DARK ENERGY AND GALAXIES

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A talk based on the publication

A solution of the coincidence problem based on the recent galactic core black hole mass density increase

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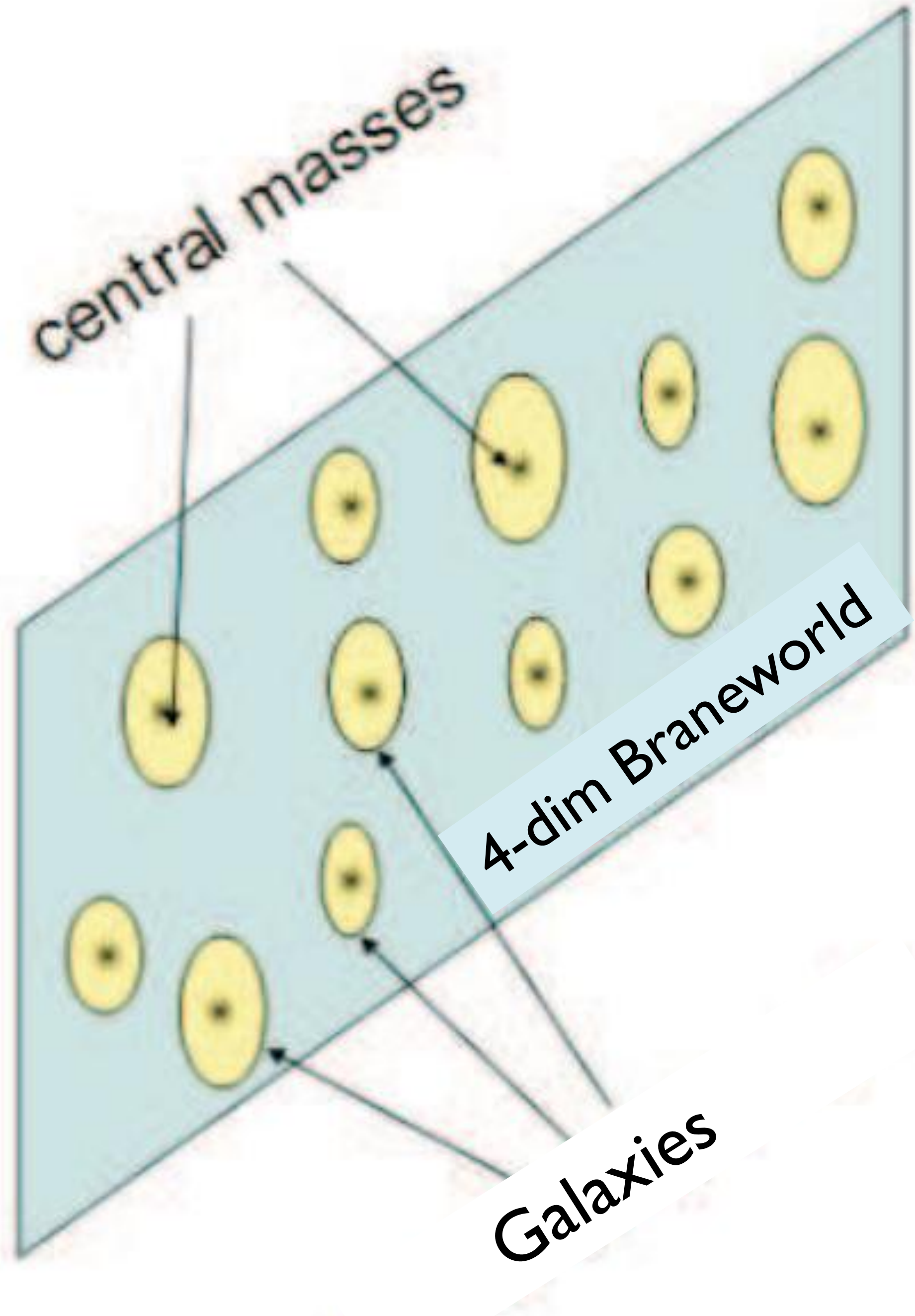
What is about?

A mechanism capable to provide a natural solution to

- cosmic acceleration
- and the coincidence problem,

Cosmos



How it works?

A specific brane-bulk energy exchange mechanism produces a total Cosmic Dark Pressure, arising when adding all normal to the brane negative pressures in the interior of galactic core black holes.

(it is worth mentioning that this work corrects a wide spread fallacy among brane cosmologists, i.e. that escaping gravitons result to positive dark pressure.)

What we have proved

This astrophysically produced negative dark pressure explains cosmic acceleration and why the dark energy today is of the same order to the matter density for a wide range of the involved parameters.

An exciting result of the analysis is that

the recent rise of the galactic core black hole mass density causes the recent passage from cosmic deceleration to acceleration.

THE REASONING (1 / 3)

Brane Universe

$$\Rightarrow$$

Unavoidable leakage of energy at regions where there are high energy interactions of the order of Mfund=M_5

THE REASONING (2 / 3)

Potential regions of high energy interaction of the order of the fundamental Planck scale are the interiors of the Galactic Core Black Holes/Compact objects

$$\Rightarrow$$

Unavoidable and natural leakage of energy towards the bulk from the Galactic central regions

THE REASONING (3 / 3)

The recent increase in the overall cosmic mass density of the galactic core black holes (due to accretion)

$$\Rightarrow$$

Recent cosmic acceleration due to the well known and widely studied phenomenon of the appearance of cosmic acceleration whenever we have brane energy outflow

Important

Note that the presented work does not produce acceleration from the motion of the brane into the bulk space or from uknown exotic forms of matter or ad hoc interactions, coming from some type of phenomenology.

