

# New Data on Old and Young Black Holes

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Recent astronomical data, which keep on appearing almost every day, show that the contemporary,  $z \sim 0$ , and early,  $z \sim 10$ , universe is much more abundantly populated by all kind of black holes, than it was expected even a few years ago.

They may make a considerable or even 100% contribution to the cosmological dark matter.

Among these BH:

- massive, from a fraction of  $M_{\odot}$  up to  $\gtrsim 10M_{\odot}$ ,
- supermassive (SMBH),  $M \sim (10^6 - 10^9)M_{\odot}$ ,
- intermediate mass (IMBH)  $M \sim (10^3 - 10^5)M_{\odot}$ ,
- and a lot between and out of the intervals.

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

Existence of such abundant primordial black holes was predicted a quarter of century ago (A.D. and J.Silk, 1993). Not only abundant PBHs but also peculiar primordial stellar-like objects are predicted,

# Content

## Content of the talk

I. Brief review of observations incompatible, or in tension, with the conventional cosmology and astrophysics.

a) Young,  $z \sim 10$  universe;

b) Contemporary universe.

II. A model of 1993 which predicted these surprises and led to log-normal mass spectrum (extended mass function, very popular nowadays).

III. Some extensions of the model, e.g. multimaximum mass spectrum.

# BH, what's that

Ancient point of view: BH are objects with so strong gravitational field that nothing can escape it.

Mitchell (1784): there may be bodies for which the second cosmic velocity is larger than the speed of light.

**They do not shine and do not reflect light, i.e. are absolutely dark, invisible.**

Not precisely true; BH can emit all kind of radiation in the process of their evaporation (nobody has yet seen it).

The most powerful sources of radiation are BH - quasars, pointlike objects which shine as a thousand of galaxies.

# BH, what's that

## Solutions of the General Relativity Equations:

BH are characterized by 3 and only 3 parameters (hairs):

mass  $M$ , electric charge  $Q$ , and spin  $a$ ,  $0 < a < 1$ .

If  $m_\gamma \neq 0$ , whatever tiny, electric hairs do not exist  
(Coulomb field disappears).

Schwarzschild (1916)  $Q = a = 0$

Reissner-Nordström (1916,1918),  $Q \neq 0$

Kerr (1963)  $a \neq 0$

Kerr-Newman (1965)  $Q \neq 0$ ,  $a \neq 0$ .

# BH, what's that

Types of BH by creation mechanism:

**Astrophysical:** created by stellar collapse when star exhausted its fuel. Masses expected just after the neutron star masses  $3M_{\odot}$  and normally quite close to it.

Instead the mass spectrum of BH in the Galaxy has maximum at  $M \approx 8M_{\odot}$  with the width:  $\sim (1 - 2)M_{\odot}$ .

Scientists do not know why.

## BH, what's that

Accretion of matter to regions with excessive density.

There is a supermassive BH (SMBH) in any large galaxy with  $M \sim 10^9 M_{\odot}$  in elliptic and lenticular galaxies and  $M \sim (10^6 - 10^7) M_{\odot}$  in elliptic galaxies, as Milky Way.

However, the known mechanisms of accretion is not efficient enough to create such monsters during the universe age  $t_U \approx 15$  Gyr.

Moreover SMBH are found in very small galaxies and one SMBH lives even in almost empty space.

SMBH are also discovered recently in quite young universe with the age about 0.5 Gyr.

Massive seed are necessary, but their origin is mysterious

## BH, what's that

Primordial black holes (PBH) created in pre-stellar epoch

The canonical picture: the density excess might accidentally happen to be large  $\delta\rho/\rho \sim 1$  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 created PBH with rather low masses and with sharp almost delta-function mass spectrum. A different mechanism (AD and J.Silk, 1993) could make PBH with masses exceeding millions solar masses and with extended mass spectrum

# BH observations

Indirect methods indicating that in a small volume a large mass is concentrated. With theory applied one concludes that there is a BH inside this volume:

1. Star motion around galactic center.
  2. Gravitational lensing of invisible objects (MACHOs)
  3. Electromagnetic radiation (X rays) from the gravitationally attracted matter heated up million degrees.
- That's how quasars work, the most powerful sources of radiation in the universe, shines as 1000 galaxies.

