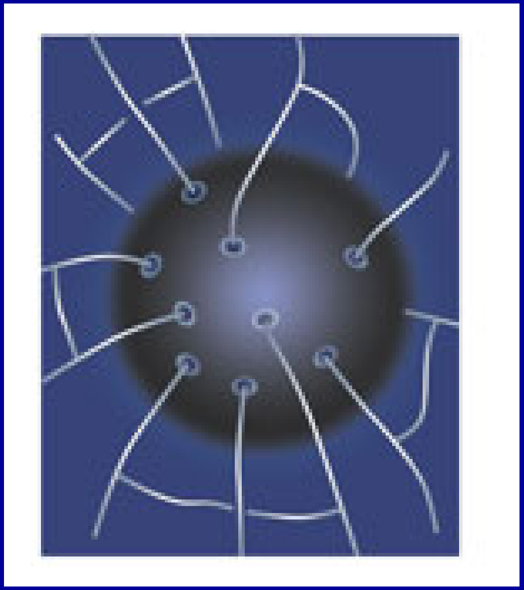
Relativité générale et trous noirs



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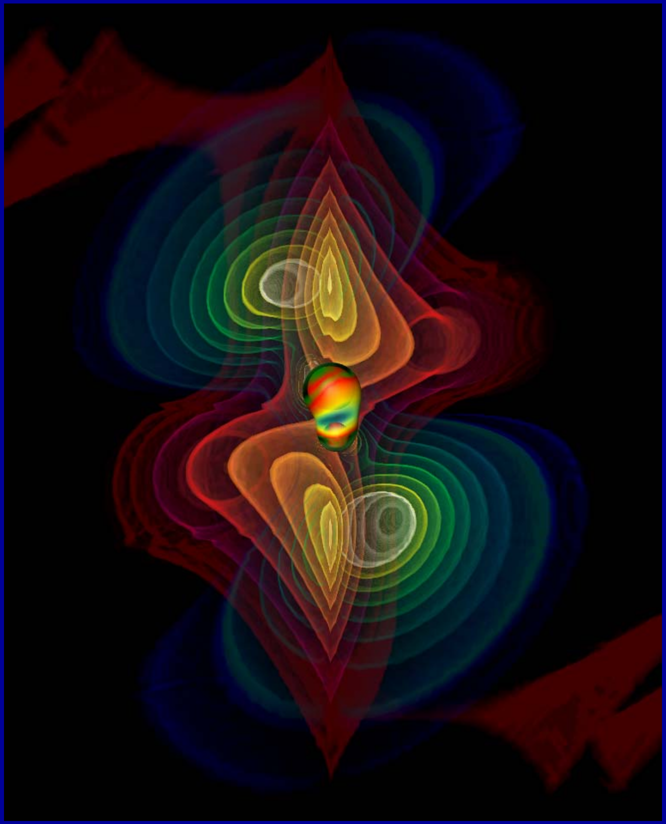
The interval



Special relativity :

- Space-time homogeneity
- Space isotropy
- Same laws in all inertial frames

→ group structure : Lorentz matrix

→ conserved quantity :

$$ds^2 = c^2 dt^2 - dx^2 - dy^2 - dz^2$$

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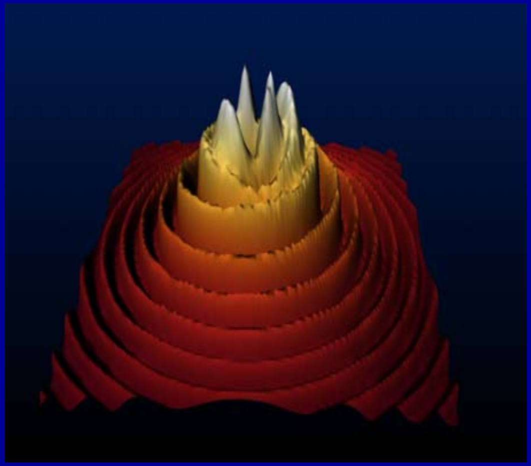
Equivalence principle



All the test masses behave identically in the gravitational fiels (m**g** = m**a** !)

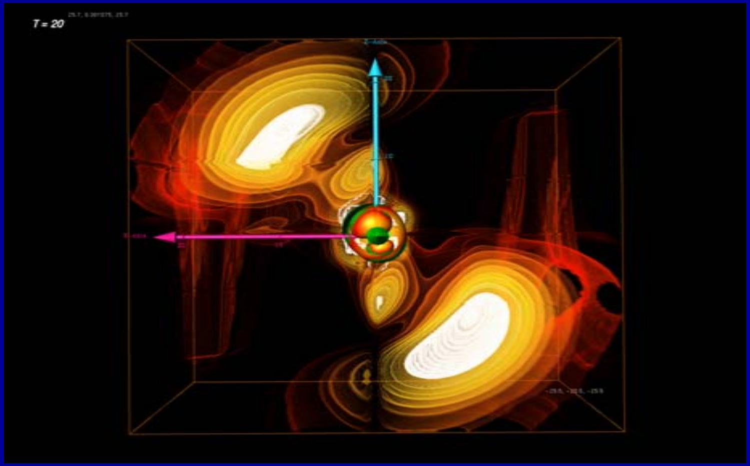
→Gravitational strength can be seen as a

→movement of the frame

New equation for the interval

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

Riemann



Curvature : Riemann

$$R^{\sigma}_{\mu\alpha\beta} \equiv \partial_{\alpha}\Gamma^{\sigma}_{\mu\beta} - \partial_{\beta}\Gamma^{\sigma}_{\mu\alpha} + \Gamma^{\sigma}_{\beta\alpha}\Gamma^{\lambda}_{\mu\beta} - \Gamma^{\sigma}_{\beta\lambda}\Gamma^{\lambda}_{\mu\alpha}$$

where $D_{\mu}V^{\nu} = \partial_{\mu}V^{\nu} + \Gamma^{\nu}_{\mu\lambda}V^{\lambda}$ **and**

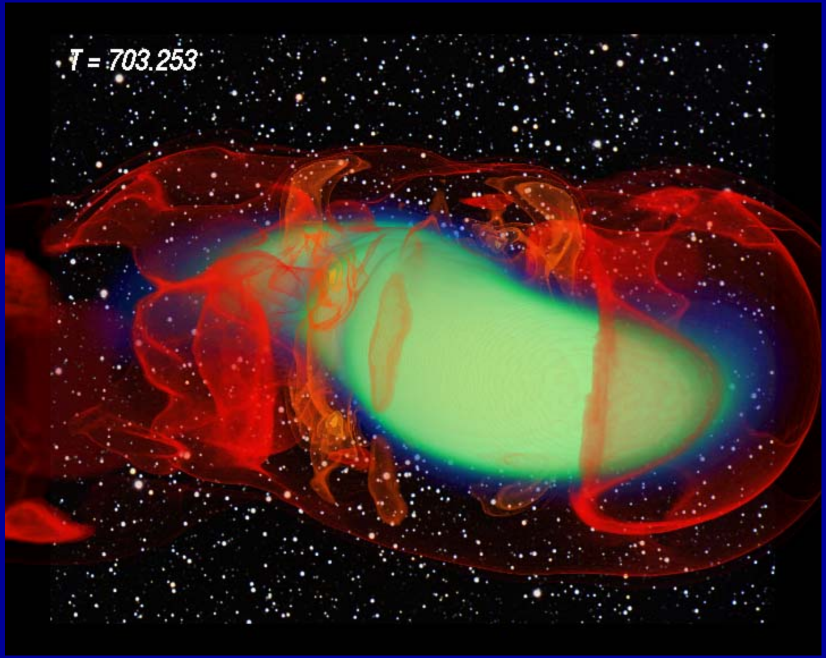
$$\partial_{\mu}V^{\nu} \to \partial_{\mu'}V^{\nu'} = \left(\frac{\partial x^{\mu}}{\partial x^{\mu'}}\partial_{\mu}\right)\left(\frac{\partial x^{\nu'}}{\partial x^{\nu}}V^{\nu}\right) = \frac{\partial x^{\mu}}{\partial x^{\mu'}}\frac{\partial x^{\nu'}}{\partial x^{\nu}}\left(\partial_{\mu}V^{\nu}\right) + \frac{\partial x^{\mu}}{\partial x^{\mu'}}\frac{\partial^{2} x^{\nu'}}{\partial x^{\mu}\partial x^{\nu}}V^{\nu}$$

Riemann vanishes if and only if spacetime is flat

View as an «operator» : R(. , . , . , .) so that R(u,ξ,u) gives the Opposite of the geodesic acceleration

$$\frac{D^{2}\xi}{d\tau^{2}} + R^{\alpha}_{\beta\gamma\delta}\frac{dx^{\beta}}{d\tau}\xi^{\gamma}\frac{dx^{\delta}}{d\tau} = 0 \leftrightarrow m\frac{D^{2}x^{\alpha}}{d\tau^{2}} = aF^{\alpha}_{\beta}\frac{dx^{\beta}}{d\tau}$$

