Problems with the sources of the observed gravitational waves and their resolution

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The standard cosmological model very well describes gross features of the universe (spectrum of perturbations at large scales, features of CMB, baryogenesis, etc) at expense of a few parameters and/but it is in some tension with the minimal standard model of particle physics (dark matter, dark energy, vacuum energy problem, baryogenesis).

The new physics is a necessity. Still, except for vacuum energy, the new physics may be almost the old one.

On the other hand, last years revealed many features which look surprising and completely mysterious.

All these mysteries in the sky can be explained by an abundant population of the universe with (super)heavy primordial black holes; normally only the usual ones with masses $\sim 10^{20}$ g were considered.

The talk is based on the papers:

S.Blinnikov, AD, N.Poraiko, K.Postnov, 2016 (to appear soon);

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.

Content

1. GW observation by LIGO.
2. Problems with the GW sources.
3. Solution of the problems and more.
4. Dense population of the universe at $z \sim 10$ by the objects which could not be there: supermassive BHs, early supernovae and gamma-bursters, evolved chemistry and dust in high z universe...
5. Problems in present day universe: MACHOs, PBH dark matter, supermassive BHs in large galaxies and in almost empty space.

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 were about weak fields. Rumors about a few 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.

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

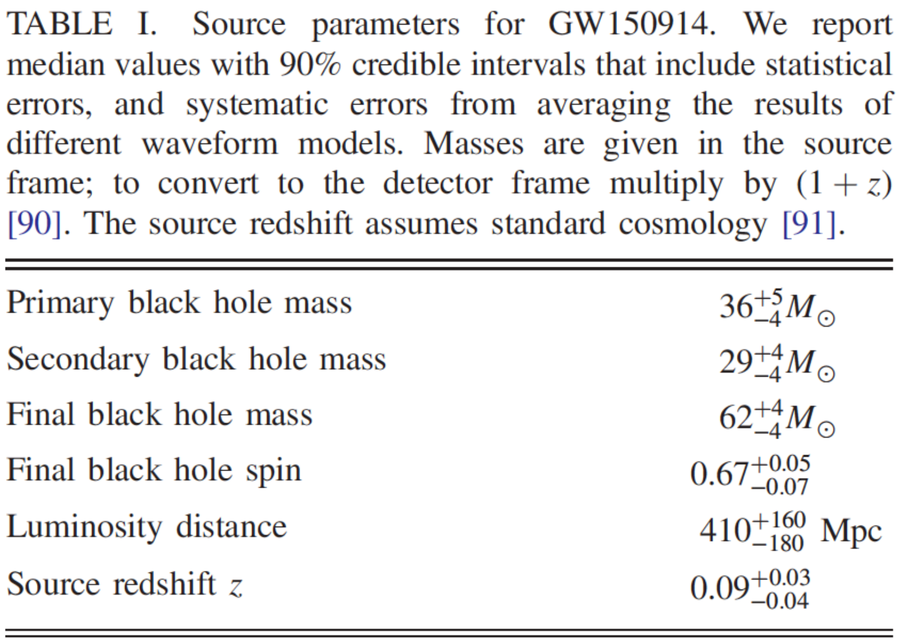


TABLE I. Source parameters for GW150914. We report median values with 90% credible intervals that include statistical errors, and systematic errors from averaging the results of different waveform models. Masses are given in the source frame; to convert to the detector frame multiply by $(1 + z)$ [90]. 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 $(3.0 \pm 0.5) M_\odot$ and a peak of gravitational-wave luminosity is $3.0^{+0.5}_{-0.4} \times 10^{56}$ erg/sec equivalent to $200 M_\odot$/sec, more than whole radiation power of the visible universe.