Still some skepticism was not eliminated, but recently it was strongly hit by the registration of gravitational waves (LIGO and Virgo) and by a photo of a black hole shadow.

# BH observations

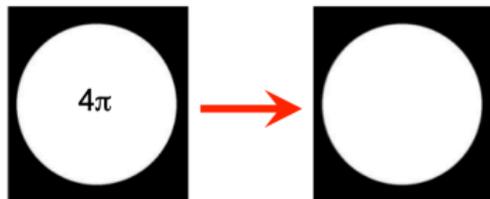
The form of the signal created by gravitational waves is best fit to the hypothesis that it is emitted by two coalescing BH with Schwarzschild metric.

Masses of both initial BH and the final one are accurately determined and their spins are measured.

It is the first experimental test of GR for a strong gravitational field. All numerous earlier tests were only in weak field limit.

# BH shadow, Shatsky-Novikov

M. Ehterington, 1933: homogeneous and isotropic background after gravitational lensing remains homogeneous and isotropic for any metric theory.



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# BH shadow, Shatsky-Novikov

If lensing is made by BH, there is a region from which the light cannot reach the observer, so the picture of the background is modified. This is the so called BH shadow



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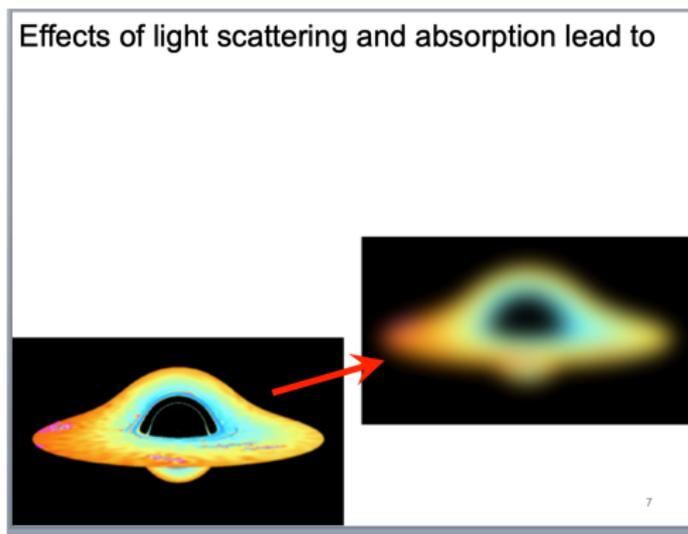
# BH shadow, Shatsky-Novikov

If the background radiation is homogeneous and infinitely large then the image would also be homogeneous and infinite while the black hole shadow must be have sharp bounds:



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# BH shadow, Shatsky-Novikov



# BH snap shot

The Event Horizon Telescope Collaboration et al.

First M87 Event Horizon Telescope Results.

The Shadow of the Supermassive Black Hole.

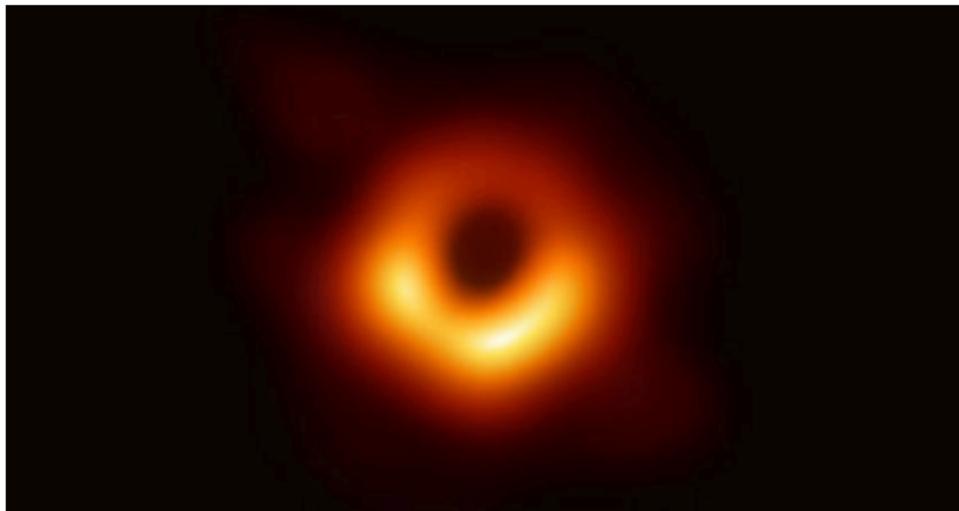
The Astrophysical Journal Letters. April 10, 2019.

