Black Hole Production of Monopoles the Early Universe

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hep-ph/2106:XXXXX SD, A. Hook

Introduction

- Dirac observed that existence of magnetic monopoles implies quantization of electric charge. ’t Hooft and Polyakov showed Grand Unified Theories necessitate magnetic monopoles. In Standard Big Bang Cosmology, magnetic monopoles can be produced in copious amount and can lead to overclosure of the universe

- Direct production of magnetic monopoles from Hawking radiation is exponentially suppressed due to their spatial extension

P.A.M. Dirac, Proc. Roy. Soc. (London) **A 133**, 60 (1931)

't Hooft, G. 1974. Nucl. Phys. B 79 : 276

Polyakov, A. M. 1974. JETP Lett. 20: 194

Johnson, March-Russel, arXiv: 1812.10500

Introduction

- In early universe, evaporation Black Holes (BH) will heat up the surrounding plasma.

- Near the central region, broken symmetries are restored. The size of symmetry restored region can be much larger than the BH.

- After the evaporation is complete, the region slowly cools down and produces topological defects by Kibble mechanism.

- The number of monopoles produced can be significant and can lead to novel scenarios, like overclosure of the universe.

Temperature profile around a BH

Radiation Transfer

Equation governing the transfer of energy in thermal systems

$$\frac{dI_\nu}{ds} = -\frac{1}{\lambda} I_\nu + j_\nu$$

I_ν = Specific Intensity j_ν = Emissivity

$\frac{1}{\lambda} = \frac{1}{n\sigma}$ = Absorption coefficient

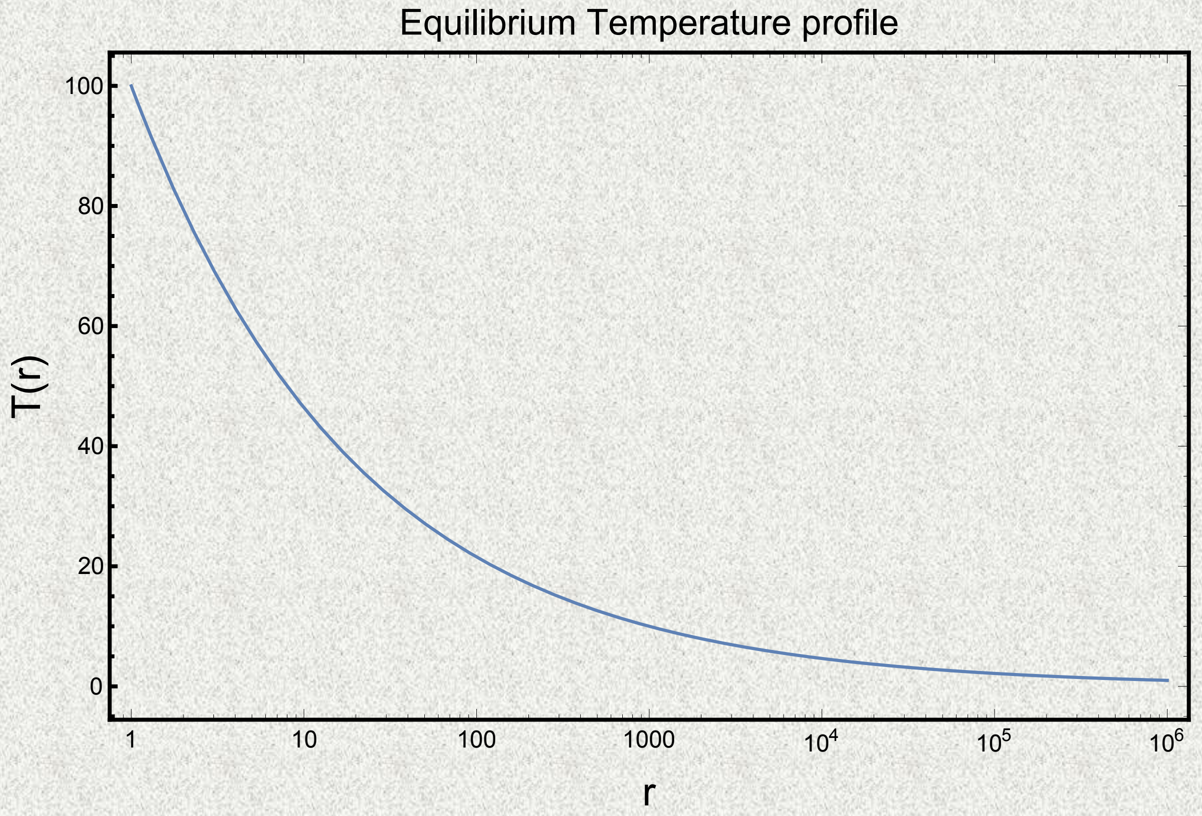
Using thermal equilibrium

$$\frac{d\rho}{dt} = -\vec{\nabla} \cdot \vec{J} = \vec{\nabla} \left(\frac{\lambda}{3} \vec{\nabla} \rho \right)$$