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

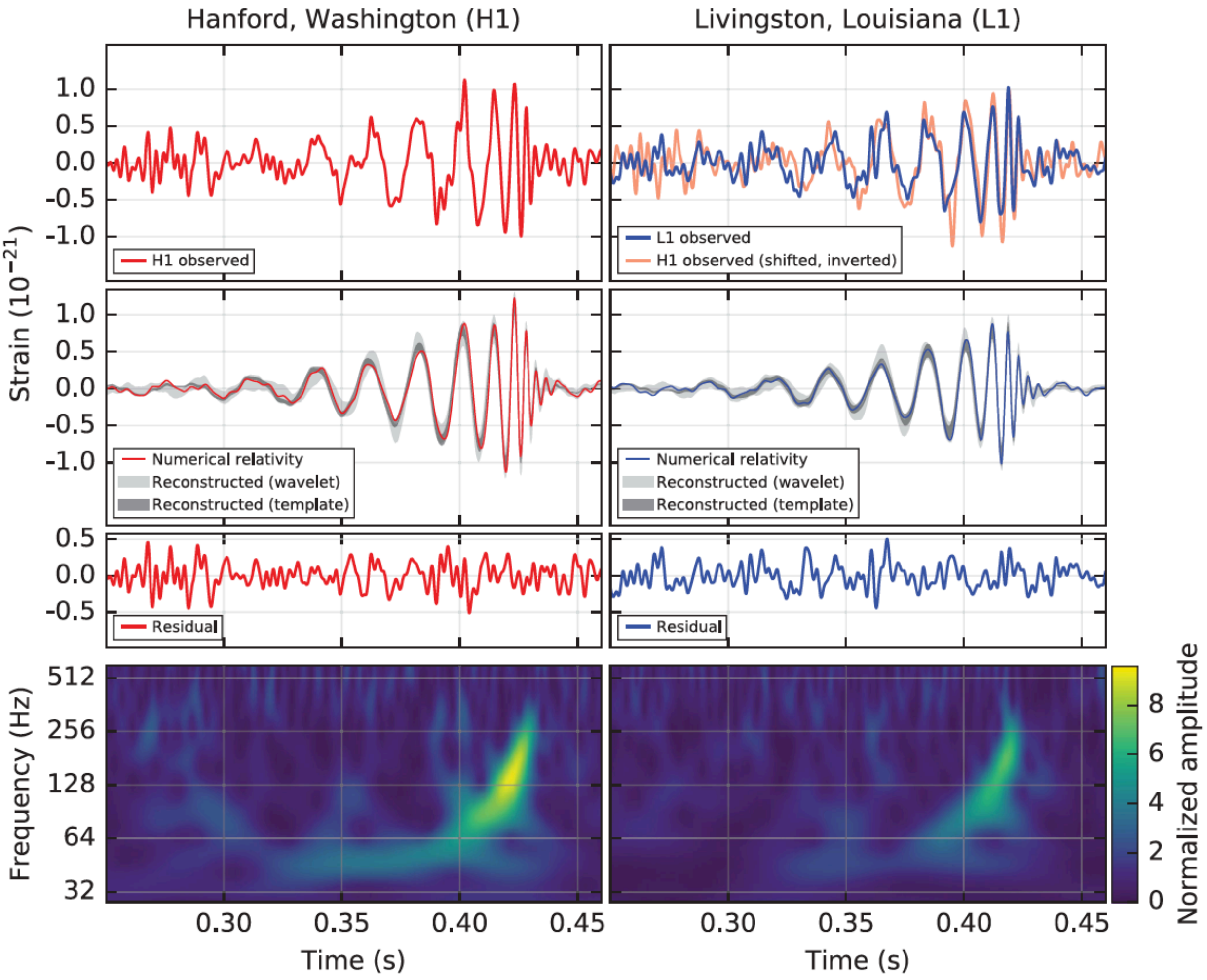
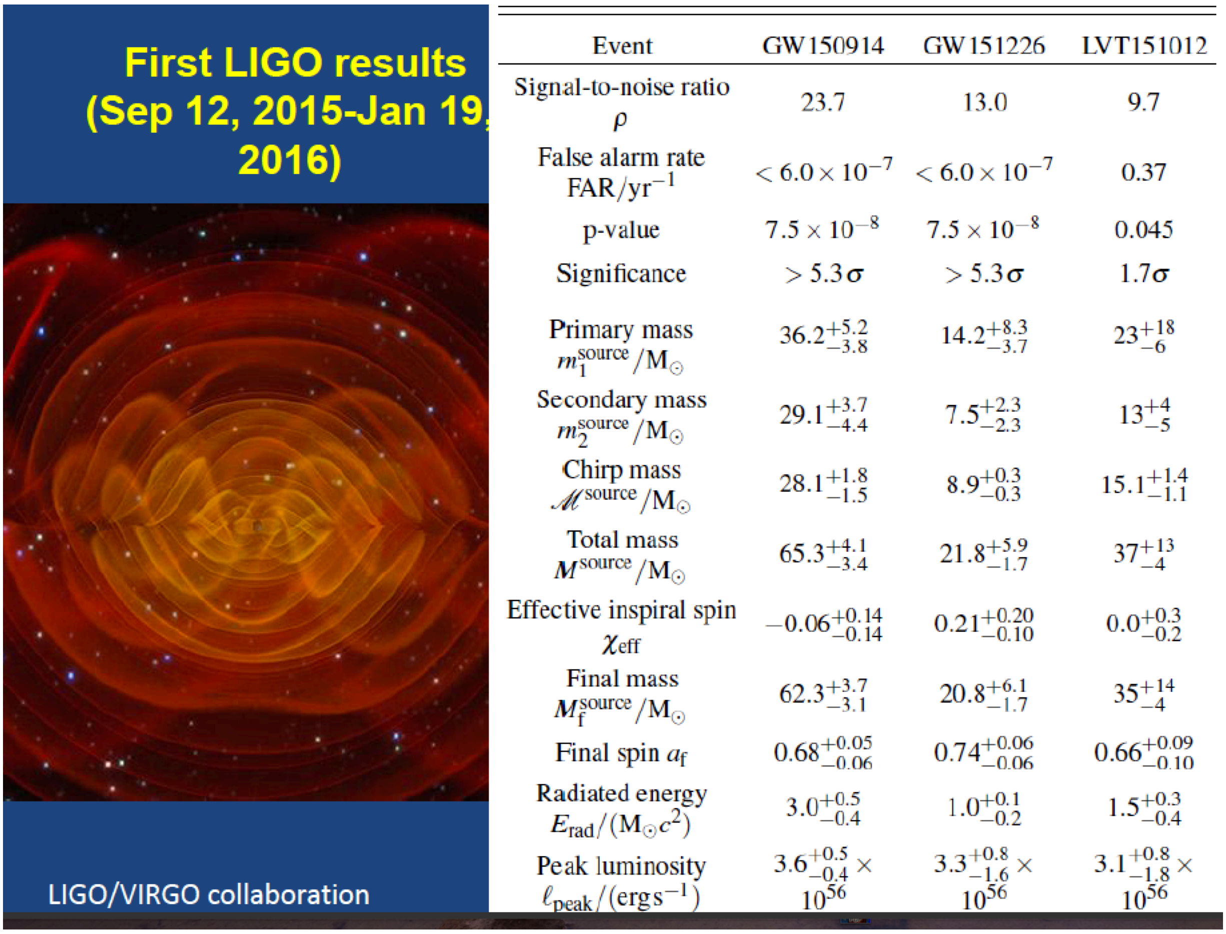


