frac{1}{2}\partial_0^2 \int d^3x\, x^k x^j T^{00}$$

Quadrupole radiation:

$$h_{kj} = \frac{2G}{3R_0} \ddot{D}_{kj},$$

where

$$\ddot{D}_{kj} = \int d^3x \left(3x^k x^j - \delta_{kj} r^3\right) \, T_{00}.$$

Energy density of GWs:

$$\varrho_{GW} = \frac{m_{Pl}^2}{32\pi} \langle \dot{h}_{ab} \, \dot{h}^{ab} \rangle.$$

Radiated energy:

$$\dot{E} = \frac{G}{45} \dddot{D}_{ij}^2.$$

Strong GWs in a very curved background: similar but much more complicated, see e.g. Landau and Lifshitz, v.2, or M. Maggiore, or recent reviews on GWs.

Strain:

$$\langle h_{ab}\, h^{ab} \rangle = 4 \int_0^{+\infty} d(\log f) f S_h.$$

Characteristic amplitude

$$\langle h_{ab}\, h^{ab} \rangle = 2 \int_0^{+\infty} d(\log f) f h_c^2,$$

so $h_c^2 = 2f\, S_h(f)$.

Recent astronomical data, which keep on appearing almost every day, show that the contemporary, $z \sim \mathbf{0}$, and early, $z \sim \mathbf{10}$, universe is much more abundantly populated by all kind of black holes, than it was expected even a few years ago.

They may make a considerable or even 100% contribution to the cosmological dark matter.

Among these BH:

- massive, from a fraction of $M_\odot$ up to $\gtrsim \mathbf{10} M_\odot$,
- supermassive (SMBH), $M \sim (\mathbf{10^6} - \mathbf{10^9}) M_\odot$,
- intermediate mass (IMBH) $M \sim (\mathbf{10^3} - \mathbf{10^5}) M_\odot$,
- and a lot between and out of the intervals.

Most natural is to assume that these black holes are primordial, PBH.

Existence of such abundant primordial black holes was predicted a quarter of century ago (A.D., J.Silk, 1993). Not only abundant PBHs but also observed peculiar primordial stars, are predicted.

Young universe

Data about young universe, $z \sim \mathbf{10}$.

The data collected during last several years indicate that the young universe at $z \sim \mathbf{10}$ is grossly overpopulated with unexpectedly high amount of:

- Bright QSOs, alias supermassive BHs, up to $M \sim \mathbf{10^{10}} M_\odot$,
- Superluminous young galaxies,
- Supernovae, gamma-bursters,
- Dust and heavy elements.

These facts are in good agreement with the our 1993 model but in tension with the Standard Cosmological Model.

Young universe

A brief review of high-z discoveries.

1. Several galaxies have been observed with natural gravitational lens "telescopes.

For example a galaxy at $z \approx \mathbf{9.6}$ which was created at $t_U \approx \mathbf{0.5}$ Gyr (W. Zheng, *et al*, "A highly magnified candidate for a young galaxy seen when the Universe was 500 Myrs old" arXiv:1204.2305).

A galaxy at $z \approx \mathbf{11}$ has been detected which was formed earlier than the universe age was $t_U \sim \mathbf{0.4}$ Gyr, three times more luminous in UV than other galaxies at $z = \mathbf{6} - \mathbf{8}$.
D. Coe *et al* "CLASH: Three Strongly Lensed Images of a Candidate $z \sim \mathbf{11}$ Galaxy", Astrophys. J. 762 (2013) 32.

Unexpectedly early creation.

Young universe

Not so young but extremely luminous galaxy "The most luminous galaxies discovered by WISE" Chao-Wei Tsai, P.R.M. Eisenhardt *et al*, arXiv:1410.1751, 8 Apr 2015.

$L = 3 \cdot 10^{14} L_\odot$; $t_U \sim 1.3$ Gyr.

The galactic seeds, or embryonic black holes, might be bigger than thought possible. P. Eisenhardt: "How do you get an elephant? One way is start with a baby elephant." However, there is no known mechanism in the standard model to make sufficiently heavy seeds. The BH was already billions of $M_\odot$, when our universe was only a tenth of its present age of 13.8 billion years. "Another way to grow this big is to have gone on a sustained binge, consuming food faster than typically thought possible." Low spin is necessary!

