Black holes in the presence of a minimal length

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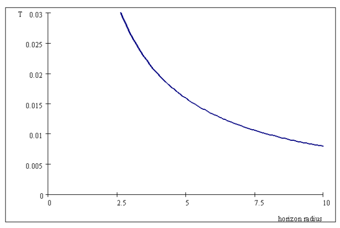
Max Planck Institut fuer Radioastronomie, Bonn June 2010

Black hole evaporation

(Mini) Black hole life



T_H vs r_H

- Balding phase
- Spin down phase
- Schwarzschild phase $T_H \sim 1/r_H$
- Planck phase (?)

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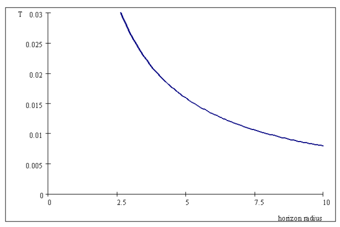

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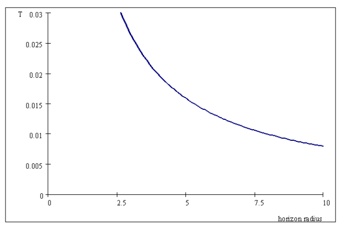

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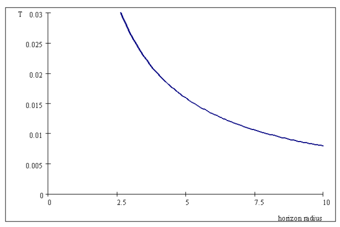

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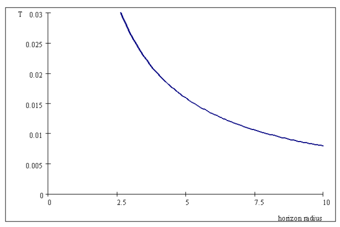

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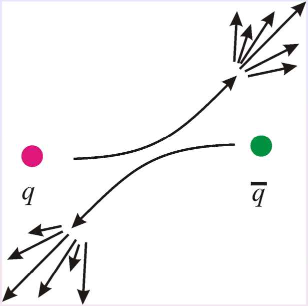
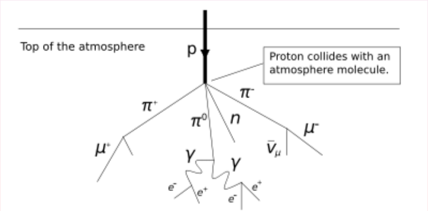
(Mini) Black holes @ LHC & Cosmic ray showers





Black Hole Spacetimes

Problem

- Curvature Singularity
- Divergent temperature at the evaporation endpoint
- Ill defined thermodynamics
- Breakdown of General Relativity at short scales

Solution

- We must invoke Quantum Gravity
- Viable approaches
  - String Theory induced Noncommutative Geometry
  - Generalized Uncertainty Principle
  - Loop Quantum Gravity
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Quasi-classical source terms

The presence of a minimal length

- Delocalization of source terms within a Quantum Gravity induced minimal length ℓ
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$$\delta(\vec{x}) \to \rho_\ell(\vec{x}^2) = \frac{M}{(4\pi\ell^2)^{3/2}} \exp\left(-\frac{\vec{x}^2}{4\ell^2}\right)$$

The energy-momentum tensor delocalization

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Einstein/fluid equations

- $$ds^2 = -e^{2\Phi(r)}\left(1 - 2m(r)/r\right)dt^2 + \frac{dr^2}{1 - 2m(r)/r} + r^2\, d\Omega^2 \quad (3)$$

- $$\frac{dm}{dr} = 4\pi\, r^2 \rho\,, \quad (4)$$
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The solution

- $(G_N = 1,\ c = 1)$

$$ds^2 = \left(1 - \frac{4M}{r\sqrt{\pi}}\gamma\right) dt^2 - \left(1 - \frac{4M}{r\sqrt{\pi}}\gamma\right)^{-1} dr^2 - r^2\, d\Omega^2 \tag{8}$$

- $\gamma \equiv \gamma\left(3/2\ ,\ r^2/4\ell^2\right)$ is the lower incomplete Gamma function:

$$\gamma\left(3/2\ ,\ r^2/4\ell^2\right) \equiv \int_0^{r^2/4\ell^2} dt\, t^{1/2} e^{-t} \tag{9}$$

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The Noncommutative Schwarzshild Geometry

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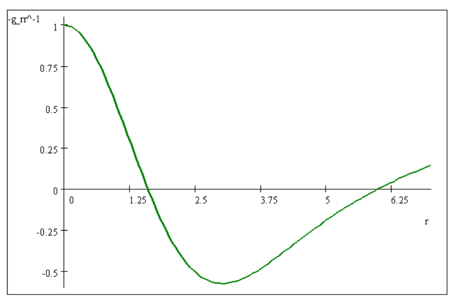

$-g_{rr}^{-1}$ vs r, for various values of M/ℓ.