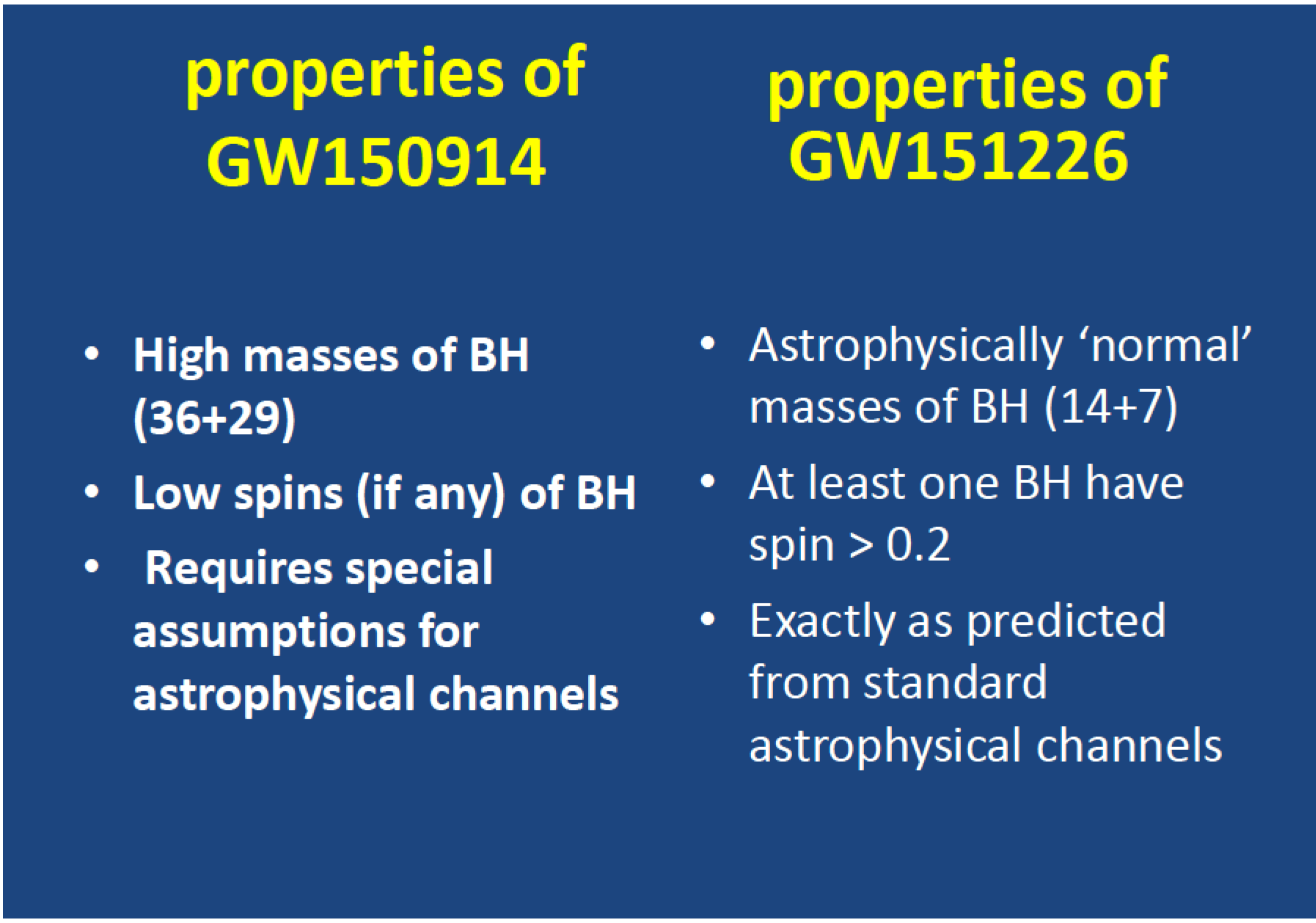
FIG. 1. The gravitational-wave event GW150914 observed by the LIGO Hanford (H1, left column panels) and Livingston (L1, right column panels) detectors. Times are shown relative to September 14, 2015 at 09:50:45 UTC. For visualization, all time series are filtered with a 35–350 Hz bandpass filter to suppress large fluctuations outside the detectors' most sensitive frequency band, and band-reject filters to remove the strong instrumental spectral lines seen in the Fig. 3 spectra. *Top row, left:* H1 strain. *Top row, right:* L1 strain. GW150914 arrived first at L1 and $6.9^{+0.5}_{-0.4}$ ms later at H1; for a visual comparison, the H1 data are also shown, shifted in time by this amount and inverted (to account for the detectors' relative orientations). *Second row:* Gravitational-wave strain projected onto each detector in the 35–350 Hz band. Solid lines show a numerical relativity waveform for a system with parameters consistent with those recovered from GW150914 [37,38] confirmed to 99.9% by an independent calculation based on [15]. Shaded areas show 90% credible regions for two independent waveform reconstructions. One (dark gray) models the signal using binary black hole template waveforms [39]. The other (light gray) does not use an astrophysical model, but instead calculates the strain signal as a linear combination of sine-Gaussian wavelets [40,41]. These reconstructions have a 94% overlap, as shown in [39]. *Third row:* Residuals after subtracting the filtered numerical relativity waveform from the filtered detector time series. *Bottom row:*A time-frequency representation [42] of the strain data, showing the signal frequency increasing over time.



