

# Primordial black holes, dark matter, and other cosmological puzzles

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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,  $M \sim (7 - 8)M_{\odot}$ ,
- supermassive,  $M \sim (10^6 - 10^9)M_{\odot}$ ,
- intermediate mass  $M \sim (10^3 - 10^5)M_{\odot}$ ,
- and a lot between and out of the intervals.

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

Existence of such primordial black holes was essentially predicted a quarter of century ago (A.D. and J.Silk, 1993).

However, this interpretation encounters natural resistance from the astronomical establishment.

Sometimes the authors of new discoveries admitted that the observed phenomenon can be explained by massive BHs, which drove the effect, but immediately retreated, saying that there was no known way to create sufficiently large density of such BHs.

# Astrophysical BH versus PBH

Astrophysical BHs are results of stellar collapse after a star exhausted its nuclear fuel. Formed in sufficiently old universe. Masses are of the order of a few solar masses.

"Usual" supermassive black holes (SMBH),  $M \sim (10^6 - 10^9) M_{\odot}$  are assumed to be the products of matter accretion to smaller BHs or matter accretion to matter excess in galactic centers. But the universe age is not long enough for their formation.

Primordial black holes (PBH) formed in the very early universe if the density excess at cosmological horizon is large,  $\delta \rho / \rho \gtrsim 1$ , at the horizon scale (Zeldovich, Novikov). Usually the masses of PBH are taken to be rather low and the spectrum is assumed to be close to delta-function.

# Alternative Mechanism

Alternative mechanism of massive PBH formation with much wider mass spectrum:

- A. Dolgov and J.Silk, PRD 47 (1993) 4244 "Baryon isocurvature fluctuations at small scalar 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 accepted faith, since they became supported by the recent astronomical data.

Massive PBHs allow to cure emerging inconsistencies with the standard cosmology and astrophysics. Dark matter made out of PBHs became a viable option.

# The Model

The model predicts an abundant formation of heavy PBHs with log-normal mass spectrum:

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

with only 3 parameters:  $\mu$ ,  $\gamma$ ,  $M_0$ .

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 any justification.

# Brief description of the mechanism

SUSY motivated baryogenesis, Affleck and Dine (AD).

SUSY predicts existence of scalars with  $\mathbf{B} \neq \mathbf{0}$ . Such bosons may condense along flat directions of the quartic potential:

$$U_\lambda(\chi) = \lambda |\chi|^4 (1 - \cos 4\theta)$$

and of the mass term,  $m^2 \chi^2 + m^{*2} \chi^{*2}$ :

$$U_m(\chi) = m^2 |\chi|^2 [1 - \cos(2\theta + 2\alpha)],$$

where  $\chi = |\chi| \exp(i\theta)$  and  $m = |m| e^{i\alpha}$ .

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)  $\chi$  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  $\chi$ :

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

is analogous to mechanical angular momentum.  $\chi$  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  $10^{-9}$ .



If  $m \neq 0$ , the angular momentum,  $B$ , is generated by a different direction of the quartic and quadratic valleys at low  $\chi$ . If CP-odd phase  $\alpha$  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  $\chi$  with CW potential coupled to inflaton  $\Phi$  (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  $\chi$  slowly diffuses to large value, according to quantum diffusion equation derived by Starobinsky, generalized to a complex field  $\chi$ .

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  $\beta$  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  $\chi$ .

Phase transition of 3/2 order.

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.

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.
- $\beta$  may be negative leading to compact antistars which could survive annihilation with the homogeneous baryonic background.

Recently there arose an avalanche of abundant PBHs.

In any single case an alternative interpretation might be possible but the overall picture is very much in favor of massive PBHs.

## Young universe, $z \sim 10$

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

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

These facts are in good agreement with the predictions listed above, but in tension with the Standard Cosmological Model.

# Supermassive BH, or QSO

About 40 quasars with  $z > 6$  are known, with BH of  $10^9 M_\odot$  and  $L \sim 10^{13-14} L_\odot$ .

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.

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

# Supermassive BH, or QSO

Three years ago another huge QSO 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.

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

## Galaxies observed at $z \sim 10$

- a galaxy at  $z \approx 9.6$ , which was created at  $t_U < 0.5$  Gyr;
- a galaxy at  $z \approx 11$ , born at  $t_U \sim 0.4$  Gyr, three times more luminous in UV than other galaxies at  $z = 6 - 8$ . **Unexpectedly early creation.**
- Not so young but extremely luminous galaxy  $L = 3 \cdot 10^{14} L_{\odot}$ ;  $t_U \sim 1.3$  Gyr.

Quoting the authors: The galactic seeds, or embryonic black holes, might be bigger than thought possible. Or another way to grow this big is to have gone on a sustained binge, consuming food faster than typically thought possible.

P. Eisenhardt: "How do you get an elephant? One way is start with a baby elephant." Low spin of the seed is necessary!

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



T. Hashimoto et al, arXiv180505966H, Nature, May, 17, 2018,  
"The onset of star formation 250 million years after the Big Bang"

Oxygen line at  $z = 9.1096 \pm 0.0006$ .