Temperature profile around a BH

Radiation Transfer

For two boundaries separated by large distance with fixed temperatures,
The equilibrium profile is $T(r) \sim r^{-1/3}$



Temperature profile around a BH

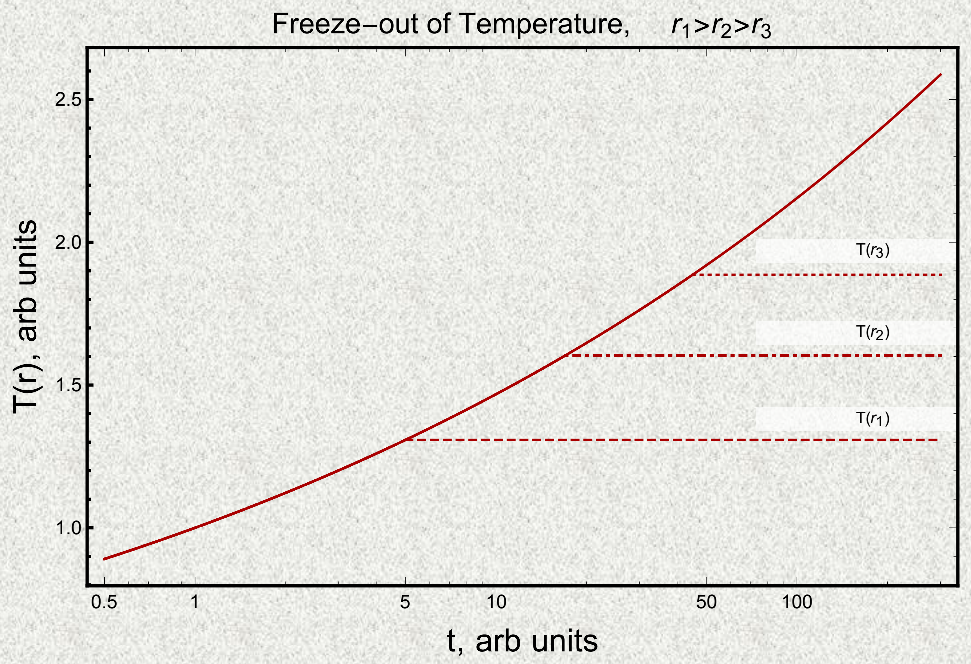
Heating

Radiation can diffuse only up to

$$r^2 \sim \lambda t_{BH} \sim \frac{M_{pl}^2}{T(r) T_{BH}^3}$$

As the BH heats up progressively faster, the outside regions ‘freeze out’. We can calculate the freeze-out temperature by

$$\left(-\frac{dM_{BH}}{dt}\right) t_{BH} \sim \frac{4}{3}\pi r^3 \rho$$



Temperature profile around a BH

Heating

And obtain $T(r) \sim \frac{M_{pl}^{4/11}}{r^{7/11}}$ as the temperature profile of the decoupled region.

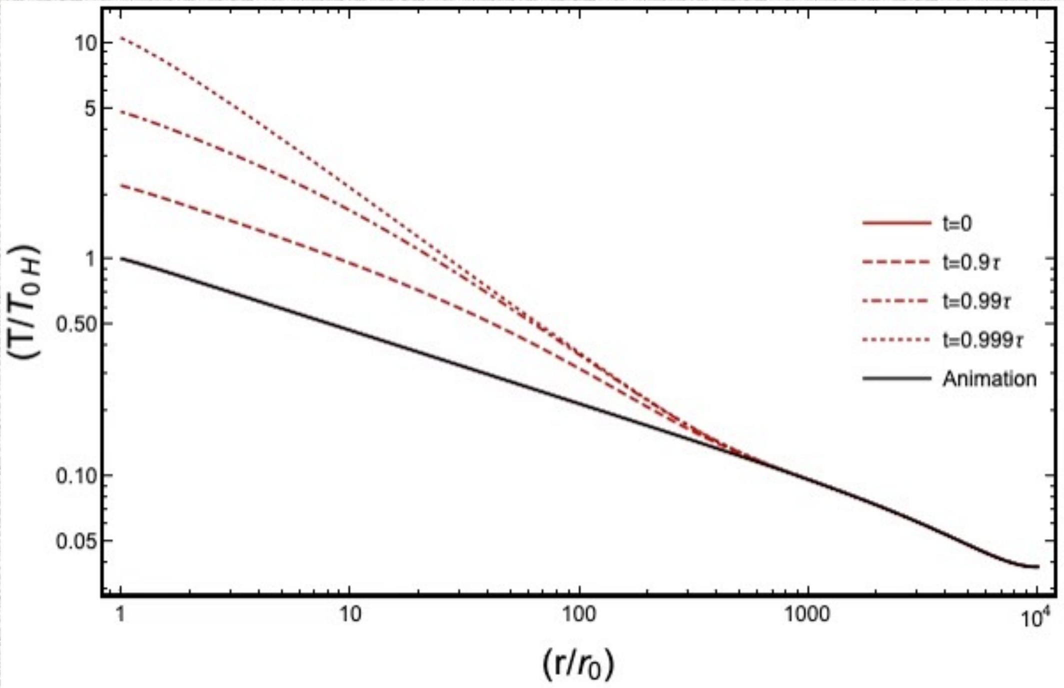
After the evaporation is complete, we are left with the decoupled temperature profile.