BH mass  $(6.5 \pm 0.7) \cdot 10^9 M_{\odot}$ ,

giant elliptical galaxy M87, distance 16.4 Mpc

# BH snap shot

hole\_shadow.pdf



# Young universe

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

# Young universe

A brief review of high- $z$  discoveries.

1. Several galaxies have been observed with natural gravitational lens “telescopes.

For example a galaxy at  $z \approx 9.6$  which was created at  $t_U \approx 0.5$  Gyr (W. Zheng, *et al*, “A highly magnified candidate for a young galaxy seen when the Universe was 500 Myrs old” arXiv:1204.2305).

A galaxy at  $z \approx 11$  has been detected which was formed earlier than the universe age was  $t_U \sim 0.4$  Gyr, three times more luminous in UV than other galaxies at  $z = 6 - 8$ .

D. Coe *et al* “CLASH: Three Strongly Lensed Images of a Candidate  $z \sim 11$  Galaxy”, *Astrophys. J.* 762 (2013) 32.

Unexpectedly early creation.

# Young universe

Not so young but extremely luminous galaxy "The most luminous galaxies discovered by WISE" Chao-Wei Tsai, P.R.M. Eisenhardt *et al*, arXiv:1410.1751, 8 Apr 2015.

$L = 3 \cdot 10^{14} L_{\odot}$ ;  $t_U \sim 1.3$  Gyr.

The galactic seeds, or embryonic black holes, might be bigger than thought possible. P. Eisenhardt: "How do you get an elephant? One way is start with a baby elephant." 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!

## Young universe

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.

"Detection of a Lensed  $z \approx 11$  Galaxy in the Rest-Optical with Spitzer/IRAC and the Inferred SFR, Stellar Mass, and Physical Size", Daniel Lam et al, arXiv:1903.08177.

## Young universe

According to F. Melia (1403.0908), "The Premature Formation of High Redshift Galaxies", 1403.0908: "Rapid emergence of high- $z$  galaxies so soon after big bang may actually be in conflict with current understanding of how they came to be. This problem is very reminiscent of the better known (and probably related) premature appearance of supermassive black holes at  $z \sim 6$ . It is difficult to understand how  $10^9 M_{\odot}$  black holes appeared so quickly after the big bang without invoking non-standard accretion physics and the formation of massive seeds, both of which are not seen in the local Universe."

## Young universe

As is stated in the paper "Monsters in the Dark" D. Waters, et al, Mon. Not. Roy. Astron. Soc. 461 (2016), L51 density of galaxies at  $z \approx 11$  is  $10^{-6} \text{ Mpc}^{-3}$ , an order of magnitude higher than estimated from the data at lower  $z$ .

Origin of these galaxies is unclear.

# Young universe

## 2. Supermassive BH and/or QSO.

Another and even more striking example of early formed objects are high  $z$  quasars. About 40 quasars with  $z > 6$  were known two years ago, each quasar containing BH with  $M \sim 10^9 M_{\odot}$ .

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

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

D.J. Mortlock, *et al*, " A luminous quasar at a redshift of  $z = 7.085$ "  
Nature 474 (2011) 616, arXiv:1106.6088

Similar situation with the others.