First LIGO results (Sep 12, 2015-Jan 19, 2016)

Event	GW150914	GW151226	LVT151012
Signal-to-noise ratio ρ	23.7	13.0	9.7
False alarm rate FAR$/\mathrm{yr}^{-1}$	$< 6.0 \times 10^{-7}$	$< 6.0 \times 10^{-7}$	0.37
p-value	7.5×10^{-8}	7.5×10^{-8}	0.045
Significance	$> 5.3\sigma$	$> 5.3\sigma$	1.7σ
Primary mass $m_1^{\mathrm{source}}/\mathrm{M}_\odot$	$36.2^{+5.2}_{-3.8}$	$14.2^{+8.3}_{-3.7}$	23^{+18}_{-6}
Secondary mass $m_2^{\mathrm{source}}/\mathrm{M}_\odot$	$29.1^{+3.7}_{-4.4}$	$7.5^{+2.3}_{-2.3}$	13^{+4}_{-5}
Chirp mass $\mathscr{M}^{\mathrm{source}}/\mathrm{M}_\odot$	$28.1^{+1.8}_{-1.5}$	$8.9^{+0.3}_{-0.3}$	$15.1^{+1.4}_{-1.1}$
Total mass $M^{\mathrm{source}}/\mathrm{M}_\odot$	$65.3^{+4.1}_{-3.4}$	$21.8^{+5.9}_{-1.7}$	37^{+13}_{-4}
Effective inspiral spin χ_{eff}	$-0.06^{+0.14}_{-0.14}$	$0.21^{+0.20}_{-0.10}$	$0.0^{+0.3}_{-0.2}$
Final mass $M_{\mathrm{f}}^{\mathrm{source}}/\mathrm{M}_\odot$	$62.3^{+3.7}_{-3.1}$	$20.8^{+6.1}_{-1.7}$	35^{+14}_{-4}
Final spin a_{f}	$0.68^{+0.05}_{-0.06}$	$0.74^{+0.06}_{-0.06}$	$0.66^{+0.09}_{-0.10}$
Radiated energy $E_{\mathrm{rad}}/(\mathrm{M}_\odot c^2)$	$3.0^{+0.5}_{-0.4}$	$1.0^{+0.1}_{-0.2}$	$1.5^{+0.3}_{-0.4}$
Peak luminosity $\ell_{\mathrm{peak}}/(\mathrm{erg\,s}^{-1})$	$3.6^{+0.5}_{-0.4} \times 10^{56}$	$3.3^{+0.8}_{-1.6} \times 10^{56}$	$3.1^{+0.8}_{-1.8} \times 10^{56}$

