PRIMORDIAL BLACK HOLES AS SOLUTION OF DARK MATTER AND REIONIZATION PROBLEMS

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Helmholtz - DIAS International Summer School «Cosmology, Strings, New Physics»

6 сентября 2016 г.

Introduction

- Study the possibility of reionization at $z \sim 10$

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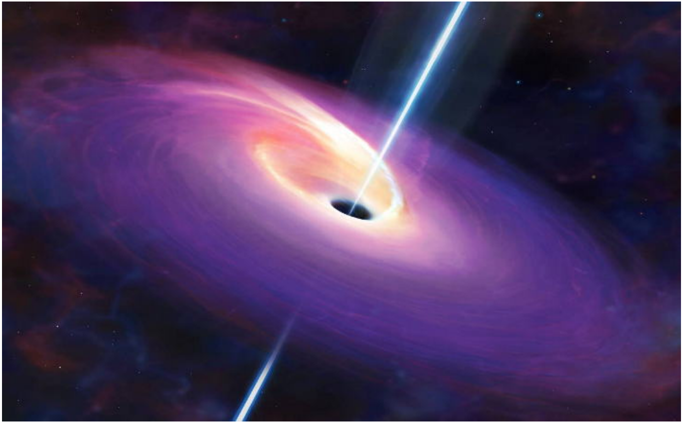
- and try to explain of dark matter (DM) with them



Reionization, evidence, reasons

The era of reionization:

epoch of the evolution of the Universe between $z = 5 \div 10$, when the matter was secondly ionized

Evidence of reionization:

- «$Ly_\alpha -$ forest»
- The polarization of the CMB

What was the source of reionization?

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- Radiation of early stars?
- Radiation of early quasars?

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What was the source of reionization?

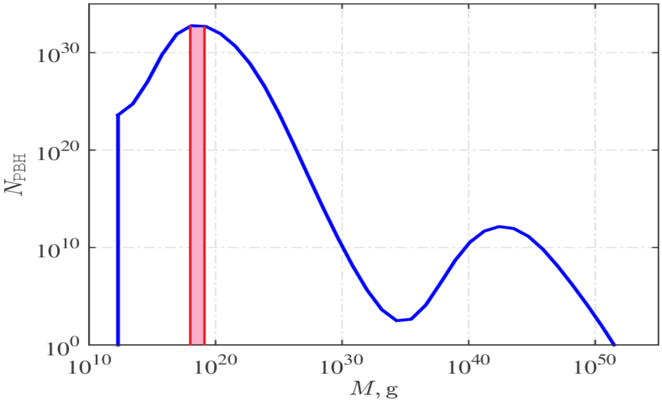
- Radiation of early stars?
- Radiation of early quasars?
- Hawking radiation of primordial black holes (PBH)?

Model of formation of primordial black holes

- The basis is the model of formation of PBH due to phase transitions in the early Universe

Model of formation of primordial black holes

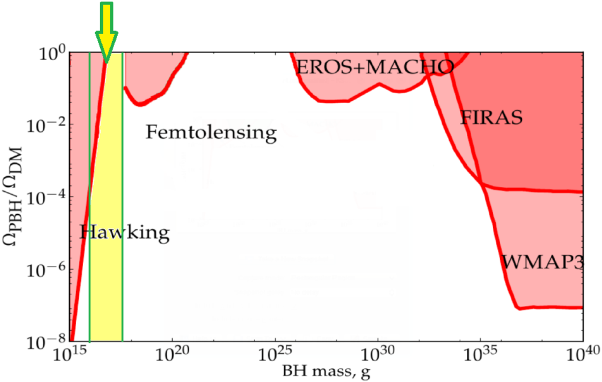
- The basis is the model of formation of PBH due to phase transitions in the early Universe
- **One possible mass distributions** obtained in this model



«Delta-functional» PBH

- Restrictions on the density of PBH

COMPTEL и EGRET



[1]

