Heating of matter in the formation of clusters of primordial black holes

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The 16th Baksan School on Astroparticle Physics, April 10-18, 2019.

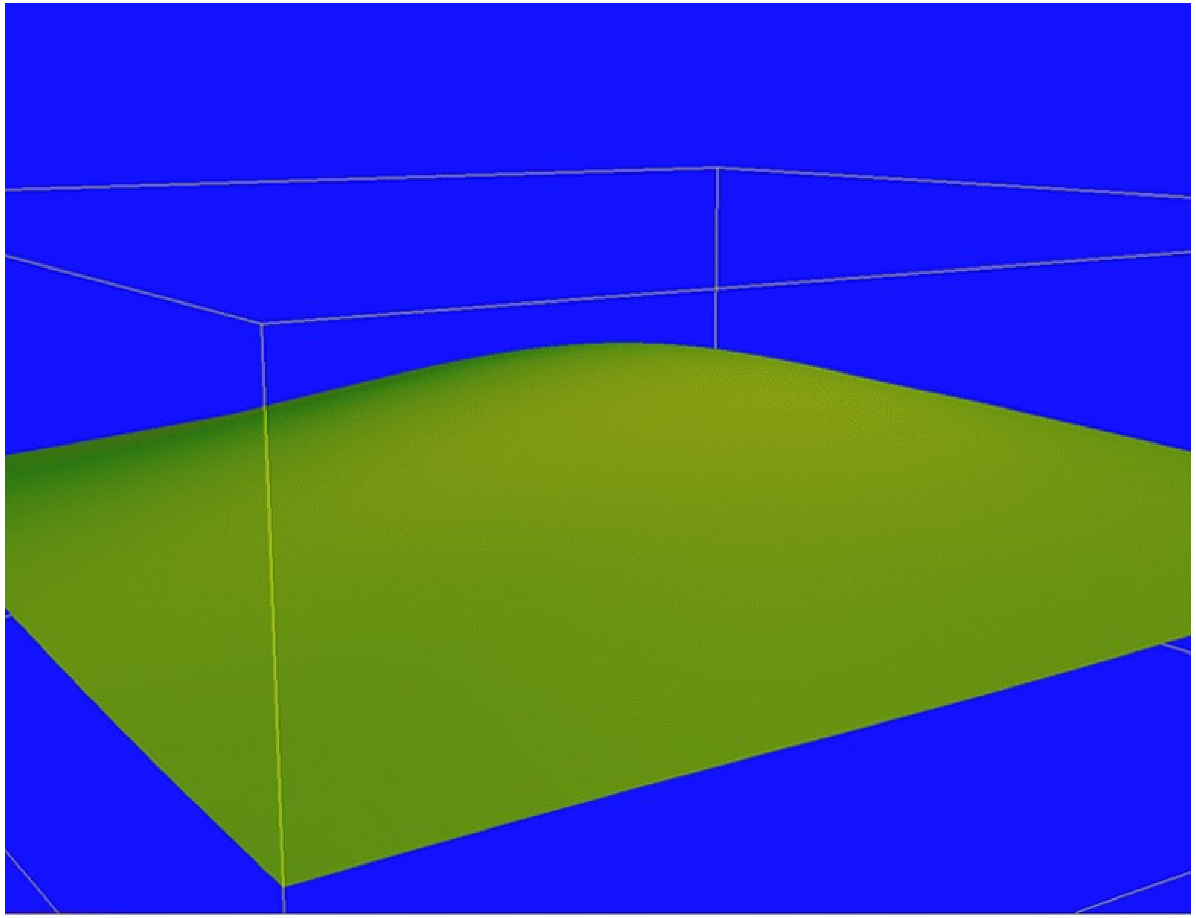
Inflation model and quantum fluctuations

$$L = \sqrt{-g}\left\{ \frac{1}{16\pi G} R + \frac{1}{2} g^{\mu\nu} \partial_\mu \varphi \, \partial_\nu \varphi - V(\varphi) \right\}$$