Our mechanism can be tested and rejected

We begin with a model described by a 5-dim Einstein-Hilbert action with matter and a 5-dim cosmological constant Λ plus the contribution describing the brane

$$S = \int d^5x \sqrt{-g}\,(M^3 R - \Lambda + \mathcal{L}_B^{mat}) + \int d^4x \sqrt{-h}\,(-V + \mathcal{L}_b^{mat})$$

where *R* is the Ricci scalar of the five-dimensional metric g_{AB} (A, B = 0, 1, 2, 3, 5) and h is the induced metric on the 3-brane and M the fundamental Planck scale (5-dim Planck mass).

We identify (x, z) with $(x, -z)$, where $z \equiv x_5$ in order to impose the usual Z_2 reflection symmetry of the AdS slice

In order to search for cosmological solutions we consider the corresponding form for the metric

$$ds^2 = -n^2(t,z)\,dt^2 + a^2(t,z)\,\gamma_{ij}dx^i dx^j + b^2(t,z)\,dz^2$$

where γ_{ij} is a maximally symmetric 3-dimensional metric with i, j = 0, 1, 2, 3 (we use k = −1, 0, 1 to parameterize the spatial curvature).

The five-dimensional Einstein equations are

$$G_{MN} = \frac{1}{2M^3} T_{MN}$$

where T_{MN} is the total energy momentum tensor,

$$T^M_N = T^M_N|_{v,b} + T^M_N|_{m,b} + T^M_N|_{v,B} + T^M_N|_{m,B}$$

$$T^M_N|_{vac,b} = \frac{\delta(z)}{b} diag(-V, -V, -V, -V, 0)$$

$$T^M_N|_{vac,B} = diag(-\Lambda, -\Lambda, -\Lambda, -\Lambda, -\Lambda)$$

$$T^M_N|_{matter,b} = \frac{\delta(z)}{b} diag(-\rho, p, p, p, 0)$$

$$T^M_N|_{matter,B} = diag(0, 0, 0, 0, T^5_5) + \begin{pmatrix} \mathbb{O} & T^0_5 \\ \frac{-n^2}{b^2} T^0_5 & \mathbb{O} \end{pmatrix}$$

The off-diagonal contribution T^0_5
expresses the brane-bulk energy exchange flow of gravitons,

while the T^5_5
component expresses the corresponding pressure along the fifth dimension.

The set of the Einstein equations at the location of the brane

$$\dot{\rho} + 3\frac{\dot{a}_o}{a_o}(\rho + p) = -\frac{2n_o^2}{b_o}\, T_5^0$$

$$\frac{1}{n_o^2}\left(\frac{\ddot{a}_o}{a_o} + \left(\frac{\dot{a}_o}{a_o}\right)^2 - \frac{\dot{a}_o}{a_o}\frac{\dot{n}_o}{n_o}\right) + \frac{k}{a_o^2} = \frac{1}{6M^3}\left(\Lambda + \frac{V^2}{12M^3}\right)$$

$$-\frac{1}{144M^6}\Big(V(3p-\rho) + \rho(3p+\rho)\Big) - \frac{1}{6M^3}T_5^5$$

Dots indicate derivatives with respect to t

Since we are interested in a model that reduces to the Randall-Sundrum vacuum in the absence of matter we require the bulk cosmological constant and the brane tension to satisfy

$$\Lambda + \frac{1}{12M^3}V^2 = 0$$

Therefore the effective cosmological constant λ on the brane is zero

$$\lambda = \left(\Lambda + V^2/12M^3\right)/12M^3$$

It is convenient to employ a coordinate frame in which $b_o = n_o = 1$

This can be achieved by using Gauss normal coordinates with $b\,(t, z) = 1$

and by going to the temporal gauge on the brane with $n_o = 1$

Thus, using $\beta \equiv M^{-6}/144$ and $\gamma \equiv V\beta$ $\gamma = \frac{4\pi G_N}{3}$

and omitting the subscript "o" for convenience in the following, we take

$$\dot{\rho} + 3\,(1 + w)\,H\,\rho = -T$$

$$q = 1 + H^{-2}\frac{k}{a^2} + H^{-2}(3w - 1)\gamma\rho + $$
$$+H^{-2}(3w + 1)\beta\rho^2 \; + H^{-2}\sqrt{\beta}\;\Pi.$$

Here, q is the usual deceleration parameter and T, Π are the discontinuities of
the zero-five and five-five components of the bulk energy-momentum tensor respectively.

$$p = w\rho \text{ and } T = 2T^0_5,\ \Pi = 2T^5_5$$

$$\dot{\rho} + 3\,(1+w)\,H\,\rho = -T$$

$$q = 1 + H^{-2}\frac{k}{a^2} + H^{-2}(3w-1)\gamma\rho + \\ + H^{-2}(3w+1)\beta\rho^2 \; + H^{-2}\sqrt{\beta}\,\Pi.$$

It is obvious from that the only way to pass from a deceleration era to an accelerated cosmic phase in a flat universe (k = 0) is the case that the dark pressure term Π becomes negative at some moment in the cosmic history.

