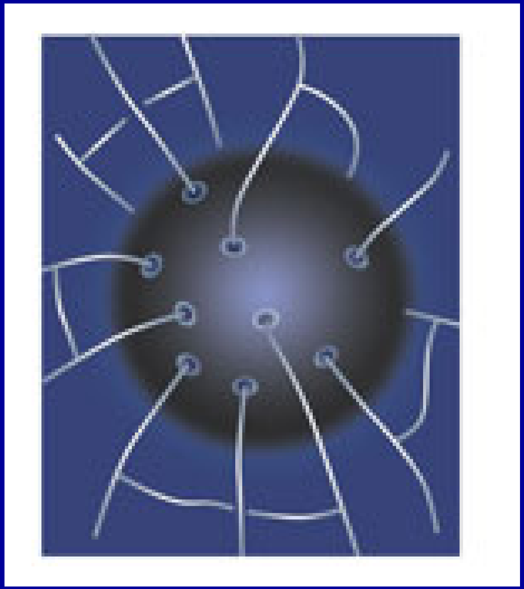
Black Holes and quantum fields



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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 *gendenken* 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.

Aurélien Barrau LPSC-Grenoble (CNRS / UJF)

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 systems

→ 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

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

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

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

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

$$L_{GR}=R$$

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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**

Black holes do evaporate

•

$$\frac{d^2N}{dQdt} = \frac{\Gamma(Q,s,M)}{h\left(e^{\frac{Q}{k_BT}} - (-1)^{2s}\right)}$$

$$T = \frac{\hbar c^3}{8\pi k_B GM}$$

Black holes do evaporate

- Emission spectrum

$$\frac{d^2N}{dQdt} = \frac{\Gamma(Q,s,M)}{h\left(e^{\frac{Q}{k_BT}} - (-1)^{2s}\right)}$$

Non-thermal part: probability to escape from the BH in the intricate metric

Greybody factors

Thermal part: breaking the vacuum fluctuations with tidal forces

$$T = \frac{\hbar c^3}{8\pi k_B GM}$$

Black holes do evaporate

- Emission spectrum

$$\frac{d^2N}{dQdt} = \frac{\Gamma(Q,s,M)}{h\left(e^{\frac{Q}{k_B T}} - (-1)^{2s}\right)}$$

$$T = \frac{\hbar c^3}{8\pi k_B GM}$$

- Mass loss rate

$$\frac{dM}{dt} = -\frac{\alpha(M)}{M^2}$$

$$M = 10^{16} g \rightarrow T = 10^{-1} GeV \rightarrow t = 10^{21} s$$

$$M = 10^{9} g \rightarrow T = 10^{4} GeV \rightarrow t = 1 s$$

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

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

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

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

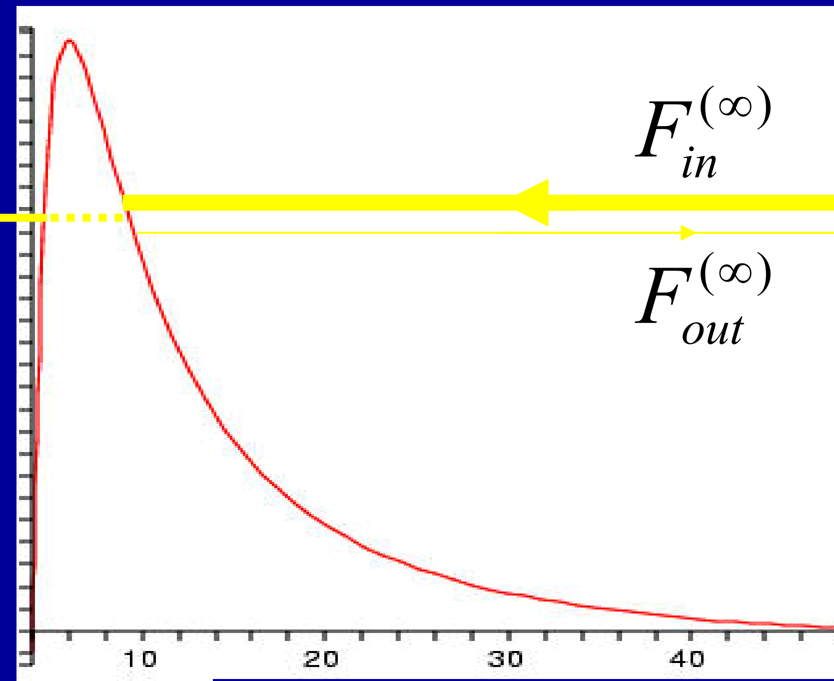
Greybody factors: example of scalar fields on the brane (3)

- 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

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

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

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

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

First order expansion in Planck constant

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

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

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

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

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

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

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

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.

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

- 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

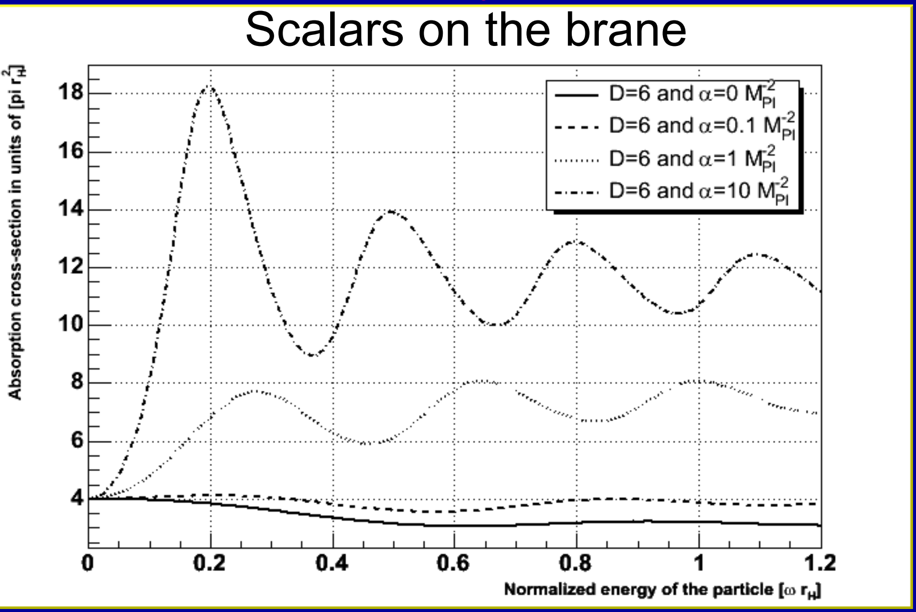
$$\sigma(\omega) = \sum_{\ell} \frac{N_{j,D}}{\omega^{D-2}} \left|A_j\right|^2$$