LIGO/VIRGO collaboration



properties of GW150914

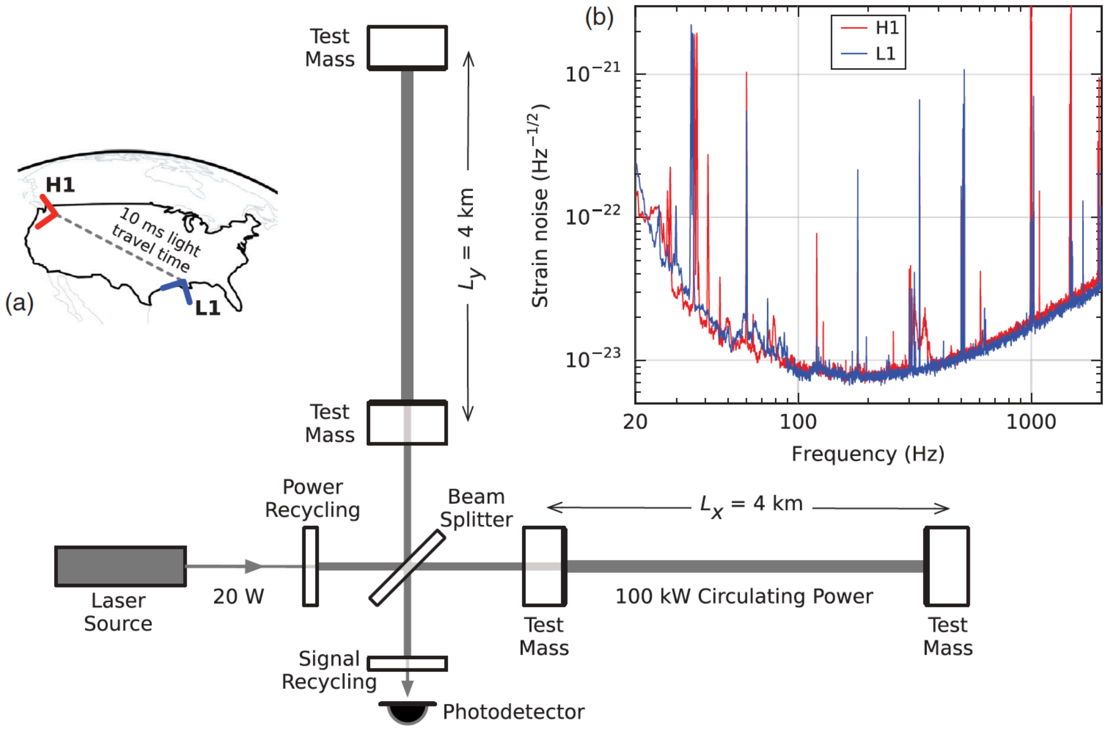
- **High masses of BH (36+29)**
- **Low spins (if any) of BH**
- **Requires special assumptions for astrophysical channels**

properties of GW151226

- Astrophysically ‘normal’ masses of BH (14+7)
- At least one BH have spin > 0.2
- Exactly as predicted from standard astrophysical channels

LIGO observatories in the United States

The detector



Thus GR works perfectly, existence of BHs and GWs is proven, 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 ($\sim 30M_\odot$).**
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 $\sim (30+30)M_\odot$ 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 predicts 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.

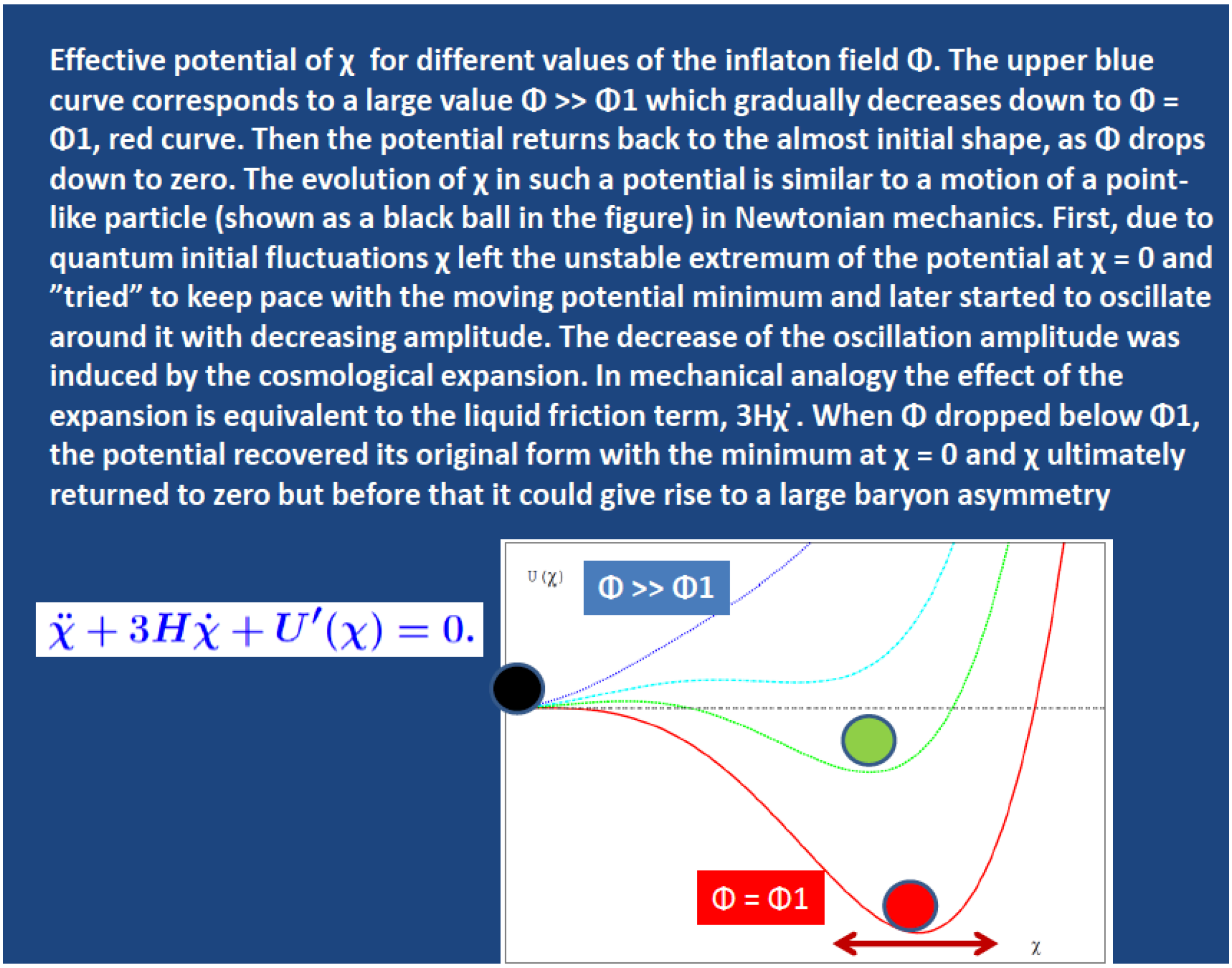
Phase transition of 3/2 order.