Stress energy



At each spacetime point, there exist a rank 2 tensor containing all the information about energy and momentum

$$T_{\mu\nu}$$

T(u, .) = T(. ,u) = -{4-momentum density} ←→ $T^{\alpha}_{\beta} u^{\beta} = -\frac{dp^{\alpha}}{dV}$

T(u,n) = T(n,u) = -{component of 4-momentum in direction n}

T(u,u) = {mass-energy density}

Conservation : div(T)=0

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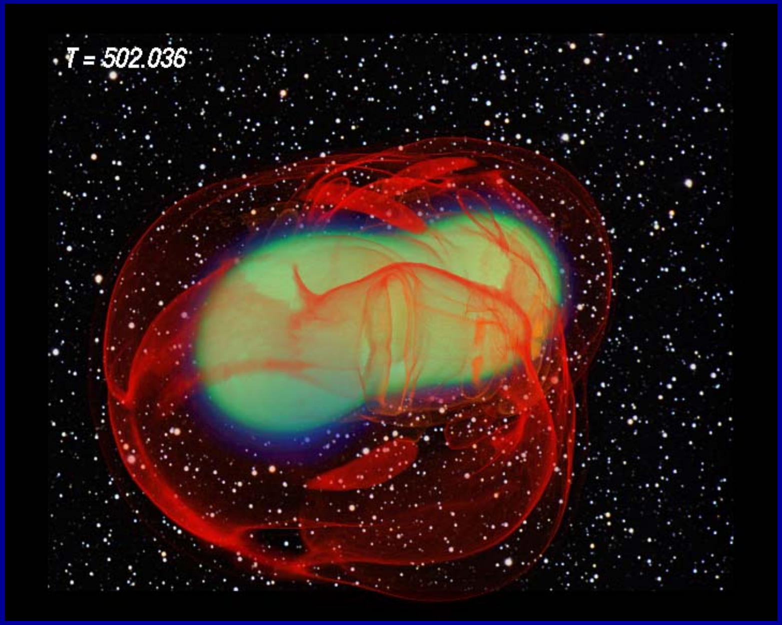
Einstein



From geometrical ingrediants we try to build a tensor that:

(1) Vanishes in flat spacetime
(2) Uses ony Riemann and metric
(3) Is specific because of (a) linearity in Riemann, (b) symmetry and rank 2 , (c) divergence free.

Only one solution :

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu}$$

où $R_{\mu\nu} = R^{\alpha}_{\mu\alpha\nu}$ **et** $R = R^{\mu}_{\mu}$

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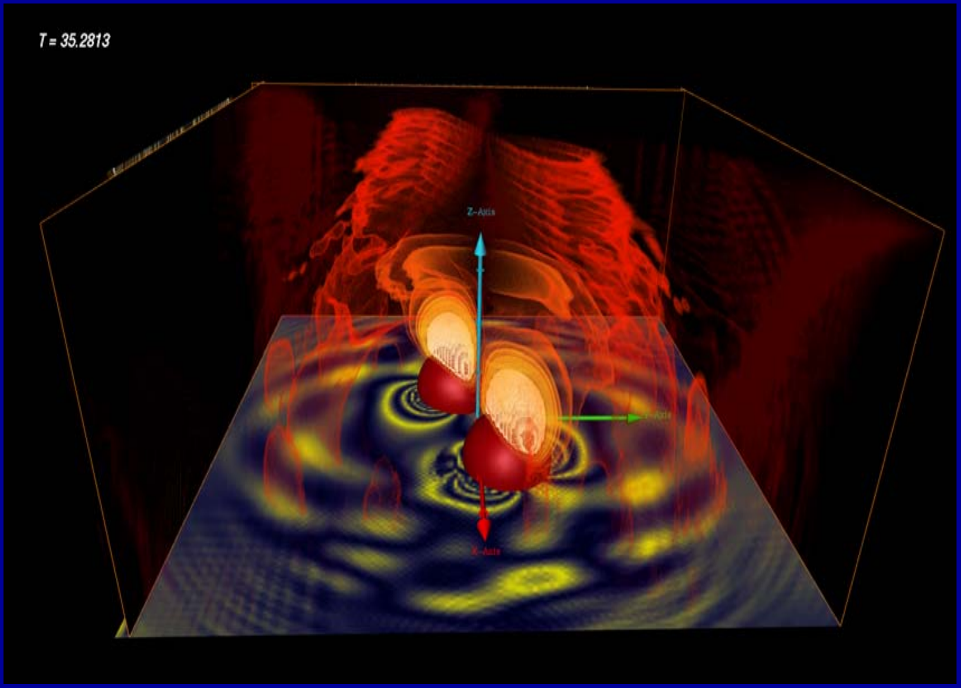
Field equations



The simplest : G α T !!!

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Exemple : black holes

$$ds^2 = \left(1 - \frac{2MG}{rc^2}\right) c^2 dt^2 - \frac{dr^2}{\left(1 - \frac{2MG}{rc^2}\right)}$$

Problems and hopes

There is not a *step* but a *gap* when trying to go from QED to quantum gravity. Things must be seen is a totally new way.

Which *gendanken* experiment ? (as in quantum mechanics, SR and GR) Which paradox should we consider ?

Quantum black holes are probably the most promising objects !

*** thermodynamics (entropy)**

*** violation of coherence**

*** IR/UV connection**

→String theory ?

→Loop quantum gravity ?

Understanding the behavior of quantum fields in the vicinity of black holes is a keypoint in theoretical physics, even at the semi-classical order.

A general framework to study quantum fields in curved backgrounds

Building the propagator at the semi-classical order
→ analogies between general relativistic quantum mechanics and non-relativistic quantum physics of stationary system

→ propagator for paths at fixed proper time and then at fixed mass (solution of the inhomogeneous KG equation)

→ check conservation laws, the domain of validity and the action functional

J. Grain & A. Barrau, Nucl. Phys. B 742 (2006) 253
« A WKB Approach to Scalar Fields Dynamics in Curved Space-Time »
J. Grain & A. Barrau, submitted to Phys. Rev. D (2006)
« A general formalism for semi-classical scalar wave functions in curved backgrounds »

As an example : Lovelock black holes in multi-dimensional space-times

The framework

Let's start with 4-dimensional General Relativity

$$\frac{d^2x^\mu}{d\tau^2}+\Gamma^\mu_{\nu\lambda}\frac{dx^\nu}{d\tau}\frac{dx^\lambda}{d\tau}=0$$

$$R_{\mu\nu}-\tfrac{1}{2}g_{\mu\nu}R=-8\pi G T_{\mu\nu}$$

$$d\tau^2=ds^2=g_{\mu\nu}dx^\mu dx^\nu$$

$$S=\frac{1}{16\pi}\int d^4x\sqrt{-g}\,R$$

$$L_{GR}=R$$

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From general relativity to Lovelock gravity

- Taylor expansion in scalar curvature
- Lovelock gravity : no ghost, 2nd order field equations, appears as the limit of some string theories, solves the endpoint of Hawking evaporation, etc.

$$L_{love} = \sum_i c_i L_i (R^i)$$

- Gauss-Bonnet theory : 2nd order truncature

$$L_{GB} = -2\Lambda + R + \alpha (R^2 - 4R^{\mu\nu} R_{\mu\nu} + R^{\mu\nu\rho\sigma} R_{\mu\nu\rho\sigma})$$

D. Lovelock, J. Math. Phys. 12 (1971) 498
B. Zwiebach, Phys. Lett. B 156 (1985) 316
S. Alexeyev & M. Pomazonov, Phys. Rev. D 55 (1997) 2110
S. Alexeyev, A. Barrau, G. Boudoul, O. Khovanskaya, M. Sazhin, Class. Quantum Grav. 19 (2002) 4444

… and many others !