[1] B. J. Carr, K. Kohri, Y. Sendouda, and J. Yokoyama, «New cosmological constraints on primordial black holes», Phys.Rev.D **81** no.10,(May,2010)104019, arXiv:0912.5297 [astro-ph.CO]

Hawking radiation

- Mass range:

$$10^{15}\,\text{g.} \lesssim M_{\text{PBH}} \lesssim 10^{18}\,\text{g.}$$

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- The composition of the Hawking radiation:
  - γ
  - $e^- \backslash e^+$
  - $\nu_e \setminus \bar{\nu_e}$
  - $\nu_\mu \setminus \bar{\nu_\mu}$
  - $\nu_\tau \setminus \bar{\nu_\tau}$
  - G

- **Contribution to heating of baryonic matter**

  Electrons and positrons will heat the matter in the process of ionization and also lose energy to the redshift and Thomson scattering on relic photons.

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- **Degree of ionization**

$$x_e = \frac{n_e}{n_H}$$

$$x_e = 1 - \text{ionized gas / Universe}$$

$$x_e = 0 - \text{neutral gas / Universe}$$

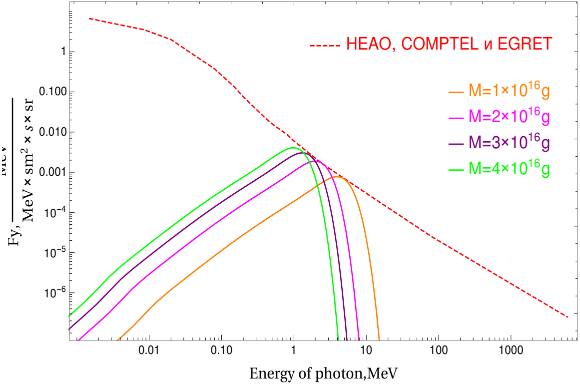
calculated in the approximation of Saha formula

«Delta-functional» PBH

- Restrictions on $\Omega_{\text{PBH}} \Longrightarrow$ of the observed diffuse gamma-ray background + density of DM

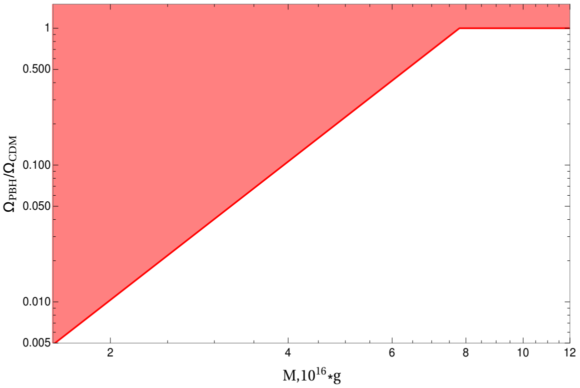
«Delta-functional» PBH

- Restrictions on $\Omega_{\text{PBH}} \Longrightarrow$ of the observed diffuse gamma-ray background + density of DM
- The flux of emitted photons and the gamma-ray background