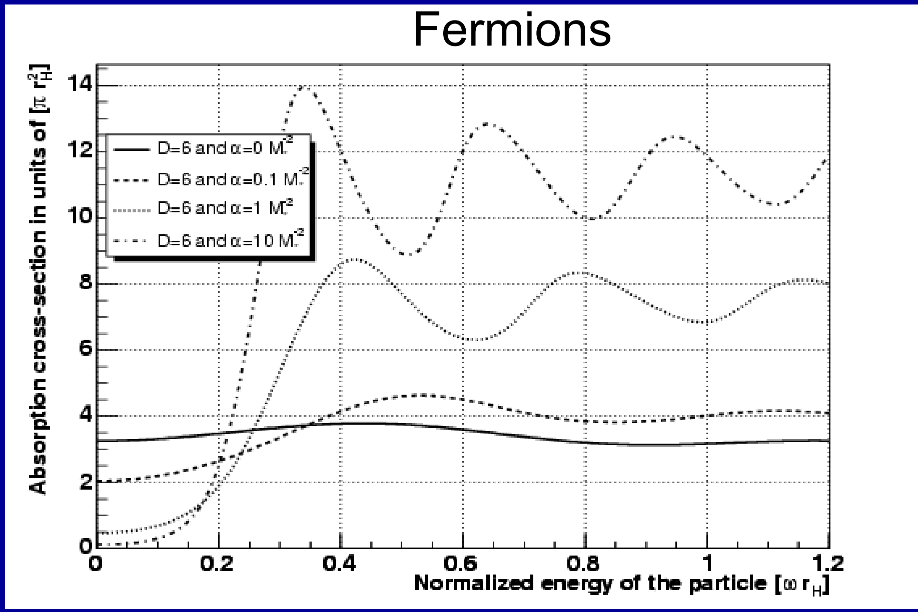
$N_{j,D}$ est la multiplicité du mode

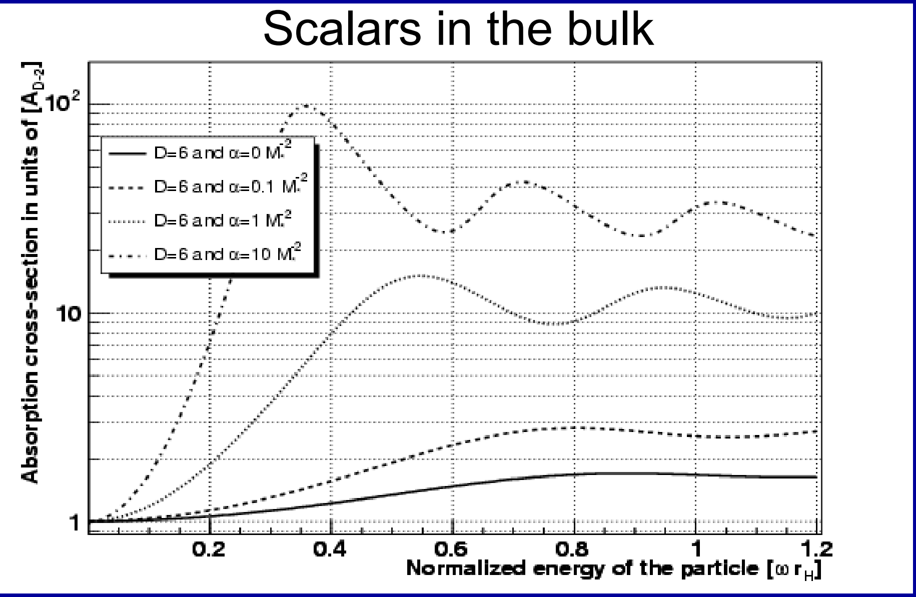
$N_{j,D} = (2j+1)\pi$ avec $j = \ell + s$ sur la brane

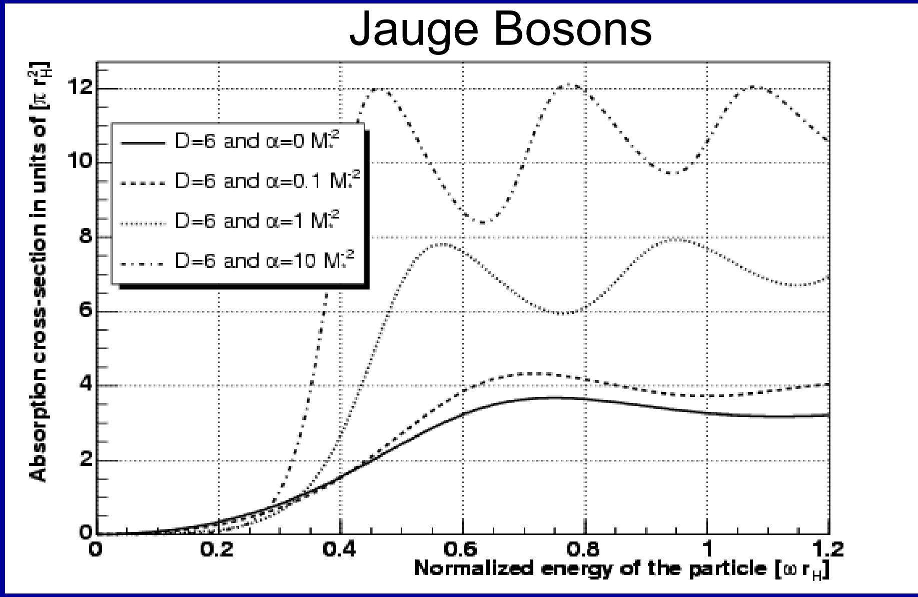
- Numerical errors under control

First consequence : Gauss-Bonnet black holes (1)



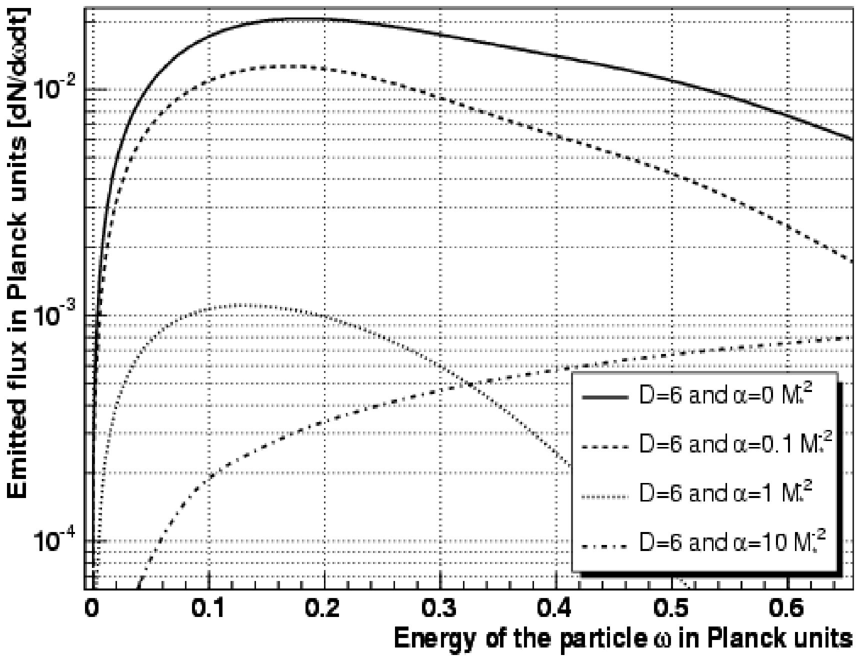




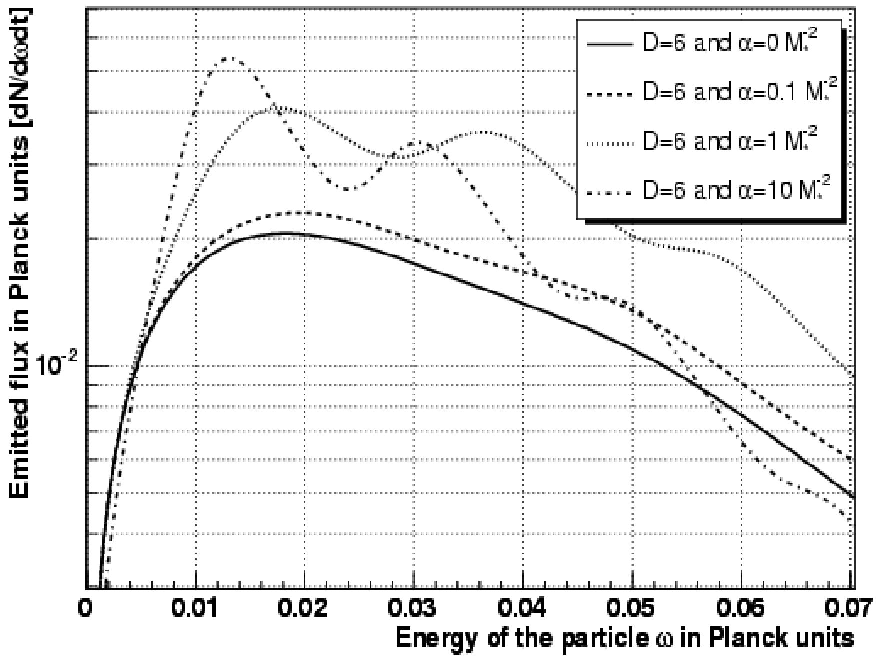


J. Grain, A. Barrau & P. Kanti, Phys. Rev. D 72 (2005) 104016

Gauss-Bonnet black holes (2)



$$M_{BH} = 10 M_D$$



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

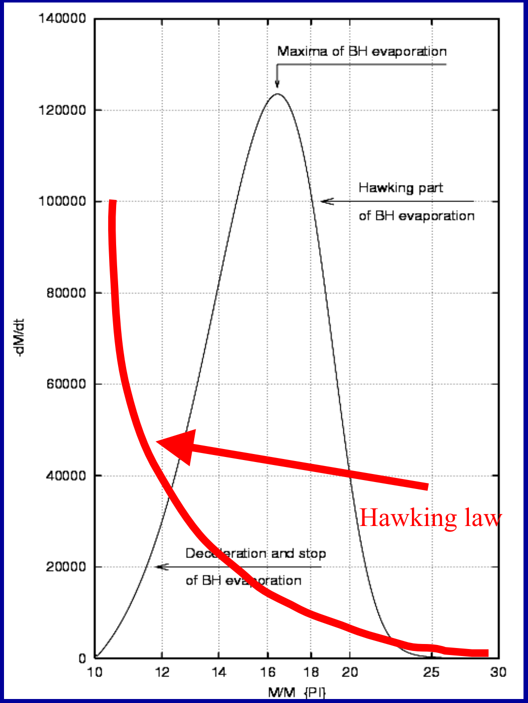
Gauss-Bonnet black holes (3) : 4-dimensions and dilatonic coupling

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

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

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

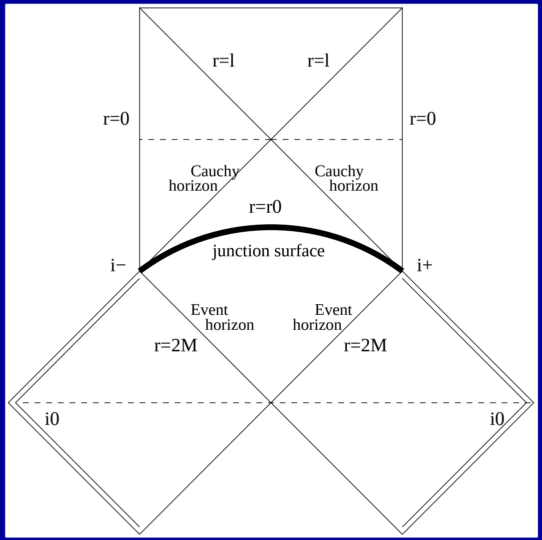
Alexeyev & Pomazonov, Phys. Rev. D 55 (1997) 2110
Alexeyev, Grav. Cosm. 3 (1997) 161



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

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.).