We assume the homogeneity of the space and the distribution of the scalar field

$$\varphi = \varphi(t)$$

$$\ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) = 0$$



A characteristic feature of the inflation process is the slow change of the scalar field

$$a \propto \exp\left(\int_{t_0}^{t} H(\varphi) dt \right)$$

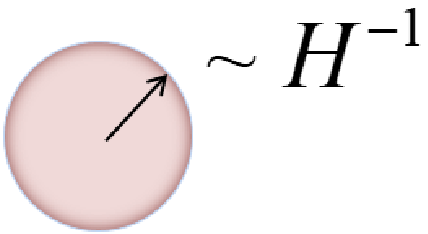
$$3H|\dot{\varphi}| >> |\ddot{\varphi}| \Rightarrow$$

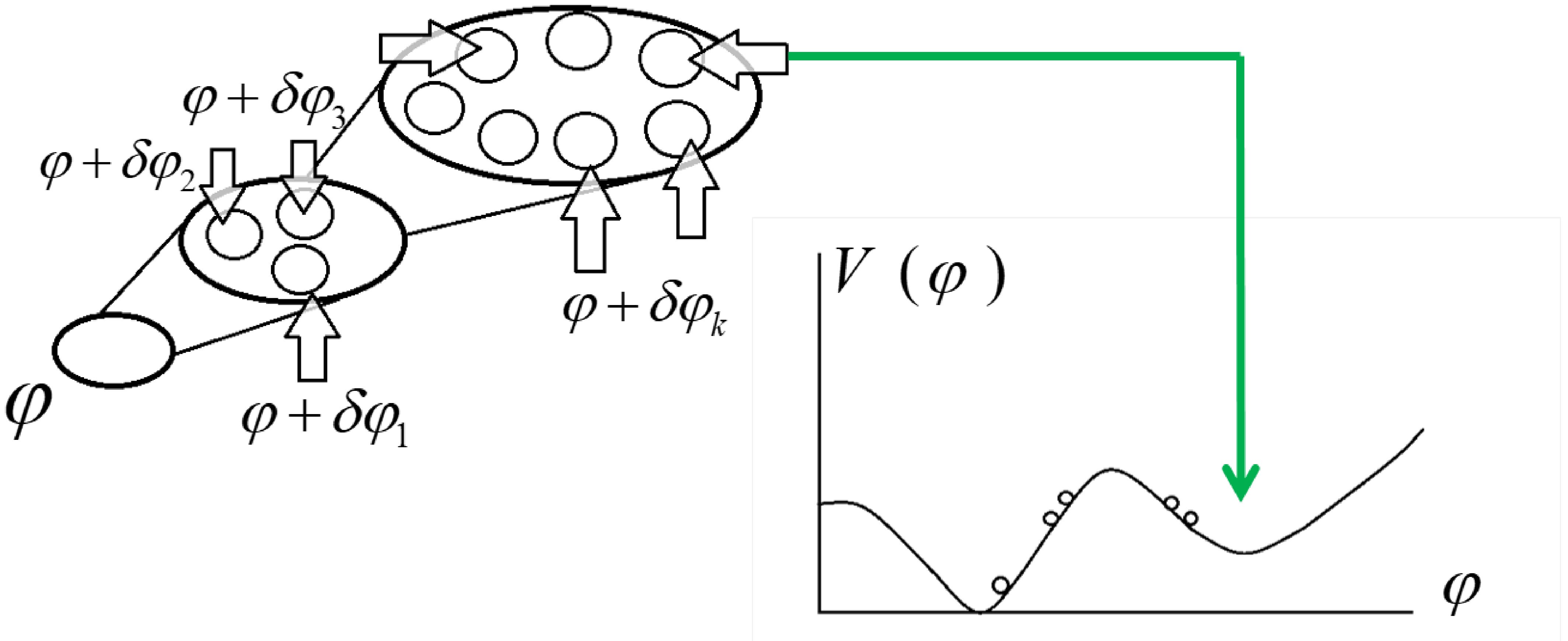
$$\dot{\varphi}^2 << V(\varphi)$$

$$H \equiv \frac{\dot{a}}{a} \approx \sqrt{\frac{8\pi G}{3} V(\varphi)}$$

When the potential becomes small enough, the Hubble parameter H will also be small. Then the field is moving rapidly to the minimum of the potential and the inflationary stage ends