Young universe

T. Hashimoto et al, arXiv180505966H, Nature, May, 17, 2018,
"The onset of star formation 250 million years after the Big Bang"
Oxygen line at $z = \mathbf{9.1096 \pm 0.0006}$. "This precisely determined redshift indicates that the red rest-frame optical colour arises from a dominant stellar component that formed about 200 million years after the Big Bang, corresponding to a redshift of about 15." "Although we are observing a secondary episode of star formation at $z = \mathbf{9.1}$, the galaxy formed the bulk of its stars at a much earlier epoch." Our results indicate it may be feasible to directly detect the earliest phase of galaxy formation, beyond the redshift range currently probed with HST, with future facilities such as the James Webb Space Telescope.

"Detection of a Lensed $z \approx \mathbf{11}$ Galaxy in the Rest-Optical with Spitzer/IRAC and the Inferred SFR (Star Formation Rate) , Stellar Mass, and Physical Size", Daniel Lam et al, arXiv:1903.08177.

Young universe

As is stated in the paper "Monsters in the Dark" D. Waters, et al, Mon. Not. Roy. Astron. Soc. 461 (2016), L51 density of galaxies at $z \approx \mathbf{11}$ is $\mathbf{10^{-6}}$ Mpc^{-3}, an order of magnitude higher than estimated from the data at lower z. Origin of these galaxies is unclear.

According to F. Melia (1403.0908), "The Premature Formation of High Redshift Galaxies", 1403.0908: "Rapid emergence of high-z galaxies so soon after big bang may actually be in conflict with current understanding of how they came to be. This problem is very reminiscent of the better known (and probably related) premature appearance of supermassive black holes at $z \sim \mathbf{6}$. It is difficult to understand how $\mathbf{10^9} M_\odot$ black holes 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."

Young universe

Almost yesterday discovery: " A dominant population of optically invisible massive galaxies in the early Universe" T. Wang, et al, 1908.02372.
"...we report submillimeter (wavelength 870um) detections of 39 massive star-forming galaxies at $z > 3$, which are unseen in the spectral region from the deepest ultraviolet to the near-infrared. They contribute a total star-formation-rate density ten times larger than that of equivalently massive ultraviolet-bright galaxies at $z > 3$. Residing in the most massive dark matter halos at their redshifts, they are probably the progenitors of the largest present-day galaxies in massive groups and clusters. Such a high abundance of massive and dusty galaxies in the early universe challenges our understanding of massive-galaxy formation.

2. Supermassive BH and/or QSO.

Another and even more striking example of early formed objects are high z quasars. About 40 quasars with $z > \mathbf{6}$ were known two years ago, each quasar containing BH with $M \sim \mathbf{10^9} M_\odot$.

The maximum redshift QSO is discovered in D.J. Mortlock, *et al*, " A luminous quasar at a redshift of z = 7.085" Nature 474 (2011) 616, with $L \approx \mathbf{6 \cdot 10^{13}} L_\odot$, $M = \mathbf{2 \cdot 10^9} M_\odot$, The quasar was formed before the universe reached **0.75** Gyr.

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).

There is already a serious problem with formation of lighter and less luminous quasars which is multifold deepened with this new "creature". The new one with $M \approx \mathbf{10^{10}} M_\odot$ makes the formation absolutely impossible in the standard approach.

Young universe

"An 800 million solar mass black hole in a significantly neutral universe at redshift 7.5", E. Bañados, et al arXiv:1712.01860. Accretion is absent!

Recent observations by SUBARU practically doubled the number of discovered high z QSO, Yoshiki Matsuoka et al, 2018 ApJ 869 150, Publications of the Astronomical Society of Japan, Volume 70, Issue SP1, 1 January 2018, S35,
The Astrophysical Journal Letters, Volume 872, Number 1, First low luminosity QSO at $z > 7$

Calculations of the 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."

Young universe

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 origin of SMBH in contemporary universe during 14 Gyr is difficult 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.

Young universe

3. Evolved chemistry, dust, supernovae, gamma-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.
Another possibility is a non-standard BBN in bubbles with very high baryonic density, which allows for formation of heavy elements beyond lithium.