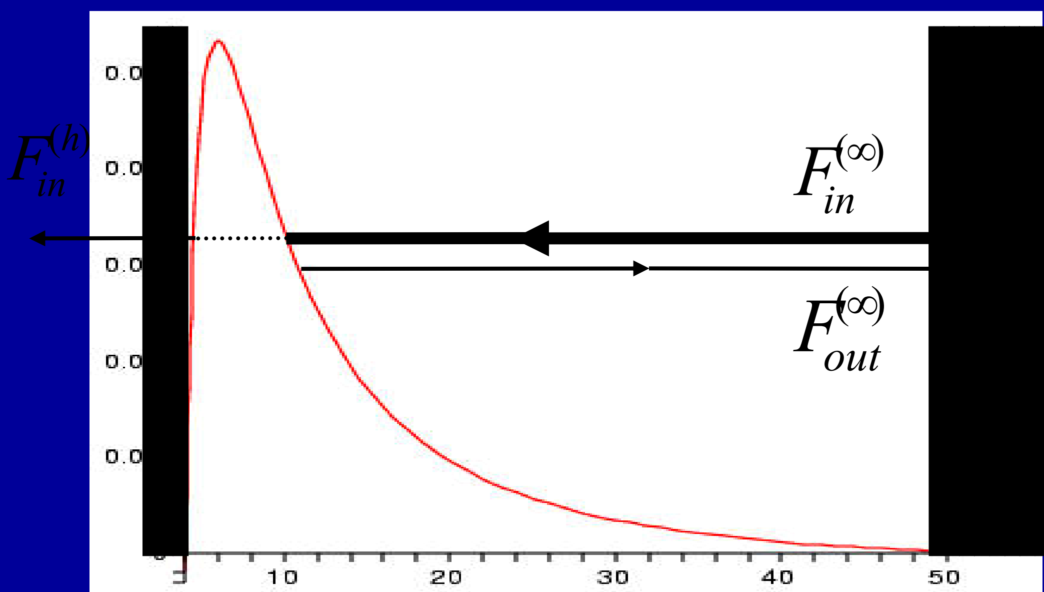
A. Barrau, gr-qc/0612045

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)

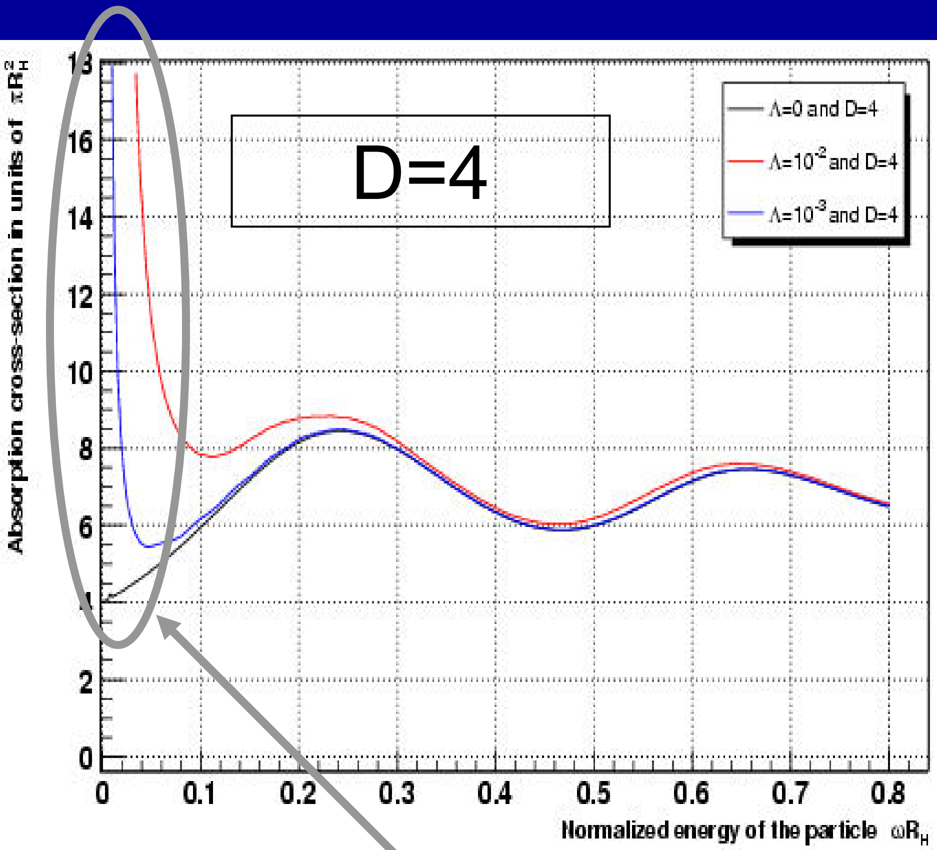
2 event horizons , 2 temperatures

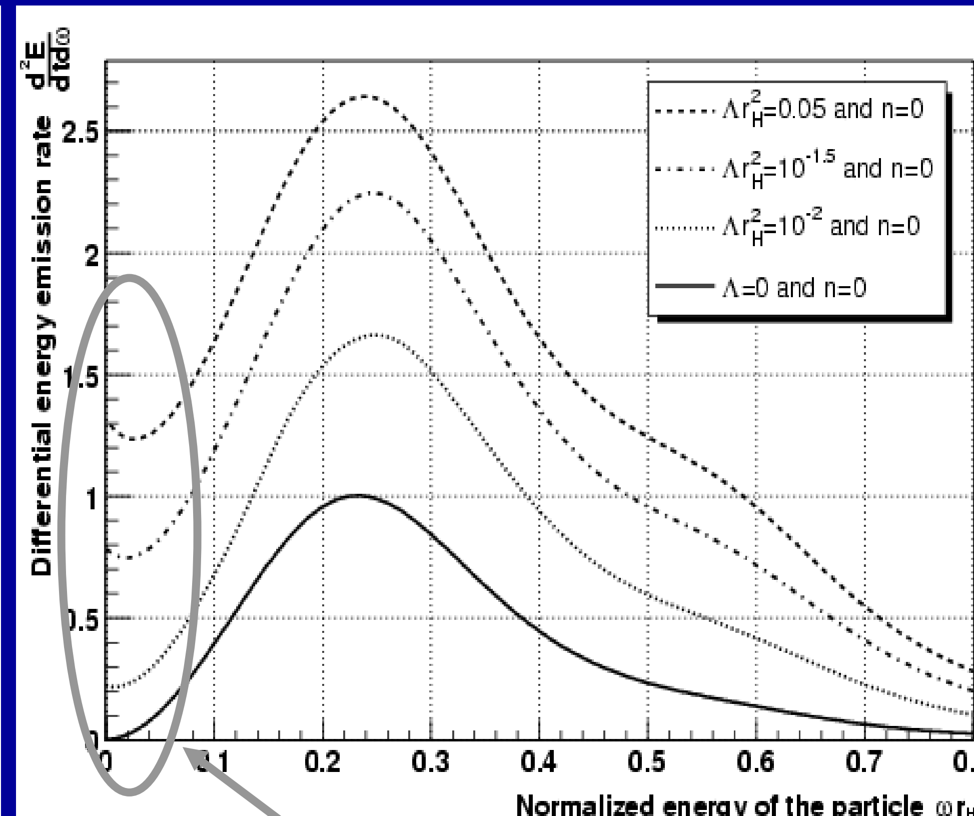


$$T_\Lambda = \frac{1}{\sqrt{h(r_0)}} \frac{1}{4\pi} \frac{dh(r)}{dr}\bigg|_{r_H}$$

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

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

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

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

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

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

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

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

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

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

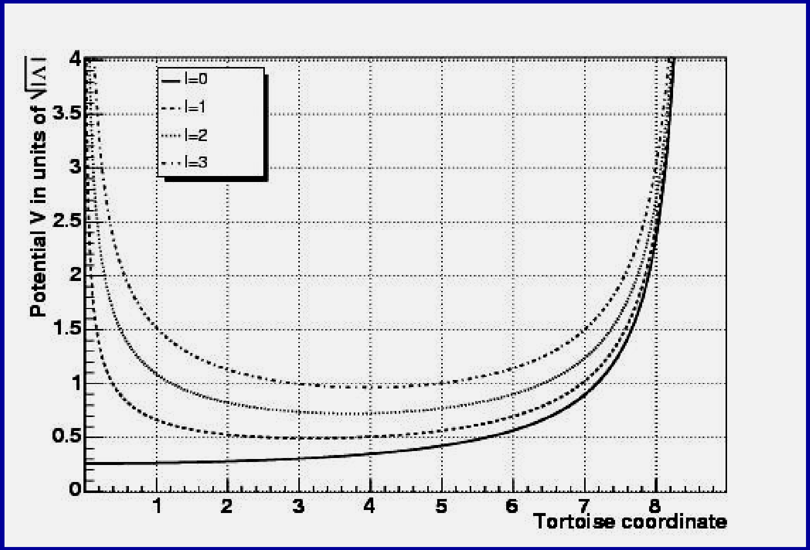
Anti-de-Sitter spaces (1)

- 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.