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:

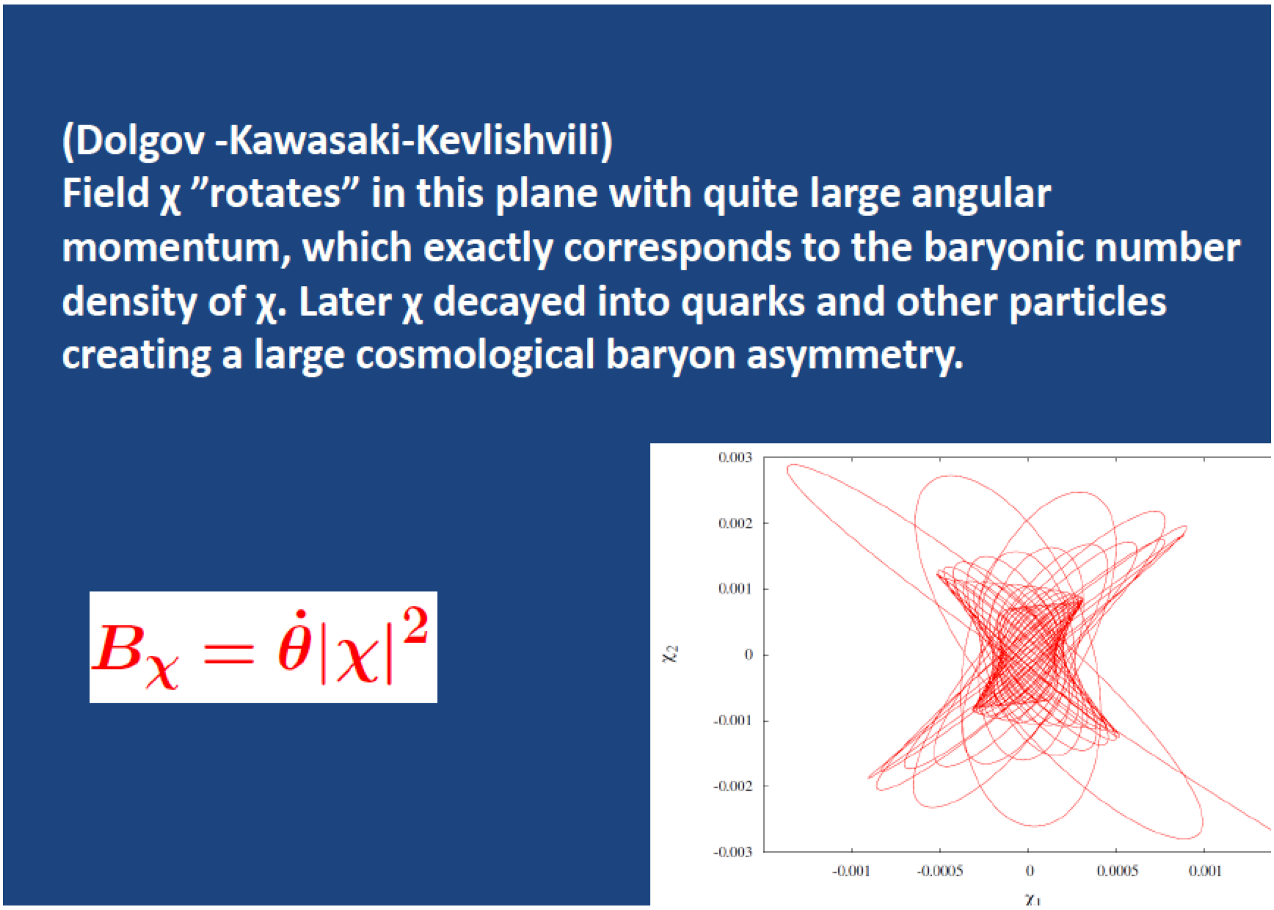
$$\frac{dN}{dM} = C_M \exp\left[-\gamma \ln^2(M/M_0)\right]$$