## Young universe

In addition to all that another monster was discovered "An ultraluminous quasar with a twelve billion solar mass black hole at redshift 6.30". Xue-BingWu et al, Nature 518, 512 (2015).

There is already a serious problem with formation of lighter and less luminous quasars which is multifold deepened with this new "creature". The new one with  $M \approx 10^{10} M_{\odot}$  makes the formation absolutely impossible in the standard approach.

Rcently: 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."

## Young universe

Recent observations by SUBARU practically doubled the number of discovered high  $z$  QSO

Yoshiki Matsuoka et al

2018 ApJ 869 150,

Publications of the Astronomical Society of Japan, Volume 70, Issue SP1, 1 January 2018, S35

The Astrophysical Journal Letters, Volume 872, Number 1, First low luminosity QSO at  $z > 7$

## Young universe

To conclude on QSO or SMBH:

The quasars are supposed to be supermassive black holes and their formation in such short time by conventional mechanisms looks problematic.

Such black holes, when the Universe was less than one billion years old, present substantial challenges to theories of the formation and growth of black holes and the coevolution of black holes and galaxies. Even the origin of SMBH in contemporary universe during 14 Gyr is difficult to explain.

It is difficult to understand how  $10^9 M_{\odot}$  black holes (to say nothing about  $10^{10} M_{\odot}$ ) appeared so quickly after the big bang without invoking non-standard accretion physics and the formation of massive seeds, both of which are not seen in the local Universe.

## Young universe

### 3. Evolved chemistry, dust, supernovae, gamma-bursters...

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

Another possibility is a non-standard BBN in bubbles with very high baryonic density, which allows for formation of heavy elements beyond lithium.

## Young universe

The universe at  $z > 6$  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  $z = 6.34$  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.

# Young universe

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

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

## Young universe

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.

# Universe today

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

- SMBH today

Every large galaxy contains a central supermassive BH with mass larger than  $10^9 M_\odot$  in giant elliptical and compact lenticular galaxies and  $\sim 10^6 M_\odot$  in spiral galaxies like Milky Way.

The origin of these BHs is not understood. Accepted belief is that these BHs are created by matter accretion to a central seed. But, 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 to make a SMBH can be found.

# Universe today

Some examples of the data:

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 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 is more plausible, when first a supermassive BH was formed and attracted matter being a seed for subsequent galaxy formation!!!

AD, J. Silk, 1993;

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

Bosch et al, Nature 491 (2012) 729.

## Universe today

### More examples:

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. **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 Ap. J. Lett. 775, L6 (2013). **The dynamical mass is  $2 \times 10^8 M_{\odot}$  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.

## Universe today

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

$L_{AGN} = (5.3 \pm 0.4) \cdot 10^{45} \text{ erg/s} \approx 10^{12} L_{\odot}$ . 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.

"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.

## AND MORE RECENT PUZZLES

(improbable systems in the standard model):

- Several (four?) binaries of SMBH.
- Quasar quartet.
- Triple SMBH [1712.03909].

# Universe today

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),  $z \approx 0.3$ .

## Universe today

"Quasar quartet embedded in giant nebula reveals rare massive structure in distant universe", J.F. Hennawi et al, Science 15 May 2015, 348 p. 779,

Discovery of a physical association of four quasars at  $z \approx 2$ . The probability of finding a quadruple quasar is  $\sim 10^{-7}$ . Our findings imply that the most massive structures in the distant universe have a tremendous supply ( $\sim 10^{11}$  solar masses) of cool dense (volume density  $\sim 1/\text{cm}^3$ ) gas, which is in conflict with current cosmological simulations.

# Universe today

## Triple Quasar.

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  $< 250$  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 supermassive black hole (SMBH) interacting system, a triple AGN, or a recoiling SMBH.

# Universe today

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.

Heretic but simpler: primordial SMBH forming binaries in the very early universe and seeding galaxy formation.

