ENTROPY PRODUCTION IN THE EARLY UNIVERSE

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BASIC CONTENTS

- A SMALL INTRODUCTION
- ELECTROWEAK PHASE TRANSITION AND ENTROPY RELEASE IN THE EARLY UNIVERSE
- PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER
- FUTURE WORKS (PLANS)

A SMALL INTRODUCTION

We know that entropy density is conserved in the course of the cosmological expansion, if the plasma is in thermal equilibrium state with negligibly small chemical potentials of all particle species.

Even though the state of matter in the early universe is quite close to the equilibrium because the reaction rate is much faster than the cosmological expansion rate but there are situations when the entropy density is not conserved.

A SMALL INTRODUCTION

But there can be several realistic regimes during the universe history where the entropy density was not conserved. For example:

1. If the universe was at some epoch dominated by primordial black holes with small masses, the entropy release can be high enough to delete all the pre-existing baryon asymmetry.

A SMALL INTRODUCTION

But there can be several realistic regimes during the universe history where the entropy density was not conserved. For example:

1. If the universe was at some epoch dominated by primordial black holes with small masses, the entropy release can be high enough to delete all the pre-existing baryon asymmetry.

2. The process of the electroweak transition from symmetric to asymmetric electroweak phase in the course of the cosmological cooling down can result in entropy production.

A SMALL INTRODUCTION

Other realistic regimes include the following:

A. A large amount of entropy could be produced if the primeval plasma underwent the first order phase transition at some early period of the cosmological evolution.

B. Some, realistic but most probably very weak entropy production, took place during the freeze-out of dark matter (DM) particles. However, usually the fraction of DM density was quite low at the freezing and the effect is tiny.

ELECTROWEAK PHASE TRANSITION AND ENTROPY RELEASE IN THE EARLY UNIVERSE

As mentioned before, entropy production takes place during electroweak phase transition. A few properties are as follows:

- In principle, the transition could be either first order or second order, even very smooth crossover.
- Theoretical calculations say that in the minimal standard model with one Higgs field the transition is the mild crossover. However, in an extended theory with several Higgses, the transition could be even first order with significant supercooling.

ELECTROWEAK PHASE TRANSITION AND ENTROPY RELEASE IN THE EARLY UNIVERSE

We take the following Lagrangian:

$$\mathcal{L} = \frac{1}{2} g^{\mu\nu} \partial_\mu \phi \, \partial_\nu \phi - U_\phi(\phi) + \sum_j i \left[g^{\mu\nu} \partial_\mu \chi_j^\dagger \, \partial_\nu \chi_j - U_j(\chi_j) \right] + \mathcal{L}_{int}$$

where the Lagrangian of the Higgs boson interactions with fields, χ_j, can be taken as:

$$\mathcal{L}_{int} = \phi \sum_j g_j \chi_j^\dagger \chi_j .$$

The summation is made over all relevant fields χ_j.

ELECTROWEAK PHASE TRANSITION AND ENTROPY RELEASE IN THE EARLY UNIVERSE

The self-potential of ϕ with the temperature corrections can be written as:

$$U_\phi(\phi) = \frac{\lambda}{4}(\phi^2 - \eta^2)^2 + \frac{T^2\phi^2}{2}\sum_j h_j\left(\frac{m_j(T)}{T}\right),$$

where according to experiment the vacuum expectation value of ϕ is equal to $\eta = 246$ GeV and the quartic self-coupling of ϕ is $\lambda = 0.13$. Here T is the plasma temperature and m_j(T) is the mass of the χ_j-particle at temperature T.

ELECTROWEAK PHASE TRANSITION AND ENTROPY RELEASE IN THE EARLY UNIVERSE

- We are mostly interested in the contribution of Fermions. Their Yukawa coupling constants to the Higgs field are determined by their masses at zero temperature, $m_f = g_f \eta$.