Extra-dimensions : the ADD model

- Hierarchy problem in the standard model

$$M_{Pl} >> E_{EW}$$

- Large extra dimensions

Arkani-Hamed, Dimopoulos, Dvali Phys. Lett. B 429, 257 (1998)

$$M_D = \left(\frac{M_{Pl}^2}{V_{D-4}} \right)^{\frac{1}{D-2}} \approx TeV$$

Characteristic size from a Fermi (D=11) to a fraction of millimeter (D=6)
→an evaporation BH is a point object compared to the extra dimensions

- Standard model fields confined on the **brane** whereas gravitons and scalars can propagate in the **bulk**

Greybody factors: example of scalar fields on the brane (1)

- D-dimensional Schwarzschild metric

$$ds^2 = h(r)dt^2 - \frac{dr^2}{h(r)} - r^2 d\Omega_{D-2}^2$$

- Projection on the 4-dimensional brane → Schwarzschild with D-dimensional metric function

$$ds^2 = h(r)dt^2 - \frac{dr^2}{h(r)} - r^2\left(d\theta^2 + \sin^2(\theta)d\varphi^2\right)$$

- Solving the field equation with this background metric → taking into account the symmetries

$$\frac{1}{\sqrt{-g}}\partial_\alpha\left[\sqrt{-g}\,g^{\alpha\beta}\partial_\beta\Phi\right] + \mu^2\Phi = 0 \text{ avec } \Phi \equiv e^{-i\omega t}Y_m^\ell(\theta,\varphi)R(r)$$

Greybody factors: example of scalar fields on the brane (2)

- Radial part of the field equations

$$\frac{h(r)}{r^2}\frac{d}{dr}\left(r^2 h(r)\frac{dR}{dr}\right)+\left(\omega^2-h(r)\frac{\ell(\ell+1)}{r^2}\right)R=0$$

- Changing the variables

$$r \rightarrow y \text{ telle que } dy = h^{-1}(r)dr$$

$$R(r) \rightarrow U(y) \text{ telle que } U(y) = r \times R(r)$$

bijection from $]r_H,+\infty[$ in $]-\infty,+\infty[$

- **Schrödinger-like equation**

$$\left[\frac{d^2}{dy^2}+\omega^2-h(r)\left(\frac{\ell(\ell+1)}{r^2}+\frac{1}{r}\frac{dh(r)}{dr}\right)\right]U(y)=0$$

Centrifugal and gravitational potential

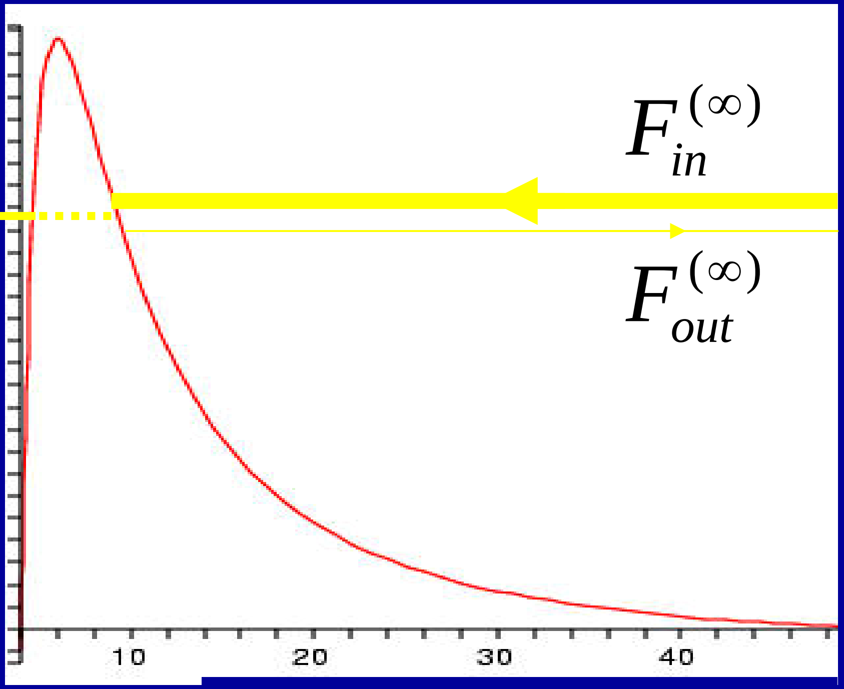
Greybody factors: example of scalar fields on the brane (3)

- Potential for a black hole
- Emission from black holes

$$\frac{dN}{dt} \equiv \frac{1}{e^{\frac{\omega}{T_H}} \pm 1} \times \sum_{\ell} \sigma_{\ell}(\omega) \times d^3k$$

Vacuum fluctuations breaking

Diffusion on the gravitational potential



Radial coordinate r

- Greybody factors as a **scattering problem** with spherical symmetry

$$\sigma_{\ell}(\omega) \propto \frac{2\ell+1}{\omega^2} |A_{\ell}|^2$$

$$|A_{\ell}|^2 = \frac{F_{in}^{(h)}}{F_{in}^{(\infty)}} = 1 - \frac{F_{out}^{(\infty)}}{F_{in}^{(\infty)}}$$

Greybody factors : particle with spin and scalars in the bulk

- Field equations in the Newman-Penrose formalism

$$\Delta^s \frac{d}{dr}\left(\Delta^{1-s}\frac{dP_s}{dr}\right)+\left(\frac{\omega^2 r^2}{h(r)}+2is\omega r-\frac{is\omega r^2}{h(r)}\frac{dh}{dr}-\lambda\right)P_s=0$$

$$\text{avec } \lambda = j(j+1)-s(s-1)$$

$$\Delta = h(r)r^2$$

- Scalar field in the bulk→ D-dimensional generalization of the Klein-Gordon equation

$$\frac{h(r)}{r^{D-2}}\frac{d}{dr}\left(h(r)r^{D-2}\frac{dP_0}{dr}\right)+\left(\omega^2-\frac{h(r)}{r^2}\ell(\ell+D-3)\right)P_0=0$$

$$\left[\frac{d^2}{dy^2}+\omega^2-h(r)\left(\frac{\ell(\ell+D-3)}{r^2}+\frac{D-2}{2r}\frac{dh}{dr}+(D-4)(D-2)\frac{h(r)}{4r^2}\right)\right]U(y)=0$$

Greybody factors : computation

Exact results

- UV region : classical particles

  Area within the last stable orbit

$$\left(\frac{1}{r}\frac{dr}{d\varphi}\right)^2 = \frac{1}{b^2} - \frac{h(r)}{r^2}$$

Allowed classical region

$$b < \min(r/\sqrt{h(r)})$$

$$\sigma_g(\omega \to \infty) = \pi \times b_{\min}^2$$

- IR region

  Field equation solved near horizon (hyper geometric functions) and at infinity (Bessel functions) and junction between both regions

Semi-classical results (WKB)

- Propagator and wave function in the system (y,t)

$$\tilde{K}(y,y';t,t') = F(y,y';t,t')e^{i\tilde{S}(y,y';t,t')}$$

$$\tilde{S} = \int V(y)\sqrt{1-(\dot{y})^2}\,dt \text{ et } \omega^2 = p^2 + V^2(y)$$

- Bohr-Sommerfeld rule

$$W(\omega) = 2\int_{y_-}^{y_+} p_\omega(y)\,dy$$

$$\text{avec } W(\omega) = (2n+1)\pi$$

- Tunneling

$$T = \exp\left(-2\int_{y_-}^{y_+} p_\omega(y)\,dy\right)$$

Greybody factors : WKB resolution

- Semi-classical propagator injected within the Schrödinger equation

$$\left[\frac{d^2}{dy^2}-\frac{d^2}{dt^2}-\frac{1}{\hbar^2}V^2(y)\right]\tilde{K}(y,y';t,t')=\delta(y-y')\delta(t-t')$$

First order expansion in Planck constant

J. Grain, A. Barrau, Nucl. Phys. B 742 (2006) 253

$$\left(\frac{\partial\tilde{S}}{\partial t}\right)^2=\left(\frac{\partial\tilde{S}}{\partial y}\right)^2+V^2(y)\ \text{Hamilton - Jacobi}$$

$$\frac{\partial}{\partial y}\left(|F|^2\frac{\partial\tilde{S}}{\partial y}\right)-\frac{\partial}{\partial t}\left(|F|^2\frac{\partial\tilde{S}}{\partial t}\right)=0\ \text{conservation law}$$

$$\partial_\alpha\tilde{j}^\alpha=0$$

$$\text{avec}\ \tilde{j}^\alpha=-|F|^2p^\alpha$$

- For stationary systems : frequency Fourier transform of the propagator→ the fixed frequency propagator is the WKB wave function.

$$\tilde{G}(y,y',\omega)=\int e^{i\omega t}\tilde{K}(y,y';t,t')\equiv\sqrt{\frac{p(y')}{p(y)}}e^{i\int_{y'}^{y}p(x)dx}$$

Greybody factors : numerical investigations (1) (mandatory in the intermediate region)

- Field equations solved numerically from the BH horizon to space infinity. The boundary conditions are : non outgoing mode at the horizon.

$$P_{s,\ell,\omega}(r) = A_{in} e^{-i\omega y} + A_{out} \Delta^{s} e^{i\omega y}$$

- For r large enough, the asymptotic solutions at infinity are fitted to the numerical solution with the modes amplitudes as free coefficients.

$$P_{s,\ell,\omega}(r) = B_{in} \frac{e^{-i\omega r}}{r^{1-2s}} + B_{out} \frac{e^{i\omega r}}{r} \text{ sur la brane}$$

$$P_{0,\ell,\omega}(r) = B_{in} \frac{e^{-i\omega r}}{\sqrt{r^{D-2}}} + B_{out} \frac{e^{i\omega r}}{\sqrt{r^{D-2}}} \text{ dans le bulk}$$

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Greybody factors : numerical investigations (2)