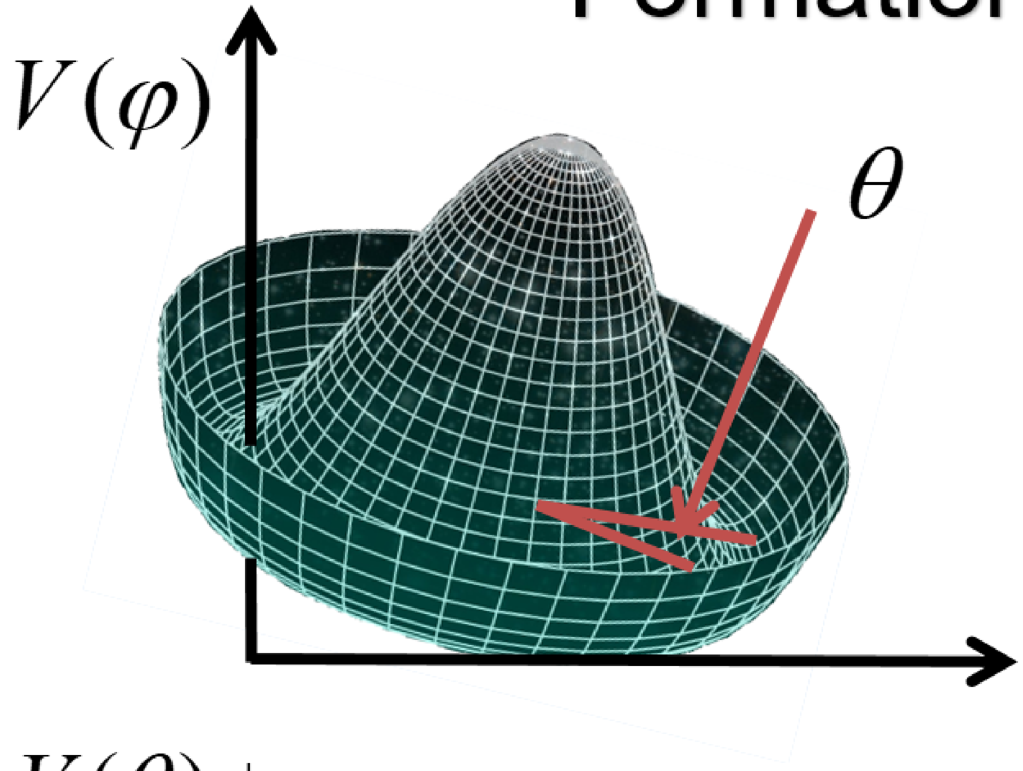
Inflationary fluctuations



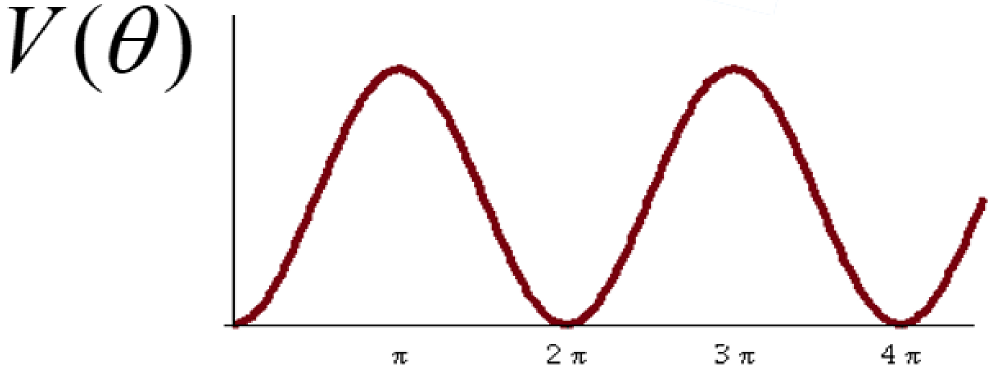


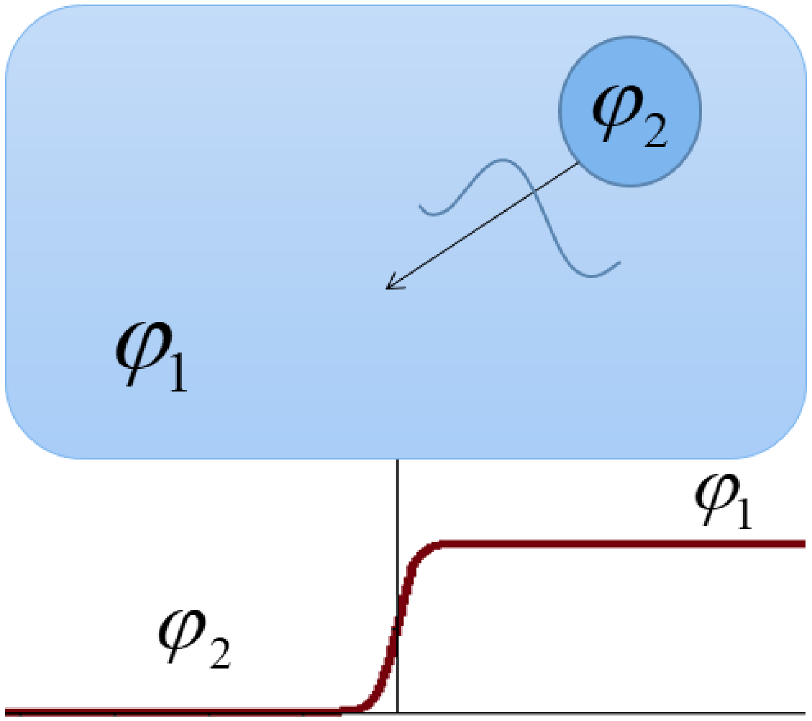
Scalar field at the end of inflation