$$\dot{\rho} + 3\,(1+w)\,\frac{\dot{a}}{a}\,\rho = -T$$

$$\frac{\dot{a}^2}{a^2} = \beta\rho^2 + 2\gamma\rho - \frac{k}{a^2} + \psi + \lambda$$

$$\dot{\psi} + 4\frac{\dot{a}}{a}\psi = 2\beta\Big(\rho + \frac{\gamma}{\beta}\Big)T - 2\sqrt{\beta}\,\frac{\dot{a}}{a}\,\Pi$$

where we have defined the generalisation of the dark radiation auxilliary field from

$$\frac{\ddot{a}}{a} = -\,(2+3w)\,\beta\rho^2 - (1+3w)\,\gamma\rho - \sqrt{\beta}\,\Pi - \psi$$

$$\frac{dq}{da} = \frac{2}{a}q(q+1) + H^{-2}\Big[2\,(2+3w)\,\beta\rho\frac{d\rho}{da} + (1+3w)\gamma\frac{d\rho}{da} + \frac{d\psi}{da} + \sqrt{\beta}\frac{d\Pi}{da}\Big]$$

$$\frac{d\rho}{da} = -\frac{1}{a}\left[3(1+w)\rho + T\ H^{-1}\right],$$

where we should replace everywhere ψ and $d\psi/da$

$$\psi = -(2+3w)\beta\rho^2 - (1+3w)\gamma\rho + H^2 q - \sqrt{\beta}\,\Pi + \lambda$$

$$\frac{d\psi}{da} = \frac{1}{a}\left[-4\psi + 2\beta\Big(\rho + \frac{\gamma}{\beta}\Big)\ T\ H^{-1} - 2\sqrt{\beta}\ \Pi\right]$$

and we substitute H^2 with the help of

$$H^2 = \frac{(3w+1)\beta\rho^2 + (3w-1)\gamma\rho + \frac{k}{a^2} - 2\lambda + \sqrt{\beta}\ \Pi}{q-1}.$$

Initial conditions

$$\Omega_m = \frac{2\gamma\rho}{H^2} = \frac{\rho}{\rho_{cr}}, \quad \Omega_\lambda = \frac{\lambda}{H^2}, \quad \Omega_k = -\frac{k}{a^2H^2}$$

and for the dark energy part

$$\Omega_{DE} = \frac{\beta\rho^2 + \psi}{H^2} = \frac{\rho_{DE}}{\rho_{cr}}.$$

$$\Omega_m + \Omega_{DE} + \Omega_\lambda + \Omega_k = 1$$

$$q = \Omega_{DE} + \sqrt{\beta}\,\Pi\, H^{-2} + (1+3w)\,\frac{\Omega_m}{2}\left(1 + \frac{\beta H^2}{2\gamma^2}\Omega_m\right) - \Omega_\lambda$$

From the Raychaudhuri differential equation we can get

$$q_0 = 1 - \frac{\Omega_{m,0}}{2} + \Pi_0 H_0^{-2} \ \beta^{1/2}$$

q_0 depends only on $\Pi_0, H_0^2, \Omega_{m,0}$

where

$\rho_0 \simeq \frac{1}{3}\rho_{cr,0}$ and for example $q_0 = -1$

$$\Pi_0 \simeq -\frac{11}{6} \ H_0^2 \ \beta^{-1/2} \ .$$

Dark energy

$$w_{DE} = \frac{1}{\frac{H^2}{H_0^2} - \frac{\Omega_{m,0}}{a^3}} \left\{ \left(\frac{\Omega_{DE}}{3} + w\Omega_m + \frac{1+3w}{6} \frac{\beta}{\gamma^2} \Omega_m^2 H^2 \right) \frac{H^2}{H_0^2} + \frac{2\sqrt{\beta}\,\Pi}{3H_0^2} \right\}$$

The physics of the outflow

It is certainly expected that in the accretion discs and more importantly in the interiors of galactic black holes and galactic core supermassive black holes various particles as electrons and protons can be thermalised/accelerated to energies around M or above.

Escape of gravitons

Particle acceleration starts in the accretion discs outside the horizon and increases as the particle crosses it. Consequently, particle collisions become capable to produce gravitons escaping to the bulk space.

Unitarity

Assuming a black hole with physics that respects unitarity in its interior, it is acceptable to use the picture of an effective quantum fluid that fills the black hole and does not concentrate at the singular center (otherwise there will be information loss from the exactly thermal Hawking radiation). WHY?

Horizon

Consider a shell of matter that collapses to form a black hole. As the shell passes through its horizon, the light cones ‘tip over’ so that any particle inside the horizon is forced to move towards the center of the hole, ending its trajectory at the singularity.

As a consequence the region near the horizon becomes the ‘vacuum’ in this classical picture; any matter near this horizon either flows off to infinity or gets sucked inside the hole.

Information paradox

Quantum effects cause the black hole to slowly radiate away energy by the creation of particle-antiparticle pairs at the horizon. But since these pairs are created out the vacuum, the emerging quanta carry no information about the matter which made the hole.

Thus in this semiclassical picture we get a loss of unitarity – the well known black hole information paradox

Information paradox

If one assumes that quantum gravity effects are confined to a small length scale like the planck length or string length, and then notes that the curvature scales at the horizon are much larger than this length for large black holes it can safely conclude that the precise theory of quantum gravity is irrelevant to the process of Hawking radiation and thus for the resolution of the paradox.