Calculation the O(1) numbers in the temperature profile requires numerical solution of the radiation transport equation.

$$\frac{\partial T^4(r,t)}{\partial t} = \nabla \cdot \left(\frac{1}{3n\sigma} \nabla (T^4(r,t)) \right)$$

Temperature profile around a BH

Heating



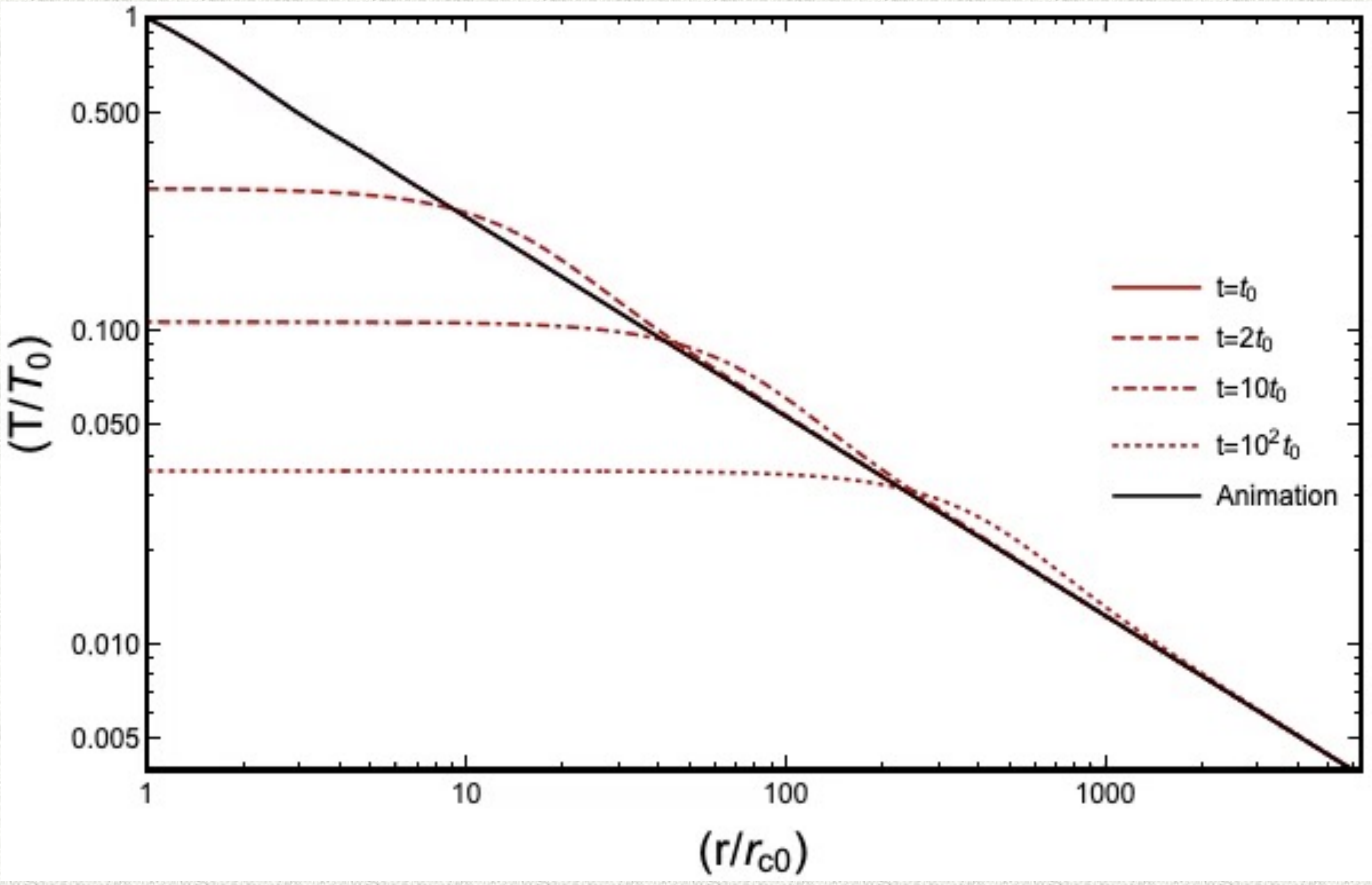
$$T(r) = 0.236 \left(\frac{\alpha^2 G_f}{g_*(T)}\right)^{1/11} \frac{M_{pl}^{4/11}}{r^{7/11}}$$

