Astrophysical Problems and Primordial Black Holes

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Recent astronomical observations in $z \sim 10$ universe opened a box of surprises which are in striking conflict with canonical expectations.

The early universe is found to be densely populated with huge bright galaxies, super-heavy black holes (QSOs), supernovae (gamma-bursters), and is very dusty. All that simply did not have enough time to be created.

Similar problems are also discovered in the present day universe.

Solution in the standard theory is unknown.

All the mysteries are explained by a model of very early heavy PBH formation with the predicted log-nomal mass-spectrum:

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

AD, J. Silk, 1993;
AD, M.Kawasaki, N.Kevlishvili, 2006(?)
S.I.Blinnikov, AD, K.A.Postnov, 2014;
SIB, AD, N.Poraiko, KAP 2016;
AD, K.A.Postnov, 2017

Content (review of the puzzles and the mechanism of solution):

1. **Discoveries in young hi-z universe.**
2. **Puzzling features of the old contemporary universe.**
3. **GW discovery by LISA and emerging problems.**
4. **A model of massive PBH creation.**
5. **Predictions and conclusion.**

I. A brief review of high-z discoveries.

1. Several galaxies have been observed with natural gravitational lens "telescopes. A few examples:

a galaxy at $z \approx 9.6$ which was created at $t_U < 0.5$ Gyr;

a galaxy at $z \approx 11$ has been detected at $t_U \sim 0.4$ Gyr, three times more luminous in UV than other galaxies at $z = 6 - 8$.

Not so young but extremely luminous galaxy $L = 3 \cdot 10^{14} L_\odot$; $t_U \sim 1.3$ 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." 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!

According to the paper "Monsters in the Dark": 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.

2. Supermassive BH and/or QSO.

About 40 quasars with $z > 6$ are already known, each quasar containing BH with $M \sim 10^9 M_\odot$.

The maximum z is $z = 7.085$ i.e. the quasar was formed before the universe reached 0.75 Gyr with

$L = 6.3 \cdot 10^{13} L_\odot$, $M = 2 \cdot 10^9 M_\odot$,

Similar situation with the others.

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. Non-standard accretion physics and the formation of massive seeds seem to be necessary. Neither of them is observed in the present day universe.

Very recently another monster was discovered "An ultraluminous quasar with a twelve billion solar mass black hole at redshift 6.30". 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 $M \approx 10^{10} M_\odot$ makes the formation absolutely impossible in the standard approach.

3. Dust, supernovae, gamma-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 macroscopic pieces of matter.

Abundant dust is observed in several early galaxies, e.g. in HFLS3 at $z = 6.34$ and in A1689-zD1 at $z = 7.55$.

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

Hence, 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 which later make molecules and dust. (We all are dust from SN explosions, but probably at much later time.) Another possibility is a non-standard BBN due to very high baryonic density, which allows for formation of heavy elements beyond lithium.

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.

II. Mysteries in the sky today and not so long ago.

1. SMBH at the present day.

Every large galaxy and some smaller ones contain a central supermassive BH whose masses are 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 superheavy BHs is not understood. These back holes are assumed to be created by matter accretion to a central seed. However, SMHBs are observed in several small galaxies and even in almost empty space, where is no material to make a SMBH.

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 $1.7 \times 10^{10} M_{\odot}$, or 60% of its bulge mass. This fact 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 looks more plausible, when first a supermassive black hole was formed and attracted matter serving as seed for subsequent galaxy formation.

More examples: F. Khan, K. Holley-Bockelmann, P. Berczik 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* Astrophys. J. Lett. 775, L6 (2013), arXiv:1307.7707.

The dynamical mass is $2\times10^8 M_\odot$ and $R\sim 24$ pc - very high density.

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

”An evolutionary missing link? A modest mass early-type galaxy hosting an oversized nuclear black hole”, J. Th. van Loon, A.E. Sansom, Xiv:1508.00698v1 [astro-ph.GA] 4 Aug 2015.