- For a given energy, the tunnel probability is determined for each multipolar order:

$$\left|A_j\right|^2 = r_H^{2(1-2s)} \left|\frac{A_{in}}{B_{in}}\right|^2$$

- The optical theorem gives the emission/absorption cross section

$$\sigma(\omega) = \sum_{\ell} \frac{N_{j,D}}{\omega^{D-2}} \left|A_j\right|^2$$

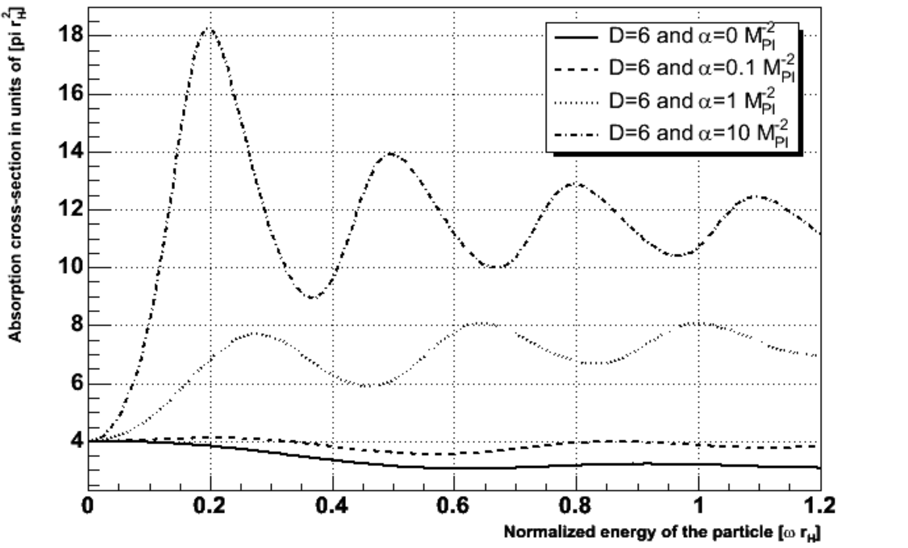
$N_{j,D}$ est la multiplicité du mode

$N_{j,D} = (2j+1)\pi$ avec $j = \ell + s$ sur la brane

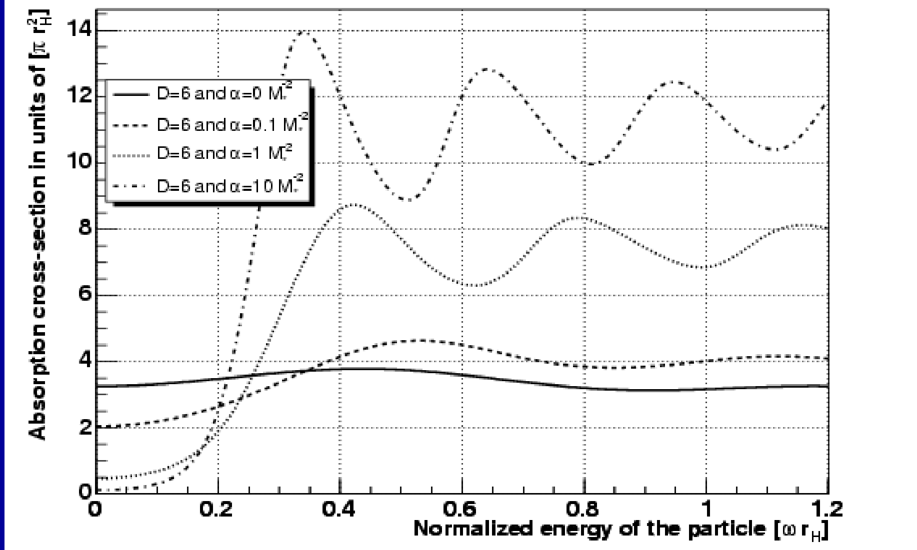
- Numerical errors under control

First consequence : Gauss-Bonnet black holes (1)