$$\sigma \equiv \frac{\alpha^2}{T^2}$$

G_f = Greybody factor
$g_*(T)$ = effective d.o.f.s

Temperature profile around a BH

Cooling



Temperature profile around a BH

Cooling

We can assume a cooling sphere of radius r_c with temperature T_0. Outside this sphere the temperature maintains its pre-cooling value.

$$T_0 \sim \frac{M_{pl}^{4/11}}{r_c^{7/11}} \qquad \frac{dE}{dt} \sim \frac{r_c^3 T_0^4}{t} \sim 4\pi r_c^2 \frac{\lambda}{3} \nabla \rho \sim r_c T_0^3$$

$$T_0(t) \sim \frac{M_{pl}^{8/15}}{t^{7/15}}$$

Cooling is easier to handle numerically.

$$T_0(t) = 0.068 \left(\alpha^{6/5} g_*^{1/3} G_f^{2/15} \right) \frac{M_{pl}^{8/15}}{t^{7/15}}$$

Monopoles from BH

Kibble-Zurek Mechanism

During second order phase transition, the correlation time diverges. As the system passes through the transition in finite time, distant points can't keep up with each other. The order parameter assumes random values above length scales

$$\xi \sim l_0 \left(\frac{\tau_{\text{char}}}{\tau_0}\right)^{\frac{\nu}{1+\mu}} \sim \frac{1}{T}\left(T\tau_{\text{char}}\right)^{1/3}$$

$$\tau_{\text{char}} = \frac{t - t_{PT}}{\epsilon}$$

$$\epsilon = \frac{T_{PT} - T}{T_{PT}}$$

In a region of size R, number of monopoles is given by

$$N_m \sim \frac{R^3}{\xi^3}$$

T. W. B. Kibble, *J. Phys. A: Math. Gen*. **9** (8): 1387–1398

W. H. Zurec *Nature*. **317** (6037): 505–508.

Monopoles from BH

Monopoles from BH

For an evaporating Black hole

$$R_{PT} \sim \frac{M_{pl}^{4/7}}{T_{PT}^{11/7}} \qquad \tau_{\rm char} \sim \frac{M_{pl}^{8/7}}{T_{PT}^{15/7}}$$

$$N_m \sim \frac{R_{PT}^3}{\xi^3} \sim \left(\frac{M_{pl}}{T_{PT}}\right)^{4/7}$$

$$N_m = 0.117 \left(\frac{G_f}{\alpha^{12} g_*^8}\right)^{1/7} \left(\frac{M_{pl}}{T_{PT}}\right)^{4/7}$$

Bounds on Reheating from BH

In BH dominated reheating

$$H^2 \sim \frac{T_{RH}^4}{M_{pl}^2} \sim \frac{1}{t_{BH}^2} \sim \frac{M_{pl}^8}{M_{BH}^6} \qquad \Longrightarrow \; \eta_{BH} = \frac{n_{BH}}{n_\gamma} \sim (T_{RH}/M_{pl})^{5/3}$$

Comparing energy density in the monopoles to the same of dark matter

$$M_m N_m Y_{BH} \leq 6 m_B Y_B$$

$$T_{RH} \lesssim 80\,\mathrm{GeV}\,\left(\frac{10^{16}\,\mathrm{GeV}}{T_{PT}}\right)^{9/35}$$

$$G_f = 3.8$$

$$g_*(T_{PT}) = 108$$

$$\alpha = \frac{1}{25}$$

Summary

- Black hole evaporation in the early universe can heat up surrounding plasma that can have larger effect than the BH itself, e.g. in producing topological defects (monopoles)

- In the BH dominated reheat, the produced monopoles can overclose the universe which restricts $T_{RH} \lesssim 100\,\mathrm{GeV}$

- It would be fun to apply this mechanism to other scenarios

Thank you