Young universe

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 $z = \mathbf{7.55}$.

Copious Amounts of Dust and Gas in a z=7.5 Quasar Host Galaxy.
B. Venemans, et al, The Ap.J Letters, Volume 851, page L8,
"... past high star formation is needed to explain the presence of $\sim 10^8 M_\odot$ of dust implied by the observations."
Catalogue of the observed dusty sources indicates that their number is an order of magnitude larger than predicted by the canonical theory.

Young universe

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 may be enough for birth of living creatures.
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.

Young universe

Dust production scenarios in galaxies at $z \sim \mathbf{6 - 8.3}$ A. Leśniewska and M.J. Michałowski A&A 624, L13 (2019).

The mechanism of dust formation in galaxies at high redshift is still unknown. Asymptotic giant branch (AGB) stars and explosions of supernovae (SNe) are possible dust producers, and non-stellar processes may substantially contribute to dust production. However, AGS are not efficient enough to produce the amounts of dust observed in the galaxies.

In order to explain these dust masses, SNe would have to have maximum efficiency and not destroy the dust which they formed.

Therefore, the observed amounts of dust in the galaxies in the early universe were formed either by efficient supernovae or by a non-stellar mechanism, for instance the grain growth in the interstellar medium.

Or non-standard big bang nucleosynthesis with large baryon-to-γ ratio leading to abundant formation of heavy elements, see below.

Universe today

Contemporary universe, $t_U = 14.6 \cdot 10^9$ years.

• SMBH today

Every large galaxy contains a central supermassive BH with mass larger than $10^9 M_\odot$ in giant elliptical and compact lenticular galaxies and $\sim 10^6 M_\odot$ in spiral galaxies like Milky Way.
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 Gyr.
Even more puzzling: SMHBs are observed in small galaxies and even in almost EMPTY space, where no material to make a SMBH can be found.

Universe today

Some examples of the data:

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 **60%** of its bulge mass. This creates serious problems for the standard scenario of formation of central supermassive BHs by accretion of matter in the central part of a galaxy.

An inverted picture is more plausible, when first a supermassive BH was formed and attracted matter being a seed for subsequent galaxy formation!!!

AD, J. Silk, 1993;

AD, M. Kawasaki, N. Kevlishvili, 2008;

Bosch et al, Nature 491 (2012) 729.

Universe today

More examples:

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. The dynamical effects of such ultramassive central black holes is unclear.

A recent discovery of an ultra-compact dwarf galaxy older than 10 Gyr, enriched with metals, and probably with a massive black in its center seems to be at odds with the standard model J. Strader, *et al* Ap. J. Lett. 775, L6 (2013). The dynamical mass is $\mathbf{2 \times 10^8} M_\odot$ and $R \sim \mathbf{24}$ pc - very high density.

Chandra: variable central X-ray source with $L_X \sim \mathbf{10^{38}}$ erg/s, which may be an AGN associated with a massive black hole or a low-mass X-ray binary.

Universe today

"An evolutionary missing link? A modest-mass early-type galaxy hosting an over-sized nuclear black hole", J. Th. van Loon, A.E. Sansom, Xiv:1508.00698v1 BH mass, $M_{BH} = (3.5 \pm 0.8) \cdot 10^8 M_\odot$, host galaxy $M_{stars} = 2.5^{+2.5}_{-1.2} \cdot 10^{10} M_\odot$, and accretion luminosity: $L_{AGN} = (5.3 \pm 0.4) \cdot 10^{45}$erg/s $\approx 10^{12} L_\odot$. The AGN is more prominent than expected for a host galaxy of this modest size.

The data are in tension with the accepted picture in which this galaxy would recently have transformed from a star-forming disc galaxy into an early-type, passively evolving galaxy.

"A Nearly Naked Supermassive Black Hole" J.J. Condon, et al arXiv:1606.04067. A compact symmetric radio source B3 1715+425 is too bright (brightness temperature $\sim 3 \times 10^{10}$ K at observing frequency 7.6 GHz) and too luminous (1.4 GHz luminosity $\sim 10^{25}$ W/Hz) to be powered by anything but a SMBH, but its host galaxy is much smaller.