"This precisely determined redshift indicates that the red rest-frame optical colour arises from a dominant stellar component that formed about 200 million years after the Big Bang, corresponding to a redshift of about 15."

"Although we are observing a secondary episode of star formation at  $z = 9.1$ , the galaxy formed the bulk of its stars at a much earlier epoch.

Our results indicate it may be feasible to directly detect the earliest phase of galaxy formation, beyond the redshift range currently probed with HST, with future facilities such as the James Webb Space Telescope.

In addition, our observations demonstrate the great power of ALMA19 to spectroscopically identify galaxies at  $z > 9$ , showing that ALMA will also play a central role in investigating the first-generation galaxies."

# Dust, supernovae, gamma-bursts...

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.

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

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

# Problems of the contemporary universe

- SMBH in every large galaxy; even 15 Gyr are not enough to make them
- SMBH in small galaxies and in almost EMPTY space,  
 $M \sim 10^9 M_{\odot}$ .
- Stars older than the Galaxy and even one star older than the Universe (sic!).
- MACHOs (low luminosity 0.5 solar mass objects) - origin unknown.
- BH mass spectrum in the Galaxy: unexpected maximum at  
 $M \sim 8 M_{\odot}$ .
- Sources of the observed GWs.
- Intermediate mass BHs:  $M \sim 10^3 M_{\odot}$ , in globular clusters and  
 $M \sim 10^4 - 10^5$  in dwarf galaxies.

# AND RECENTLY MORE PUZZLES

Several (four?) binaries of SMBH.

Quasar quartet.

Plane concentration of galactic-satellites?

Massive BHs in dwarfs: ten IMBH,  $M = 3 \times 10^4 - 2 \times 10^5 M_\odot$  and 40 found recently  $10^7 < M < 3 \cdot 10^9$  [Chandra, 1802.01567].

$0.8 \cdot 10^9 M_\odot$  BH in NEUTRAL universe at  $z = 7.5$  [1712.01860].

Triple SMBH [1712.03909].

Faint QSO,  $z=6$ ,  $M = 10^9 M_\odot$  needs either super-Eddington accretion or  $10^5 M_\odot$  seed, 1802.02782.

# Galaxies without or little dark matter

- Genzel, R., et al, "Strongly baryon-dominated disk galaxies at the peak of galaxy formation ten billion years ago". Nature 543 (2017), 397.
- M. Swinbank, "Distant galaxies lack dark matter", Nature 543 (2017), 318-319.
- P. van Dokkum et al, "An enigmatic population of luminous globular clusters in a galaxy lacking dark matter", Nature 555 (2018) no.7698, 629-632 arXiv:1803.10240, 27 Mar 2018
- J.L. Bernal, et al "Cosmological implications of Primordial Black Holes", JCAP 1710 (2017) no.10, 052 arXiv:1709.07465.

**Criticism:** N.F. Martin, et al "Current velocity data on dwarf galaxy NGC1052-DF2 do not constrain it to lack dark matter", arXiv:1804.04136 11 Apr 2018.

# High velocity stars in the Galaxy

- "Old, Metal-Poor Extreme Velocity Stars in the Solar Neighborhood", Kohei Hattori et al., arXiv:1805.03194, 8 May 2018.
- "Gaia DR2 in 6D: Searching for the fastest stars in the Galaxy", T. Marchetti, E. M. Rossi and A. G. A. Brown arXiv:1804.10607 Date: Fri, 27 Apr 2018.

$V \approx 500$  km/sec;  $V_{\text{virial}} \sim 100 - 200$  km/sec;  $V_{\text{NSI}} \sim 1000$  km/sec.

The origin of such stars is puzzling. They may be accelerated by interaction with IMBH, but there are not enough IMBH in the conventional theory.

# Intermediate Mass Black Holes

Igor V. Chilingarian, et al. "A Population of Bona Fide Intermediate Mass Black Holes Identified as Low Luminosity Active Galactic Nuclei" [arXiv:1805.01467](#),  
"...we identified a sample of 305 IMBH candidates having masses

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

which reside in galaxy centers and are accreting gas that creates characteristic signatures of a type-I active galactic nucleus."

P.A. Christopher et al [The Black Hole in the Most Massive Ultracompact Dwarf Galaxy M59-UCD3](#), [arXiv:1804.02399](#).

A.V. Afanasiev, et al "A 3.5-million Solar Masses Black Hole in the Centre of the Ultracompact Dwarf Galaxy Fornax UCD3", [arXiv:1804.02938](#).

He-Yang Liu, et al, [A Uniformly Selected Sample of Low-Mass Black Holes in Seyfert 1 Galaxies. II. The SDSS DR7 Sample](#), [arXiv:1803.04330](#),

"A new sample of 204 low-mass black holes (LMBHs) in active galactic nuclei (AGNs) is presented with black hole masses in the range of  $(1 - 20) \times 10^5 M_{\odot}$ ."

