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Creation of multiple de Sitter universes inside a Schwarzschild black hole

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Abstract. A classical model for the interior structure of a Schwarzschild black hole which consists in creating multiple de Sitter universes with lightlike boundaries is proposed [1].The interaction of the boundaries is studied and a scenario leading to disconnected de Sitter universes is described.

The interior structure of a black hole and its final state after evaporation are still two intriguing problems.Their study requires the knowledge of physics at Planckian scales and it is generally believed that only a junction of quantum theory to gravity will provide a proper solution.Quantum effects become important as one penetrates deeply inside the horizon of a black hole and it is hoped that they will prevent the formation of a singularity which,in classical general relativity, is the unavoidable end state of gravitational collapse according to Penrose's theorem (let us recall that a singular behavior already happens at the Cauchy horizon of a charged or rotating black hole).

Following these ideas a classical singularity-free model for the internal evolution of a Schwarzchild black hole was proposed by Frolov, Markov and Mukhanov (FMM) [2] a few years ago.It relies upon two assumptions-i)limiting curvature hypothesis [3] -ii)transition to a de Sitter state in the final stage of gravitational collapse. Justifications of these two assumptions can be found in the existence of corrective terms in the effective action for gravity, i.e. Polchinsky [4],Mukhanov and Brandenberger [5]. It has also been shown [6] that the vacuum polarization inside the horizon of a Schwarzschild black hole can have a

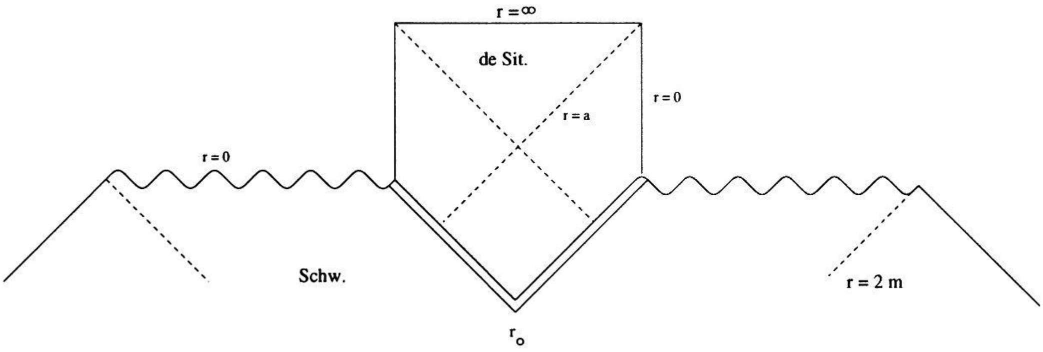

Figure 1: Creation of a pair of lightlike shells at a 2-sphere r_0.These shells form the boundaries of a de Sitter closed universe in the future of the creation.

self-regulation effect on the rise of curvature and that once the quantum fluctuations have died away the de Sitter state is the simplest possibility.For a Schwarzchild black hole with mass m the curvature reaches Planckian values, l_{Pl}^{-2}, when the radial coordinate r is of the order of $r_0 = l_{Pl}(2m/l_{Pl})^{1/3}$ which corresponds to a value far inside the horizon but still in the classical regime, $(l_{Pl} << r_0 << 2m)$ for a typical black hole.

A key ingredient of the FMM model is that the transition from the vacuum phase to the false-vacuum phase occurs instantaneously along the homogeneous spacelike shell straddling the hypersurface $r = r_0$.One should however expect that this transition, which is induced by quantum fluctuations,occurs in a random way both in space and in time.A way of generalizing the FMM model which allows the existence of inhomogeneities consists in introducing the spontaneous creation of pairs of lightlike shells.A recent study [7] of shells in the lightlike limit has shown that such a process is possible provided that some geometric matching relations are fulfilled. For static spherically symmetric spacetimes with metric of the form

$$ds^2 = -f(r)dt^2 + f(r)^{-1}dr^2 + r^2(d\theta^2 + sin\theta^2 d\varphi^2 \tag{0.1}$$

as it is the case for Schwarzschild and de Sitter,a pair of lightlike shells is created at the 2-sphere r_0 provided that the functions f to the past (here Schwarzschild, $f_S(r) = 1 - 2m/r$) and to the future (here de Sitter,$f_{dS}(r) = 1 - r^2/a^2$) of the creation take identical values at r_0 ,see fig.1.

This implies the following matching relation

$$r_0 = a(2m/a)^{1/3} \tag{0.2}$$

where the de Sitter parameter a is of the order of the Planck length. Immediately after their creation the two lightlike shells form the boundaries of a closed de Sitter universe.Their surface energy density is zero at r_0 and becomes increasingly negative as energy is pumped to create the false-vacuum phase.