Universe today

A Cool Accretion Disk around the Galactic Centre Black Hole,
E.M. Murchikova, et al Nature 570, 83 (2019).
A supermassive black hole SgrA* with the mass $\sim \mathbf{4 \times 10^6} \boldsymbol{M_\odot}$ resides at the centre of our galaxy. Building up such a massive black hole within the $\sim \mathbf{10^{10}}$ year lifetime of our galaxy would require a mean accretion rate of $\mathbf{4 \times 10^{-4}} M_\odot$ per year.
At present, X-ray observations constrain the rate of hot gas accretion to $\dot{\boldsymbol{M}} \sim \mathbf{3 \times 10^{-6}} \boldsymbol{M_\odot}$ per year and polarization measurements constrain it near the event horizon to $\dot{\boldsymbol{M}}_{\boldsymbol{horizon}} \sim \mathbf{10^{-8}} \boldsymbol{M_\odot}/\mathrm{yr}$.
The universe age is short by two orders of magnitude.

Universe today

AND MORE RECENT PUZZLES
(improbable systems in the standard model):

- Several (four?) binaries of SMBH.
- Quasar quartet.
- Triple SMBH [1712.03909].

Universe today

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), $z \approx \mathbf{0.3}$.

Universe today

"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.

Universe today

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. Such a structure can only satisfy one of the three scenarios: a triple supermasive black hole (SMBH) interacting system, a triple AGN, or a recoiling SMBH.

Universe today

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

• Intermediate mass black holes (MBH) $M = (10^3 - 10^5)M_\odot$
Nobody expected them 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, "dentified 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

"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.

Universe today

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 predicted density of IMBHs is sufficient to seed the formation of all globular clusters in galaxies.

Universe today

• 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

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 $\boldsymbol{H = 67.3}$ and $\boldsymbol{t_U = 13.8}$; and if $\boldsymbol{H = 74}$, then $\boldsymbol{t_U = 12.5}$, more than 10 $\boldsymbol{\sigma}$.

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

• Other strange 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

Very unusual star:

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?

Universe today

"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".
Authors suggest that these stars are not completely burned down remnants of SNIa, but the probability for such events seems to be quite low.
They could be chemically peculiar primordial stars wandering in Galactic halo

Universe today

The discovery of this month.

"A hyper-runaway white dwarf in Gaia DR2 as a Type Iax supernova primary remnant candidate" N.J. Ruffini, A.R. Casey, arXiv:1908.00670

"We report the likely first known example of an unbound white dwarf that is consistent with being the fully-cooled primary remnant to a Type Iax supernova. The candidate, LP 93-21, is travelling with a galactocentric velocity of $v_{gal} \simeq 605$ km s^{-1}, and is gravitationally unbound to the Milky Way, We rule out an extragalactic origin. The Type Iax supernova ejection scenario is consistent with its peculiar unbound trajectory, given anomalous elemental abundances are detected in its photosphere via spectroscopic follow-up. This discovery reflects recent models that suggest stellar ejections likely occur often."

This could be a peculiar WD or a remnant of a primordial star.

Universe today

• 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: $f < 0.2$, $0.15 M_\odot < M < 0.9 M_\odot$;
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 who are they is not known.

- 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.

Universe today

Very recent discovery:
"A young galaxy cluster in the old Universe", T. Hashimoto, et al, arXiv:1908.01666. Here we report a discovery of a "blue cluster", that is a local galaxy cluster with an unprecedentedly high fraction of blue star-forming galaxies yet hosted by a massive dark matter halo. The blue fraction is 0.57, which is 4.0 σ higher than those of the other comparison clusters under the same selection and identification criteria. The probability to find such a high blue fraction in an individual cluster is only 0.003%, which challenges the current standard frameworks of the galaxy formation and evolution in the ΛCDM Universe.
Such blue cluster is in accord with our prediction of predominantly helium rich "bubbles" in the universe.