Quantum fluid

This effective fluid may be on a high temperature below or close to M.

At these energies it is possible to obtain rapid energy favored production of bulk gravitons from collisions of energetic brane matter.

Loss rate per volume

In a hot plasma the production rate per 3-volume is the thermal average of the cross section times the lost energy of the particles.

Therefore, the total energy loss rate due to bulk graviton radiation is

$$\Delta\dot{\rho}_{pls} = 0.112\frac{\Theta^4}{2M^3}\rho_{pls} = 0.112\ g_*\frac{\pi^2}{60}\frac{\Theta^8}{M^3}$$

Now, let $\Delta\dot{\rho}_{tot}$ be the leakage of energy from the total volume of the warm plasma of a black hole. In order to evaluate T we have to add all these leakages from all galactic halo black holes and all black holes at the galactic central regions and divide with the Hubble volume H^{-3}, thus $T = H^3 \sum \Delta\dot{\rho}_{tot}$.

$$T \simeq 0.112\, g_* \frac{\pi^2}{60} \frac{\Theta^8_{mean}}{M^3} [N_{haloBH} V_{haloBH} + N_{coreBH} V_{coreBH}]\, H^3 \quad \text{or}$$

$$T \simeq \frac{0.112}{2M^3} \Theta^4_{mean} [N_{haloBH} M_{haloBH} + N_{coreBH} M_{coreBH}]\, H^3$$

$$T \simeq \frac{0.112}{2M^3} \Theta^4_{mean} (\rho_{haloBH} + \rho_{coreBH})$$

The magnitude of the three dimensional pressure inside the black hole is equal to the magnitude of the pressure of the effective fluid. Since our collapsing fluid is not an ideal fermi gas, we adapt an index $\widehat{\gamma}$ for determining the three dimensional pressure in the interior of both halo and core black holes, i.e.

$$p_{pls}^{BH} = \xi(\rho_{pls}^{BH})^{\widehat{\gamma}} \, .$$

Since the aim is to determine
the dark pressure towards the fifth dimension we should divide the three dimensional pressure with the characteristic kinetic length scale L of the plasma towards the bulk p_{pls}^{BH}/L. This length L is

$$L = \frac{M^3}{\rho_{pls}}$$

Therefore we get

$$\Pi^{BH} = -\xi \frac{(\rho_{pls}^{BH})^{\widehat{\gamma}+1}}{M^3}$$

Finally,

$$\Pi = -\xi\left[\frac{(\rho_{pls}^{hBH})^{\widehat{\gamma}+1}}{M^3} N_{haloBH} V_{haloBH} + \frac{(\rho_{pls}^{cBH})^{\widehat{\gamma}+1}}{M^3} N_{coreBH} V_{coreBH}\right] H^3$$

$$= -\xi\left[\frac{(\rho_{pls}^{hBH})^{\widehat{\gamma}}}{M^3} N_{haloBH} M_{haloBH} + \frac{(\rho_{pls}^{cBH})^{\widehat{\gamma}}}{M^3} N_{coreBH} M_{BHcore}\right] H^3$$

The phenomenon under discussion most importantly results to the appearance of a negative pressure orthogonal to the fifth dimension. At the position of the brane the five-dimensional pressure $\Pi = 2T^{55}$ equals the momentum flux carried from the bulk to the brane. Because of momentum conservation this pressure equals the opposite of the momentum flux carried by the escaping gravitons from the brane to the bulk. Therefore, $\Pi < 0$.

Spherical collapse on the brane with brane-bulk energy exchange

Now, the energy density, the dark radiation and the dark pressure concern the plasma in the interior of collapsing region. Thus, the system of differential equations that the evolution of the collapsing region should respect is

$$\dot{\rho}_{pls} + 3\left(\rho_{pls} + p_{pls}\right)\frac{\dot{R}}{R} = -T_{pls}$$

$$\frac{\dot{R}^2}{R^2} = \beta\rho_{pls}^2 + 2\gamma\rho_{pls} - \frac{\kappa}{R^2} + \psi$$

$$\dot{\psi} + 4\frac{\dot{R}}{R}\psi = 2\beta\left(\rho_{pls} + \frac{\gamma}{\beta}\right)T_{pls} - 2\sqrt{\beta}\,\frac{\dot{R}}{R}\,\Pi_{pls}$$