Aurélien Barrau LPSC-Grenoble (CNRS / UJF)

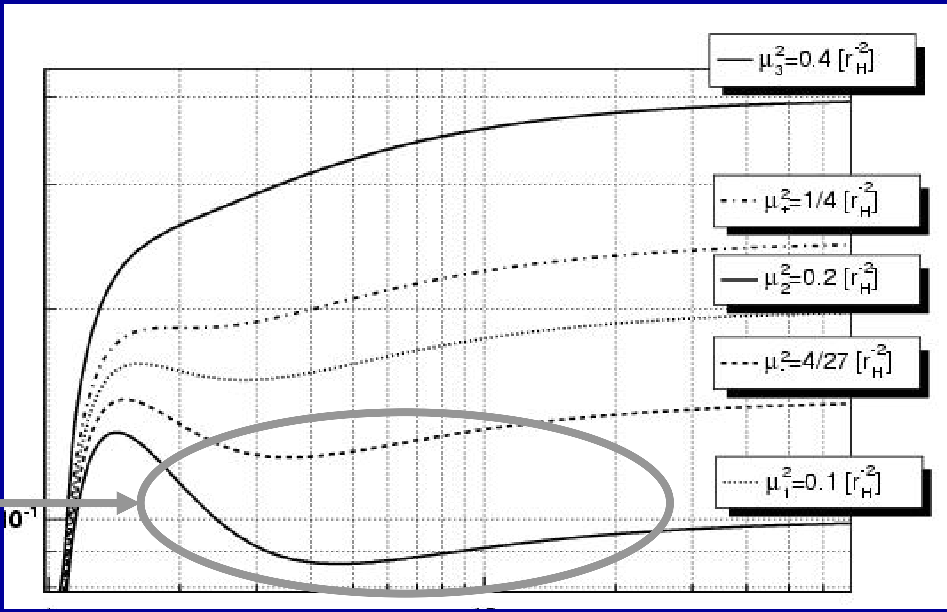
Back to Schwarzschild black holes : new quantum bound states

- For massive particles

J. Grain & A. Barrau, submitted to Phys. Lett (2007)

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

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

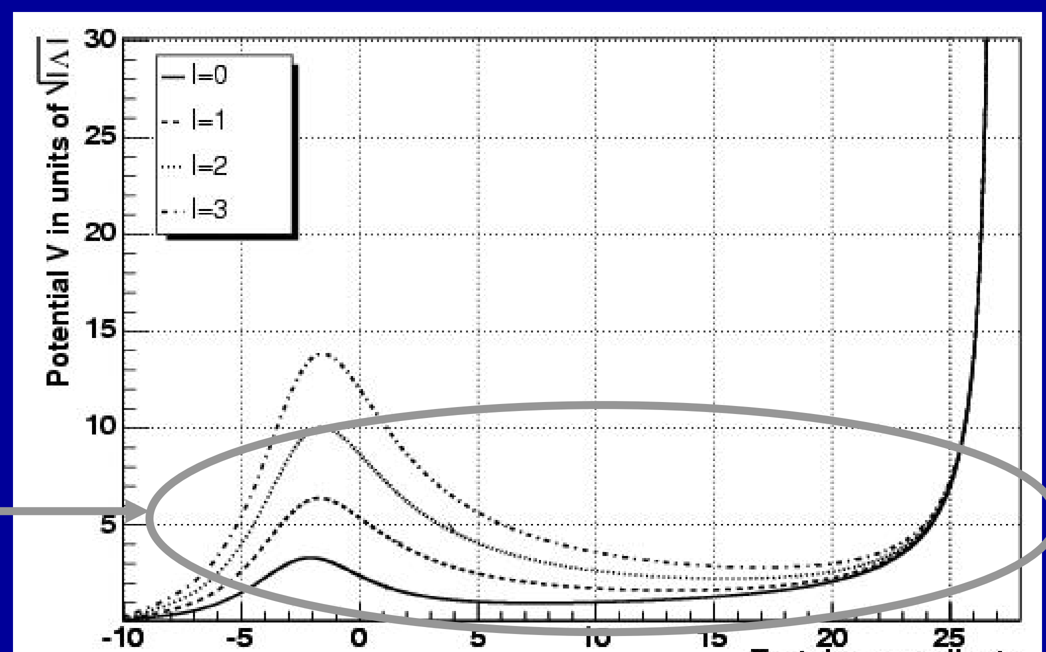
$$V_\ell^2(r) = \left(1 - \frac{2M}{r} + \frac{r^2}{R^2}\right)\left(\frac{\ell(\ell+1)}{r^2} + \frac{2M}{r^3} + \frac{2}{R^2}\right)$$

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

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

Singular transition from SAdS to AdS !

resonances



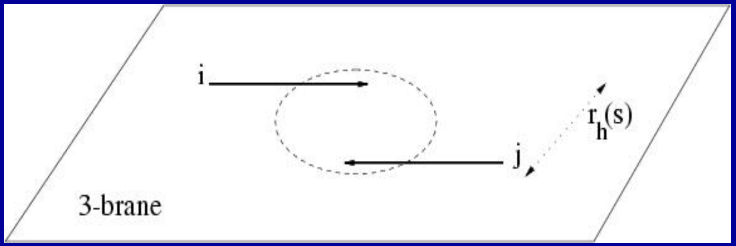
Tortoise coordinate

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

- Geometric cross section

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

$\sqrt{s} > M_D$

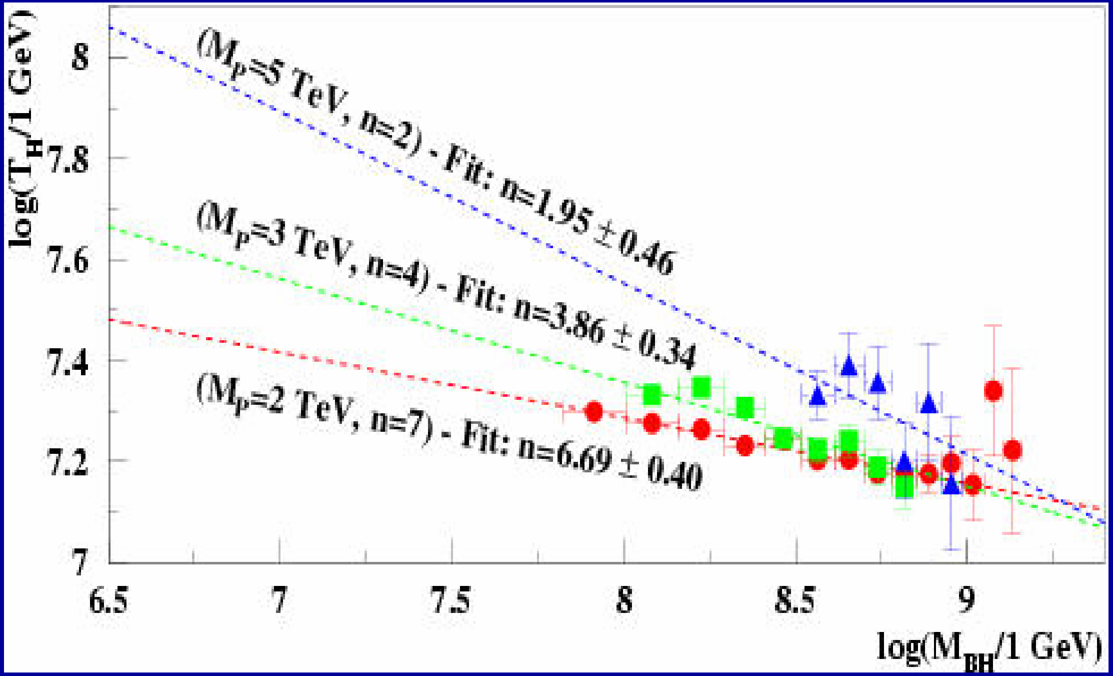


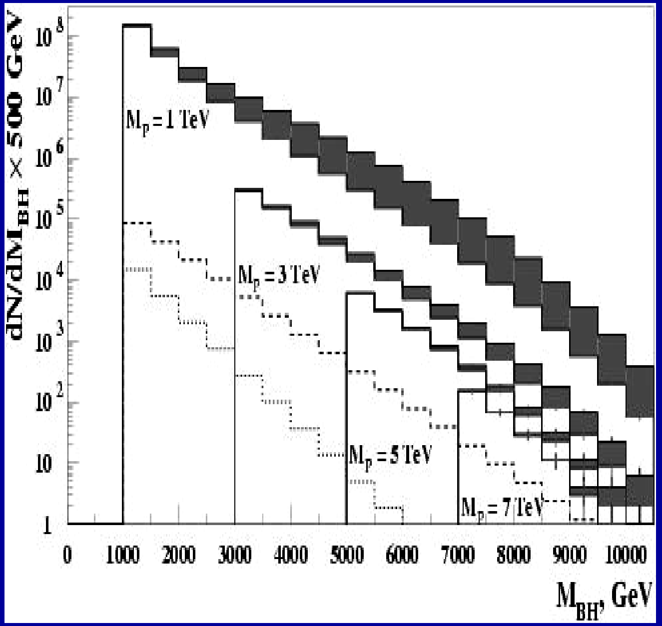
- Estimate of the number of produced black holes
- Reconstruction of the dimensionality