BH mass, $M_{BH} = (3.5\pm0.8)\cdot10^{8}M_{\odot}$, host galaxy $M_{stars} = 2.5^{+2.5}_{-1.2}\cdot10^{10}M_{\odot}$, and accretion luminosity:

$L_{AGN} = (5.3\pm0.4)\cdot10^{45}\mathrm{erg/s} \approx 10^{12}L_{\odot}$.

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.

Very fresh publication: "A Nearly Naked Supermassive Black Hole", J. J. Condon, J. Darling, Y. Y. Kovalev, L. Petrov, 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.

Globular clusters and massive BHs.

Very recent news: BH with $M \approx 2000 M_\odot$ in the core of the globular cluster 47 Tucanae.

Origin unknown. Our prediction(AD, K. Postnov): if the parameters of the mass distribution 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 density of IMBHs is sufficient to seed the formation of globular clusters in galaxies.

It is assumed that all PBH with $M > 10^4 M_\odot$ strongly accreted matter and grew up to billion solar masses.

MACHOs. A similar or maybe even connected problem is related to the nature of 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 and 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.

MACHO group has announced 13 - 17 microlensing events in the Large Magellanic Cloud (LMC), a much larger number than expected if MACHOs would be normal weakly shining stars. The fractional contribution of the density of these compact ”lenses” with respect to the dark matter density) was estimated to be in the range
$0.08 < f < 0.50$ (95% CL)
for $0.15M_\odot < M < 0.9M_\odot$.

EROS (Expérience pour la Recherche d'Objets Sombres) collaboration has placed only an upper limit on the halo fraction, $f < 0.2$ (95% CL) for the objects in the specified above MACHO mass interval, while EROS2 gives $f < 0.1$ in the mass range $10^{-6} M_{\odot} < M < 1 M_{\odot}$.

AGAPE collaboration, working on microlensing in M31 (Andromeda) galaxy, finds the halo Macho fraction in the range $0.2 < f < 0.9$, while MEGA group marginally conflicts with them with an upper limit $f < 0.3$. Newer results for EROS-2 and OGLE (Optical Gravitational Lensing Experiment) in the direction of the Small Magellanic Cloud are: $f < 0.1$ at 95% confidence level for Machos with the mass $10^{-2} M_{\odot}$ and $f < 0.2$ for Machos with the mass $\sim 0.5 M_{\odot}$.

Summary of limits on MACHOs

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 $\sim 0.5 M_\odot$.

Thus MACHOs for sure exist.

Their density is comparable to the density of the halo dark matter but their nature is unknown.

They could be brown dwarfs, dead stars, or primordial black holes.

The first two options are in conflict with the accepted theory of stellar evolution, if MACHOs were created in the conventional way.

More mysteries:

It was found that the BH masses are concentrated in the narrow range $(7.8 \pm 1.2) M_\odot$ (1006.2834)

This result agrees with another paper where a peak around $8 M_\odot$, a paucity of sources with masses below $5 M_\odot$, and a sharp drop-off above $10 M_\odot$ are observed, arXiv:1205.1805. These features are not explained in the standard model of BH formation by stellar collapse.

3. 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 13.8 ± 4 Gyr.
J.J. Cowan, C. Sneden, S. Burles, *et al* Ap.J. 572 (2002) 861, astro-ph/0202429.

The age of inner halo of the Galaxy 11.4 ± 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.

Metal deficient high velocity subgiant in the solar neighborhood HD 140283 has the age 14.46 ± 0.31 Gyr.
H. E. Bond, E. P. Nelan, D. A. VandenBerg, G. H. Schaefer, D. Harmer, 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 $t_U = 13.8$;
if $H = 74$, then $t_U = 12.5$.

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, $10.6^{+1.5}_{-1.3}$ Gyr.

(Age of the Earth: 4.54 Gyr.)