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



Effective potential of χ for different values of the inflaton field Φ. The upper blue curve corresponds to a large value Φ >> Φ1 which gradually decreases down to Φ = Φ1, red curve. Then the potential returns back to the almost initial shape, as Φ drops down to zero. The evolution of χ in such a potential is similar to a motion of a point-like particle (shown as a black ball in the figure) in Newtonian mechanics. First, due to quantum initial fluctuations χ left the unstable extremum of the potential at χ = 0 and "tried" to keep pace with the moving potential minimum and later started to oscillate around it with decreasing amplitude. The decrease of the oscillation amplitude was induced by the cosmological expansion. In mechanical analogy the effect of the expansion is equivalent to the liquid friction term, $3H\dot{\chi}$. When Φ dropped below Φ1, the potential recovered its original form with the minimum at χ = 0 and χ ultimately returned to zero but before that it could give rise to a large baryon asymmetry

$$\ddot{\chi} + 3H\dot{\chi} + U'(\chi) = 0.$$



(Dolgov -Kawasaki-Kevlishvili)
Field χ ”rotates” in this plane with quite large angular momentum, which exactly corresponds to the baryonic number density of χ. Later χ decayed into quarks and other particles creating a large cosmological baryon asymmetry.

$$B_\chi = \dot{\theta}|\chi|^2$$

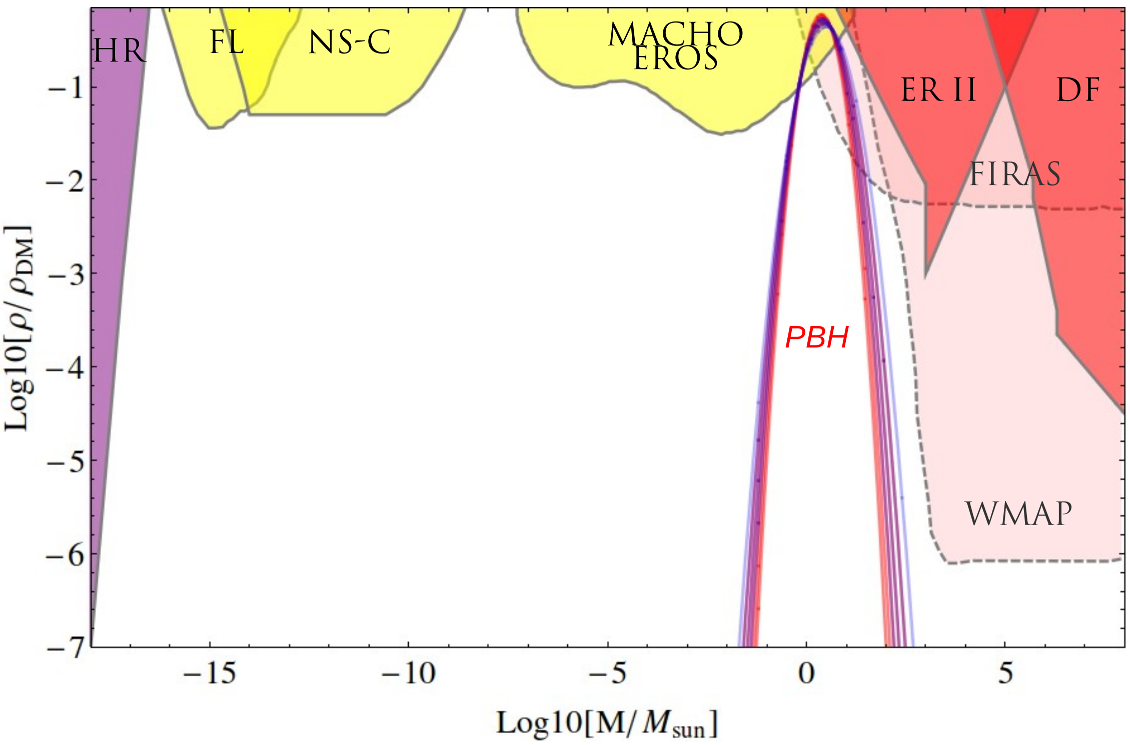
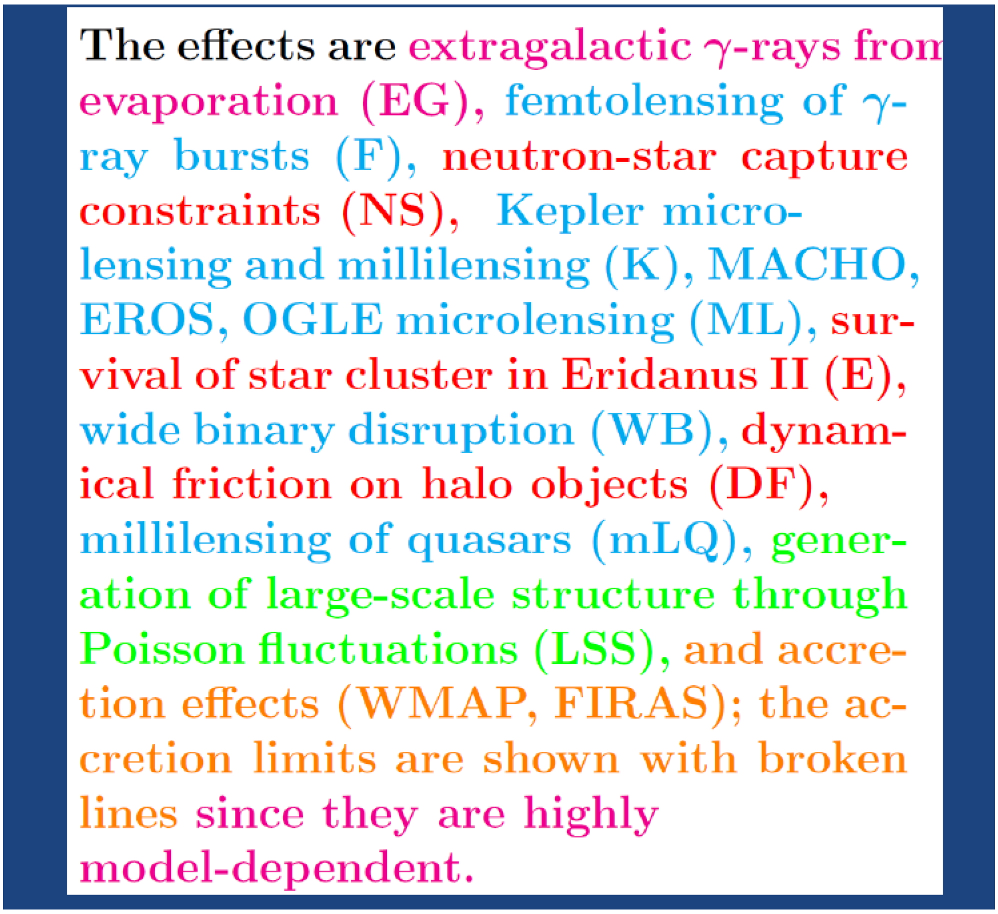


Figure 1: Constraints on PBH fraction in DM, $f = \rho_{\rm PBH}/\rho_{\rm DM}$, where the PBH mass distribution is taken as $\rho_{\rm PBH}(M) = M^2 dN/dM$ The existing constraints (extragalactic γ-rays from evaporation (HR), femtolensing of γ-ray bursts (F), neutron-star capture constraints (NS-C),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



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.

Mysteries at $z \sim 10$ and today.