Oppenheimer-Snyder type of collapse

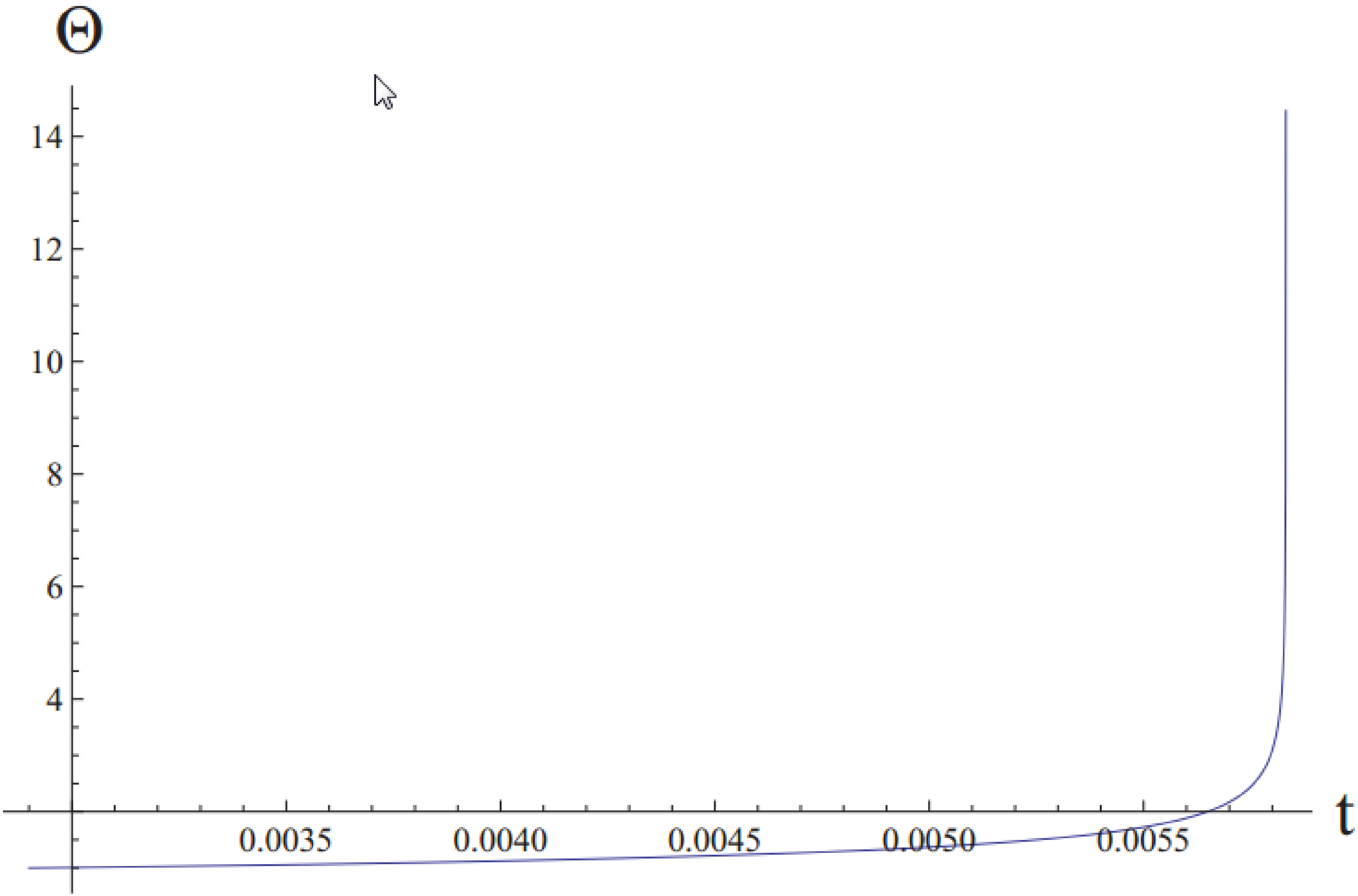
$$\dot{\Theta}_{mean} + \frac{3}{4}\Theta_{mean}\left(1 + \xi\sigma^{\widehat{\gamma}-1}\Theta_{mean}^{4(\widehat{\gamma}-1)}\right)\frac{\dot{R}}{R} + 0.014\frac{\Theta_{mean}^5}{M^3} = 0$$

$$\frac{\dot{R}^2}{R^2} = \beta\sigma^2\Theta_{mean}^8 + 2\gamma\sigma\Theta_{mean}^4 - \frac{\kappa}{R^2} + \psi$$

$$\dot{\psi} + 4\frac{\dot{R}}{R}\psi = 0.112\beta\sigma\left(\sigma\Theta_{mean}^4 + \frac{\gamma}{\beta}\right)\frac{\Theta_{mean}^8}{M^3}$$

$$+2\sqrt{\beta}\,\xi\,\sigma^{\widehat{\gamma}+1}\,\frac{\dot{R}}{R}\Theta_{mean}^{4(\widehat{\gamma}+1)}\frac{1}{M^3}$$

Increase of the temperature of the collapsing quantum fluid with the effective equation of state



AMOUNT OF PRODUCED COSMIC ACCELERATION

$$\log_{10}(\rho_{coreBH}) = -\mu\, z + \log_{10}(\rho_{coreBH}|_{z=0})$$

valid for $z < 2$

Since $\rho_{coreBH}|_{z=0} = 4.3 \times 10^5 M_\odot Mpc^{-3}$ is the current galactic core black hole matter density and $\rho_{coreBH}|_{z=2} = 1.5 \times 10^5 M_\odot Mpc^{-3}$ is the density at redshift $z = 2$ we obtain