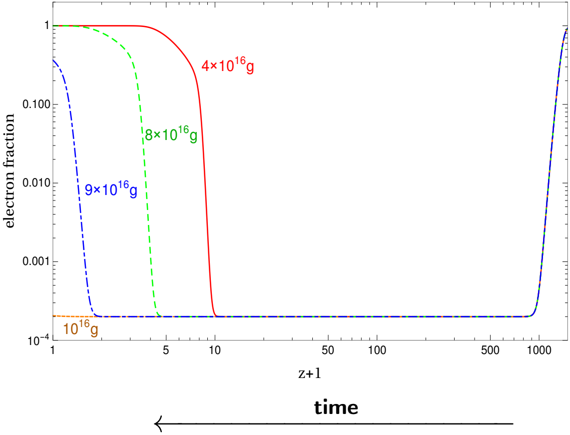
«Delta-functional» PBH

- Restrictions on Ω_{PBH}



«Delta-functional» PBH

- Contribution to reionization for different masses M_{PBH}



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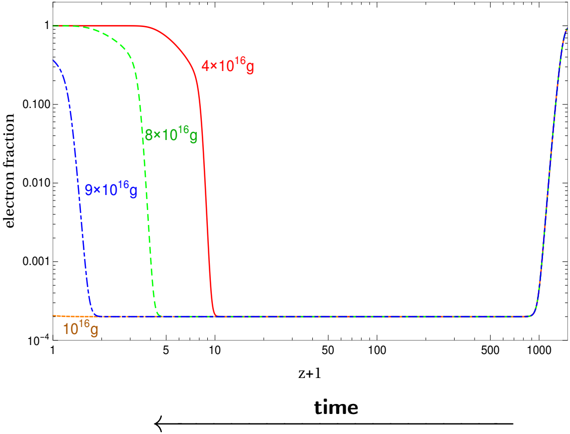


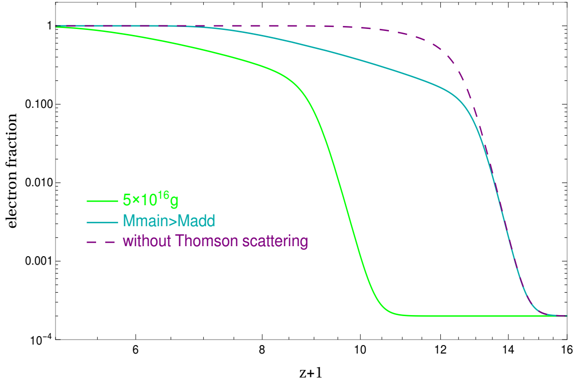
- Contribution to the density of DM: **from 11% to 22%**

The case of discrete mass distribution

- The system of two primordial black holes

The case of discrete mass distribution

- The system of two primordial black holes
- Contribution to reionization of baryonic matter



The case of discrete mass distribution

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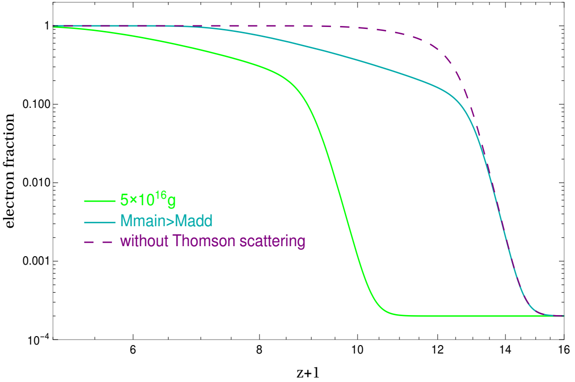
- Contribution to reionization of baryonic matter



- Contribution to the density of DM: $\sim$ **32%**

The power-law distribution of mass

- Different **falling**, **growing** and **uniform** distribution

The power-law distribution of mass

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- $M_{min}...2 \cdot M_{min}$

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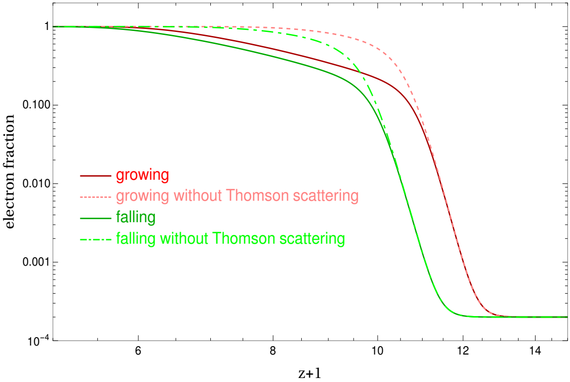
- $M_{min}...10 \cdot M_{min}$

The power-law distribution of mass

A wide mass range

- Contribution to reionization of baryonic matter



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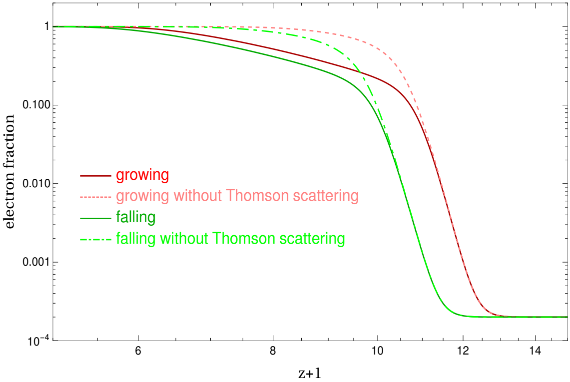