Formation of closed walls



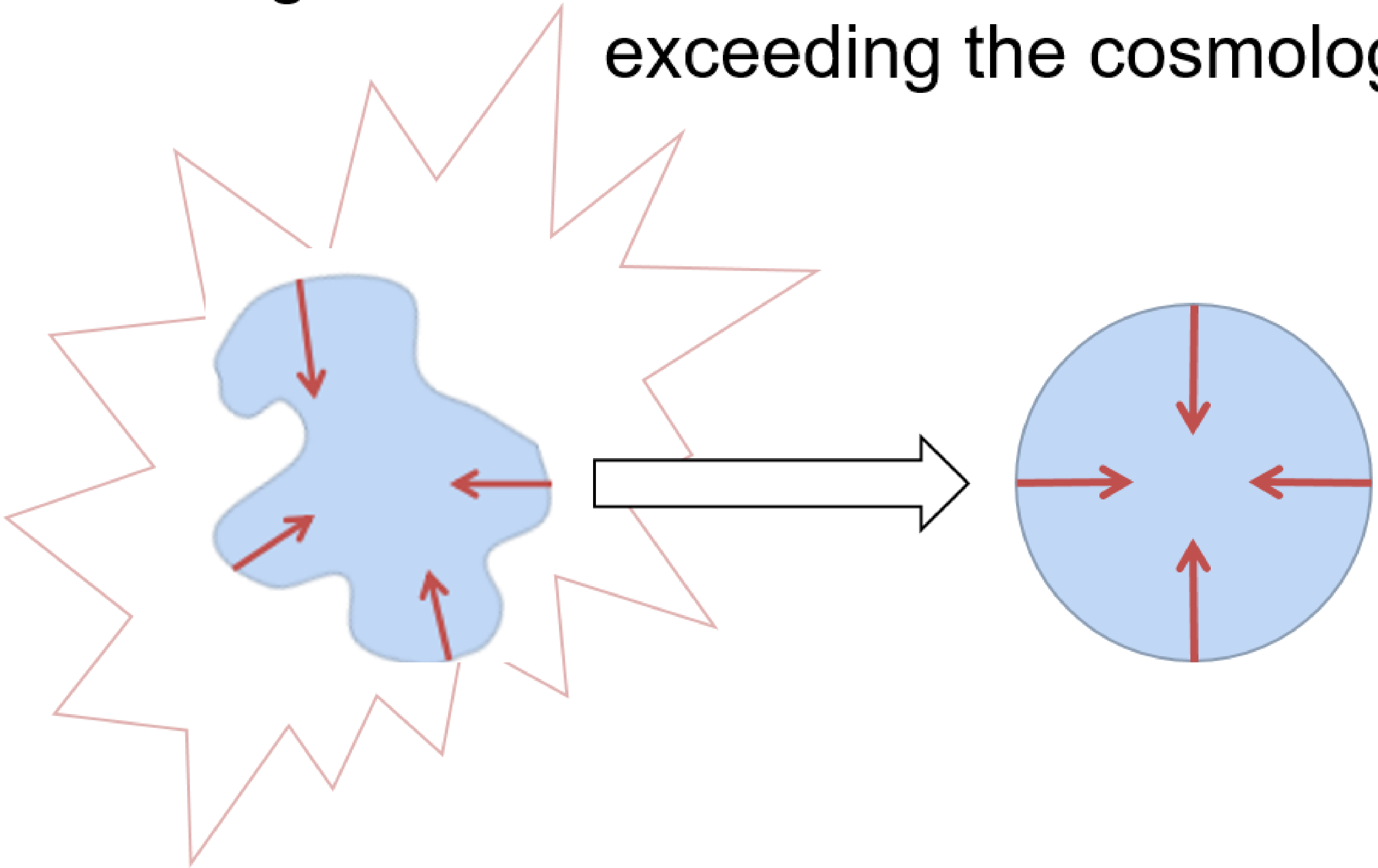
$$V(\varphi) = \lambda\left(|\varphi|^2 - \frac{f^2}{2}\right)^2 + \Lambda^4(1 - \cos\theta)$$





