New data on young and old black holes and other unexpected creatures

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Recent astronomical data, which keep on appearing almost every day, show that the contemporary, $z \sim 0$, and early, $z \sim 10$, 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 $\gtrsim 10 M_\odot$,
- supermassive (SMBH), $M \sim (10^6 - 10^9) M_\odot$,
- intermediate mass (IMBH) $M \sim (10^3 - 10^5) M_\odot$,

Conventional mechanism of creation of these PHs is not efficient. 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 now peculiar primordial stars, are predicted.

Types of BH by creation mechanism

I. Astrophysical BHs: created by stellar collapse when 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: $\sim (1-2)M_\odot$.
It is unknown how the traditional mechanism can lead to such unexpected form of the mass spectrum.

II. Accretion of matter to regions with excessive density.
There are supermassive BHs (SMBH) in all large galaxy with $M \sim 10^9 M_\odot$ in elliptic and lenticular galaxies and $\mathbf{M} \sim (10^6 - 10^7)\mathbf{M}_\odot$ in elliptic galaxies, as Milky Way.
However, the known mechanisms of accretion are not efficient enough to create such monsters during the universe age $t_U \approx 15$ Gyr. Very massive seeds are necessary, but their origin is mysterious.
Moreover SMBH are found in very small galaxies and one SMBH lives even in almost empty space.

Types of BH by creation mechanism

III. Primordial black holes (PBH) created in pre-stellar epoch
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, 1967, mechanism, elaborated later by Carr and Hawking, 1974).
Usually this mechanism is assumed to create 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).
Such form of the mass spectrum and similar ones, the so called extended spectra, became quite popular nowadays

Universe today

An example of accretion efficiency.

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 $\dot{\boldsymbol{M}}_{\boldsymbol{horizon}} \sim \mathbf{10^{-8}} \boldsymbol{M_\odot}/\text{yr}$.

The universe age is short by two orders of magnitude.

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 recent photo of the shadow of BH with $M \approx 6 \cdot 10^9 M_\odot$. Origin of these BHs is mysterious. Accepted faith is that these BHs are created by matter accretion to a central seed. But the accretion efficiency is insufficient at least by two orderes of magnitude to make them during the Universe life-time, 14 Gyr. More puzzling: SMHBs are observed in small galaxies and even in almost EMPTY space, where no material to make a SMBH can be found. An inverted picture is more plausible, when first a smBH 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 PUZZLES - improbable systems in the standard model:

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 $\sim 10^{-7}$. The data 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.

TRIPLE Quasar. E. Kalfountzou, M.S. Lleo, M. Trichas, " 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 < 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

• 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

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 $(\mathbf{2-3}) \times \mathbf{10^3} M_\odot$ is about $\mathbf{10^4 - 10^5}$ per one SMPBH with mass $> \mathbf{10^4} M_\odot$.
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 $H = 67.3$ and $t_U = 13.8$; and if $H = 74$, then $t_U = 12.5$, more than 10 σ.

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

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

Universe today

- 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

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 $\boldsymbol{v_{gal} \simeq 605 km\, s^{-1}}$, 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: $f < \mathbf{0.2}$, $\mathbf{0.15 M_\odot < M < 0.9 M_\odot}$;
EROS2:$f < \mathbf{0.1}$, $\mathbf{10^{-6} M_\odot < M < M_\odot}$;
AGAPE: $\mathbf{0.2 < f < 0.9}$,
for $\mathbf{0.15 M_\odot < M < 0.9 M_\odot}$;
EROS-2 and OGLE: $f < \mathbf{0.1}$ for $M \sim \mathbf{10^{-2} M_\odot}$ and
$f < \mathbf{0.2}$ for $\sim \mathbf{0.5 M_\odot}$.
MACHOs surely exist, but who are they, is not known.

- Mass spectrum of astrophysical (?) BH in the Galaxy

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, but fits the hypothesis of their primordial origin.

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 $M > \mathbf{100} M_\odot$ and a low metal abundance to avoid too much mass loss during the evolution. Such heavy stars might be present in young star-forming galaxies but they are not observed in the necessary amount. 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 $(\mathbf{36}+\mathbf{29})M_\odot$ 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 $\mathbf{50}M_\odot$ and $\mathbf{30}M_\odot$ and and GW151216 (?).

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!
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 $z \approx 11$ is 10^{-6} Mpc^{-3}, an order of magnitude higher than estimated from the data at lower z. Origin of these galaxies is unclear.

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.

Young universe

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

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

Recent Summary: "Dust production scenarios in galaxies at $z \sim 6 - 8.3$ 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.

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 PRIMORDIAL BLACK HOLES 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. The model leads to: Swiss cheese universe filled by small bubbles with high $\beta \equiv N_B/N_\gamma$ up to unity, occupying a small fraction of the total volume. Normal $\beta \sim \mathbf{10^{-9}}$.

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

(of the first season)