# Universe today

- Intermediate mass black holes (MBH)  $M = (10^3 - 10^5) M_{\odot}$

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

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

10 IMBH, 3 years ago,  $M = 3 \times 10^4 - 2 \times 10^5 M_{\odot}$   
and 40 found recently  $10^7 < M < 3 \cdot 10^9$  [Chandra, 1802.01567].

More and more: I.V. Chilingarian, et al. "A Population of Bona Fide Intermediate Mass Black Holes Identified as Low Luminosity Active Galactic Nuclei" arXiv:1805.01467, "identified a sample of 305 IMBH candidates with  $3 \times 10^4 < M_{\text{BH}} < 2 \times 10^5 M_{\odot}$ ,

He-Yang Liu, et al, A Uniformly Selected Sample of Low-Mass Black Holes in Seyfert 1 Galaxies. arXiv:1803.04330, "A new sample of 204 low-mass black holes (LMBHs) in active galactic nuclei is presented with black hole masses in the range of  $(1 - 20) \times 10^5 M_{\odot}$ ."

## Universe today

"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  $(3.2 \pm 0.6) \times 10^4 M_{\odot}$ . 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.**

# Universe today

Only one or two massive BH are observed in Globular clusters.

Definite evidence of BH with  $M \approx 2000 M_{\odot}$  was found in the core of the globular cluster 47 Tucanae.

Origin in standard model is unknown.

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

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

## Universe today

- Old stars in the Milky Way:

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

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

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

## Universe today

Metal deficient **high velocity** subgiant in the solar neighborhood HD 140283 has the age  **$14.46 \pm 0.31$  Gyr.**

H. E. Bond, et al, *Astrophys. J. Lett.* 765, L12 (2013),  
arXiv:1302.3180.

The central value exceeds the universe age by two standard deviations, if  $H = 67.3$  and  $t_U = 13.8$ ; and if  $H = 74$ , then  $t_U = 12.5$ , more than  $10 \sigma$ .

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,  **$10.6_{-1.3}^{+1.5}$  Gyr.** (Age of the Earth: 4.54 Gyr.)

A SN explosion must precede formation of this planet.

# Universe today

- Other strange stars.

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

Other high velocity stars in the Galaxy.

"Old, Metal-Poor Extreme Velocity Stars in the Solar Neighborhood", Kohei Hattori et al., arXiv:1805.03194,.

"Gaia DR2 in 6D: Searching for the fastest stars in the Galaxy", T. Marchetti, et al., arXiv:1804.10607.

They can be accelerated by a population of IMBH in Globular clusters, if there is sufficient number of IMBHs.

# Universe today

## Very unusual star:

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  $M_{\text{host}} = 0.15^{+0.27}_{-0.10} M_{\odot}$  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. May it be primordial helium star?

## Universe today

"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".

Authors suggest that these stars are not completely burned down remnants of SNIa, but the probability for such events seems to be quite low.

They could be chemically peculiar primordial stars wandering in Galactic halo

# Universe today

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

$f$  = mass ratio of MACHOS to DM.

Macho group:  $0.08 < f < 0.50$  (95% CL) for  $0.15M_{\odot} < M < 0.9M_{\odot}$ ;

EROS:  $f < 0.2$ ,  $0.15M_{\odot} < M < 0.9M_{\odot}$ ;

EROS2:  $f < 0.1$ ,  $10^{-6}M_{\odot} < M < M_{\odot}$ ;

AGAPE:  $0.2 < f < 0.9$ ,

for  $0.15M_{\odot} < M < 0.9M_{\odot}$ ;

EROS-2 and OGLE:  $f < 0.1$  for  $M \sim 10^{-2}M_{\odot}$  and

$f < 0.2$  for  $\sim 0.5M_{\odot}$ .

MACHOs surely exist but who are they is not known.

# Universe today

- Mass spectrum of astrophysical (?) BH

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 easily explained in the standard model of BH formation by stellar collapse.

# Universe today

- Grav. waves from BH binaries, great discovery → great problems. GW discovery by LIGO has proven that the sources of GW are most probably PBH. S.Blinnikov, 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 ( $\sim 30M_{\odot}$ ).