- Contribution to the density of DM for the «falling» mass distribution:∼**52%**

The power-law distribution of mass

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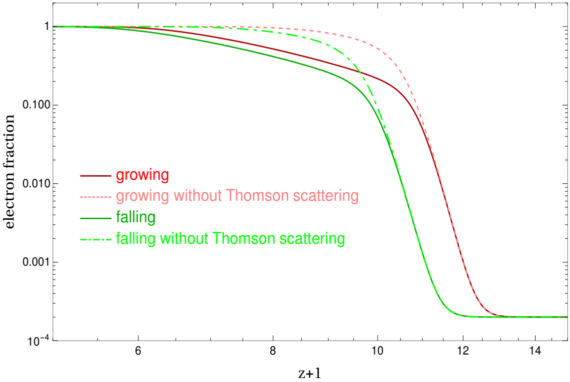
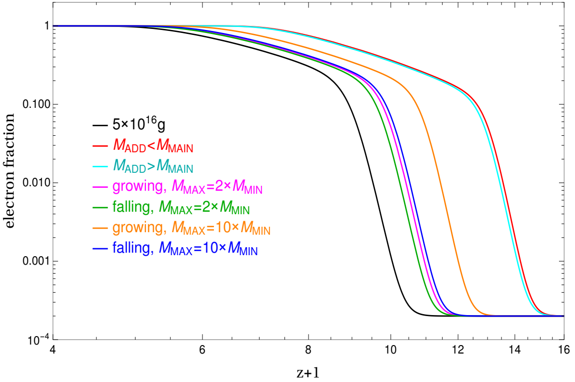


- Contribution to the density of DM for the «falling» mass distribution:$\sim$**52%**
- ...for the «growing»... : $\sim$**16 %**

Comparison of contributions to reionization

for different mass distributions

- Contribution to reionization of baryonic matter



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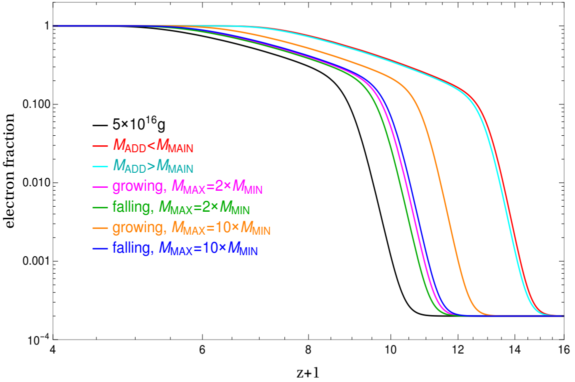

- The best result was obtained for the discrete mass distributions

Conclusions:

- **We considered different mass distributions of primordial black holes**

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- We calculated the contribution to the reionization and contribution to the density of dark matter