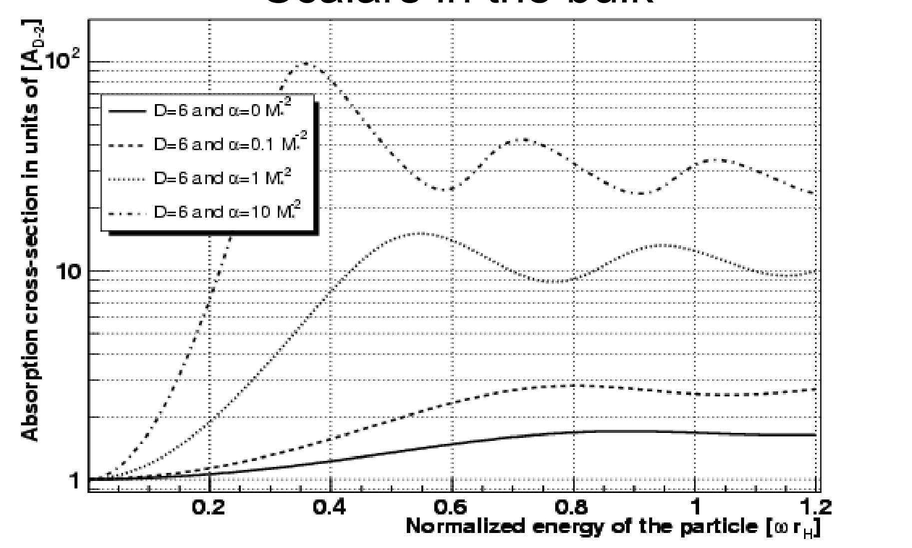
Scalars on the brane



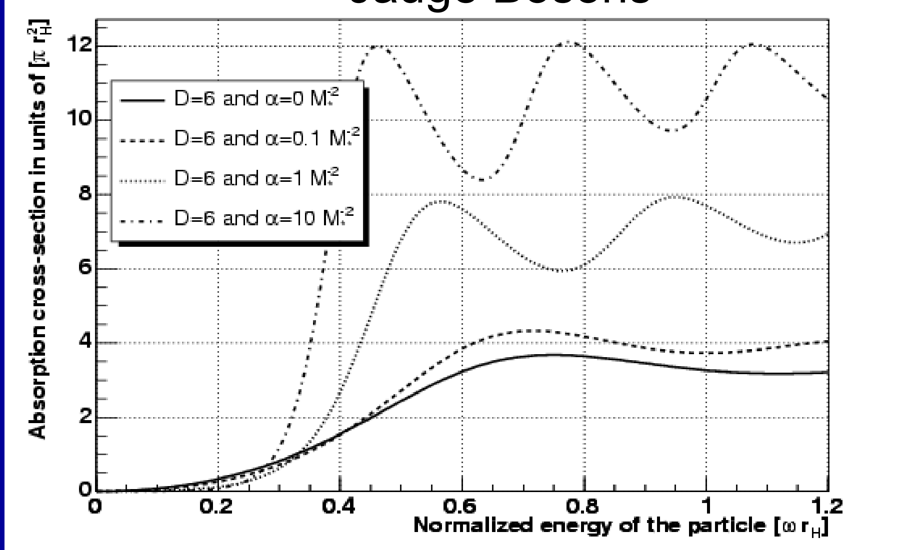
Fermions



Scalars in the bulk

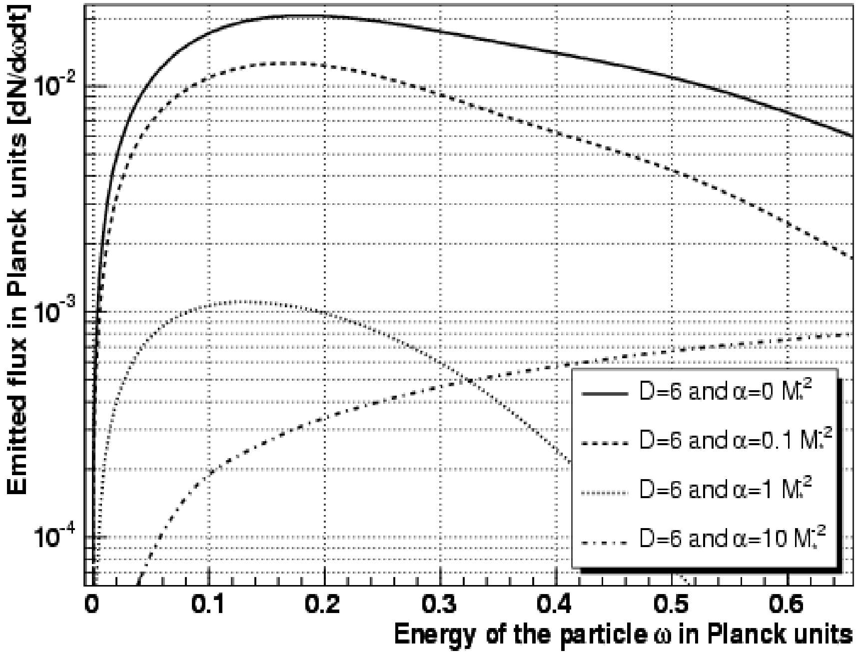


Jauge Bosons

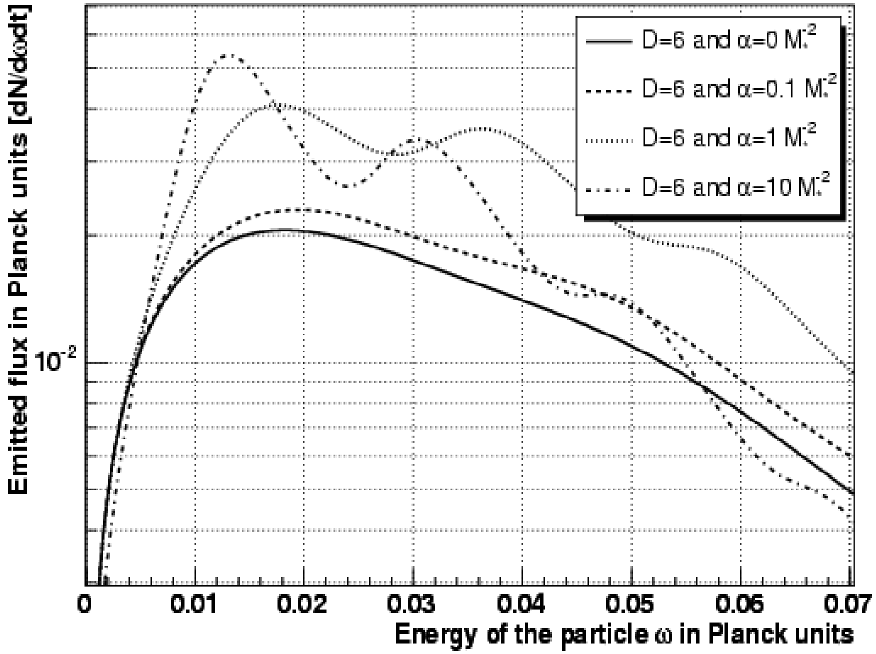


J. Grain, A. Barrau & P. Kanti, Phys. Rev. D 72 (2005) 104016

Gauss-Bonnet black holes (2)



$$M_{BH} = 10 M_D$$



$$M_{BH} = 10^4 M_D$$

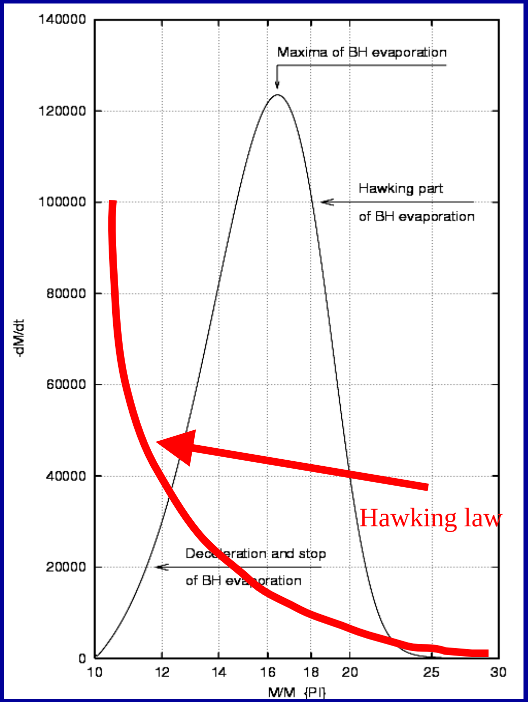
Gauss-Bonnet black holes (3) : 4-dimensions and dilatonic coupling

$$S = \int d^4x \sqrt{-g}\left\{-R + 2\partial_\mu \partial^\mu \Phi + \lambda e^{-2\Phi} S_{GB}\right\}$$

$$S_{GB} = R_{ijkl}R^{ijkl} - 4R_{ij}R^{ij} + R^2$$

$$r_h^{\inf} = \sqrt{\lambda}\sqrt{4\sqrt{6}}\,\Phi_h(\Phi_\infty)$$

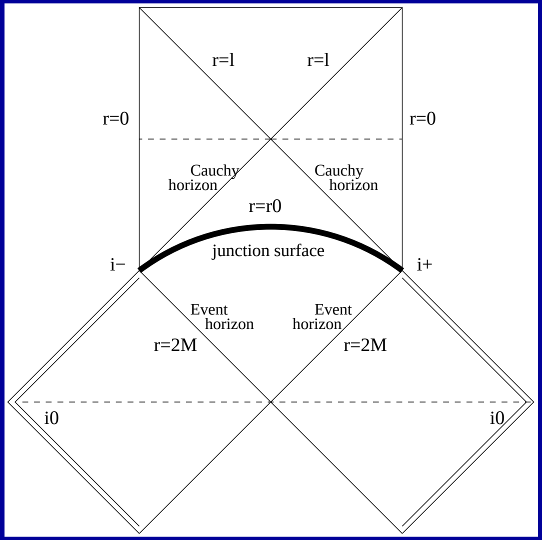
Alexeyev & Pomazonov, Phys. Rev. D 55 (1997) 2110
Alexeyev, Grav. Cosm. 3 (1997) 161



$$\mathrm{Im}(S) = \mathrm{Im}\int_{M}^{M-\omega}\int_{r_{in}}^{r_{out}} \frac{dr}{\dot{r}}\, dH$$

S. Alexeyev, A. Barrau, G. Boudoul, O. Khovanskaya, M. Sazhin, Class. Quantum Grav. 19 (2002) 4444

Gauss-Bonnet black holes (4) : Universe makers ?



Adapted from Frolov, Markov, Mukhanov, Phys. Lett. B 216 (1989) 272

Lee Smolin (the father of LQG) idea of cosmic natural selection needs a Universe inside a black hole. This assumes a finite value of the Riemann invariant. Lovelock gravity does not support this hypothesis (as implicitly demonstrated by Alexeyev et al.).

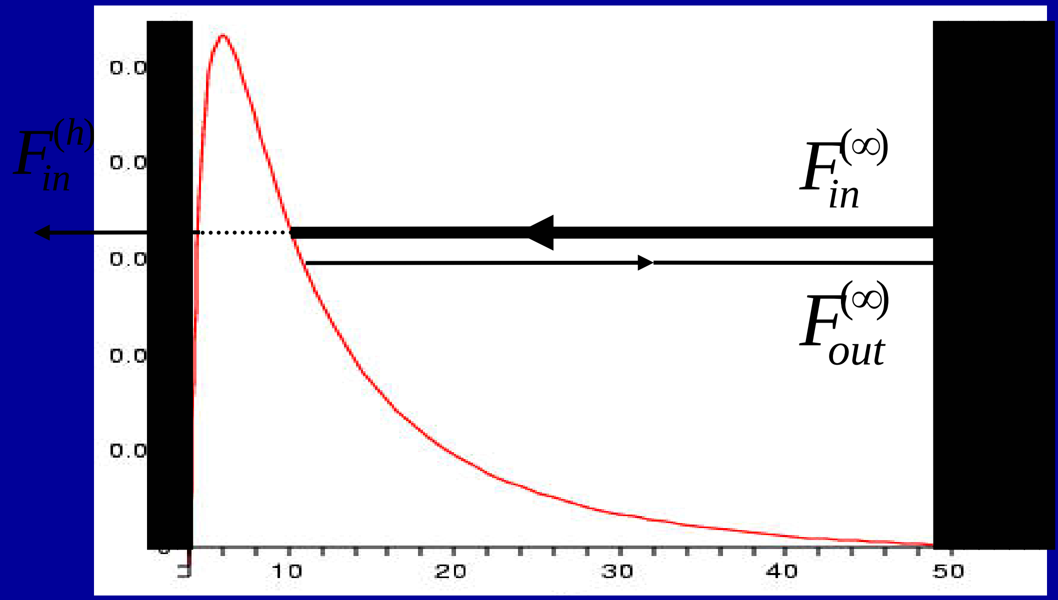
A. Barrau, gr-qc/0612045

Schwarzschild-de-Sitter black holes (1)

$$ds^2 = \left(1 - \frac{\gamma}{r^{D-3}} - \frac{2\Lambda}{(D-1)(D-2)} r^2\right) dt^2 - \frac{dr^2}{\left(1 - \frac{\gamma}{r^{D-3}} - \frac{2\Lambda}{(D-1)(D-2)} r^2\right)} - r^2 d\Omega^2_{D-2}$$

Metric function h(r)