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  $M > 100M_{\odot}$  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 observed in the necessary amount. Primordial BH with the observed by LIGO masses may be easily created with sufficient density.

# Universe today

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  $(36 + 29)M_{\odot}$  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.

# Universe today

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, arXiv:1904.00570 [astro-ph.HE] ). This result is in agreement with the GW170729 LIGO event produced by the binary with masses  $50M_{\odot}$  and  $30M_{\odot}$  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.

# Creation Mechanism

The mechanism of massive PBH formation with wide mass spectrum:

- A. Dolgov and J.Silk, PRD 47 (1993) 4244 "Baryon isocurvature fluctuations at small scaler and baryonic dark matter."
- A.Dolgov, M. Kawasaki, N. Kevlishvili, Nucl.Phys. B807 (2009) 229, "Inhomogeneous baryogenesis, cosmic antimatter, and dark matter".

Heretic predictions of 1993 are turning into the 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.

Unusual stellar type compact objects could also be created.

Swiss cheese universe: small bubbles with high  $\beta \equiv N_B/N_\gamma \sim 1$ .

In many respects similar picture, but not dynamics, was suggested recently: J. García-Bellido, B. Carr, S. Clesse, "A common origin for baryons and dark matter" arXiv:1904.11482, but questionable.

# Creation Mechanism

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:  $\mu$ ,  $\gamma$ ,  $M_0$ . Can be generalized to multi-maximum spectrum.

This form is a result result of quantum diffusion of baryonic scalar field during inflation. Probably such spectrum is a general consequence of diffusion.

Log-normal mass spectrum of PBHs was rediscovered by S. Clesse, J. Garcia-Bellido, Phys. Rev. D92, 023524 (2015).

Now in many works such spectrum is postulated without justification.

# Creation Mechanism

SUSY motivated baryogenesis, Affleck and Dine (AD).

SUSY predicts existence of scalars with  $\mathbf{B} \neq \mathbf{0}$ . 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  $m = |m|e^\alpha$ .

If  $\alpha \neq \mathbf{0}$ , 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)  $\chi$  is away from origin and, when inflation is over, starts to evolve down to equilibrium point,  $\chi = \mathbf{0}$ , according to Newtonian mechanics:

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

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  $10^{-9}$ .

## Creation Mechanism

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  $\chi$ .

# 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  $\beta$  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.**

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.
- $\beta$  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 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-bursters and supernovae, early bright galaxies, and evolved chemistry including dust.
- 5. There is persuasive data in favor of the inverted picture of galaxy formation, when first a supermassive BH seeds are formed and later they accrete matter forming galaxies.

# SUMMARY

- 6. An existence of supermassive black holes observed in all large and some small galaxies and even in almost empty environment is naturally explained.
- 7. "Older than  $t_U$ " stars may exist; the older age is mimicked by the unusual initial chemistry.
- 8. Existence of high density invisible "stars" (machos) is understood.
- 9. Explanation of origin of BHs with  $2000 M_\odot$  in the core of globular cluster and the observed density of GCs is presented.
- 10. A large number of the recently observed IMBH was predicted.
- 11. A large fraction of dark matter or 100% can be made of PBHs.
- 12. Clouds of matter with high baryon-to-photon ratio.
- 13. A possible by-product: plenty of (compact) anti-stars, even in the Galaxy, not yet excluded by observations.

# Extreme conclusions

- Black holes in the universe are mostly primordial (PBH).
- Primordial BHs make all or dominant part of dark matter (DM).
- QSO created in the very early universe.
- Metals and dust are made much earlier than at  $z = 10$ .
- Inverted picture of galaxy formation: seeding of galaxies by SMPBH or IMPBH;
- Seeding of globular clusters by  $10^3 - 10^4$  BHs, dwarfs by  $10^4 - 10^5$  BH.