Banks, Fischler hep-th/9906038

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

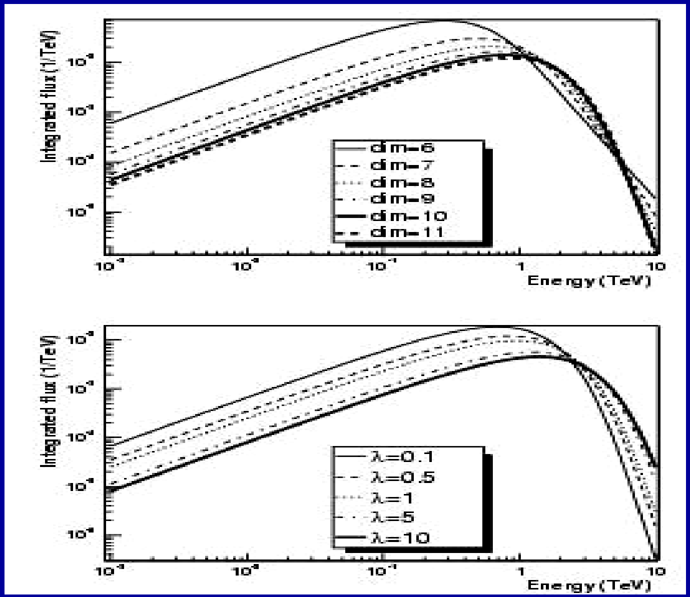
Dimopoulos, Landsberg Phys. Rev. Lett 87, 161602 (2001)

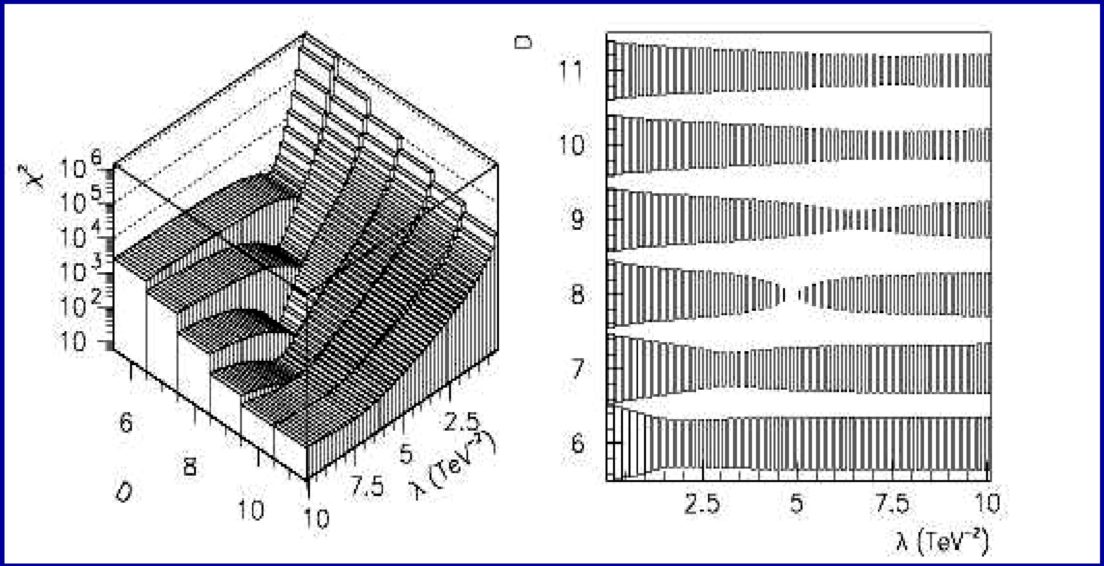




Black holes at the LHC (2)

- 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)

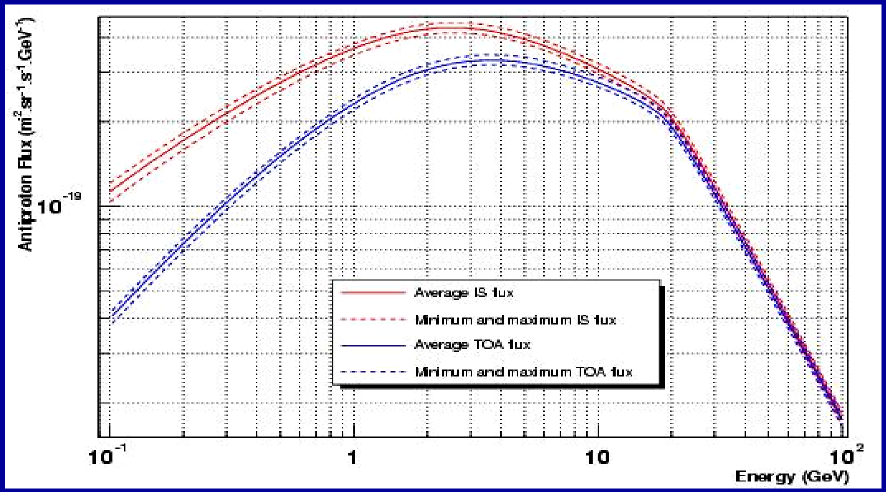
Also : Particle physics (light SUSY particles, Higgs, etc.) with BH as resonances

What about the interstellar medium ?

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

- 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

PBHs (Primordial Black Holes) could have formed in the early Universe !

- Direct formation by density fluctuations
- Softening of the equation if state
- Inflation fluctuations
- Phase transitions
- Topological defects collisions
- Critical phenomena

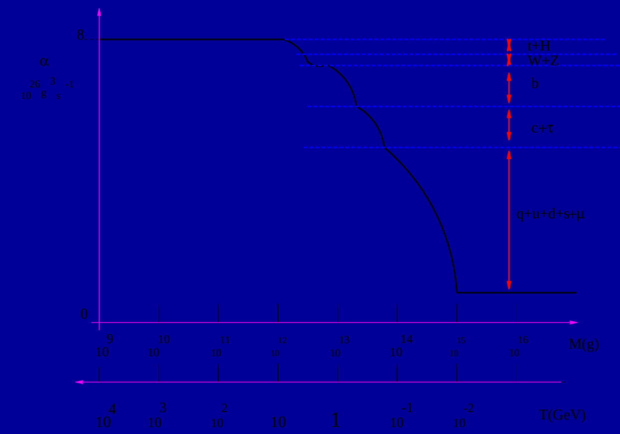
etc…

How to look for them ? Let's consider their cosmic-ray emission !

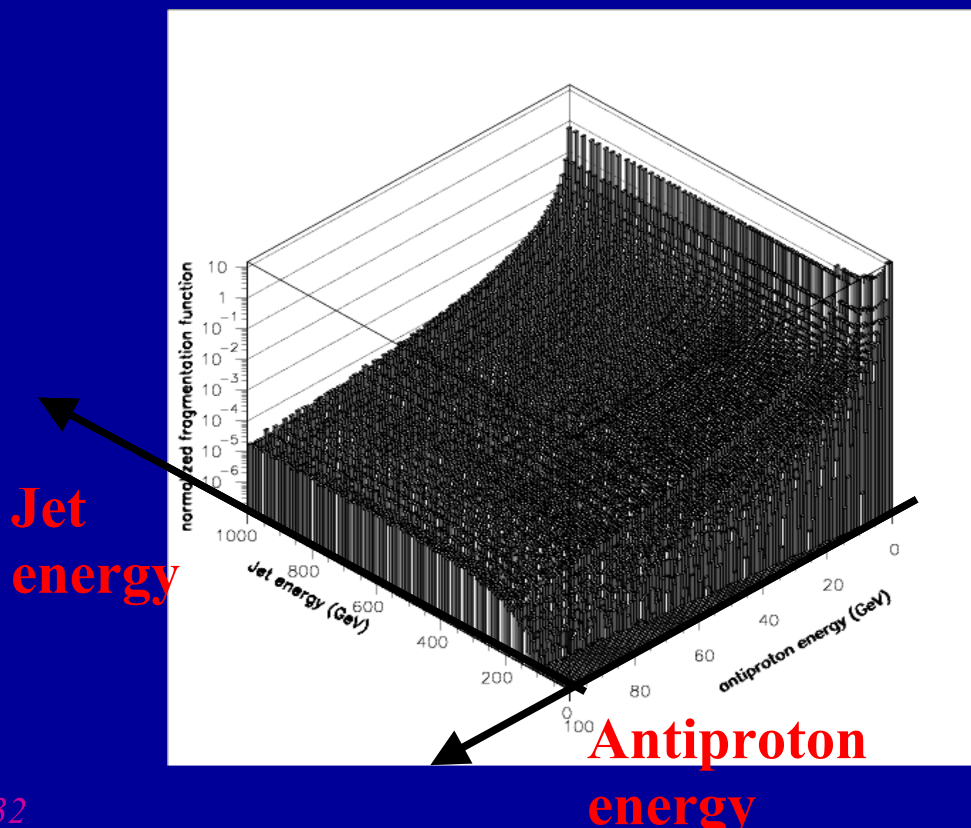
Aurélien Barrau LPSC-Grenoble (CNRS / UJF)