- The masses of all particles depend on the temperature, $m_j = m_j(T)$, because the masses are proportional to the expectation value of the Higgs field and the latter is proportional to the temperature dependent value of ϕ at the minimum of the potential:

$$\phi^2_{min}(T) = \eta^2 - (T^2/\lambda) \sum_j h_j \left(\frac{m_j(T)}{T} \right)$$

ELECTROWEAK PHASE TRANSITION AND ENTROPY RELEASE IN THE EARLY UNIVERSE

And correspondingly:

$$m_f^2(T) = g_f^2 \phi_{min}^2(T) = g_f^2 \left[\eta^2 - (T^2/\lambda) \sum_j h_j \left(\frac{m_j(T)}{T} \right) \right].$$

Here $j = f$ is the index of χ_f-particle which acquires mass through a non-zero expectation value of ϕ. The summation in the r.h.s. of this equation is made over all particles, χ_j and ϕ.

ELECTROWEAK PHASE TRANSITION AND ENTROPY RELEASE IN THE EARLY UNIVERSE

The oscillations of ϕ around ϕ_{min} are quickly damped, so we take $\dot{\phi} = \dot{\phi}_{min}$ and neglect $\dot{\phi}^2$ in what follows, because the evolution of ϕ_{min} is induced by the universe expansion which is quite slow.

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And after a series of tedious calculations, we find out, in the range from GeV to keV scale, we find that the total amount of entropy is increased by about ***13%***.

And please note: In extended versions of the electroweak theory (e.g., with several Higgs fields) the entropy release may be considerably larger. (This work is under process).

PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER

Sufficiently light primordial black holes (PBH) could evaporate in the very early universe resulting in huge amount of entropy production and dilute the pre-existing baryon asymmetry and/or the frozen density of stable relics.

PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER

Some key points to note:

- We considered PBHs of small masses, such that they evaporated before BBN.

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Some key points to note:

- We considered PBHs of small masses, such that they evaporated before BBN.
- They decayed before our time but they can have noticeable impact in the present.
- They can pour sufficient entropy into the plasma and diminish the the pre-existing baryon asymmetry and diminish the relative (with respect to the relic photon background) density of dark matter particles

PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER

- Baryon asymmetry could be generated in PBH evaporation.
- Dark matter could also be created in this process.

But neglect these processes and consider only dilution of baryons and dark matter particles by the PBH evaporation.

PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER

The size of the reduction is calculated for 3 different scenarios:

1. Delta function mass spectrum with instant decay approximation.
2. Delta function mass spectrum with exact solution (instant decay is lifted).
3. Extended mass spectrum.

PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER

We consider here the simplest model of PBHs with fixed mass M_0 with the number density at the moment of creation:

$$\frac{dN_{BH}}{dM} = \mu_1^3\,\delta(M - M_0),$$

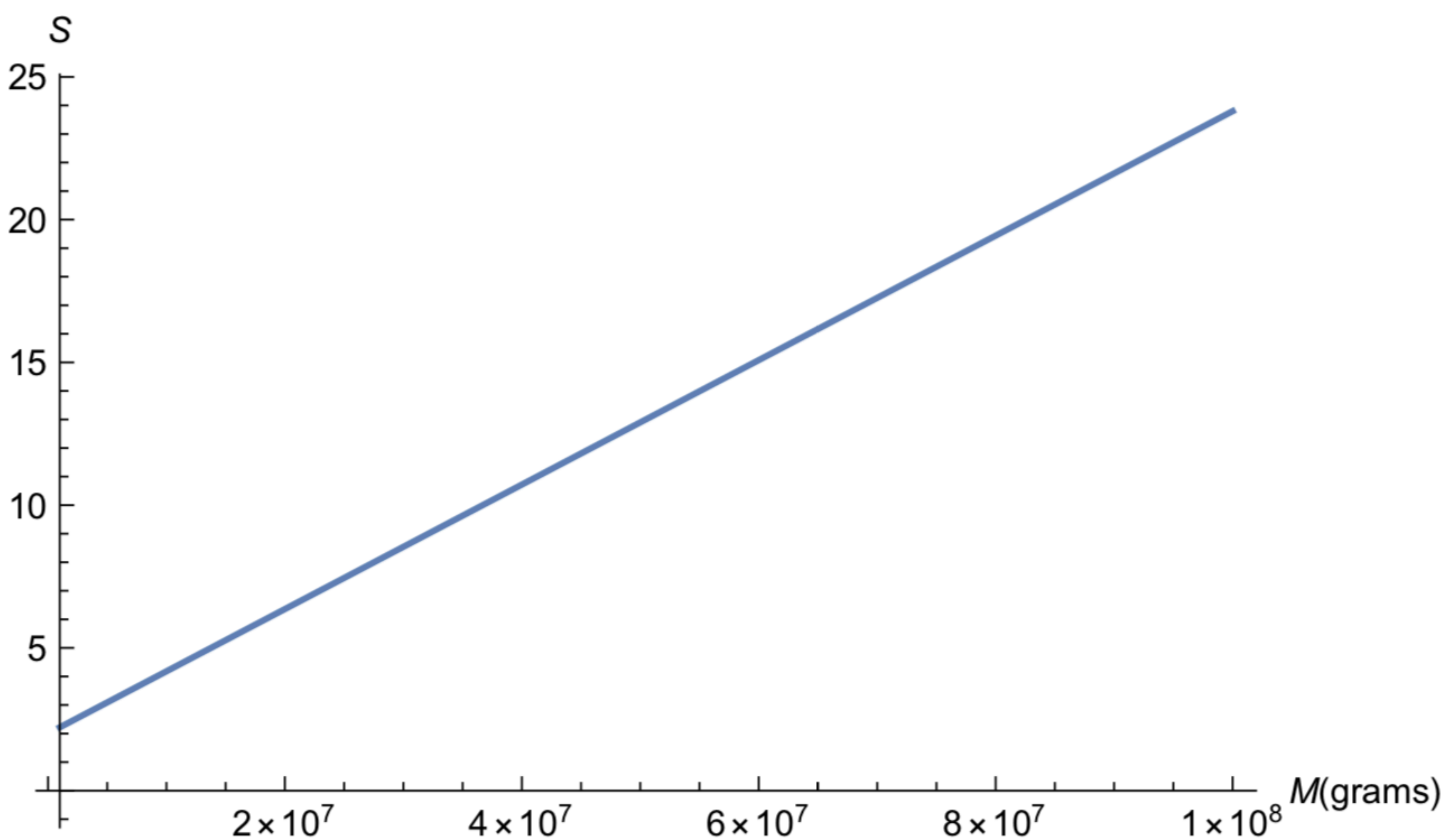
where μ_1 is a constant parameter with dimension of mass.

All the black holes were created at the same moment and the fraction of the PBH energy (mass) density at production was:

$$\frac{\rho_{BH}^{(in)}}{\rho_{rel}^{(in)}} = \epsilon \ll 1$$

PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER

Without going into much technical details, the entropy production is represented below:



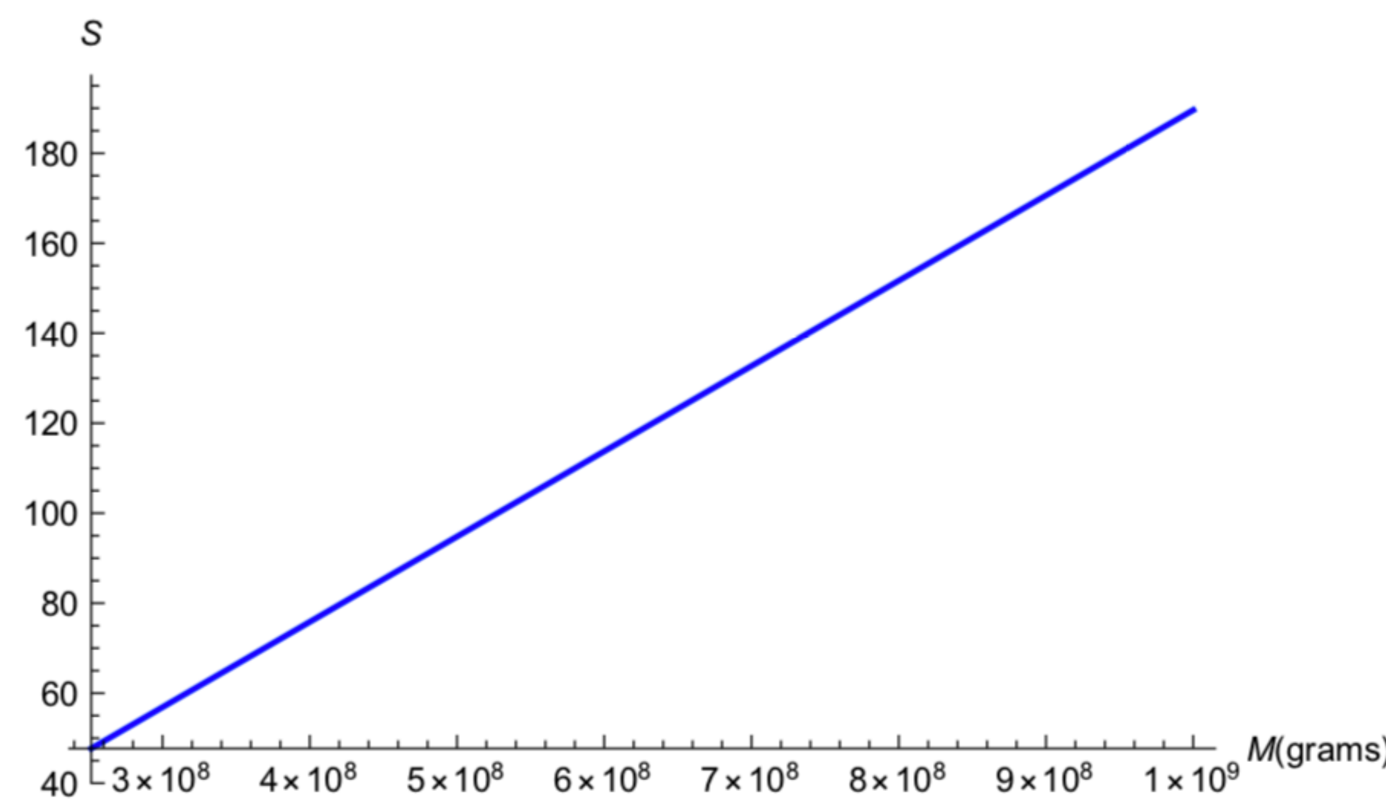
PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER

Here we relax the instant decay approximation and solve numerically equations describing evolution of the cosmological energy densities of non-relativistic PBHs and relativistic matter. We take a dimensionless time $\eta = t/\tau_{BH}$ and the equations can be written as:

$$\frac{d\rho_{BH}}{d\eta} = -(3H\tau + 1)\rho_{BH},$$
$$\frac{d\rho_{rel}}{d\eta} = -4H\tau\rho_{rel} + \rho_{BH}.$$