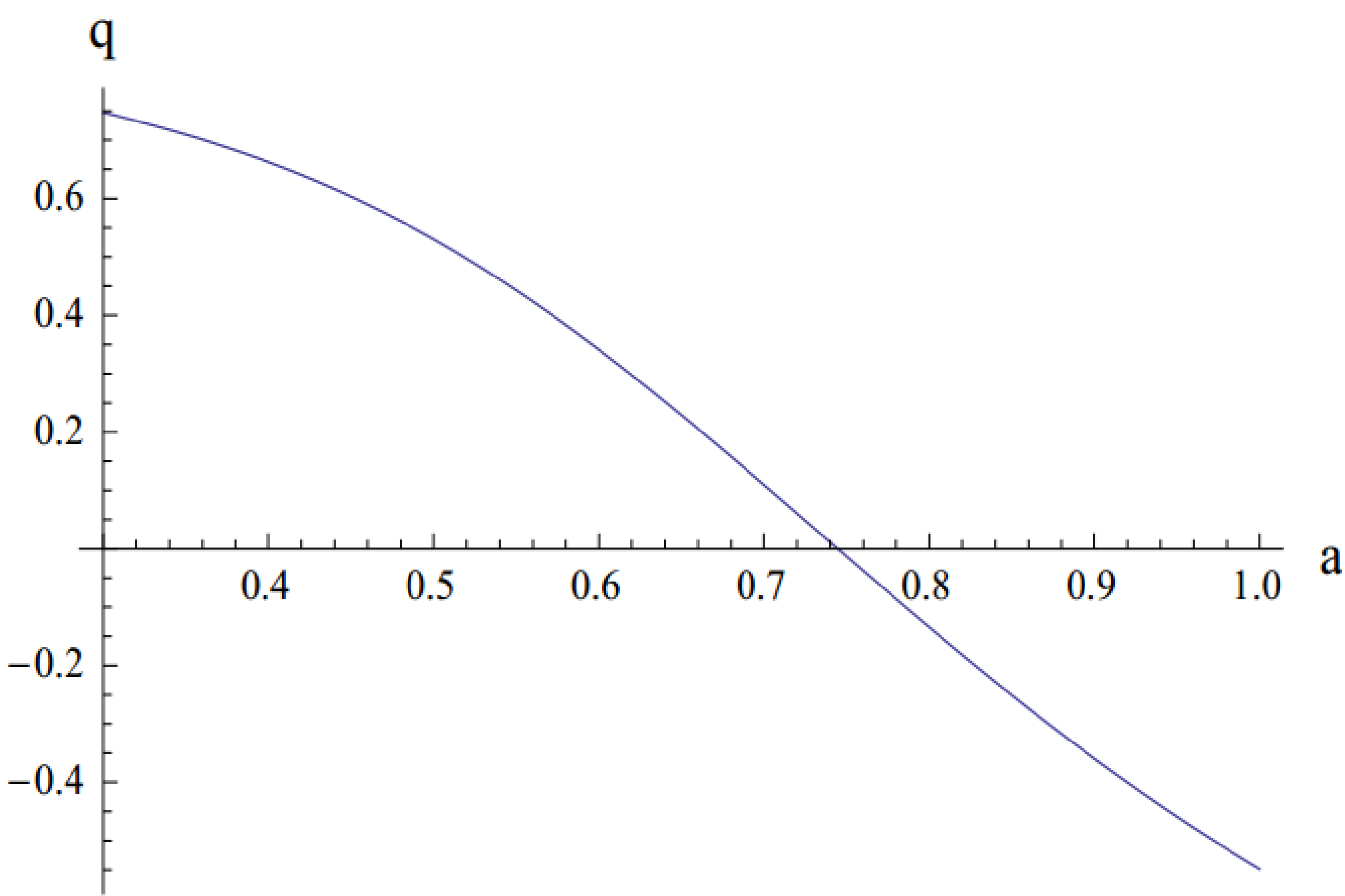
$$\mu = \frac{\log_{10}(\rho_{coreBH}|_{z=0}) - \log_{10}(\rho_{coreBH}|_{z=2})}{2}$$

