Astronomical data in favor of abundant population of PBH in the universe and the mechanism of their formation.

A. D. Dolgov

Novosibirsk State University, Novosibirsk, Russia
ITEP, Moscow, Russia

supported by the RSF Grant, 19-42-02004

Focus week on primordial black holes
December 2-6, 2019
Kavli IPMU
Japan

Outline and history

Almost all I black holes (BHs) observed in the universe with masses from a fraction of $M_\odot$ up to billions of $M_\odot$ must be primordial (PBH) or, if very massive, seeded by PBHs. Attempts to create them in the frameworks of conventional cosmology and astrophysics encounter serious problems.

Existence of such PBHs with extended log-normal mass spectrum was predicted in 1992 by AD and J. Silk, "Baryon isocurvature fluctuations at small scales and baryonic dark matter", Phys.Rev. D47 (1993) 4244, preprint CFPA-TH-92-04, **PBH dark matter was suggested;**
also AD, M. Kawasaki, N. Kevlishvili, "Inhomogeneous baryogenesis, cosmic antimatter, and dark matter" Nucl. Phys. B807 (2009) 229.

A review on the solution of some cosmological and astrophysical conundra by PBHs is presented in: A.D. Dolgov "Massive and supermassive black holes in the contemporary and early Universe and problems in cosmology and astrophysics" Usp. Fiz. Nauk 188 (2018) 121, Phys. Usp. 61 (2018) 115 (English translation)

Types of BH by creation mechanism

• Astrophysical BHs: created by stellar collapse when star exhausted its nuclear fuel. The expected masses should be just above the neutron star masses $3M_\odot$ and quite close to it, **in strong contrast to observations.**

• Accretion of matter to regions with excessive density. The supermassive BH (SMBH) observed in large galaxies with masses $M \sim 10^9 M_\odot$ in elliptic and lenticular galaxies and $\mathbf{M \sim (10^6 - 10^7) M_\odot}$ in elliptic galaxies, like Milky Way are supposed to be created by accretion.

• 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 mechanism, elaborated later by Carr and Hawking).

Usually this mechanism is assumed to create PBH with rather low masses and with sharp almost delta-function mass spectrum.

PBH creation in AD-JS scenario

A different mechanism of PBH formation (AD, J.Silk, 1993) could make PBH with masses up to millions solar masses and with log-normal mass spectrum:

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

with only 3 constant parameters: μ, γ, M_0.
Log-normal spectra are are generic in many stochastic physical processes.
The mechanism is based in the interaction of the Affleck-Dine scalar baryon χ with the inflaton field Φ:

$$U_{int} = |\chi|^2 \prod_j \lambda_j (\Phi - \Phi_j)^2 / m_{Pl}^{(2j-2)}.$$

For $j = 1$ the interaction is a general renormalizable one. With $j > 1$ the spectrum is a superposition of log-normal ones (AD, M. Kawasaki, N. Kevlishvili):

$$\frac{\mathrm{dN}}{\mathrm{dM}} = \sum_j \mu_j^2 \exp\left[-\gamma_j ln^2\left(\frac{M}{M_j}\right)\right].$$

PBH creation in AD-JS scenario

If the potential of χ has (almost)) flat directions, $H \gg m_\chi$ the field would acquire large value due to quantum diffusion and after H dropped below m_χ its amplitude, χ evolved down to zero creating on the way large value of the baryon asymmetry $\beta = N_B/N_\gamma$, which might be of order unity

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 would have normal $\beta \approx 6 \cdot 10^{-10}$, generated by small χ.

This mechanism of PBH formation is very much different from all others.

The fundament of PBH creation was build at inflation by creating large variation of the baryonic chemical potential. Since quarks are massless it led to the isocurvature fluctuations at cosmologically small scales, with practically vanishing density perturbations.

Density perturbations are generated rather late after the QCD phase transition when quarks turned into massive baryons.

PBH creation in AD-JS scenario

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: High Baryon Bubbles (HBB).