S.G. Rubin, A.S. Sakharov and M.Yu.Khlopov , Sov. Phys. JEPT 92, 921 (2001)

The initial distribution of the scalar field formed during the inflation stage allows the formation of closed walls of sizes significantly exceeding the cosmological horizon

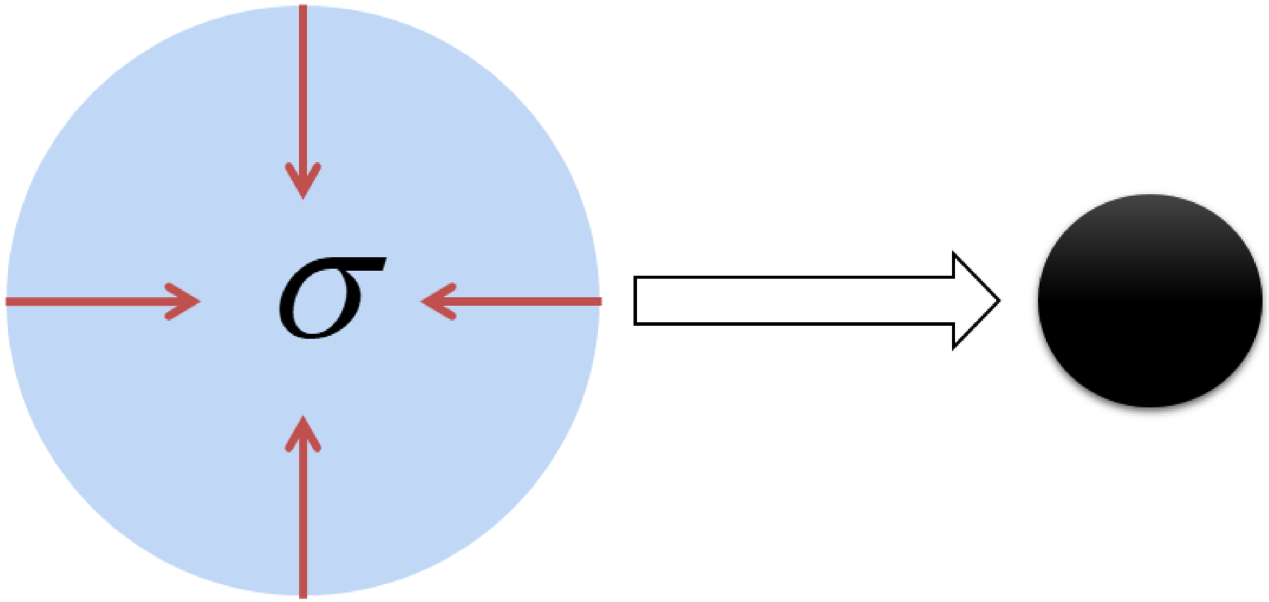


Having entered the horizon the wall tends firstly to acquire a spherical shape and after to contract toward the center

During fluctuations, which allow the wall to acquire a spherical shape, it loses energy and heats the environment