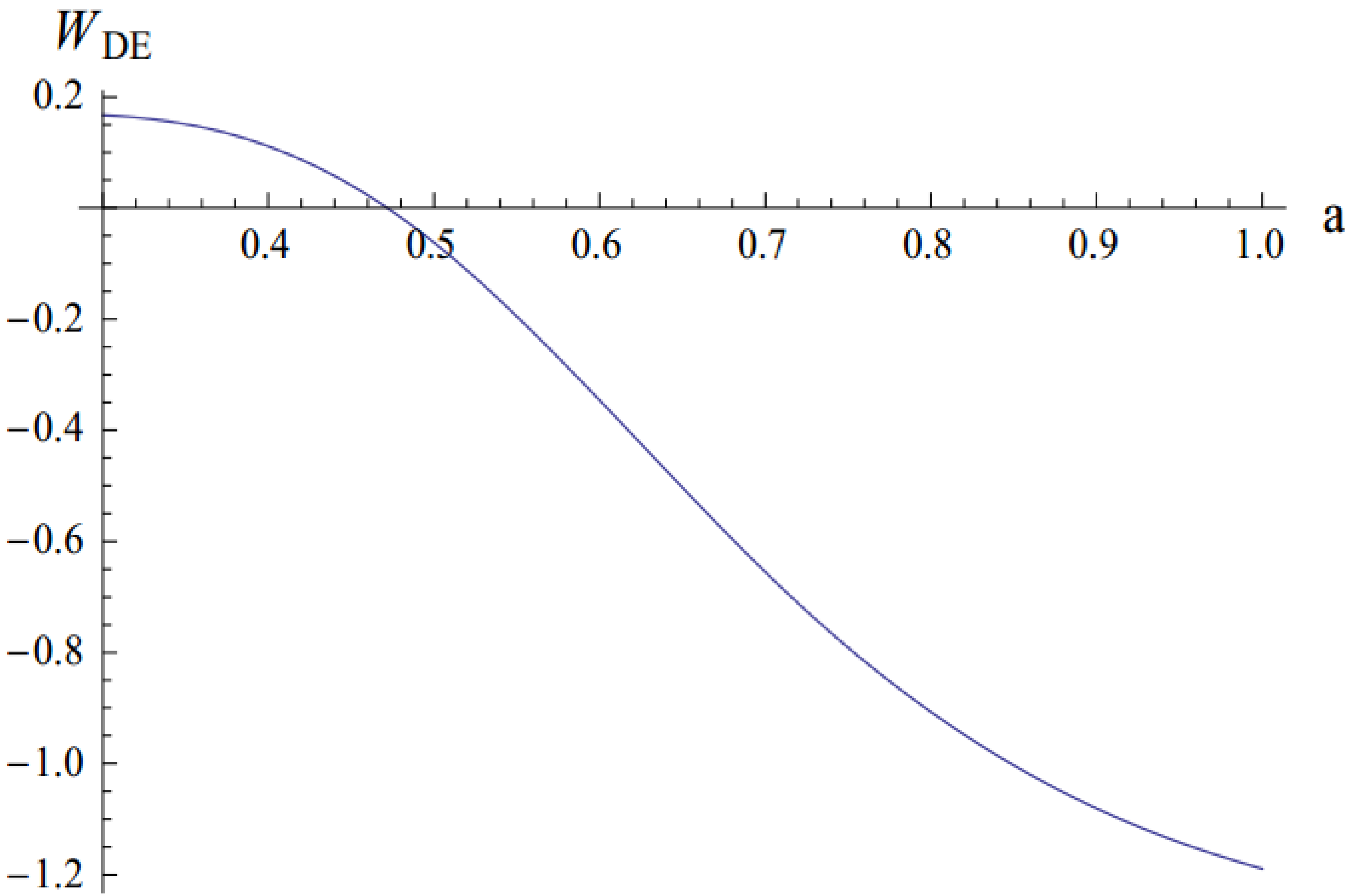
Coincidense problem solved

It is also worth mentioning that both T, Π are zero before large scale structure since black holes have not appeared yet. Only after the large scale structure and the growth of a significant population of astrophysical black holes the mechanism is able to result to cosmic acceleration. The latter observation provides a natural solution to the coincidence problem.

Results

assumption	assumption	assumption	output	output	output
$\hat{\gamma}$	$M(\mathrm{TeV})$	$\Theta_{mean}(\mathrm{GeV})$	$T_{e,0}(\mathrm{GeV}^5)$	$\Pi_0(\mathrm{GeV}^5)$	$w_{DE,0}$
0.21	10	10^{-8}	10^{-98}	-10^{-71}	-1
0.18	10	3.5×10^{-10}	10^{-103}	-10^{-71}	-1
0.13	10	10^{-13}	10^{-118}	-10^{-71}	-1
0.07	50	10^{-9}	10^{-104}	-10^{-69}	-1
0.05	50	10^{-12}	10^{-116}	-10^{-69}	-1
0.01	100	10^{-10}	10^{-109}	-10^{-68}	-1
0.001	120	10^{-10}	10^{-109}	-10^{-68}	-1


q
0.6
0.4
0.2
−0.2
−0.4
a
0.4
0.5
0.6
0.7
0.8
0.9
1.0



W_{DE}
0.2
−0.2
−0.4
−0.6
−0.8
−1.0
−1.2
0.4
0.5
0.6
0.7
0.8
0.9
1.0
a

- the index $\hat{\gamma}$ has to be less than unity and this would be connected with the physical properties of the assumed quantum fluid in the black hole interior.
- The outflow T is orders less than the produced dark pressure Π. The latter is responsible for the cosmic acceleration

astrophysical observation	assumption	assumption	output	output	output
$N_{BH}M_{BH}$	$\hat{\gamma}$	$\Theta_{mean}(\mathrm{GeV})$	$T_{e,0}(\mathrm{GeV}^5)$	$\Pi_0(\mathrm{GeV}^5)$	$w_{DE,0}$
$N_{coreBH}M_{BHcore} = 10^{18}M_{\odot}$	0.1	10^{-10}	10^{-105}	-10^{-69}	-1
$N_{coreBH}M_{BHcore} = 10^{18}M_{\odot}$	0.07	10^{-14}	10^{-121}	-10^{-69}	-1
$N_{coreBH}M_{BHcore} = 10^{15}M_{\odot}$	0.026	10^{-8}	10^{-101}	-10^{-69}	-1
$N_{haloBH}M_{haloBH} = 10^{23}M_{\odot}$	0.2	4.5×10^{-12}	10^{-106}	-10^{-69}	-1

First constraint

A first bound can be found demanding that the lifetime of a galactic core black hole loosing energy according to our scenario is larger than the typical lifetime of such black holes $t_{coreBH} \sim 10^{10}$ years. An estimate of the

$$t_{\text{lifetime}} = \frac{2M^3}{0.112\Theta^4_{mean}} > t_{coreBH}.$$

This bound is easily satisfied for all expected values of $T_{e,0}$, for example for $M \sim 50TeV$ and $\Theta_{mean} \sim 10^{-9}GeV$ the lifetime estimate is 10^{20} years!