PBH formed only at or after the QCD phase transition which took place at $T = 100 - 200$ **MeV.**

Not only PBH, but also compact stellar-type objects could be formed, enriched with helium and heavy elements, since BBN occured with high β.

The maximum mass of HBBs depends upon the duration of inflation after Φ passed through Φ_1 and easily could be about $10^4 M_\odot$.

However, much smaller PBH might be created, e.g. $M = 10^{20} - 10^{22}$ g, due to higher external pressure outside HBB (!?). Q-balls (M.K.)

In some versions of the model the HBBs with different signs of β be created - i.e. antimatter bubbles.

In this case the Galaxy could be full of antistars which may still avoid observations.

Problems with Supermassive Black Holes (SMBH)

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

In every large galaxy a central SMBH is observed (or even not a single one) with mass which can be larger than $10^9 M_\odot$ in giant elliptical and compact lenticular galaxies and **a few**$\times 10^6 M_\odot$ in spiral galaxies like Milky Way. The origin of these BHs is poorly understood.

The accepted faith is that these BHs are created by matter accretion to a central seed. However, 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 for SMBH creation can be found.

It is tempting to conclude that all these SMBH are primordial and that they could seed galaxy formation and the type of the galaxy is determined by the mass of the central BH, according to the conjecture of refs:

AD, J. Silk, 1993; AD, M. Kawasaki, N. Kevlishvili, 2008;

Bosch et al, Nature 491 (2012) 729.

Supermassive black holes (SMBH)

Estimate of the necessary accretion rate.

The conventional formation mechanism by matter accretion to the central density excess demands 10 - 100 time more than the universe age, see e.g. E.M. Murchikova, et al "A Cool Accretion Disk around the Galactic Centre Black Hole", Nature 570, 83 (2019).

Building up the SMBH SgrA* with the mass $\sim \mathbf{4 \times 10^6} \boldsymbol{M_\odot}$ at the centre of our galaxy within the $\sim \mathbf{10^{10}}$ year lifetime of the Milky Way would require a mean accretion rate of $\mathbf{4 \times 10^{-4}} M_\odot$ per year.

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 Galaxy age is short by two orders of magnitude.

Supermassive black holes (SMBH)

Striking examples of the highest mass SBMHs in the contemporary universe:

"A 40-billion solar mass black hole in the extreme core of Holm 15A, the central galaxy of Abell 85", K. Mehrgan *et al*, arXiv:1907.10608v2
$(\mathbf{4 \pm 0.8}) \times \mathbf{10^{10}} \boldsymbol{M_\odot}$, distance 252.8 Mpc

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
$(\mathbf{6 \pm 0.7}) \times \mathbf{10^{9}} \boldsymbol{M_\odot}$, giant elliptical galaxy M87, distance 16.4 Mpc.

Not so far from us. Much more can be expected at larger distances.

Supermassive black holes (SMBH)

A few more puzzles of contemporary universe.

• 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. R. C. E. van den Bosch *et al*, Nature, **491**, 729 (2012). It is in a very strong tension with the standard scenario of formation of central supermassive BHs by accretion of matter to the central part of a galaxy.

• "An evolutionary missing link? A modest-mass early-type galaxy hosting an over-sized nuclear black hole", J. Th. van Loon, A.E. Sansom, arXiv:1508.00698v1 BH mass, $\mathbf{M_{BH} = (3.5 \pm 0.8) \cdot 10^8 M_\odot}$, host galaxy $\mathbf{M_{stars} = 2.5^{+2.5}_{-1.2} \cdot 10^{10} M_\odot}$, and $\mathbf{L_{AGN} \approx 10^{12} L_\odot}$.

Such powerful AGN is not 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.

Supermassive black holes (SMBH)

A few more puzzles of contemporary universe.

• 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.