2 event horizons , 2 temperatures



$$T_\Lambda = \frac{1}{\sqrt{h(r_0)}} \frac{1}{4\pi} \frac{dh(r)}{dr}\bigg|_{r_H}$$

$$\left[-\frac{d^2}{dy^2} + V(\ell, h(r))\right] U(y) = \omega^2 U(y)$$

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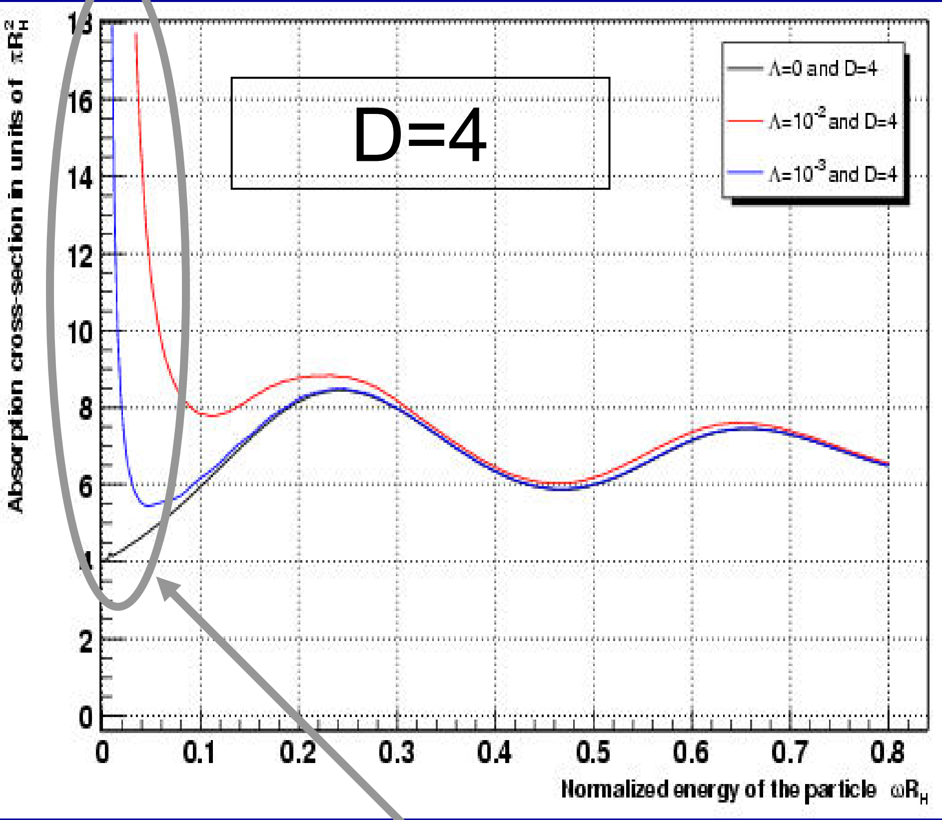
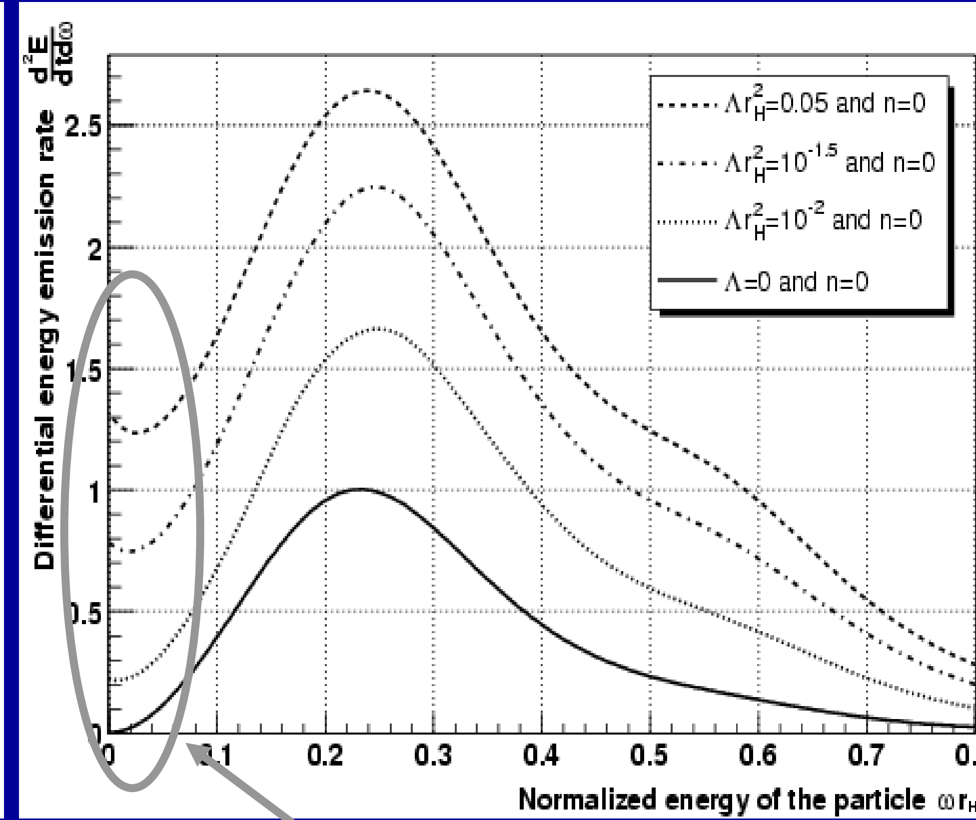
Schwarzschild-de-Sitter black holes (2)





The 2nd horizon leads to an infrared divergence

Ultra-soft quanta due to the IR behavior

P. Kanti, J. Grain & A. Barrau, Phys. Rev. D 71 (2005) 104002

Analytical checks for SdS black holes

$$R(r \to r_H) = \frac{A_1}{r_H}\left\{1 - i\omega\left[\frac{\ln\left(r - r_H\right)}{2\kappa_H} - \frac{\ln\left(r_{dS} - r_H\right)}{2\kappa_{dS}} + \sum_{m=1}^{D-3}\frac{\ln\left(r_H + r_m\right)}{2\kappa_m}\right]\right\}$$

$$R(r \to r_{dS}) = \frac{1}{r_{dS}}\left\{(B_1 + B_2) - i\omega(B_1 - B_2)\left[\frac{\ln\left(r_{dS} - r_H\right)}{2\kappa_H} - \frac{\ln\left(r_{dS} - r\right)}{2\kappa_{dS}} + \sum_{m=1}^{D-3}\frac{\ln\left(r_{dS} + r_m\right)}{2\kappa_m}\right]\right\}$$

$$R(r \to r_H) = A_1\frac{e^{-i\omega y}}{r_H} \to \frac{A_1}{r_H}\left(1 - i\omega y\right) \text{quand } \omega \to 0$$

$$R(r \to r_{dS}) = B_1\frac{e^{-i\omega y}}{r_{dS}} + B_2\frac{e^{i\omega y}}{r_{dS}} \to \frac{1}{r_{dS}}\left[(B_1 + B_2) - i\omega y\left(B_1 - B_2\right)\right] \text{quand } \omega \to 0$$

$$C_1 = \begin{cases} -i\omega r_H A_1 \\ -i\omega r_{dS}\left(B_1 - B_2\right) \end{cases} \text{et } C_2 = \begin{cases} \dfrac{A_1}{r_H} + O(\omega) \\ \dfrac{B_1 + B_2}{r_{dS}} + O(\omega) \end{cases}$$

$$y = \frac{\ln\left(r - r_H\right)}{2\kappa_H} - \frac{\ln\left(r_{dS} - r\right)}{2\kappa_{dS}} + \sum_{m=1}^{D-3}\frac{\ln\left(r + r_m\right)}{2\kappa_m}$$

$$\left|A_0(\omega \to 0)\right|^2 = \frac{4r_H^2 r_{dS}^2}{\left(r_{dS}^2 + r_H^2\right)^2}$$

$$\frac{d}{dr}\left(r^2 h(r)\frac{dR}{dr}\right) = 0 \Rightarrow R(r) = C_1\left[\frac{\ln\left(r - r_H\right)}{2\kappa_H r_H^2} - \frac{\ln\left(r_{dS} - r\right)}{2\kappa_{dS} r_{dS}^2} + \sum_{m=1}^{D-3}\frac{\ln\left(r + r_m\right)}{2\kappa_m r_m^2}\right] + C_2$$

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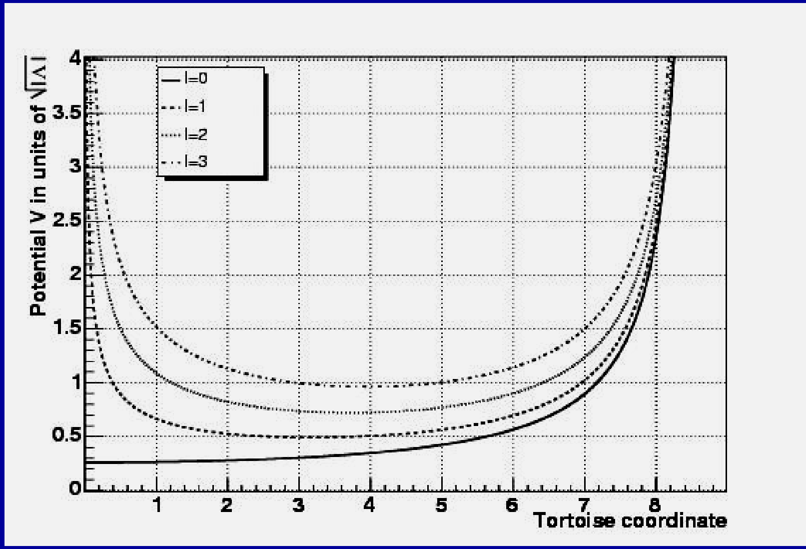
Anti-de-Sitter spaces (1)

- Metric function

$$h(r) = 1 + \frac{r^2}{R^2} \text{ avec } R^2 = -\frac{3}{\Lambda}$$

$$V_\ell^2(y) = \frac{1}{R^2 \cos(y/R)} \left(\frac{\ell(\ell+1)}{\tan^2(y/R)} + 2 \right)$$

$$y = R \arctan(r/R)$$



Tortoise coordinate

$$W(\omega) = \int_{y_-(\omega)}^{y_+(\omega)} \sqrt{\omega^2 - V_\ell^2(y)}\, dy = \left(n + \frac{1}{2}\right)\pi$$

$$\omega_{n,\ell} = (2n + \ell + 3)/R$$

- Stationary states with a discrete normal frequency spectrum.