Second constraint

the measured luminosity has been observed to be always a fraction (called efficiency and ranging from somewhat below 0.01 for the low luminosity AGNs to 0.1 for the large luminosity AGNs - strong accretors) of the Eddington luminosity $L_E \sim \frac{M_{BH}}{10^8 M_\odot} 10^{46}$erg sec^{-1}. As a result, in any case for the purpose of estimating this second constraint, the net gain of energy rate $\dot{M}_{BH}$ can be assumed to be around L_E and therefore the second bound becomes

$$\Delta\dot{\rho}_{pls}^{BH} V_{BH} = 0.112 \frac{\Theta_{mean}^4}{2M^3} M_{BH} \ll L_E.$$

A black hole with mass $M_{BH} \sim 10^7 M_{\odot}$, losing energy with average temperature of the effective plasma $\Theta_{mean} \sim 10^{-9} GeV$ and $M = 50 TeV$, is associated with an energy loss rate equal to 10^{34} erg sec^{-1}. Such losses are orders of magnitude smaller numbers compared to accretion rates. Therefore, they cannot alter significantly the black hole mass and make impossible the violation of any measured relations between central galactic back hole mass and galactic halo mass or of the observed expression of black hole density as a function of redshift

The calculations of the scenario could have failed for various reasons:

•if a very high temperature was needed in the interior of the black hole,

•or if a small fundamental Planck scale was needed

•or a large T was needed conflicting of course with galactic dynamics,

•or if for the given variation of the cosmic black hole density as a function of redshift the cosmic evolution failed to posses a long deceleration era accompanied by a recent acceleration one.

However, the concrete and conservative numerical values used lead the scenario to success.

But why small outflows from all black holes are able to accelerate the universe?

The brane is assumed to have zero geometric cosmological constant/zero total tension

Remember from basic physics that it costs almost "nothing" to stretch a membrane with hypothetical zero tension

Future tests

- It would be interesting to investigate existence of statistical significant correlations of the rise of galactic core black hole masses and the time evolution of the decceleration parameter

- It worths also searching for statistical significant correlations of peaks in the rise of galactic core black hole masses with possible peaks in the time evolution of the deceleration parameter

END

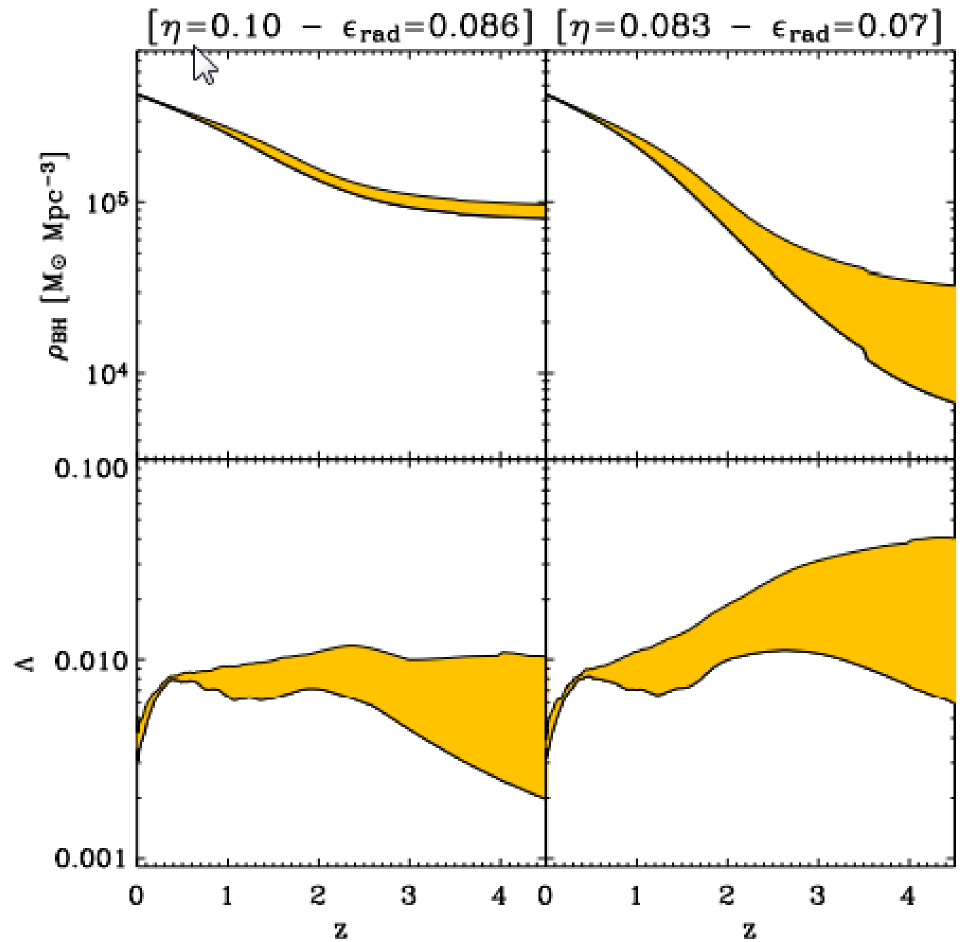


Figure 3. Top panels: the redshift evolution of the SMBH mass density. Bottom panels, the evolution of the average Eddington ratio of the SMBH population, defined in eq. (13). On the left we show the results of a calculation performed fixing the accretion efficiency to $\eta = 0.1$, which, for the particular model of accretion modes we assume correspond to an average radiative efficiency of $\epsilon_{\rm rad} \simeq 0.086$, while on the right we show the case of $\eta = 0.083$, corresponding to $\epsilon_{\rm rad} \simeq 0.07$. See text for details.