Astronomical data accumulated during the last few years revealed that the early, $z \sim 10$, universe is unexpectedly dense, populated by evolved objects which are much younger than allowed by theory.

There are bright but too young galaxies, QSO/supermassive BHs,

and gamma-bursters (supernovae).

Moreover, the early universe contains much more dust than can be reasonably expected.

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

Very recently 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 $M \approx 10^{10} M_\odot$ makes the formation absolutely impossible in the standard approach.

Back to the future.

Every large galaxy and some smaller ones contain a central supermassive BH with masses which 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.

SHBs are observed in every large and (NB!!!) in several small galaxies, where is no material to make a SMBH.

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.

Some more seemingly unrelated but probably the same kind problems in the contemporary universe. There are stars in the Milky Way, older than the Galaxy and even older than the universe (more than two sigma) and even one very old rocky planet.

BH mass distribution in the Galaxy and MACHOs also does not fit the standard astrophysics.

Conclusion

1. Supersymmetric baryogenesis could lead to abundant fomation of PBHs and compact stellar-like objects in the early universe after 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: SPBH, early created gamma-bursters and supernovae, early bright galaxies, and evolved chemistry including dust.

5. Inverted picture of galaxy formation is advocated.

6. SMBH observed in almost empty environment is naturally explained.

7. "Older than t_U" stars may exist.

7. Existence of high density invisible "stars" (machos) is understood.

6. DM made of PBH.

All the data strongly demand abundant cosmological population of PBH with wide mass spectrum.

Testable predictions:

A. Rate and masses of new GW events.

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

THE END