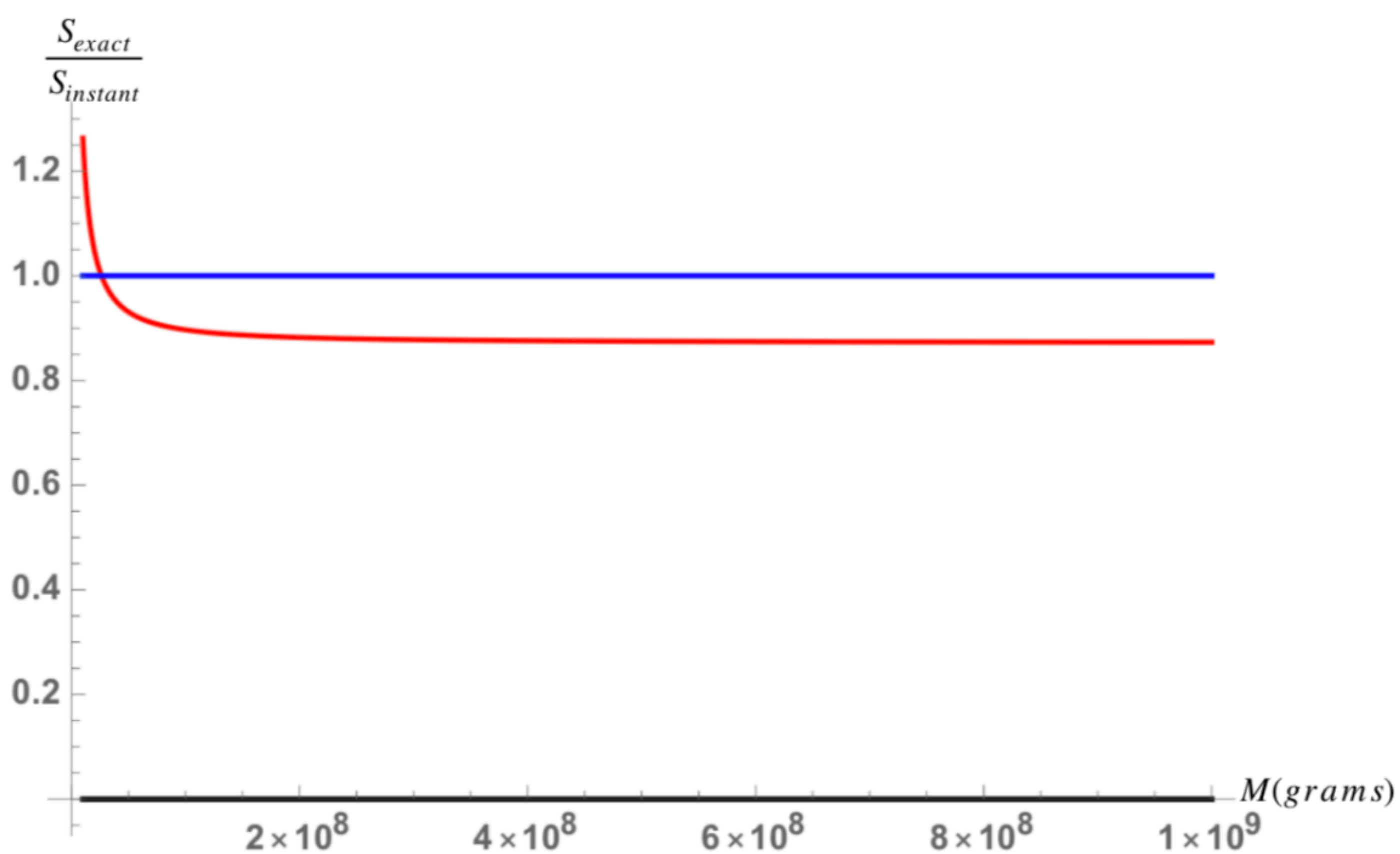
PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER

We solve them numerically to find the entropy production and it is shown below:



PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER

For $\epsilon = 10^{-12}$, the ratio of the entropy suppression factor of the exact fixed mass calculations to the instant decay and change of the expansion regime as a function of mass is shown below (The blue line describes the hypothetical ratio equal to unity):



EXTENDED MASS SPECTRUM

Moving to a more realistic approach, we consider a couple of illustrative examples in what follows, assuming that the function:

$$F(x) = \epsilon(M)/z(\eta_f(M))$$

is confined between $x_{min} = (M_{min}/M_0)$ and $x_{max} = (M_{max}/M_0)$.

EXTENDED MASS SPECTRUM

- We take two examples for F:

$$F_1(x) = \epsilon_0/(x_{max} - x_{min})$$

Note F_1=0 for x outside of this interval. Evidently x=1 should be inside this interval.

- Another interesting form of F is:

$$F_2(x) = \frac{\epsilon_0}{N} a^2 b^2 (1/a - 1/x)^2 (1/x - 1/b)^2.$$

Here N is the normalization factor, chosen such that the maximum value of $F_2/\epsilon = 1$.