## Newest papers

arXiv:1904.11482. 25 Apr 2019 "A common origin for baryons and dark matter" J. García-Bellido, B. Carr, S. Clesse

We propose a scenario in which the gravitational collapse of large inhomogeneities at the quark-hadron epoch generates both the baryon asymmetry and dark matter in the form of PBH. The collapse to a PBH is induced by fluctuations of a light spectator scalar field in rare regions and is accompanied by the violent expulsion of surrounding material, which might be regarded as a sort of "primordial supernova". The acceleration of protons to relativistic speeds provides the ingredients for efficient baryogenesis around the collapsing regions and its subsequent propagation to the rest of the Universe. This scenario naturally explains why the observed BAU is of order the PBH collapse fraction and why the baryons and DM have comparable densities. The predicted PBH mass distribution ranges from sub-solar to several hundred solar masses. This is compatible with current observational constraints and could explain the rate, mass and low spin of the black hole mergers detected by LIGO-Virgo.

## Newest papers

arXiv:1904.10298 (\*cross-listing\*) Date: Tue, 23 Apr 2019 13:23:35 GMT (495kb,D)

Title: Primordial black hole tower: Dark matter, earth-mass, and LIGO black holes Authors: Yuichiro Tada and Shuichiro Yokoyama Categories: astro-ph.CO hep-ph Comments: 12 pages, 3 figures

We investigate a possibility of primordial black hole (PBH) formation with a hierarchical mass spectrum in multiple phases of inflation. As an example, we find that one can simultaneously realize a mass spectrum which has recently attracted a lot of attention, stellar-mass PBHs ( $\sim O(10)M_{\odot}$ ) as a possible source of binary black holes detected by LIGO/VIRGO collaboration, asteroid-mass ( $\sim O(10^{-12})M_{\odot}$ ) as a main component of dark matter, and earth-mass ( $\sim O(10^{-5})M_{\odot}$ ) as a source of ultrashort-timescale events in OGLE microlensing data. The recent refined swampland conjecture may support these multi-phase inflationary scenario with hierarchical mass PBHs as a transition signal of each inflationary phase.

## Newest papers

arXiv:1705.05567 replaced with revised version Tue, 9 Apr 2019  
Title: Primordial black hole constraints for extended mass functions  
Authors: Bernard Carr, Martti Raidal, Tommi Tenkanen, Ville Vaskonen and Hardi Veermäe Categories: astro-ph.CO hep-ph Comments: 9 pages, 3 figures. v2: Added discussion about combined constraints. Accepted for publication in Phys. Rev. D. v3: Corrected a minor mistake in the plots for power-law mass functions Journal-ref: Phys. Rev. D 96, 023514 (2017)

## Newest papers

Bernard Carr, Martti Raidal, T. Tenkanen, V Vaskonen, Hi.Veermäe We revisit the cosmological and astrophysical constraints on the fraction of the dark matter in primordial black holes (PBHs) with an extended mass function. We consider a variety of mass functions, all of which are described by three parameters: a characteristic mass and width and a dark matter fraction. Various observations then impose constraints on the dark matter fraction as a function of the first two parameters. We show how these constraints relate to those for a monochromatic mass function, demonstrating that they usually become more stringent in the extended case than the monochromatic one. Considering only the well-established bounds, and neglecting the ones that depend on additional astrophysical assumptions, we find that there are three mass windows, around  $4 \times 10^{-17} M_{\odot}$ ,  $2 \times 10^{-14} M_{\odot}$  and  $(25 - 100) M_{\odot}$ , where PBHs can constitute all dark matter. However, if one includes all the bounds, PBHs can only constitute of order 10% of the dark matter.