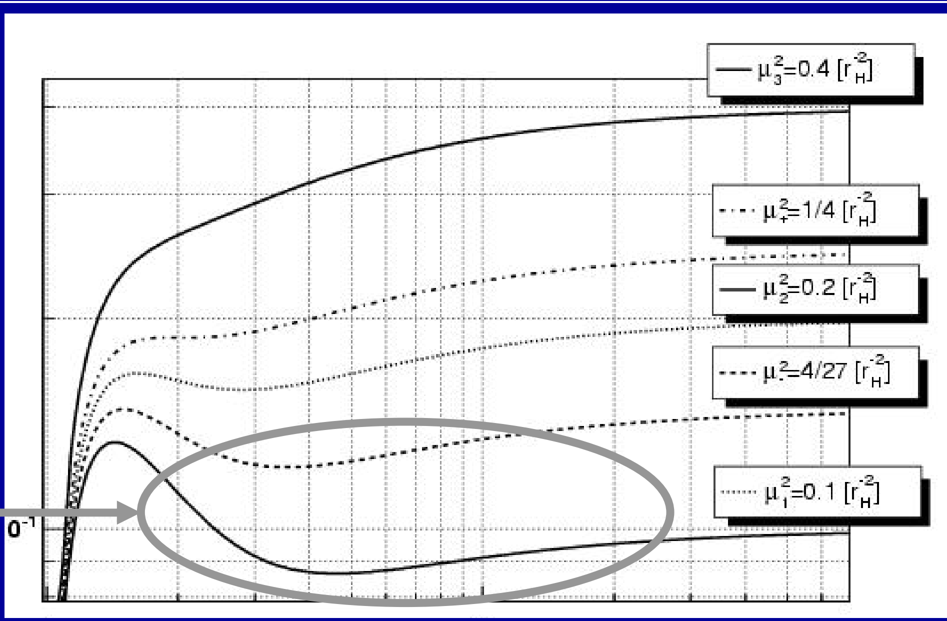
Back to Schwarzschild black holes : new quantum bound states

- For massive particles

J. Grain & A. Barrau, submitted to Phys. Rev. Lett (2006)

$$V_\ell^2(r) = \left(1 - \frac{2M}{r}\right)\left(\frac{\ell(\ell+1)}{r^2} + \frac{2M}{r^3} + \mu^2\right)$$

Potential well due to the gravitational binding energy



Radial coordinate

- Quasi-bound states : bandwidth and characteristic lifetime can be computed at the WKB order

- Exist even at the monopolar order : no classical equivalent → **spherical halo of scalar particles around the black hole.**

Schwarzschild-Anti-de-Sitter black holes

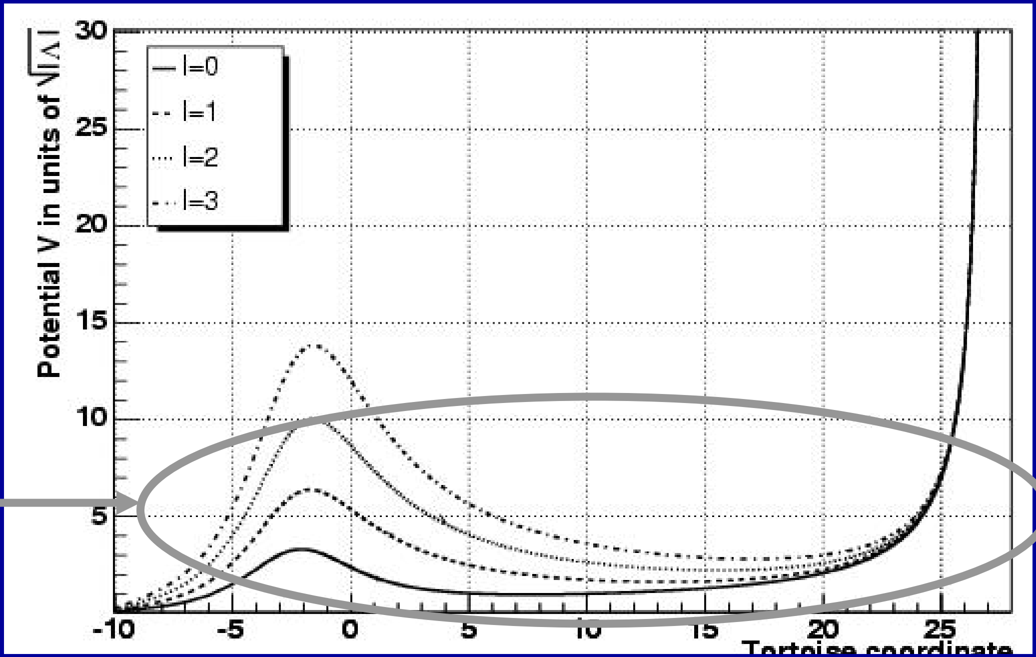
$$V_\ell^2(r) = \left(1 - \frac{2M}{r} + \frac{r^2}{R^2}\right)\left(\frac{\ell(\ell+1)}{r^2} + \frac{2M}{r^3} + \frac{2}{R^2}\right)$$

$$y = R^2\left[\alpha(R, r_H)\ln\left(\frac{r - r_H}{\sqrt{r^2 + r r_H + r_H^2 + R^2}}\right) + \beta(R, r_H)\arctan\left(\frac{2r + r_H}{\gamma(R, r_H)}\right)\right]$$

- The hierarchy plays a fundamental role in the multipolar dependence of the potential well.

Singular transition from SAdS to AdS !

resonances



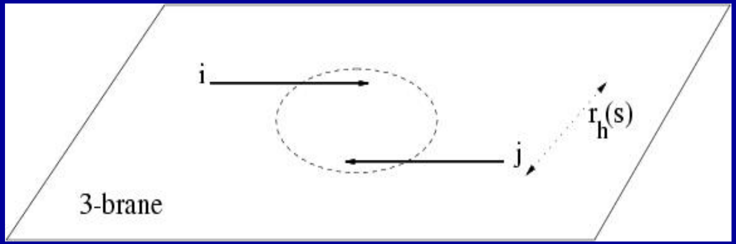
Tortoise coordinate

EXPERIMENTAL INVESTIGATIONS
BH @ the LHC if the Planck scale ~ TeV !