• "A Nearly Naked Supermassive Black Hole" J.J. Condon, et al The Astrophysical Journal 834 (2017) 184

A compact symmetric radio source B3 1715+425 is too bright (brightness temperature $\sim \mathbf{3 \times 10^{10}}$ K at observing frequency 7.6 GHz) and too luminous (1.4 GHz luminosity $\sim \mathbf{10^{25}}$ W/Hz) to be powered by anything but a SMBH, but its host galaxy is much smaller.

Not enough matter around to create such SMBH!

Universe today, SMBH binaries, triplet, and quartet

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

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.

Universe today, SMBH triplet

Triple Quasar, much less probable than a binary.

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, SMBH quartet

"Quasar quartet embedded in giant nebula reveals rare massive structure in distant universe", J.F. Hennawi et al, Science 15 May 2015, 348 p. 779, Discovery of a a physical association of four quasars at $z \approx \mathbf{2}$. The probability of finding a quadruple quasar is $\sim \mathbf{10^{-7}}$. Our findings imply that the most massive structures in the distant universe have a tremendous supply ($\sim \mathbf{10^{11}}$ solar masses) of cool dense (volume density $\sim \mathbf{1}/\mathrm{cm}^{\mathbf{3}}$) gas, which is in conflict with current cosmological simulations.

Supermassive black holes (SMBH) at high z

High redshift mysteries.

High redshift observations at $\boldsymbol{z = 5 - 10}$ revealed about a hundred of SMBH formed when the universe was 10 times younger than now.

About 40 quasars with $\boldsymbol{z > 6}$ were known 3 years ago, each quasar containing BH with $\boldsymbol{M \sim 10^9 M_\odot}$. Maximum redshift is $\boldsymbol{z = 7.085}$ i.e. the quasar was formed before **0.75** Gyr with $\boldsymbol{L = 6.3 \cdot 10^{13} L_\odot}$, $\boldsymbol{M = 2 \cdot 10^9 M_\odot}$, D.J. Mortlock, *et al*, Nature 474 (2011) 616.

Recent observations by SUBARU practically doubled the number of discovered high z QSO, Y. Matsuoka et al 2018 ApJ 869 150, APJL 872, No. 1, First low luminosity QSO at $z > 7$

In addition to all that another monster was discovered:

"An ultraluminous quasar with a twelve billion solar mass black hole at redshift 6.30". Xue-BingWu et al, Nature 518, 512 (2015).

The formation problem became multifold deeper with this new "creature".

Supermassive black holes (SMBH) at high z

Accretion rate: M.A. Latif, M Volonteri, J.H. Wise, [1801.07685], published in MNRAS ".. halo has a mass of $\mathbf{3 \times 10^{10}}$ $\boldsymbol{M_\odot}$ at $\boldsymbol{z = 7.5}$; MBH accretes only about 2200 $\boldsymbol{M_\odot}$ during 320 Myr."

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 SMBHs in the local universe during 14 Gyr is unknown.

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.

Supermassive black holes (SMBH) at high z

A striking example:

"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!

Intermediate mass BH (IMBH), $M = (10^3 - 10^5) M_\odot$

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

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 are massless $3 \times 10^4 < M_{\rm BH} < 2 \times 10^5 M_\odot$,

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 $(1 - 20) \times 10^5 M_\odot$."

Intermediate mass BH (IMBH), $M = (\mathbf{10^3 - 10^5}) M_\odot$

"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.

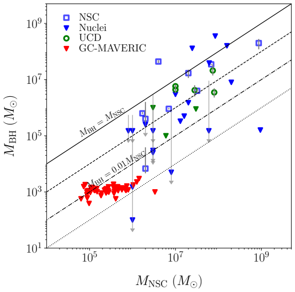
Intermediate mass BH IMBH

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

Only one or two massive BH are observed in Globular clusters. Definite evidence of BH with $M \approx \mathbf{2000} M_\odot$ was found in the core of the globular cluster 47 Tucanae.