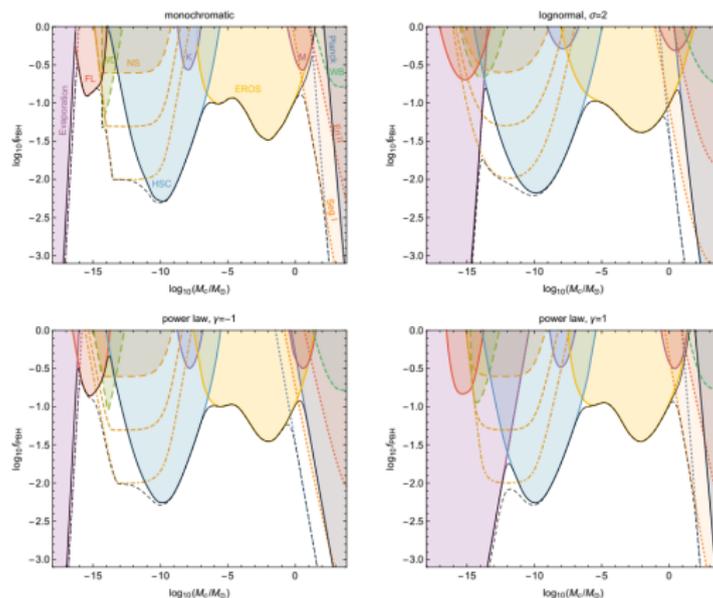


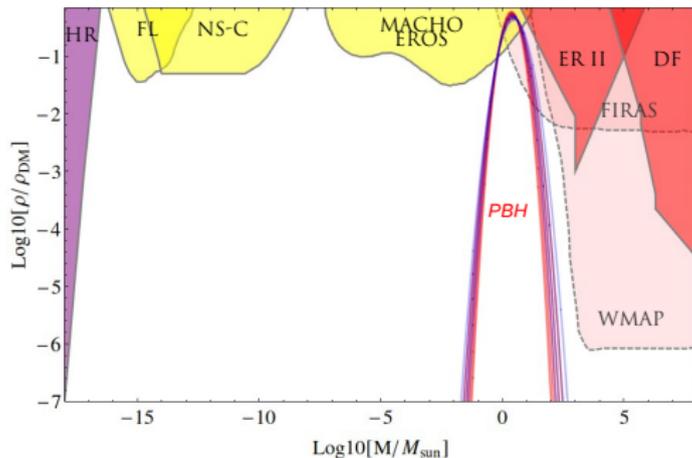
FIG. 1. *Upper left panel:* Constraints from different observations on the fraction of PBH DM,  $f_{\text{PBH}} \equiv \Omega_{\text{PBH}}/\Omega_{\text{DM}}$ , as a function of the PBH mass  $M_*$ , assuming a monochromatic mass function. The purple region on the left is excluded by evaporations [8], the red region by femtolensing of gamma-ray bursts (FL) [40], the brown region by neutron star capture (NS) for different values of the dark matter density in the cores of globular clusters [41], the green region by white dwarf explosions (WD) [42], the blue, violet, yellow and purple regions by the microlensing results from Subaru (HSC) [43], Kepler (K) [44], EROS [45] and MACHO (M) [46], respectively. The dark blue, orange, red and green regions on the right are excluded by Planck data [36],

## Newest papers

[arXiv:1903.10509](#) "Lyman- $\alpha$  forest constraints on Primordial Black Holes as Dark Matter" R. Murgia, G. Scelfo, M. Viel, A. Raccanelli

The renewed interest in the possibility that primordial black holes (PBHs) may constitute a significant part of the dark matter has motivated revisiting old observational constraints, as well as developing new ones. We present new limits on the PBH abundance, from a comprehensive analysis of high resolution, high redshift Lyman- $\alpha$  forest data. Poisson fluctuations in the PBH number density induce a small-scale power enhancement which departs from the standard cold dark matter prediction. Using a grid of hydrodynamic simulations exploring different values of astrophysical parameters, we obtain a marginalized upper limit on the PBH mass of  $f_{\text{PBH}} M_{\text{PBH}} \sim 60 M_{\odot}$  ( $170 M_{\odot}$ ) at  $2\sigma$  (depending on priors), which significantly improves previous constraints from the same physical observable. We also extend our predictions to non-monochromatic PBH mass distributions, ruling out large regions of the parameter space for some of the most viable PBH extended mass functions.

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.