A SN explosion must must precede formation of this planet.

GW discovery by LIGO has proven thar GR works perfectly, existence of BHs and GWs is established, but ”in much wisdom is much grief”, mostly created by GW150914.

There are essentially three problems in the standard theory:

1. Origin of heavy BHs ($\sim 30 M_{\odot}$).

2. Low spins of the coalescing BHs.

3. Formation of BH binaries from the original stellar binaries.

The first problem is a heavy BH origin. Such BHs are believed to be created by massive star collapse, though a convincing theory is still lacking.
To form so heavy BHs, the progenitors should have $M > 100 M_\odot$ 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 yet observed in sufficiently high number.

Another problem is the low value of the BH spins in GW150914. It strongly constrains astrophysical BH formation from close binary systems. However, the dynamical formation of double massive low-spin BHs in dense stellar clusters is not excluded. The second reliable LIGO detection, GW151226, turned out to be closer to the standard binary BH system.

Last but not the least, 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 $(36+29)M_\odot$ is analyzed in the literature and is found to be negligible.**

All these problems are solved if the observed sources of GWs are the binaries of primordial black holes (PBH). Here a model of PBH formation is presented which naturally reproduces the puzzling properties of GW150914, the rate of binary BH merging events inferred from the first LIGO science run, and provides seeds for early supermassive BH formation.

In addition, the mechanism explains an avalanche of mysteries discovered recently and may provide all or a large fraction of cosmological DM

The model is based on the supersymmetric (Affleck-Dine) scenario for baryogenesis modified by introduction of a general renormalizable coupling to the inflaton field, see below. It was suggested in 1993 (AD and J.Silk) and discussed in more details in several our papers applied to an explanation of existence of the observed "old" objected in the young universe.

As a byproduct it may predict abundant antimatter objects in the Galaxy.

Baryogenesis with SUSY condensate, Affleck and Dine (AD). SUSY predicts existence of scalars with **$B \neq 0$.** 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.

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 10^{-9}.

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 regions are possible with dominance of one of them.

Matter and antimatter domain may exist but globally B $\neq 0$.

Affleck-Dine field χ with CW potential coupled to inflaton Φ (AD and Silk; AD, Kawasaki, Kevlishvili):

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

$$+\lambda_1\left(\chi^4 + h.c.\right) + (m^2\chi^2 + h.c.).$$

Coupling to inflaton is the general renormalizable one.

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.

This could lead lead to an early formation of compact stellar-type objects and naturally to a comparable amount of anti-objects, such that the bulk of baryons and (equal) antibaryons are in the form of compact stellar-like objects or PBH, plus the sub-dominant observed homogeneous baryonic background, the amount of antimatter may be comparable or even larger than of KNOWN baryons, but such "compact" (anti)baryonic objects would not contradict any existing observations.

The distributions of high baryon density bubbles over length and mass have log-normal form:

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

where C_M, γ, and M_0 are constant parameters. The spectrum is practically model independent, it is basically determined by inflation.