The overall contraction of the closed wall may begin only when the horizon size will be equal to the domain size R_w with total energy:

$$E_w \propto 4\pi R_w^2 \sigma$$



$$\sigma = 4\Lambda^2 f$$

The wall contracts up to the minimal size of the order of the wall width:

$$d = \frac{2f}{\Lambda^2}$$

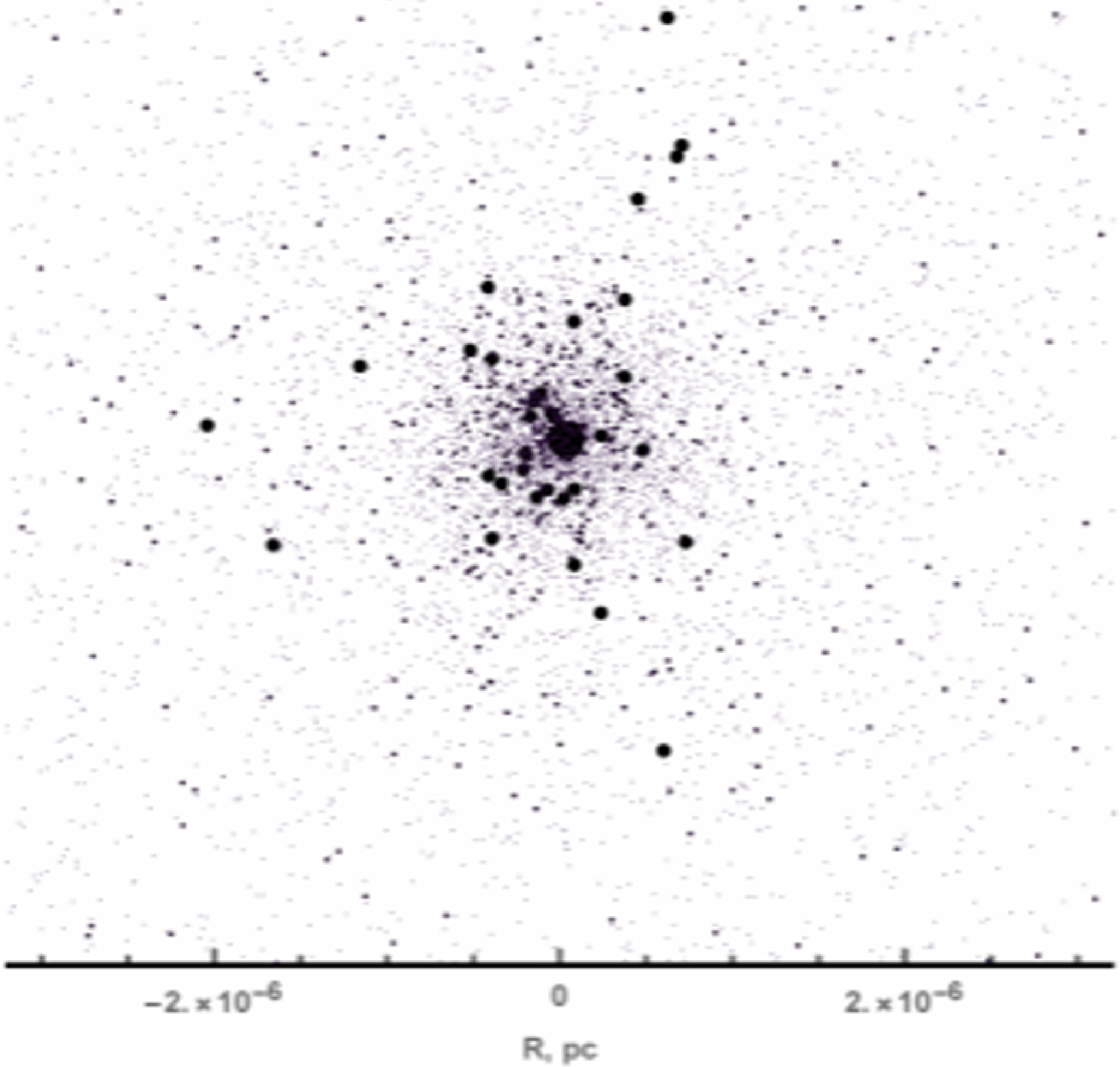
The black holes are formed under condition:

$$d \leq r_g \approx 2\frac{E_w}{M_{Pl}^2}$$

As a result, the energy of a closed wall may be focused within a small volume inside the gravitational radius which is the necessary condition for a black hole creation

And around them formed a heated area

The typical spatial black holes distribution within cluster, the result of numerical simulations



Temperature inside PBH clusters

The Chapman-Enskog method makes it possible to obtain a solution to the transport equation and being quite general can be applied to the relativistic transport equation