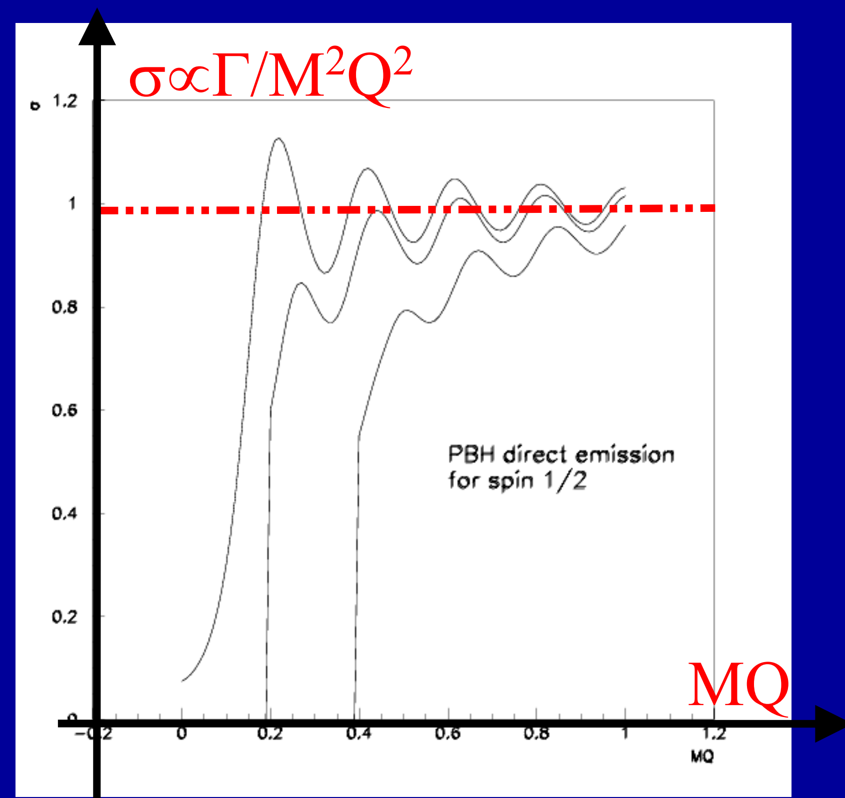
Antiproton individual emission

Antiprotons are rare : good S/N



$$\frac{d^2N_{\bar{p}}}{dEdt} = \sum_j \int_{Q=E}^{\infty} \alpha_j \frac{\Gamma_j(Q,T)}{h}\left(e^{\frac{Q}{kT}} - (-1)^{2s}\right)^{-1} \frac{dg_{j\bar{p}}(Q,E)}{dE} dQ$$





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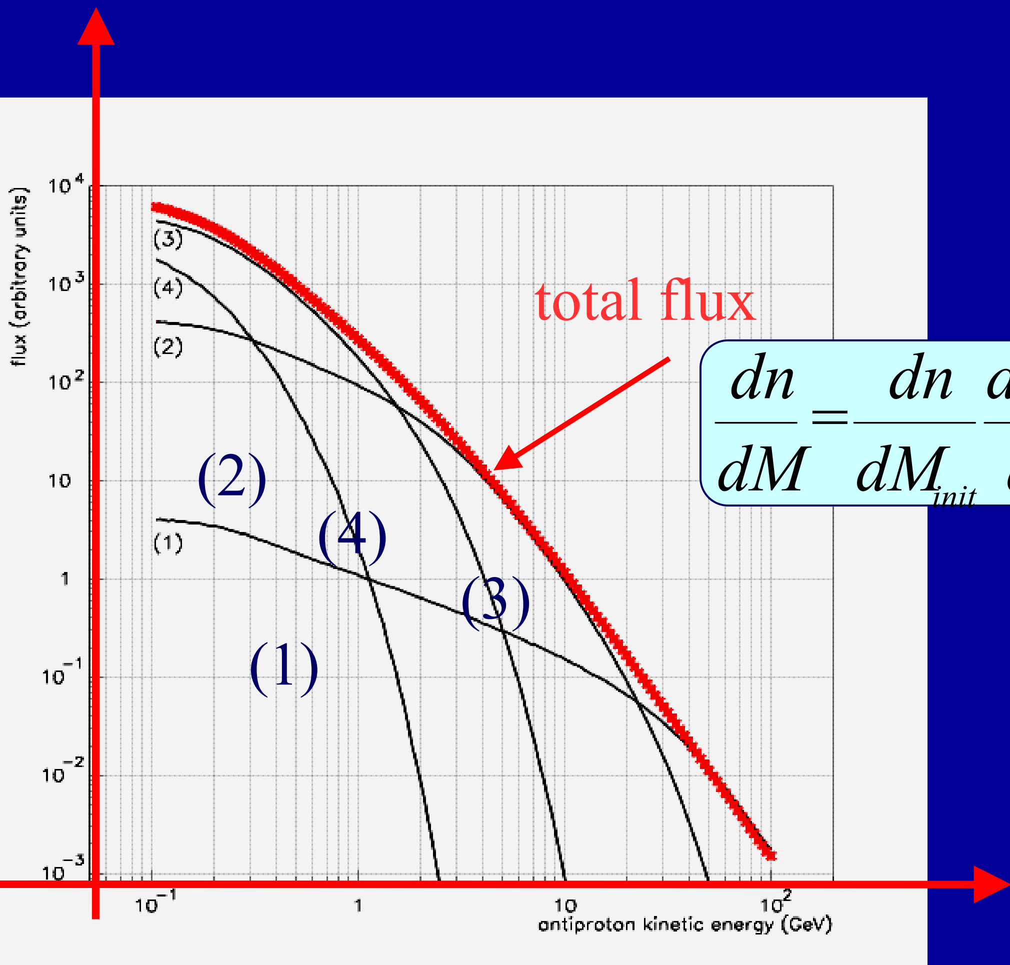
Cumulative source

$$q^{prim}(r,z,E) = \int \frac{d^2N(M,E)}{dEdT}\frac{d^2n(r,z)}{dMdV}dM$$

$$M_* \approx 5\times10^{14}\,g$$



Antiprotons kinetic energy (GeV)