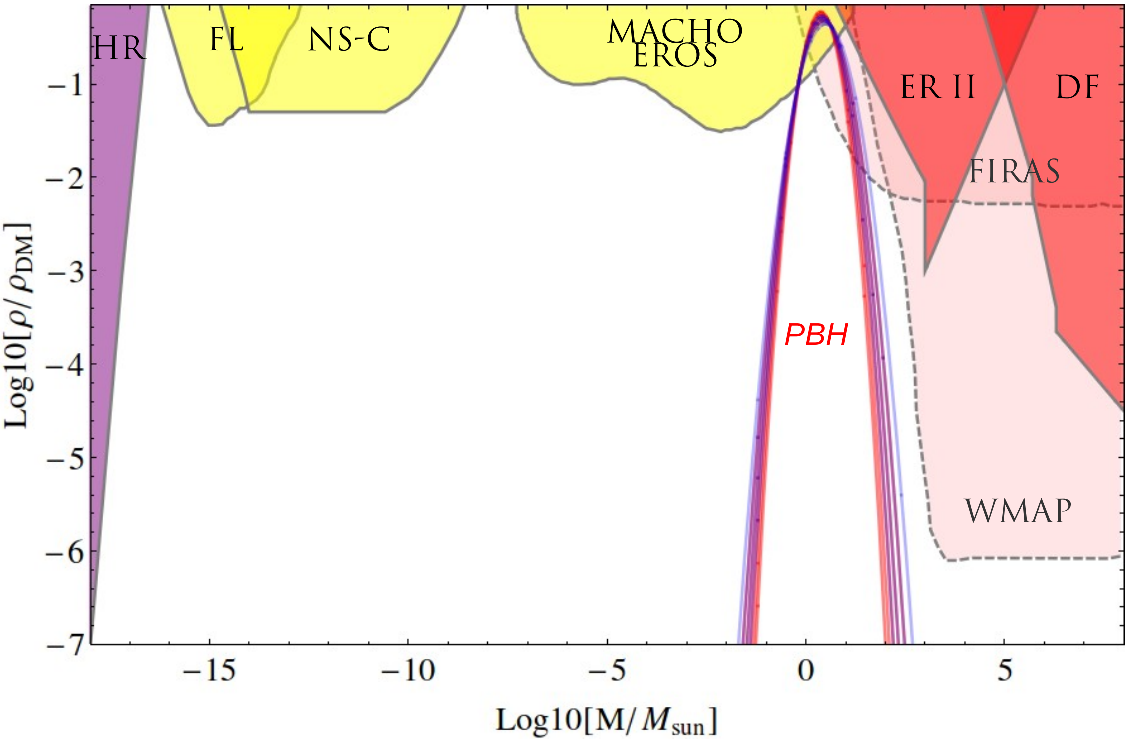

Figure 1: Constraints on PBH fraction in DM, $f = \rho_{\mathrm{PBH}}/\rho_{\mathrm{DM}}$, where the PBH mass distribution is taken as $\rho_{\mathrm{PBH}}(M) = M^2 dN/dM$ The existing constraints (extragalactic γ-rays from evaporation (HR), femtolensing of γ-ray bursts (F), neutron-star capture constraints (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 ADBD parameters $\mu = 10^{-43}$ 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).

Conclusion

1. A natural baryogenesis model leads to abundant fomation of PBHs and compact stellar-like objects in the early universe after the QCD phase transition, $t \gtrsim 10^{-5}$ sec.

2. These objects have log-normal mass spectrum.

3. Adjusting the spectrum parameter is possible to 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.

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.

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 noticeable fraction of dark matter or all of it can be made of PBHs.

Concluson to conclusion: Large amount of astronomical data strongly demand abundant cosmological population of PBH with wide mass spectrum. Such PBH nicely explain the mysteries accumulated during a few last years.

Testable predictions:

A. Rate and masses of new GW events.

B. Possible existence of antimatter in our neighborhood, even in the Galaxy.

C. PBH with $M = 2000 - 3000\, M_\odot$ in the cores of globular clusters.

THE END

The talk is based on the papers:

S.Blinnikov, AD, N.Poraiko, K.Postnov, 2016;

AD, Beasts in Lambda-CDM Zoo, 2016;

S. Blinnikov, AD, K.Postnov, 2014, Antimatter and antistars in the universe and in the Galaxy;

AD, Blinnikov, 2013, Stars and Black Holes from the very Early Universe;

C.Bambi, AD, 2007, Antimatter in the Milky Way;

AD, M. Kawasaki, N. Kevlishvili, 2008, Inhomogeneous baryogenesis, cosmic antimatter, and dark matter;

AD, J.Silk, 1992, Baryon isocurvature fluctuations at small scales and baryonic dark matter.