The process of creation of one de Sitter bubble which we have just described can be repeated at any point of spacetime where the curvature becomes planckian.If now two de Sitter bubbles are created closely enough their lightlike boundaries may intersect and various

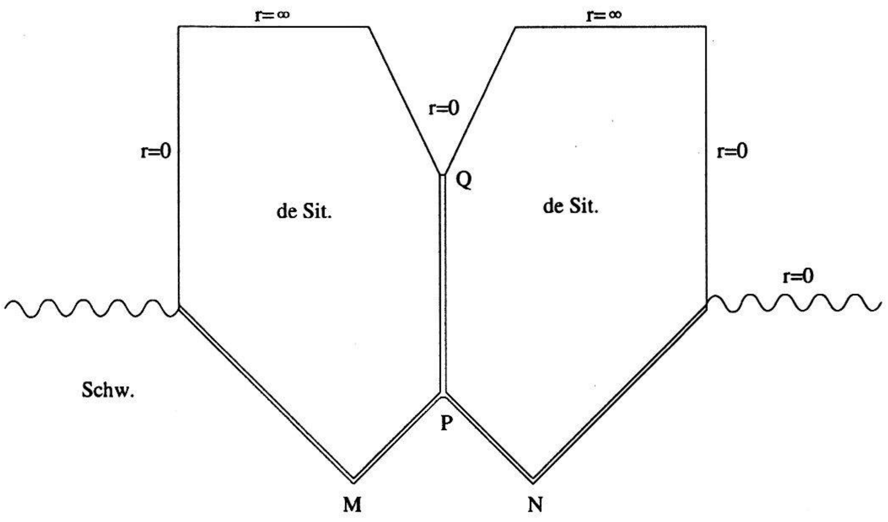

Figure 2: Merging into a single timelike shell at the 2-sphere P,r_1, of the two lightlike shells forming the boundaries of the two de Sitter bubbles which were initially created at M and N.The timelike shell contracts to zero radius at Q and the de Sitter universes get disconnected.

scenarios can be imagined to occur at the intersection.An interesting one leading to the formation of two disconnected de Sitter universes corresponds to the case when the two ingoing lightlike shells merge into a single timelike shell separating the two de Sitter universes (fig.2).

Such a scenario is realized provided that matching relations between the geometry of the adjacent spacetimes are satisfied and also initial conditions for the timelike shell are given.If the intersection takes place at the 2-sphere r_1 with $r_1 < r_0$, then the initial velocity $\dot{r}_1$ and the initial inertial mass $M(r_1)$ of the timelike shell have to be equal to

$$\dot{r}_1^2 = -[4f_S(r_1)]^{-1}[f_{dS}(r_1) + f_S(r_1)]^2 \tag{0.3}$$

$$M(r_1) = 2m(r_1) \mid f_{dS}(r_1) \mid^{-1/2} \tag{0.4}$$

where $m(r_1)$ is the surface-energy density of the lighlike shells at the intersection.

The future evolution of the timelike shell is governed by the following equation

$$\dot{r}^2 + V(r) = -1 \tag{0.5}$$

where the effective potential $V(r)$ is equal to

$$V(r) = -r^2/a^2 - 4\pi r^2 \sigma^2 \tag{0.6}$$

σ being the surface-energy density of the timelike shell. As a result of the above equations the colliding de Sitter bubbles can either remain connected or get disconnected.The condition to get their separation is that they are created at a spatial distance Δt being larger than some minimum value Δt_{min} equal to

$$\Delta t_{min} = a(a/m). \tag{0.7}$$

As $a \sim l_{Pl} \ll m$,the minimum value Δt_{min} is very small and one may conclude that this scenario preferably produces disconnected universes.

It is interesting to compare the maximum number N_{max} of disconnected closed de Sitter universes which can be created during the time of evaporation T_{evap} of the black hole to the number N^H of emitted quanta of the Hawking radiation.As $T_{evap} \sim t_{Pl}(m/m_{Pl})^{1/3}$, where t_{Pl} and m_{Pl} are the Planck time and mass resp., at most $N_{max} \sim (m/m_{Pl})^4$ new de Sitter universes can be formed.For typical black holes this number is much larger than $N^H \sim (m/m_{Pl})^2$ and the information which is lost during the evaporation of the black hole could have enough available space to escape.This remark might be of interest to the information-loss puzzle.

The creation of de Sitter universes which has been described in this work only concerns a Schwarzschild black hole.It could also be applied to a charged or/and rotating black hole.However it has been shown in these two cases that,due to the mass inflation phenomenon [8] the curvature of spacetime becomes infinite near the Cauchy horizon. Therefore our model should be applied at this place instead of the vicinity of the singularity $r = 0$.

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