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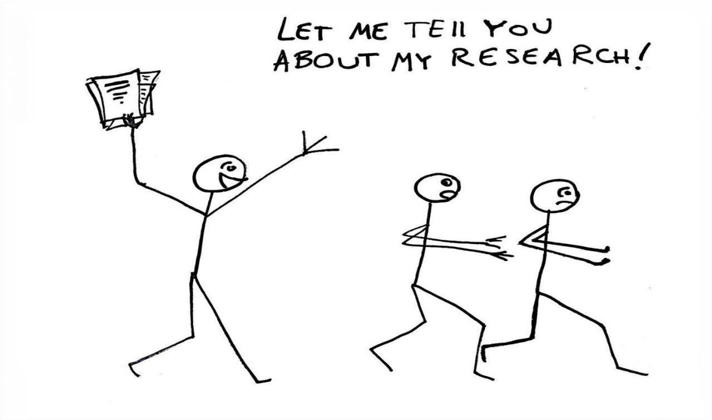
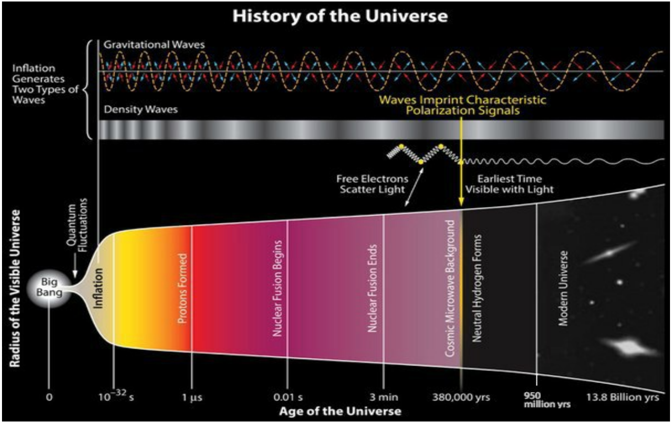
- We considered different mass distributions of primordial black holes
- We calculated the contribution to the reionization and contribution to the density of dark matter
- We found the optimal mass distribution, which gives the strongest ionization effect

Thank you for your attention!!!



Model of formation of primary black holes



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[2] S. G. Rubin, A. S. Sakharov, and M. Y. Khlopov, *"The Formation of Primary Galactic Nuclei during Phase Transitions in the Early Universe"*, Sov. Phys. JETP 92 (June, 2001) 921–929, arXiv:hep-ph/0106187

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- The system of two primordial black holes
  $M_{add} + M_{main}$

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- The system of two primordial black holes $M_{add} + M_{main}$
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- $M_{add} > M_{opt}$, $M_{add} \Longrightarrow$ lower ionizing power, weak restrictions on the density

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- $M_{add} < M_{main}$

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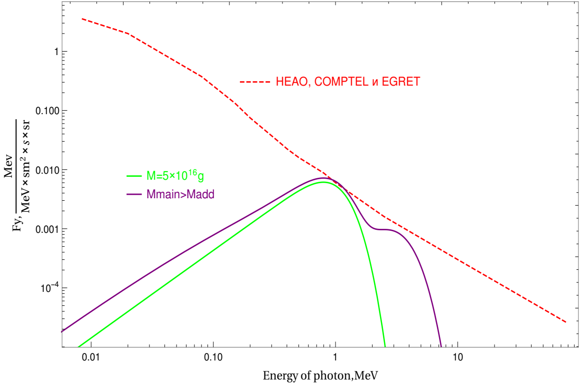
The system of two primordial black holes

- $M_{add} < M_{main}$
- The stream of emitted photons and the gamma-ray background



Discrete mass distribution

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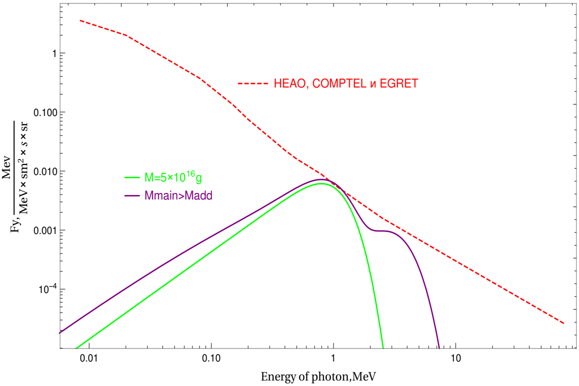