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 a theccepted faith, since they became supported by the recent astronomical data.
Massive PBHs allow to cure emerging inconsistencies with the standard cosmology and astrophysics.
Dark matter made out of PBHs became a viable option.
Unusual stellar type compact objects could also be created.
Swiss cheese universe: small bubbles with high $\beta \equiv N_B/N_\gamma \sim 1$.
In many respects the picture, but not dynamics, is similar to that described by Juan Garcia Bellido yesterday.

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 only 3 parameters: μ, γ, M_0. Can be generalized to multi-maximum spectrum.

This form is a result result of quantum diffusion of baryonic scalar field during inflation. Probably such spectrum is a general consequence of diffusion.

Log-normal mass spectrum of PBHs was rediscovered by S. Clesse, J. Garcia-Bellido, Phys. Rev. D92, 023524 (2015).

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.

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, according to quantum diffusion equation derived by Starobinsky, generalized to a complex field χ.

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.

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

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.

SUMMARY

- 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.

SUMMARY

- 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 older age is mimicked by the unusual initial chemistry.
- 8. Existence of high density invisible "stars" (machos) is understood.
- 9. Explanation of origin of BHs with 2000 $M_\odot$ in the core of globular cluster and the observed density of GCs is presented.
- 10. A large number of the recently observed IMBH was predicted.
- 11. A large fraction of dark matter or 100% can be made of PBHs.
- 12. Clouds of matter with high baryon-to-photon ratio.
- 13. A possible by-product: plenty of (compact) anti-stars, even in the Galaxy, not yet excluded by observations.

Extreme conclusions

- Black holes in the universe are mostly primordial (PBH).
- Primordial BHs make all or dominant part of dark matter (DM).
- QSO created in the very early universe.
- Metals and dust are made much earlier than at $z = 10$.
- Inverted picture of galaxy formation: seeding of galaxies by SMPBH or IMPBH;
- Seeding of globular clusters by $10^3 - 10^4$ BHs, dwarfs by $10^4 - 10^5$ BH.

THE END

or

TO BE CONTINUED

Newest papers

arXiv:1904.11482 (*cross-listing*) Date: Thu, 25 Apr 2019 17:50:23 GMT (508kb,D)

Title: A common origin for baryons and dark matter Authors: Juan García-Bellido, Bernard Carr, Sebastien Clesse Categories: astro-ph.CO gr-qc hep-th Comments: 6 pages, 2 figures, comments welcome

The origin of the baryon asymmetry of the Universe (BAU) and the nature of dark matter are two of the most challenging problems in cosmology. We propose a scenario in which the gravitational collapse of large inhomogeneities at the quark-hadron epoch generates both the baryon asymmetry and dark matter in the form of primordial black holes (PBHs). This is due to the sudden drop in radiation pressure during the transition from a quark-gluon plasma to non-relativistic hadrons. The collapse to a PBH is induced by fluctuations of a light spectator scalar field in rare regions and is accompanied by the violent expulsion of surrounding material, which might be regarded as a sort of "primordial supernova". The acceleration of protons to relativistic speeds provides the ingredients

Newest papers

arXiv:1904.10298 (*cross-listing*) Date: Tue, 23 Apr 2019 13:23:35 GMT (495kb,D)
Title: Primordial black hole tower: Dark matter, earth-mass, and LIGO black holes Authors: Yuichiro Tada and Shuichiro Yokoyama Categories: astro-ph.CO hep-ph Comments: 12 pages, 3 figures
We investigate a possibility of primordial black hole (PBH) formation with a hierarchical mass spectrum in multiple phases of inflation. As an example, we find that one can simultaneously realize a mass spectrum which has recently attracted a lot of attention, stellar-mass PBHs ($\sim O(10)M_\odot$) as a possible source of binary black holes detected by LIGO/VIRGO collaboration, asteroid-mass ($\sim O(10^{-12})M_\odot$) as a main component of dark matter, and earth-mass ($\sim O(10^{-5})M_\odot$) as a source of ultrashort-timescale events in OGLE microlensing data . The recent refined swampland conjecture may support these multi-phase inflationary scenario with hierarchical mass PBHs as a transition signal of each inflationary phase.