- Geometric cross section

$$\sigma_{BH}(s) \approx \pi \times r_H^2(s)$$

$\sqrt{s} > M_D$

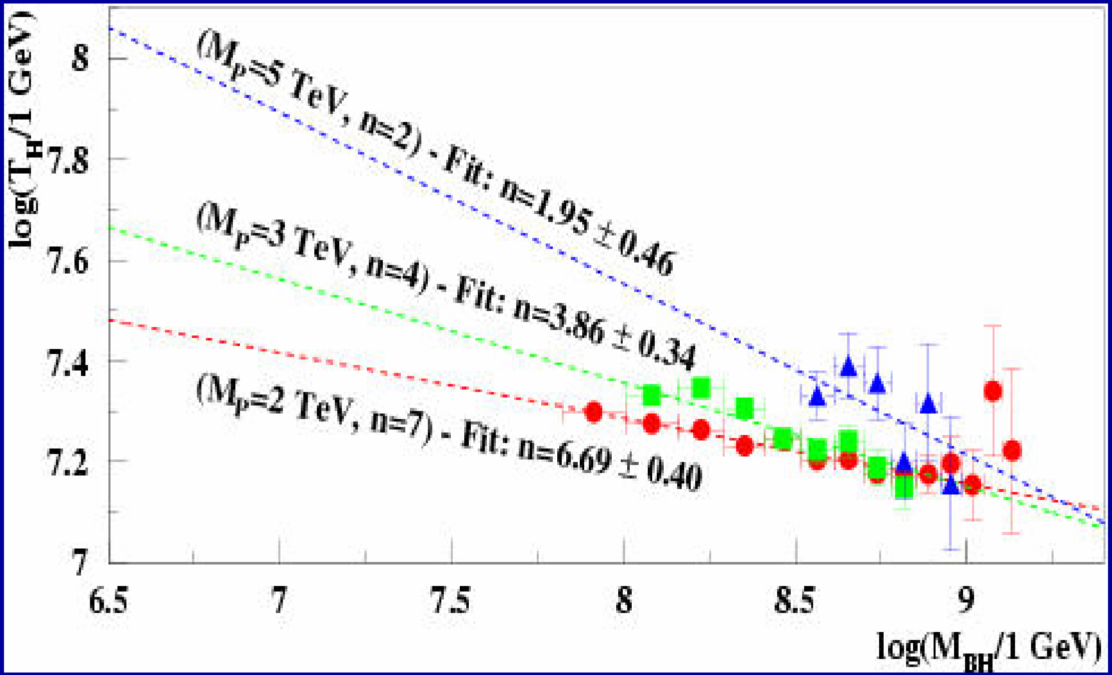


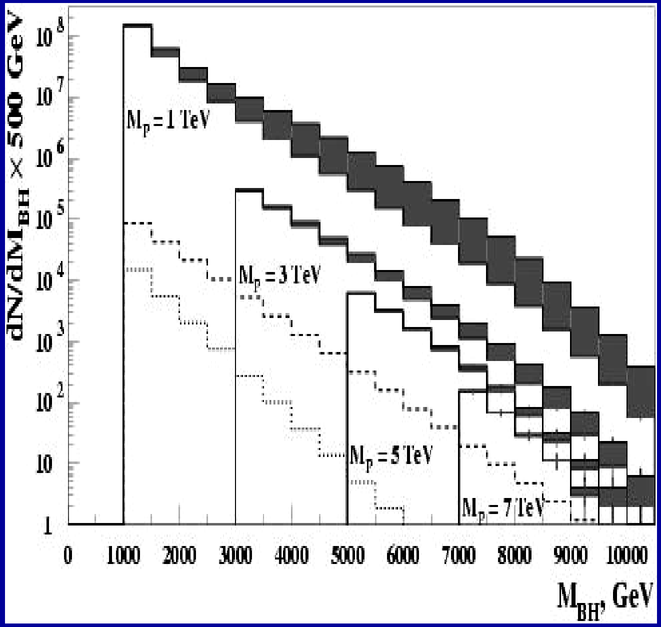
- Estimate of the number of produced black holes
- Reconstruction of the dimensionality

Banks, Fischler hep-th/9906038

Giddings, Thomas Phys. Rev. D 65, 056010 (2002)

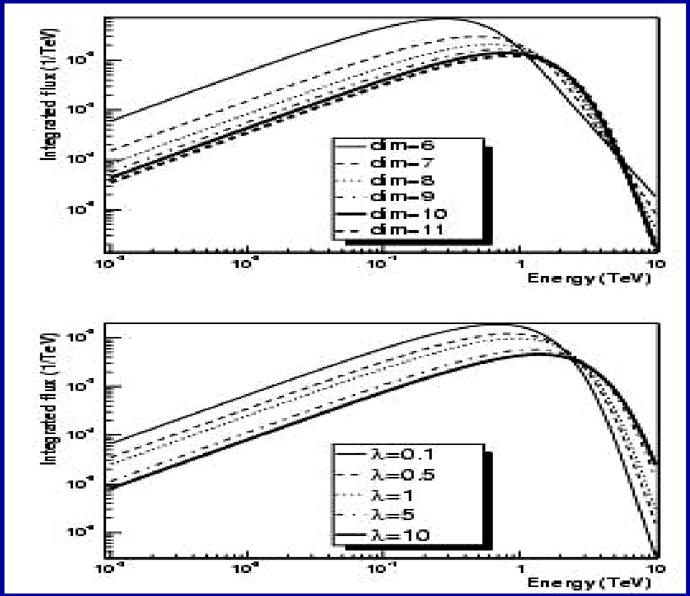
Dimopoulos, Landsberg Phys. Rev. Lett 87, 161602 (2001)

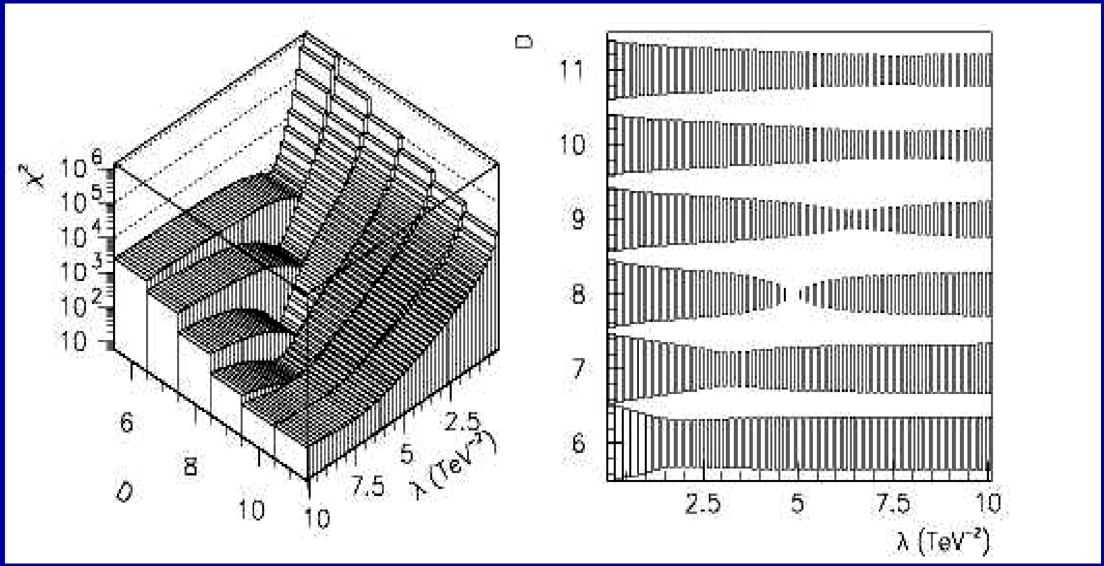




Black holes at the LHC (2)

- Taking everything into account : it works !
- The statistical analysis allows to reconstruct both the dimensionality of space-time and the Gauss-Bonnet coupling constant.





A. Barrau, J. Grain, S. Alexeyev Phys. Lett. B 584 (2004) 114

Now we should consider Kerr-Gauss-Bonnet black holes :

S. Alexeyev, N. Popov, A. Barrau, J. Grain, in prep. for Phys. Rev. Lett (2007)

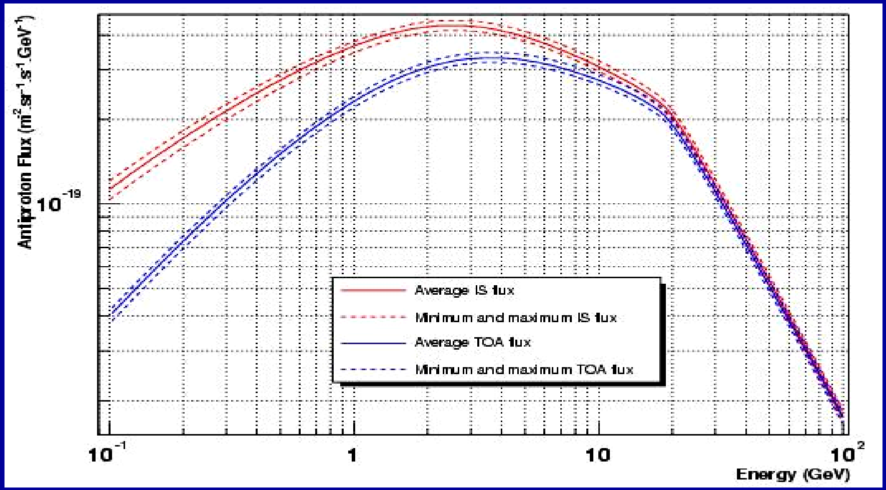
Also : Particle physics (light SUSY particles, Higgs, etc.) with BH as resonances

What about the interstellar medium ?

$$CR \quad + \quad ISM \quad \rightarrow \quad \mu BH$$

- Black holes formed in the Galaxy should evaporate and contribute to the cosmic-ray background

$$\frac{dN_{\bar{p}}}{dQ'dt} \equiv \left\{ \frac{dN_{CR}}{dE} \otimes \left[\sigma_{BH}(E) \times n(ISM) \right] \right\} \otimes \left\{ Boosted \left(\frac{d^2 N_{q,g}}{dE'dt} \otimes f_{E'}(Q) \right)(Q') \right\}$$



- Compatible with CR flux
- Compatible with entropy in the early universe
- Compatible with dark matter

A. Barrau, J. Grain, C. Féron, Astrophys. J. 630 (2005) 1015