In first approximation, the relativistic generalization of the Fourier-law for the heat flux and the linear expression for the viscous tensor have the form:

$$I_q^\mu = \lambda\left(\nabla^\mu T - \frac{T}{hn}\nabla^\mu p\right)$$

$$\Pi^{\mu\nu} = 2\eta\overline{\nabla^{\overset{\circ}{\mu}} u^\mu} + \eta_v \Delta^{\mu\nu}\nabla_\sigma u^\sigma$$

$$D = u^\mu \partial_\mu \quad \nabla^2 = \nabla^\mu \nabla_\mu$$

$$\nabla^\mu = \Delta^{\mu\nu}\partial_\nu \quad \Delta^{\mu\nu} = g^{\mu\nu} - u^\mu u^\nu$$

The relativistic equation of motion and equation of energy:

$$hnc^{-2}Du^{\mu} = \nabla^{\mu}p - \Delta^{\mu}_{\nu}\nabla_{\sigma}\Pi^{\nu\sigma} + (hn)^{-1}\Pi^{\mu\nu}\nabla_{\nu}p - c^{-2}\left(\Delta^{\mu}_{\nu}DI^{\nu}_{q} + I^{\mu}_{q}\nabla_{\nu}u^{\nu} + I^{\nu}_{q}\nabla_{\nu}u^{\mu}\right)$$

$$nDe = -p\nabla_{\mu}u^{\mu} + \Pi^{\mu\nu}\nabla_{\nu}u_{\mu} - \nabla_{\mu}I^{\mu}_{q} + 2c^{-2}I^{\mu}_{q}Du_{\mu}$$

After linearization and taking into account the Fourier–law for the heat flux and the linear expression for the viscous pressure tensor the equations of energy take the form:

$$\frac{DT}{T} = \frac{k_B}{c_v}\left[\nabla_{\mu}u^{\mu} - \frac{\lambda}{p}\left(\nabla^2 T - \frac{T}{hn}\nabla^2 p\right)\right]$$

If the hydrodynamic four-velocity is constant the energy equation reduce to the relativistic heat-conduction equation:

$$nc_v DT = \lambda\left(\nabla^2 T - \frac{T}{hn}\nabla^2 p\right)$$

$$e = mc^2\,\frac{K_3(mc^2/k_BT)}{K_2(mc^2/k_BT)} - k_BT \quad , \quad c_v = \partial e/\partial T \quad , \quad h = e + pn^{-1} = mc^2\,\frac{K_3(mc^2/k_BT)}{K_2(mc^2/k_BT)}$$

Since the term before the pressure gradient has a divergence, we can consider only 2 limiting cases of low and high temperatures. Using the asymptotic behavior of special functions in case of low temperatures T $\ll 10^6 eV$ we have:

Since the term before the pressure gradient has a divergence, we can consider only 2 limiting cases of low and high temperatures. Using the asymptotic behavior of special functions in case of low temperatures we have:

$$\frac{Tk_B}{hn} \longrightarrow \frac{1}{nmc^2/Tk_B}$$

And in case of high temperatures T $\gg 10^6 eV$ we have:

And in case of high temperatures we have:

$$\frac{Tk_B}{hn} = \frac{Tk_B}{4k_BTn}$$

Limiting the temperature range of 1-100 keV and finding an expression for the dependence of the thermal diffusivity for ionized