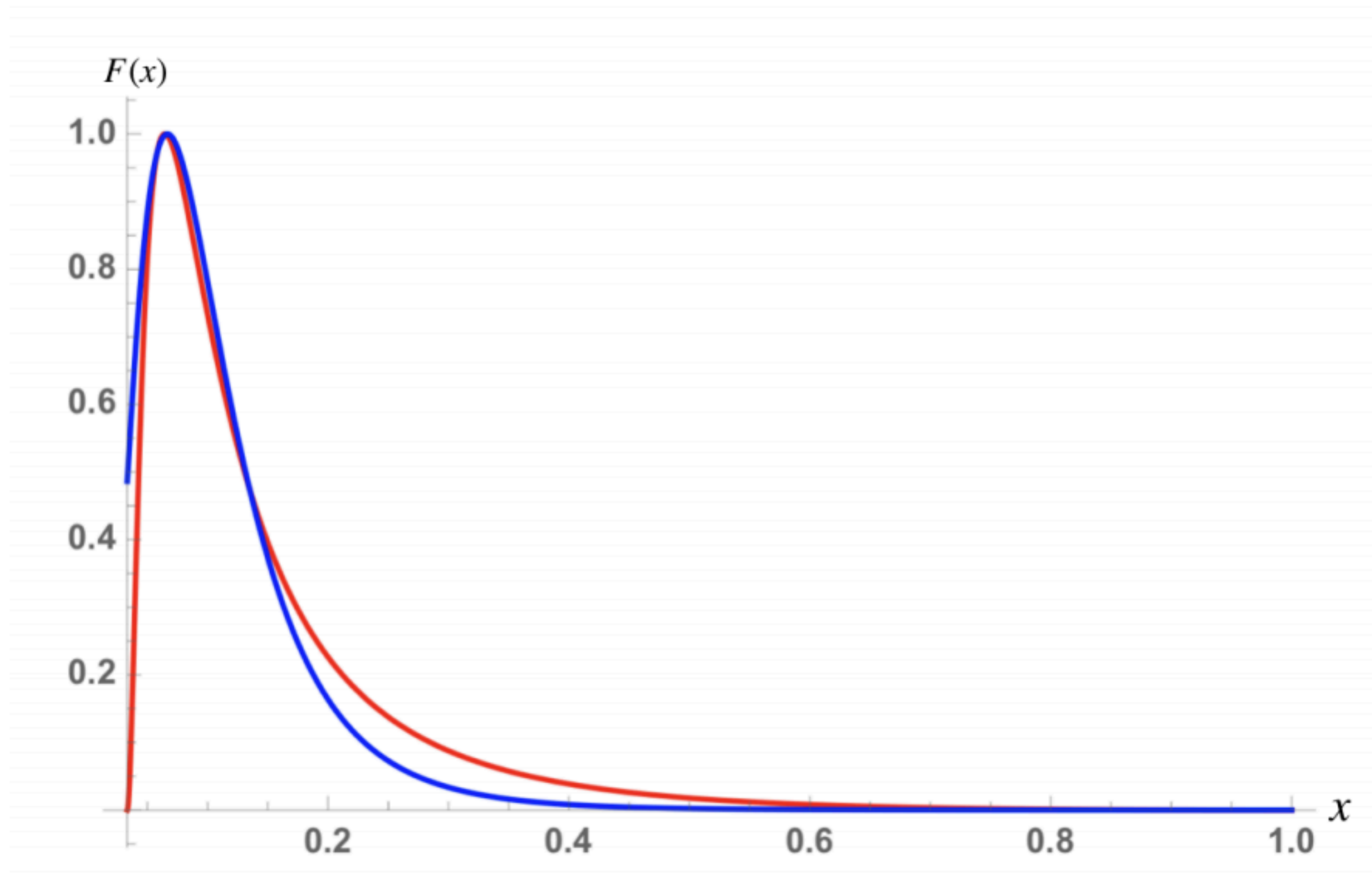
EXTENDED MASS SPECTRUM

- F_2 can be quite close numerically to the log-normal distribution with a proper choice of parameters. As a working example we take a=1, b=30 and compare F_2 with the log-normal function:

$$F_{LN} = \epsilon \exp[-1.5(\log^2(15x))]$$

With the chosen parameters $F_2(x)$ and $F_{LN}(x)$ are presented in next figure:

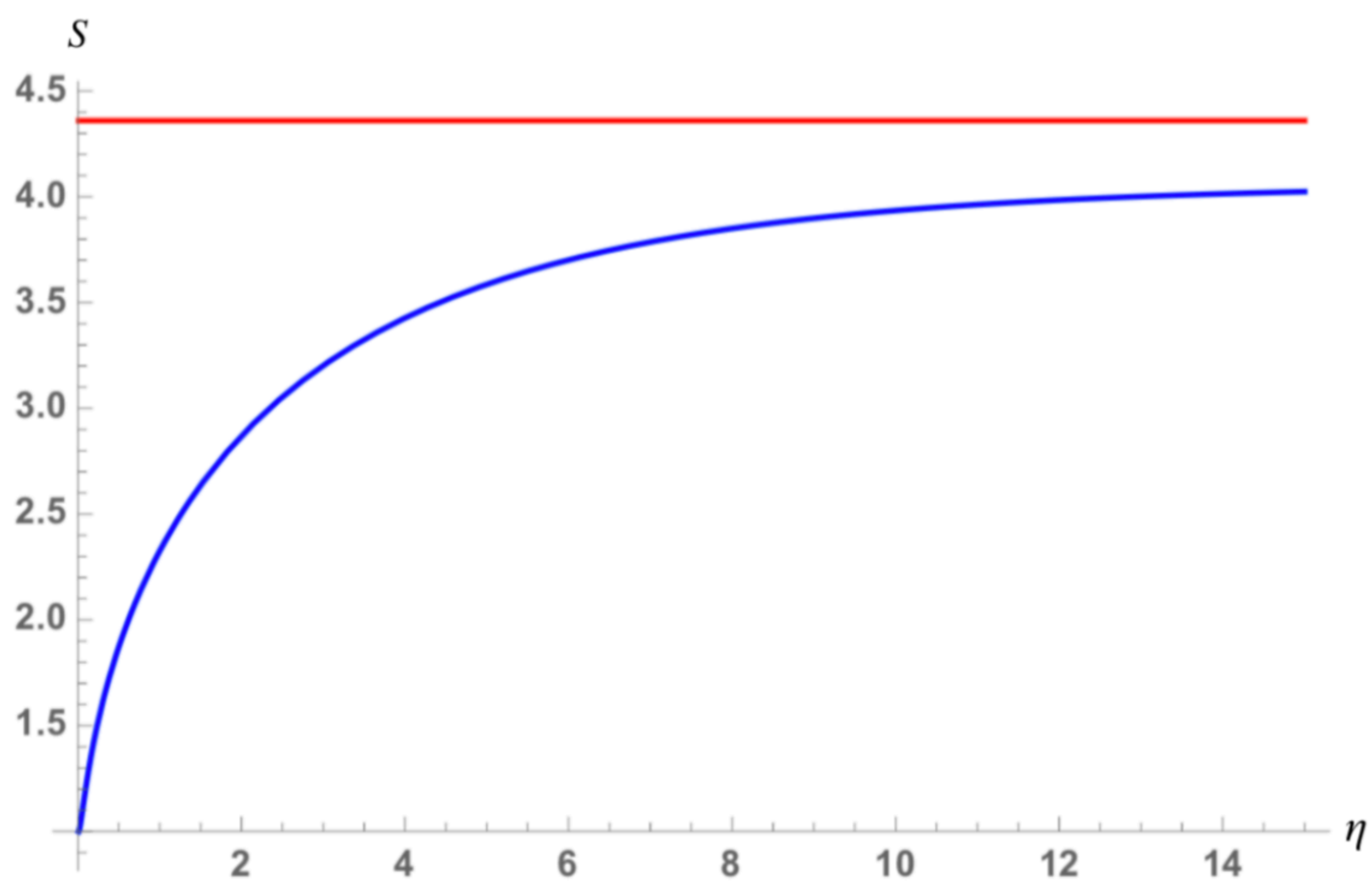
EXTENDED MASS SPECTRUM



The model mass spectrum function F_2 (red) and the log-normal spectrum (blue) as functions of $x = M/M_0$.