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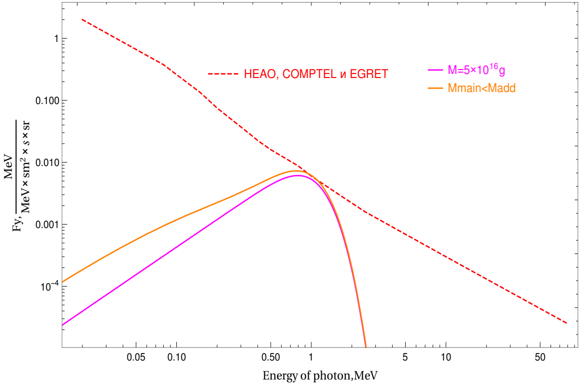
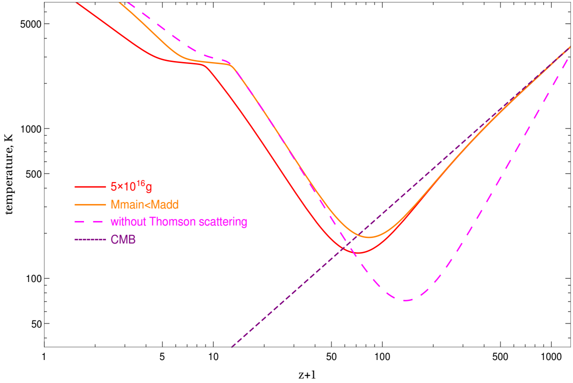


Discrete mass distribution

$M_{add} > M_{main}$

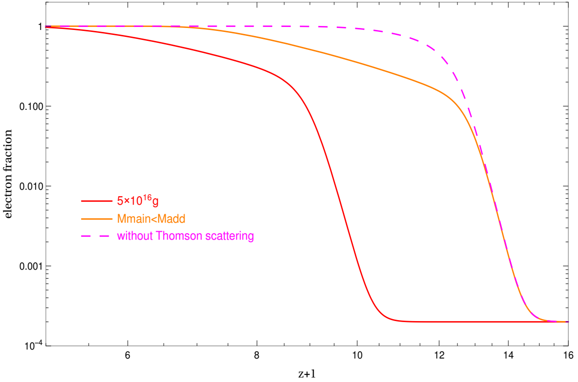
- Contribution to heating baryonic matter



Discrete mass distribution

$M_{add} > M_{main}$

- Contribution to reionization of baryonic matter



- Contribution to the density of DM: $\sim$**40%**

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The case of discrete mass distribution

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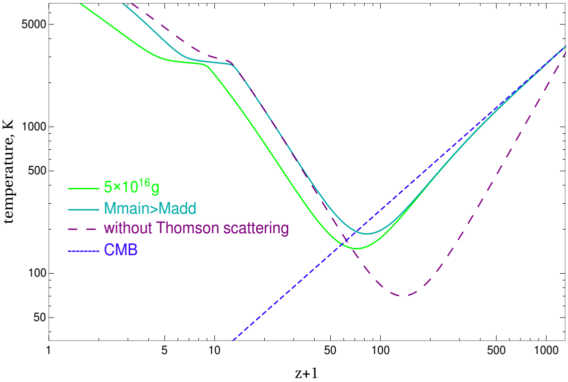
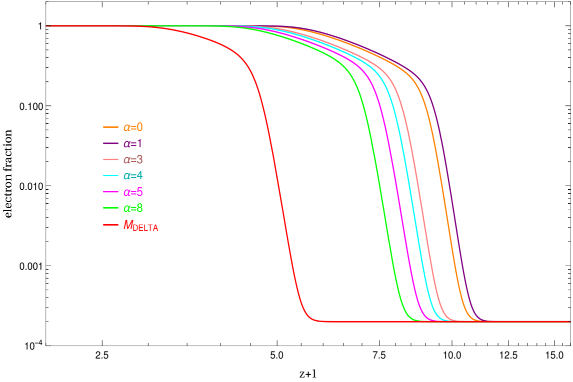
- Contribution to heating of baryonic matter



The power-law distribution of mass

A narrow mass range

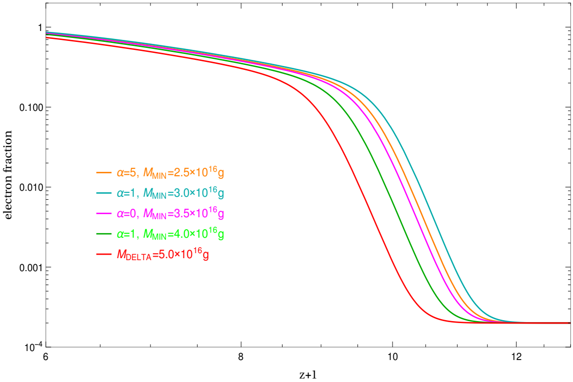
- Choosing the optimal **growing** for mass range $4 \cdot 10^{16}$ g. $\leq M \leq 8 \cdot 10^{16}$ g.