$$\frac{dn}{dM} = \frac{dn}{dM_{init}}\frac{dM_{init}}{dM}$$

$$\frac{dn}{dM} \propto M^2 \leftrightarrow M < M_*$$

(1) $\rightarrow$ $M \in [M_{Pl}, 10^{12}\,g]$

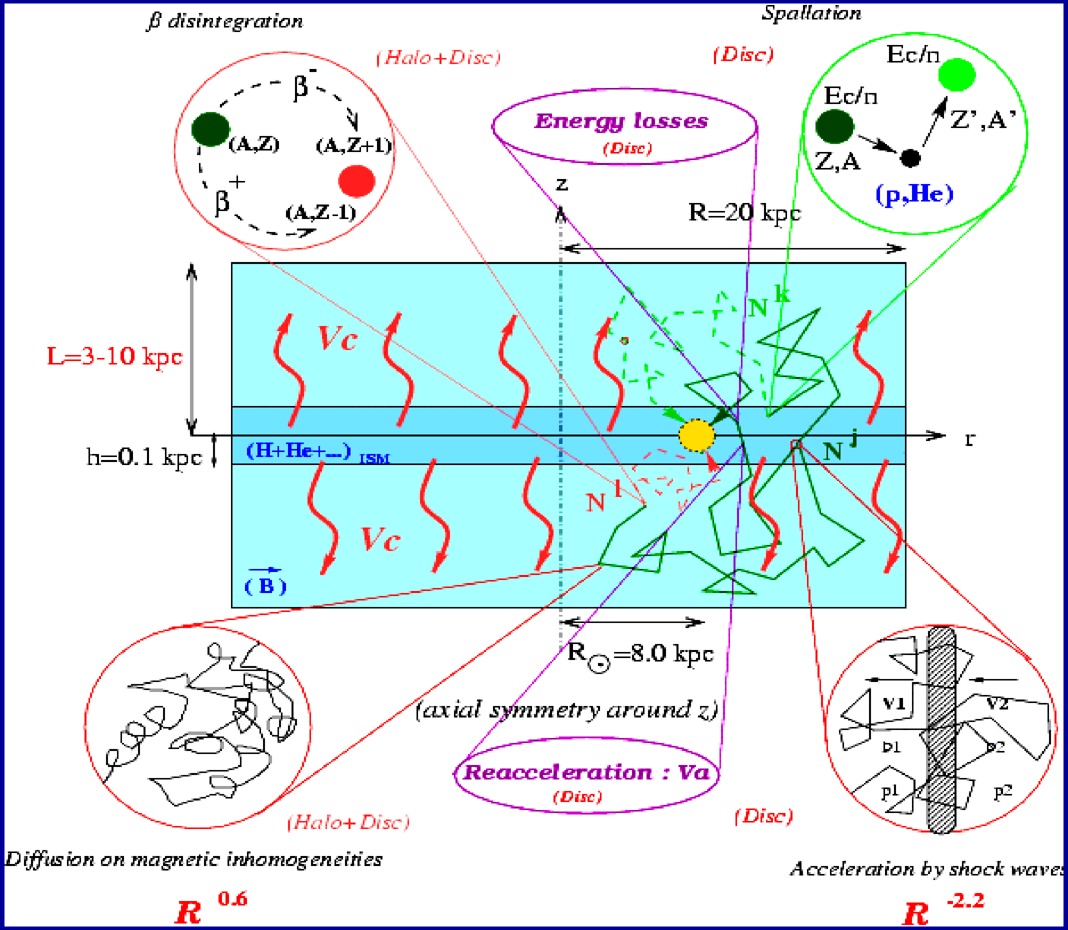
(2) $\rightarrow$ $M \in [10^{12}\,g, 10^{13}\,g]$

(3) $\rightarrow$ $M \in [10^{13}\,g,\ 5\times10^{13}\,g]$

(4) $\rightarrow$ $M > 5\times10^{13}\,g$

- **The horizon size after inflation is also taken into account**
- **A possible QCD halo around the BH is also considered**

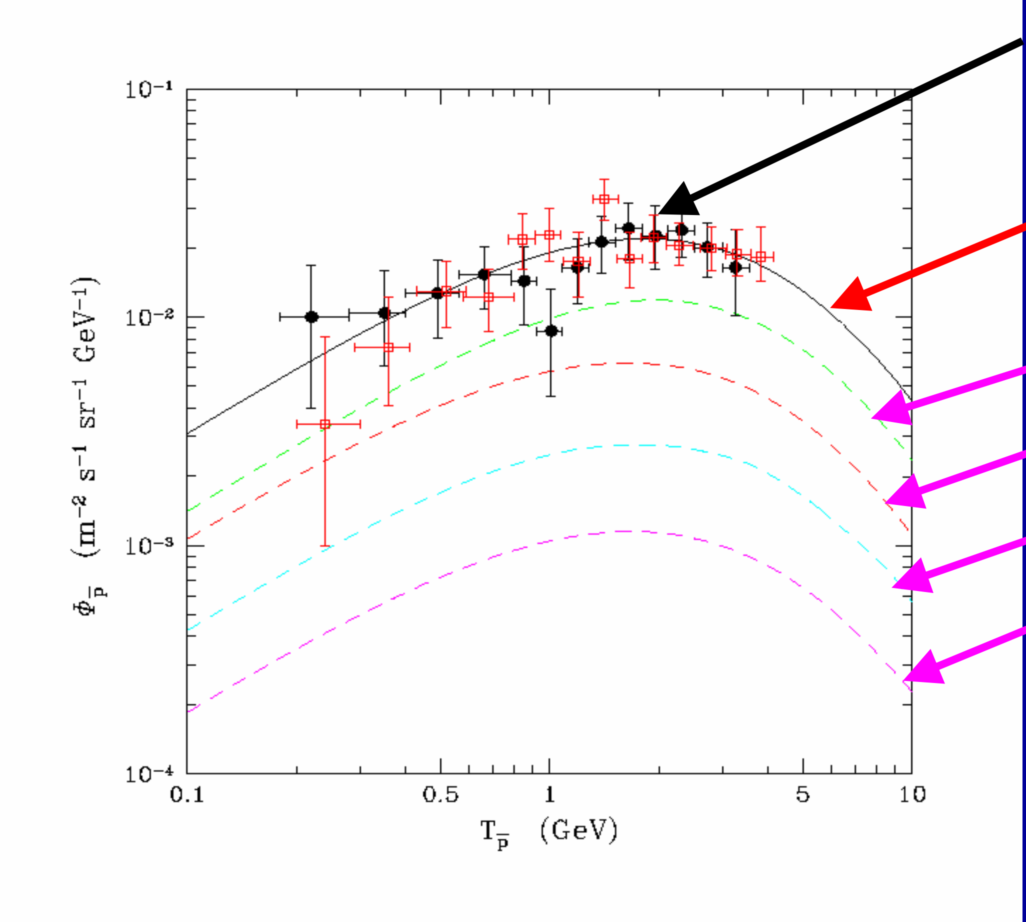
Now, let the antiprotons propagate in the Milky way…



Drawing by D. Maurin
"Annecy" model

Maurin, Taillet, Donato, Salati, Barrau, Boudoul, review article for "Research Signapost" (2002) [astro-ph/0212111]

Secondary antiprotons flux



Experimental data

Antiprotons flux

p-p component

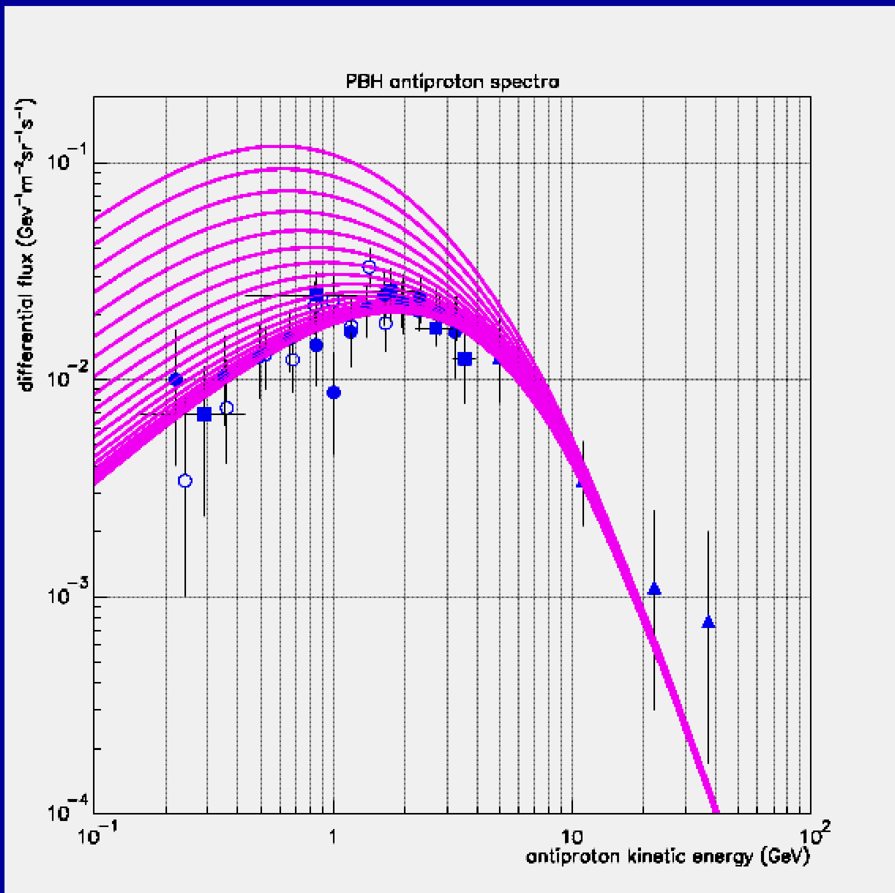
p-He component

He-p component

He-He component

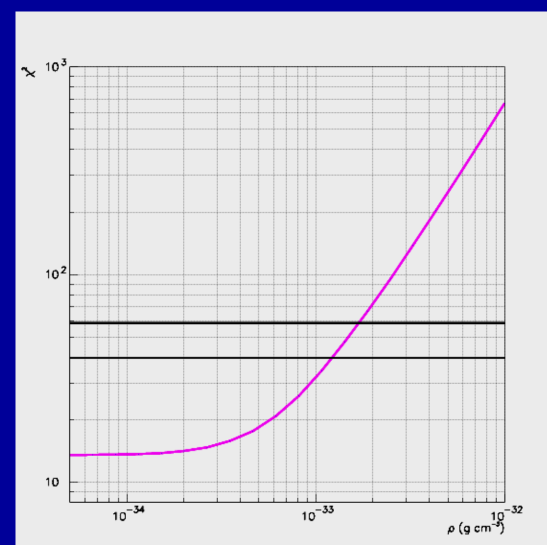
F.Donato, D. Maurin, P. Salati, A. Barrau, G. Boudoul, R.Taillet, Astrophys. J. (2001) 536, 172