$M = 3\,\ell \Rightarrow$ two horizons;

$M = \ell \Rightarrow$ ...;

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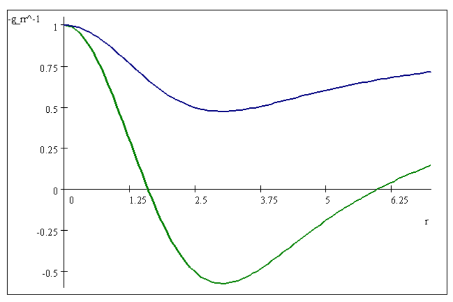

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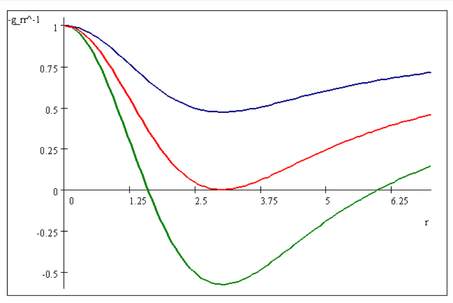

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$M = 1.9\,\ell \Rightarrow$ one degenerate horizon $r_0 \approx 3.0\,\ell$, extremal BH.

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At the black hole centre

- *The Ricci scalar near the origin is*

$$R(0) = \frac{4M}{\sqrt{\pi}\,\ell^3} \qquad (10)$$

- *The curvature is constant and positive (deSitter geometry)*
- *If $M < M_0 \Rightarrow$ no BH and no naked singularity (mini-gravastar?)*

Large mass regime, $M \gg M_0$

- inner horizon $\to$ origin
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The Hawking temperature

$$T_H = \frac{1}{4\pi\, r_H}\left[1 - \frac{r_H^3}{4\,\ell^3}\,\frac{e^{-r_H^2/4\ell^2}}{\gamma\left(3/2\,;r_H^2/4\ell^2\right)}\right] \tag{11}$$

- *If $r_H^2/4\ell^2 >> 1 \Rightarrow T_H = \frac{1}{4\pi\, r_H}$ coincides with the Hawking result*
- *If $r_H \simeq \ell \Rightarrow T_H$ reaches a maximum $\simeq 0.015 \times 1/\ell$ corresponds to a mass $M \simeq 2.4 \times \ell$ and $r_H \simeq 4.7\ell$*
- **SCRAM phase**: *cooling down to absolute zero at $r_H = r_0 = 3.0\ell$ and $M = M_0 = 1.9\,\ell$, the extremal BH*
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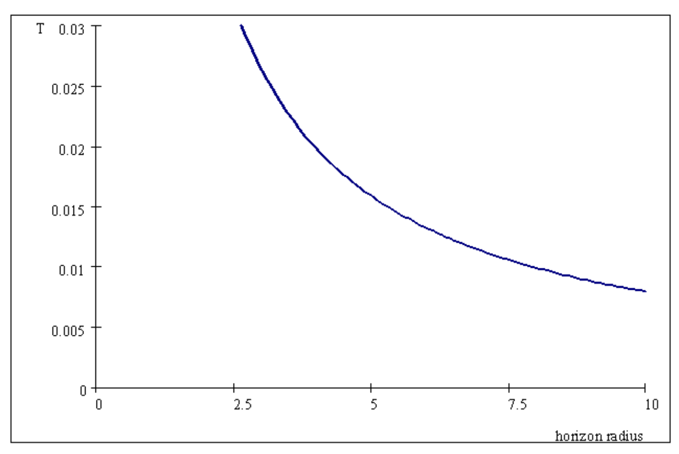
$$T_H = \frac{1}{4\pi\, r_H}\left[1 - \frac{r_H^3}{4\,\ell^3}\,\frac{e^{-r_H^2/4\ell^2}}{\gamma\left(3/2\,;\, r_H^2/4\ell^2\right)}\right] \qquad (11)$$