AD, K.Postnov "Globular Cluster Seeding by Primordial Black Hole Population" JCAP 1704 (2017) 036: if the parameters of the mass distribution of PBHs are chosen to fit the LIGO data and the density of SMBH, then the number of PBH with masses $(\mathbf{2} - \mathbf{3}) \times \mathbf{10^3} M_\odot$ is about $\mathbf{10^4} - \mathbf{10^5}$ per one SMPBH with mass $> \mathbf{10^4} M_\odot$.
This predicted density of IMBHs is sufficient to seed the formation of all globular clusters in galaxies.

Intermediate mass BH (IMBH)



The ratio of black hole to cluster mass. The median ratio of MBH to nuclear star cluster mass for objects with black holes detected is ∼25%, but with a factor of two scatter. The globular clusters are consistent with a 0.1% mass fraction for a small fraction of the Milky Way globular cluster system. From review by J.E Greene, *et al* "Intermediate-Mass Black Holes", 1911.09678.

Mass spectrum of BHs 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 explained in the standard model of BH formation by stellar collapse, but nicely fit the hypothesis of primordial BH formation with log-normal spectrum and $M_0 \approx \mathbf{8}M_\odot$.

MACHOs

• MACHOs: discovered through gravitational microlensing by Macho and Eros groups. They are invisible (very weakly luminous or even non-luminous) objects with masses about a half of the solar mass in the Galactic halo, in the center of the Galaxy, and very recently in the Andromeda (M31) galaxy. Their density is significantly greater than the density expected from the known low luminosity stars and astrophysical BH of similar mass. f = mass ratio of MACHOS to DM.

Macho group: $0.08 < f < 0.50$ (95% CL) for $0.15 M_\odot < M < 0.9 M_\odot$;
EROS: $f < 0.2$, $0.15 M_\odot < M < 0.9 M_\odot$;
EROS2:$f < 0.1$, $10^{-6} M_\odot < M < M_\odot$;
AGAPE: $0.2 < f < 0.9$,
for $0.15 M_\odot < M < 0.9 M_\odot$;
EROS-2 and OGLE: $f < 0.1$ for $M \sim 10^{-2} M_\odot$ and
$f < 0.2$ for $\sim 0.5 M_\odot$.
MACHOs surely exist but who are they is not known.
A large variance of the results by different groups.

Spectrum parameterss

According to AD and S. Porey, arXiv:1905.10972, the spectrum parameters can be fixed from the conditions:

• $M_0 = (6-8)\, M_\odot$ as dictated by the galactic mass spectrum of BHs;

• the observed number density of large galaxies is equal to the number density of the heavy black holes with masses exceeding some boundary value, assumed as $M_b = 10^4 M_\odot$; it demands $\gamma \approx 0.5$

• the total cosmological mass density of black holes in the universe makes the fraction $\mathbf{f} \sim (\mathbf{0.1-1})$ of the dark matter density. The nicest choice $\mathbf{f = 1}$. As for constraints: "All constraints have caveats and may change" (B. Carr). I agree completely. For this choice the density of IMBH well fits the data.

However, the density of MACHOs is much smaller than the observed one. One possibility to avoid the problem is to assume that the MACHO distribution is unisotropic and they are observed only where their density is high.

V.S. Berezinsky, V.I. Dokuchaev, Yu. N.. Eroshenko "Small-scale clumps of dark matter", Phys.Usp. 57 (2014) 1, Usp.Fiz.Nauk 184 (2014) 3; arXiv:1405.2204 - may also help to avoid strong microlensing bounds.

Another, probably less attractive option, is a superposition of log-normal spectra.

Spectrum parameters

Another set of parameters by K. Postnov, N. Mitichkin, and V. Simkin - best fit to the number of BH binaries (GW sources) from A.H. Nitz et al, arXive 1910.05331 - 15 sources, the merging rate of binary PBH as a function of cosmic time is calculated using the model of Ioka et al 1998 arXiv:astro-ph/9807018 P.R.D (58, Issue 6, (1998).

The best fit: $M_0 = 15$ and $\gamma = \mathbf{1}$

and $\boldsymbol{M_0} = \mathbf{10}$ and $\gamma = \mathbf{0.5}$

perfectly agree with the observed BHBH chirp masses from Table 2, but are worse for sources in Table 3.