Newest papers

arXiv:1705.05567 replaced with revised version Tue, 9 Apr 2019 19:01:23 GMT (464kb,D)
Title: Primordial black hole constraints for extended mass functions
Authors: Bernard Carr, Martti Raidal, Tommi Tenkanen, Ville Vaskonen and Hardi Veermäe Categories: astro-ph.CO hep-ph Comments: 9 pages, 3 figures. v2: Added discussion about combined constraints. Accepted for publication in Phys. Rev. D. v3: Corrected a minor mistake in the plots for power-law mass functions Journal-ref: Phys. Rev. D 96, 023514 (2017)

Newest papers

We revisit the cosmological and astrophysical constraints on the fraction of the dark matter in primordial black holes (PBHs) with an extended mass function. We consider a variety of mass functions, all of which are described by three parameters: a characteristic mass and width and a dark matter fraction. Various observations then impose constraints on the dark matter fraction as a function of the first two parameters. We show how these constraints relate to those for a monochromatic mass function, demonstrating that they usually become more stringent in the extended case than the monochromatic one. Considering only the well-established bounds, and neglecting the ones that depend on additional astrophysical assumptions, we find that there are three mass windows, around $4 \times 10^{17} M_\odot$, $2 \times 10^{14} M_\odot$ and $(25100) M_\odot$, where PBHs can constitute all dark matter. However, if one includes all the bounds, PBHs can only constitute of order 10% of the dark matter.

Newest papers

arXiv:1903.10509 (*cross-listing*) Date: Mon, 25 Mar 2019 18:00:01 GMT (907kb,D)
Title: Lyman-α forest constraints on Primordial Black Holes as Dark Matter Authors: Riccardo Murgia, Giulio Scelfo, Matteo Viel, Alvise Raccanelli Categories: astro-ph.CO gr-qc Comments: 8 pages, 5 figures, 1 table Report-no: CERN-TH-2019-029
The renewed interest in the possibility that primordial black holes (PBHs) may constitute a significant part of the dark matter has motivated revisiting old observational constraints, as well as developing new ones. We present new limits on the PBH abundance, from a comprehensive analysis of high resolution, high redshift Lyman-α forest data. Poisson fluctuations in the PBH number density induce a small-scale power enhancement which departs from the standard cold dark matter prediction. Using a grid of hydrodynamic simulations exploring different values of astrophysical parameters, we obtain a marginalized upper limit on the PBH mass of $f_{\rm PBH} M_{\rm PBH} \sim 60\ M_\odot$ ($170\ M_\odot$) at 2σ (depending on priors),

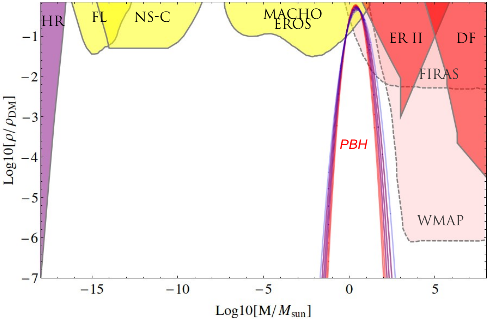


Figure: Constraints on PBH fraction in DM. The existing constraints (extragalactic γ-rays from evaporation (HR), femtolensing of γ-ray bursts (F), neutron-star capture constraints (NS-C), MACHO, EROS, OGLE microlensing (MACHO, EROS) survival of star cluster in Eridanus II (E), dynamical friction on halo objects (DF), and accretion effects (WMAP, FIRAS)) The PBH distribution is shown for $\mu = 10^{-43}$ Mpc^{-1}, $M_0 = \gamma + 0.1 \times \gamma^2 - 0.2 \times \gamma^3$ with $\gamma = 0.75 - 1.1$ (red solid lines), and $\gamma = 0.6 - 0.9$ (blue solid lines).

The effects are extragalactic γ-rays from evaporation (EG), femtolensing of γ-ray bursts (F), neutron-star capture constraints (NS), Kepler microlensing and millilensing (K), MACHO, EROS, OGLE microlensing (ML), survival of star cluster in Eridanus II (E), wide binary disruption (WB), dynamical friction on halo objects (DF), millilensing of quasars (mLQ), generation of large-scale structure through Poisson fluctuations (LSS), and accretion effects (WMAP, FIRAS); the accretion limits are shown with broken lines since they are highly model-dependent.