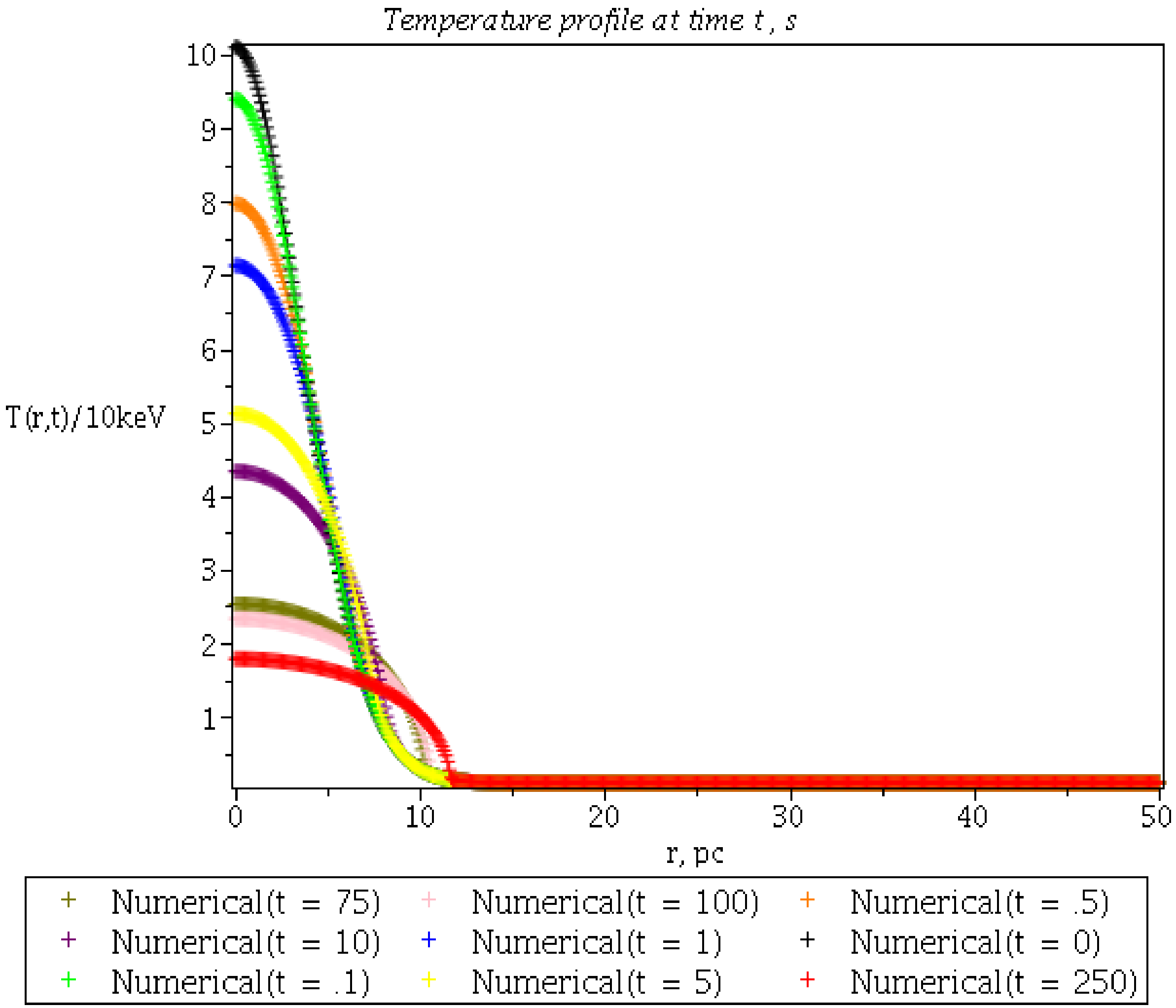
$$\frac{\partial T}{\partial t} = \chi \nabla T^{5/2} \nabla T$$

with boundary and initial conditions

$$T(r,0) = T_{in} \exp(-r^2 / r_0^2) + T_{out}$$

$$\left.\frac{\partial T(r,t)}{\partial t}\right|_{r=0} = 0 \quad , \quad T(r,t)\big|_{r=\infty} = \frac{T_{out}}{a(t)}$$

Find a numerical solution:



Conclusions and plans:

- Since for the development of the Universe temperature played a major role in the formation of the chemical composition
- It's proposed to consider in more detail the distribution of heat after heating finished. Since a large temperature difference between the heated area and the surrounding space can cause a shock wave, it is proposed to further determine the speed of the thermal front
- After that to determine possible anomalies in such areas and compare with the observed data

Thank you for attention!

$$ds^2 = -e^{f(r,t)}(dr^2 + r^2 d\theta^2 + r^2 \sin^2\theta d\varphi^2) + dt^2$$

$$ds^2 = -a^2(r,t)\left[dr^2 + r^2(d\theta^2 + \sin^2\theta d\varphi^2)\right] + dt^2$$

$$g_{\mu\nu} = \mathrm{diag}(1, -a^2(r,t), -a^2(r,t)r^2, -a^2(r,t)r^2\sin^2\theta)$$

$$a(t) = \left[1 + \frac{3\gamma}{2}\sqrt{\frac{8\pi G\rho_0}{3}}(t - t_0)\right]^{2/3\gamma}$$

$\gamma = 4/3$ (1) для RD–стадии (MD–стадии).