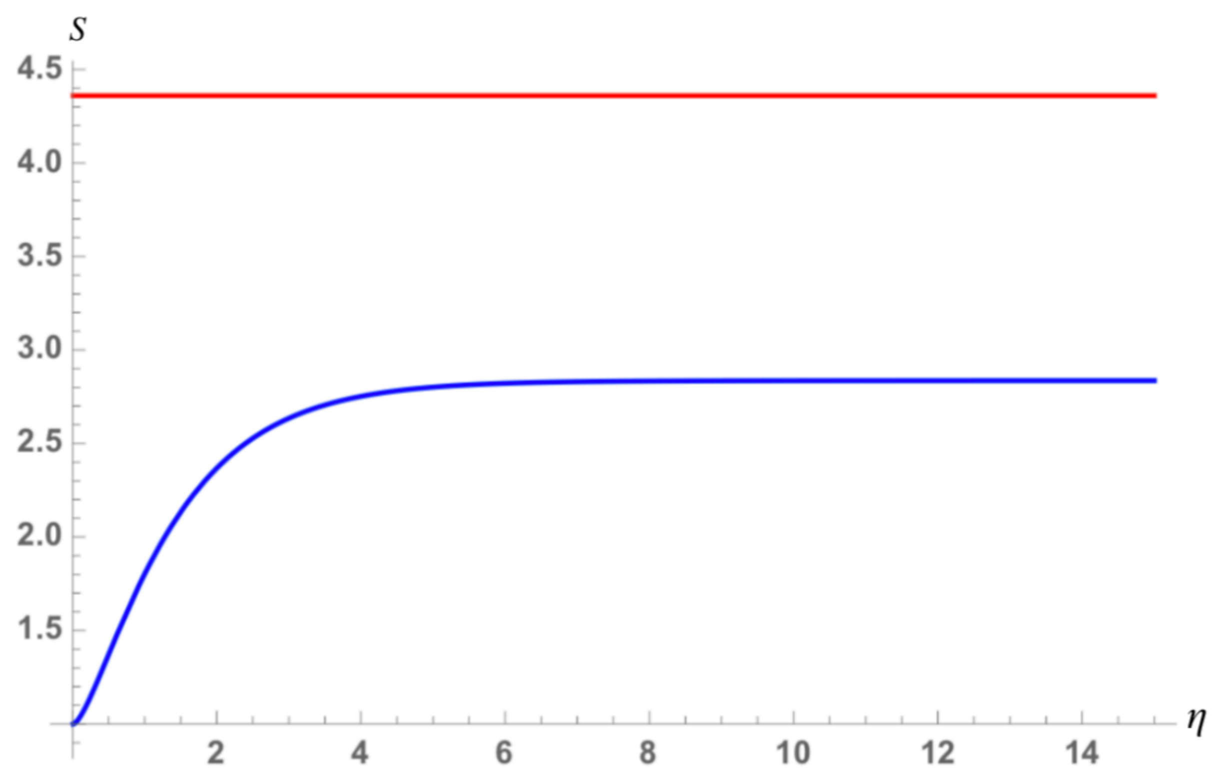
PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER

The entropy production (temporal evolution) for $M_0 = 10^7 g$ and $\epsilon = 10^{-12}$ for F1(x) is shown below. Red line is the entropy suppression factor approximately calculated in the instant approximation:



PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER

The entropy production (temporal evolution) for $M_0 = 10^7 g$ and $\epsilon = 10^{-12}$ for F2(x) is shown below. Red line is the entropy suppression factor approximately calculated in the instant approximation:



As it is shown in this work, the suppression of thermal relic density or of the cosmological baryon asymmetry may be significant if they were generated prior to PBH evaporation.

PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER

Some concluding remarks:

A. The significant restriction of the parameter space of MSSM by LHC created some doubts about dark matter made of LSP. And WIMPs with mass<TeV are excluded.

B. The mechanism considered here allows to save relatively light WIMPs and open more options for SUSY dark matter.

PBH EVAPORATION, BARYON ASYMMETRY AND DARK MATTER

Some concluding remarks:

This dilution of cosmological baryon asymmetry by an excessive entropy release may look not so essential because theoretical estimates are uncertain but there are couple of scenarios which can be of interest:

1. There is the Affleck-Dine scenario of baryogeneis, which naturally leads to the magnitude of the asymmetry, $\beta \sim 10^{-9}$ much higher than the observed one.

2. The scenario for Baryo-thru-Leptogenesis. One can predict the magnitude and sign of the lepton asymmetry.

FUTURE WORK (PLANS)

- EWPT and Baryogenesis in 2HDM.
- Study Baryogenesis in the framework of f(R) gravity.
- Study the Hubble parameter paradox.

THANK

YOU

FOR

YOUR

ATTENTION