Gravitational waves and BH binaries

• Grav. waves from BH binaries, great discovery $\rightarrow$ great problems. GW registration by LIGO has proven that the sources of GW are most probably PBH. 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 ($\sim 30 M_\odot$).

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 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. But PBHs with the observed by LIGO masses may be easily created with sufficient density.

Gravitational waves and 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 (PBH). They were at rest in the comoving volume and may have non-negligible probability to become gravitationally binded.

Gravitational waves and BH binaries

3. The low value of the BH spins in GW150914 and in almost all (except for three) other events. It strongly constrains astrophysical BH formation from close binary systems. Astrophysical BH are expected to have considerable angular momentum but still 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, JCAP06(2019)044, arXiv:1904.00570 [astro-ph.HE]). This result is in agreement with the GW170729 LIGO event produced by the binary with masses $\mathbf{50}\boldsymbol{M_\odot}$ and $\mathbf{30}\boldsymbol{M_\odot}$ and and GW151216 (?). Earlier M. Mirbabayi, et al. (1901.05963) and V. De Luca et al. (1903.01179D) much weaker angular momentum gain was obtained.

Strange stars

• Old stars in the Milky Way:

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

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

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

Universe today, too old stars

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

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

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

Universe today, high velocity stars

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

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

Universe today, strange stars

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

We find host star and planet masses of $M_{\rm host} = 0.15^{+0.27}_{-0.10} M_\odot$ and $m_p = 18^{+34}_{-12} M_\oplus$.
The life-time of main sequence star with the solar chemical content is larger than t_U already for $M < 0.8 M_\odot$.
The origin is puzzling. May it be primordial helium star? [1mm] "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".

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 predictions mentioned above, but in tension with the Standard Cosmological Model.

Young universe. Galaxies.

Early galaxies (a few examples, many more are known):
Galaxy at $z \approx \mathbf{9.6}$ created earlier than $\sim \mathbf{0.5}$ Gyr, W. Zheng, *et al*
Galaxy at $z \approx \mathbf{11}$ formed earlier than the universe age was $t_U \sim \mathbf{0.4}$ Gyr, D. Coe *et al* Astrophys. J. 762 (2013) 32.
Not so young but extremely luminous galaxy Chao-Wei Tsai, P.R.M. Eisenhardt *et al*, arXiv:1410.1751, $L = 3 \cdot 10^{14} L_\odot$; $t_U \sim 1.3$ Gyr.
The galactic seeds, or embryonic black holes, might be bigger than thought possible. The BH was already billions of $M_\odot$, when our universe was only a tenth of its present age. "Another way to grow this big is to have gone on a sustained binge, consuming food faster than typically thought possible." Low spin is necessary!
According to D. Waters, et al, MNRAS 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.

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

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

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

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

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

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

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

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

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

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

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

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

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 QSO=SMB, early created gamma-bursters and supernovae, early bright galaxies, metals and evolved chemistry including dust. All that was created much before $z \sim 10$.
- 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.
- 6. An existence of supermassive black holes observed in all large and some small galaxies and even in almost empty environment is

SUMMARY

- 6. "Older than t_U" stars may exist; the older age is mimicked by the unusual initial chemistry.
- 7. Existence and density of machos might be understood.
- 8. Explanation of the origin of BHs with 2000 $M_\odot$ in the core of globular cluster and the observed density of GCs is presented.
- 9. A large number of the recently observed IMBH was predicted.
- 10 Black holes in the universe are mostly primordial (PBH).
- 11. A large fraction of dark matter even 100% can be made of PBHs.
- 12. Clouds with high baryon-to-photon ratio may be observable.
- 13. Seeding of globular clusters by $\mathbf{10^3 - 10^4}$ BHs, dwarfs by $\mathbf{10^4 - 10^5}$ BH.

  14. A possible by-product: plenty of (compact) anti-stars, even in the Galaxy, not yet excluded by observations.

HAPPY END