# Sources of the "LIGO" (et al) GWs

Several events of GW registration by LIGO and Virgo has proven that GR works perfectly, existence of BHs and GWs is established, but revealed essentially three problems of the SCM:

- 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.

S.Blinnikov, A.D., N.Porayko, K.Postnov.

See however, T.Broadhurst, J.M. Diego, G. Smoot. 1802.05273.

Gravitational lensing of GW from log-normal BHs with central mass  $8M_{\odot}$  - much smaller mass, mimicked by gravitational lensing of GWs.



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  $M > 100M_{\odot}$  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.
- Maybe the mirror matter progenitors will do(!?).

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, but difficult.
- The second reliable LIGO detection, GW151226, turned out to be closer to the standard binary BH system.
- The other three demonstrate the same property.

## 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. Recall large pulsar velocities,  $v \sim 1000$  km/s
- BH formation from PopIII stars and subsequent formation of BH binaries with  $(36 + 29) M_{\odot}$  is analyzed and found to be negligible.

All these problems are solved if the observed sources of GWs are the binaries of primordial black holes (PBH).

# Globular clusters and massive BHs

Recent news: BH with surprisingly high mass  $M \approx 2000 M_{\odot}$  was observed in the core of the globular cluster 47 Tucanae.

Origin in standard model is unknown.

Our prediction (AD, K.Postnov): if the parameters of the mass distribution of PBHs are chosen to fit the LIGO data and the density of SMBH, then the number of PBH with masses  $(2 - 3) \times 10^3 M_{\odot}$  is about  $10^4 - 10^5$  per one SMPBH with mass  $> 10^4 M_{\odot}$ .

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

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 usual BH of similar mass.

"A Nearly Naked Supermassive Black Hole" J.J. Condon, et al  
arXiv:1606.04067.

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

## 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,  $3.63 \times 10^7 M_{\odot}$ . (1709.06258).

C. Rodriguez et al. A compact supermassive binary black hole system. Ap. J. 646, 49 (2006),  $d \approx 230$  Mpc.

M.J. Valtonen, "New orbit solutions for the precessing binary black hole model of OJ 287", Ap.J. 659, 1074 (2007),  $z \approx 0.3$ .

M.J. Graham et al. "A possible close supermassive black-hole binary in a quasar with optical periodicity". Nature 518, 74 (2015),  $z \approx 0.3$ .

## Orthodox point of view:

merging of two spiral galaxies creating an elliptical galaxy, leaving two or more SBHs in the center of the merged elliptical. No other way in the traditional approach. Even one SMBH is hard to create.

## Heretic but simpler:

primordial SMBH forming binaries in the very early universe and seeding galaxy formation.

"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, discovered in a survey for emission at redshift  $z \approx 2$ .

Quasars are rare objects separated by cosmological distances, so the chance of finding a quadruple quasar is  $\sim 10^{-7}$ .

It implies that the most massive structures in the distant universe have a tremendous supply ( $\sim 10^{11} M_{\odot}$ ) of cool dense ( $n \approx 1/\text{cm}^3$ ) gas, in conflict with current cosmological simulations.

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.

AD, J. Silk, 1974;

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

Bosch et al, Nature 491 (2012) 729.



## 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  $8M_{\odot}$ , a paucity of sources with masses below  $5M_{\odot}$ , and a sharp drop-off above  $10M_{\odot}$  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  $M_0 \approx 8M_{\odot}$ .

# SUMMARY

- 1. Natural baryogenesis model leads to abundant formation 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-bursts 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 in fact predicted.
- 11. A noticeable fraction of dark matter or all of it can be made of PBHs.
- 12. Clouds of matter with high baryon-to-photon ratio. A possible by-product: plenty of (compact) anti-stars, even in the Galaxy.

# 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.

## Yesterday news

### Very unusual star:

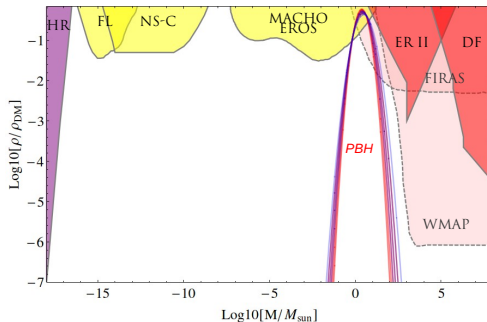
D.P. Bennett, A. Udalski, I.A. Bond, et al, "A Planetary Microlensing Event with an Unusually Red Source Star: MOA-2011-BLG-291", arXiv:1806.06106 Fri, 15 Jun 2018 20:00:00 GMT (1243kb,D)

We find host star and planet masses of  $M_{\text{host}} = 0.15^{+0.27}_{-0.10} M_{\odot}$  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.

THE END  
or  
TO BE CONTINUED



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

The effects are extragalactic  $\gamma$ -rays from evaporation (EG), femtolensing of  $\gamma$ -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.