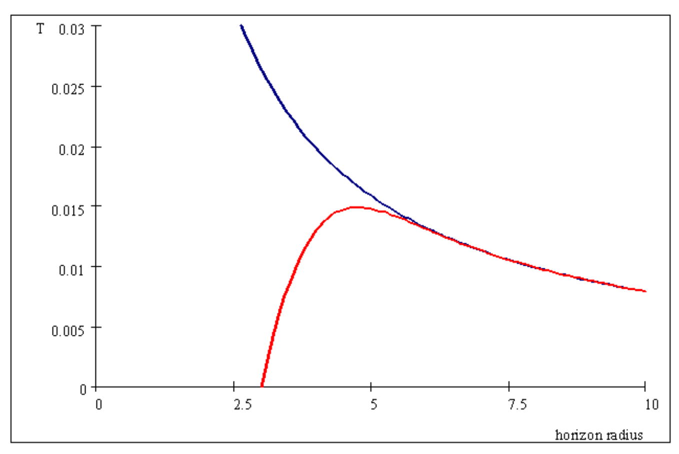
- *If* $r_H^2/4\ell^2 >> 1 \Rightarrow T_H = \frac{1}{4\pi\, r_H}$ *coincides with the Hawking result*
- *If* $r_H \simeq \ell \Rightarrow T_H$ *reaches a maximum* $\simeq 0.015 \times 1/\ell$ *corresponds to a mass* $M \simeq 2.4 \times \ell$ *and* $r_H \simeq 4.7\ell$
- **SCRAM phase**: *cooling down to absolute zero at* $r_H = r_0 = 3.0\ell$ *and* $M = M_0 = 1.9\,\ell$*, the extremal BH*
- *If* $r < r_0$ *there is no black hole.*

The Schwarzshild Geometry in the presence of ℓ



T_H vs r_H for the commutative case

The Schwarzshild Geometry in the presence of ℓ



T_H vs r_H for the commutative and **NC** case.

The Schwarzshild Geometry in the presence of ℓ

Back reaction

- *relevant back-reaction in Planck phase.*
- *SCRAM phase* $\Rightarrow$ *a suppression of quantum back-reaction*
- *At maximum temperature, the thermal energy is* $E = T_H^{Max} \simeq 0.015\,/\ell$, *while the mass is* $M \simeq 2.4\,\ell\,M_P^2$
- $E \sim M \Rightarrow \ell \approx 0.2\,L_P \sim 10^{-34}$ *cm.*
- *For this reason we can safely use unmodified form of the metric during all the evaporation process.*

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Extradimensional Solutions

- $ds^2_{(m+1)} = g_{00}\, dt^2 - g_{00}^{-1}\, dr^2 - r^2 d\Omega^2_{m-1}$
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$$g_{00} = 1 - \frac{1}{M_*^{m-1}} \frac{2M}{r^{m-2}\Gamma\left(\frac{m}{2}\right)} \tag{12}$$

- Properties of the solutions
- Geometric and thermodynamic behavior equivalent to the 4d one.
  - $\Longrightarrow$ there exists a mass threshold M_0 below which BH do not form.
  - $\Longrightarrow$ there exists a zero temperature black hole remnant

BH remnants

- $1/\ell \sim M_* \sim 1$ TeV
- remnant cross section $\sigma_{BH} \simeq \pi r_0^2 \sim 10$ nb $\longrightarrow$ 10 BHs per second at LHC.

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Maximum Temperatures for different m in the neutral case

	3	4	5	6	7	8	9	10
T_H^{max} (GeV)	18×10^{16}	30	43	56	67	78	89	98
T_H^{max} ($10^{15} K$)	$.21 \times 10^{16}$	.35	.50	.65	.78	.91	1.0	1.1

Remnant Masses and radii for different m

	3	4	5	6	7	8	9	10
M_0 (TeV)	2.3×10^{16}	6.7	24	94	3.8×10^2	1.6×10^3	7.3×10^3	3.4×10^4
r_0 (10^{-4} fm)	4.88×10^{-16}	5.29	4.95	4.75	4.62	4.52	4.46	4.40

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Potential catastrophic risk @ LHC

Black hole life times

- $$\frac{dM}{dt} = -A_H \, \Phi, \qquad \Phi = 2 \int \frac{d^m p}{(2\pi)^m} \frac{e^{-\frac{1}{8}\ell^2 p^2} \, p}{e^{p\beta_m} - 1} \tag{13}$$

Numerical results

- Assuming $M_{in} = 10$ TeV, for both brane and bulk emission

$$t_{\rm decay} \lesssim 10^{-16} \, {\rm sec} \; . \tag{14}$$

for any $m = 3 - 10$.

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Regular black hole spacetimes

Black hole solutions in the presence of ℓ

- Regular Schwarzschild and Reissner-Nordstroem solutions
- one, two or no horizon
- a regular deSitter core in place of the coordinate singularity
- The singular behavior of the Hawking temperature is cured.
- Found also the dirty, extradimensional cases and wormholes.

Recent solutions (2010)

- Spinning case
- Charged spinning case
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