The power-law distribution of mass

A narrow mass range

- Choosing the optimal mass range with the optimum form of distribution



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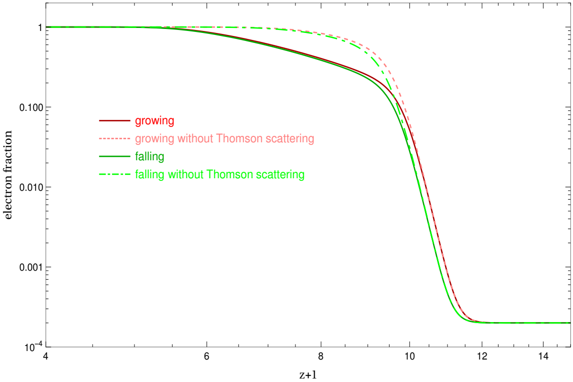

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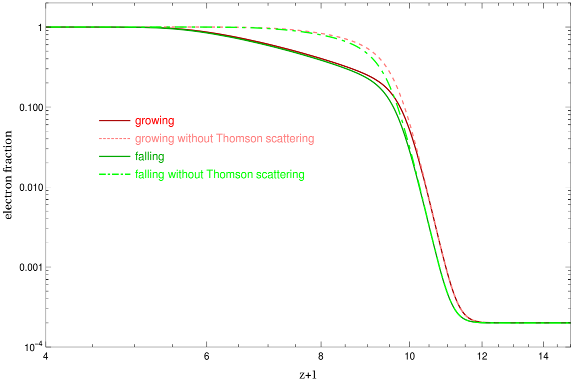

- Contribution to the density of DM for the «falling» mass distribution:$\sim$**20 %**

The power-law distribution of mass

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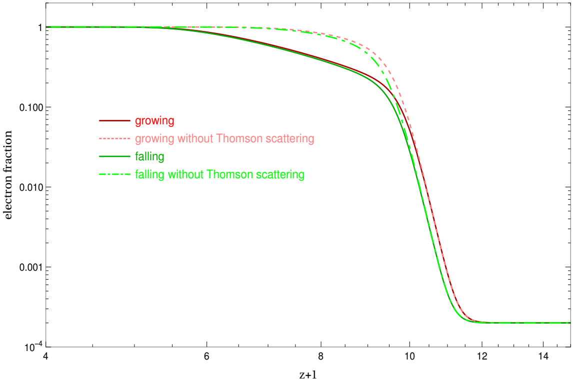
- Contribution to reionization of baryonic matter



- Contribution to the density of DM for the «falling» mass distribution:$\sim$**20 %**
- ...for the «growing»... : $\sim$**25%**

Specifications of $e^{\pm}$:

- The proportion $e^{\pm}$ from the total number of particles emitted by PBH:

$$k_{\mathsf{e}}^{\pm} \approx 0.36\hat{g}_{\mathsf{e}}\left(M\right) \qquad (1)$$

where

$$\hat{g}_{\mathsf{e}}\left(M\right) = \left(1 + 0.40\,\frac{M}{M_{17}}\right)^{27.6} \exp\left(-10.9\,\frac{M}{M_{17}}\right)$$

- The energy of the emitted $e^{\pm}$

$$< E_0 >= 4T\,\hat{h}_{\mathsf{e}}\,\left(M\right) \qquad (2)$$

where

$$\hat{h}_{\mathsf{e}}\,\left(M\right) = \exp\left(-1.45\,\frac{M}{M_{17}} - \frac{M^2}{M_{17}^2}\right)$$

$$T = 0.106\,\frac{M_{17}}{M} MeV \qquad (3)$$

Specifications of γ:

- The proportion γ from the total number of particles emitted by PBH:

$$x_\gamma = 0.08 \tag{4}$$

- The energy of the emitted γ

$$\langle E_\gamma \rangle \approx 8T \tag{5}$$

where

$$T = 0.106 \frac{M_{17}}{M} MeV \tag{6}$$

The relations for the photon flux F_γ

Taking into account the contribution of dark energy density to the total density of matter in the universe is a stream:

$$F_\gamma\left(E\right)^{mod} = \frac{c}{4\pi}\rho_{crit}\iint \frac{x_\gamma}{\langle E_\gamma\rangle}\frac{\dot{M}}{M}\, f_{Pl}\left(M\right)\,\frac{d\Omega_{PBH}}{dM}\,dM\times$$

$$\cdots\times\frac{\frac{3}{2}t_u\sqrt{\Omega_\Lambda}\,\ln^{-1}\left(\frac{1+\sqrt{\Omega_\Lambda}}{\sqrt{\Omega_m}}\right)}{\sqrt{\Omega_\Lambda+\Omega_m\left(z+1\right)^3}}\,dz \qquad (7)$$

$$\frac{dW}{dM} = \frac{1}{N_{tot}}\frac{dN}{dM} = CM^{-\alpha} \qquad (8)$$

$$\frac{d\Omega_{PBH}(M)}{dM} = \frac{M}{\bar{M}}\frac{dW}{dM}\Omega_{PBH} \tag{9}$$

The average mass:

$$\bar{M} = \int_{10^{16}}^{10^{17}} \frac{dW}{dM} M dM \tag{10}$$

Rate of mass evaporation:

$$\dot{M} = \frac{1}{3}\left(\frac{M_u}{M}\right)^2 \frac{Mu}{tu} \tag{11}$$

Planck distribution:

$$f_{Pl} = \frac{dW}{d\omega} = \frac{Const \cdot E_0^2}{exp\left(\frac{E_0}{T}\right) - 1} \tag{12}$$

The relations for the calculation of the degree of ionization x_e

The degree of ionization of the of matter found by Saha formula:

$$\frac{x_e^2}{1+x_e} = \frac{1}{n_H}\left(\frac{m_e T}{2\pi}\right)^{\frac{3}{3}} exp\left(-\frac{R_g}{T}\right) \qquad (13)$$

The equation describing the variation of temperature of baryonic matter:

$$\frac{dT}{dt} = \frac{2}{3}\frac{\dot{\Omega}_{abs} m_p}{x_H \Omega_B (1+x_e)} - \frac{8\pi^2}{45} T_\gamma^4 \sigma_T \frac{x_e}{1+x_e}\frac{T-T_\gamma}{m_e} - 2HT \qquad (14)$$

The rate of energy radiation:

$$d\dot{\Omega}_{ev} = \frac{\dot{M}}{M} d\Omega_{PBH}\left(M\right) \tag{15}$$

The rate of energy absorption:

$$d\dot{\Omega}_{abs}^{(e-ion)}\left(z\right) = k_e d\dot{\Omega}_{ev} \frac{\omega_1}{E_0 + m_e} \frac{3\xi\left(z\right)\bar{z}^{\frac{3}{2}}}{2 + 3\xi\left(z\right)} \tag{16}$$

$$\xi\left(z\right) = \frac{-1 + \sqrt{1 + \frac{4\,E_0}{\omega_1\,\bar{z}^{\frac{3}{2}}}\left(\frac{2}{3} + \frac{E_0}{\omega_2}\bar{z}^{\frac{5}{2}}\right)}}{2\left(1 + \frac{3}{2}\frac{E_0}{\omega_2}\bar{z}^{\frac{5}{2}}\right)} \tag{17}$$

$\omega_1 = 0.016$ MeV - specific ionization energy,
$\omega_2 = 90$ MeV - the energy density of CMB.