Spectrum and limit on the PBH density



$$2h\delta(z)q(r,0,E)=2h\delta(z)\Gamma_{\bar p}^{ine}N(r,0,E)+\left\{V_c\frac{\partial}{\partial z}-K\left(\frac{\partial^2}{\partial z^2}+\frac{1}{z}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right)\right)\right\}N(r,z,E)$$

$$q(r,E)=\int_{Threshlod}^{\infty}\frac{d\sigma}{dE}\left\{p(E)+H_{ISM}\to\bar p\right\}n_H\left\{4\pi\Phi_p(r,E)\right\}dE$$



+ tertiaries

$$\Omega < 4\times10^{-9}$$

A. Barrau, *et al.*, Astronom. Astrophys., 388, 767 (2002)

Gamma-ray new upper limit

Taking into account the expected background from (Pavlidou & fields, ApJ 575, L5-8 (2002)):

- galaxies

- quasars

The EGRET gamma-ray flux at 100 MeV can be converted into (after integration over redshift, evolution and absorption) :

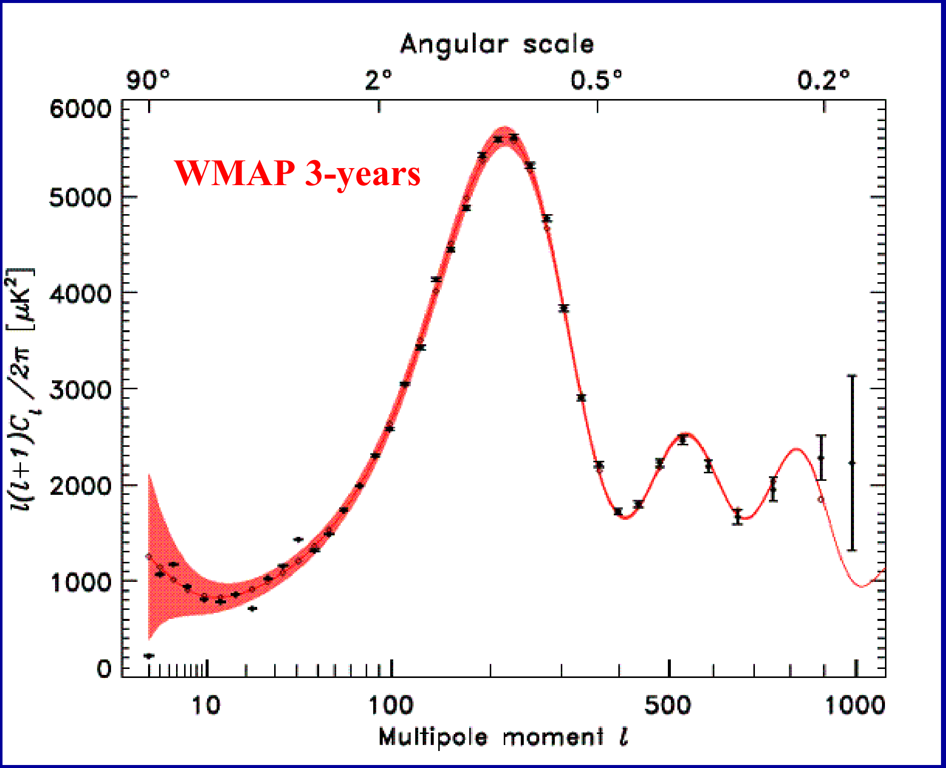
Omega_PBH < 3.3 E –9 , improving by a factor 3 the Page & MacGibbon upper limit.

This limit is nearly the same as with antiprotons but it relies on very different physics and assumptions.

Barrau & Boudoul, IRCR 2003 proc., [asto-ph/0304528]

COSMOLOGICAL CONSEQUENCES

Unlike the CMB or the large scale structures, PBH give information on small scale



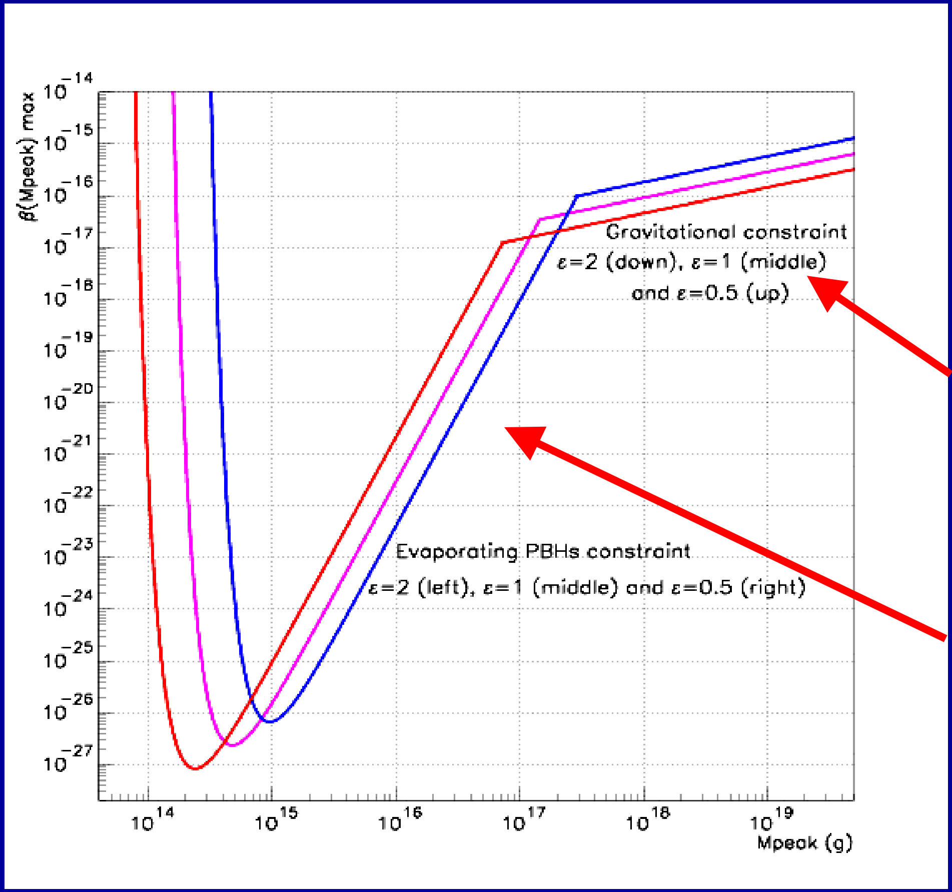
PRIMORDIAL BLACK HOLES ARE A UNIQUE COSMOLOGICAL PROBE

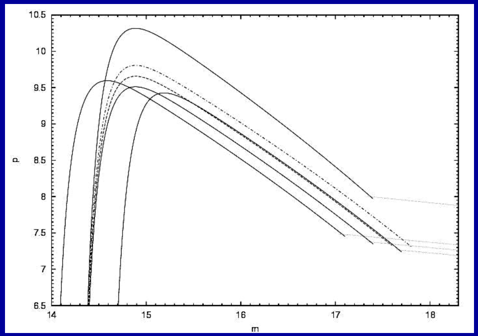
Aurélien Barrau LPSC-Grenoble (CNRS / UJF)

Density fluctuations in the early Universe constrained by PBHs

β (mass fraction of the Universe going into black holes)

Using Starobinsky model for the bump





Mpeak (g)

Barrau, Blais, Boudoul, Polarski, Phys. Lett. B, 551, 218 (2003)

The old problem of gravitinos in cosmology…

$$\frac{dn_{3/2}}{dt} + 3Hn_{3/2} = <\Sigma v> n_{rad}^2 - \frac{m_{3/2}}{E_{3/2}} \frac{n_{3/2}}{\tau_{3/2}}$$

Photons :

- gamma-gamma pair creation

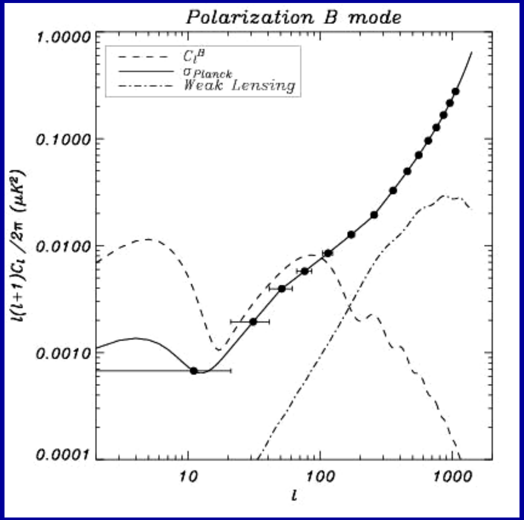
- pair creation on nuclei

- scattering

- compton

- inverse-Compton

The reheating temperature of the Universe cannot be too high



D + gamma → n+p

T + gamma → n+D

T + gamma → p+n+n

3He + gamma → p+D

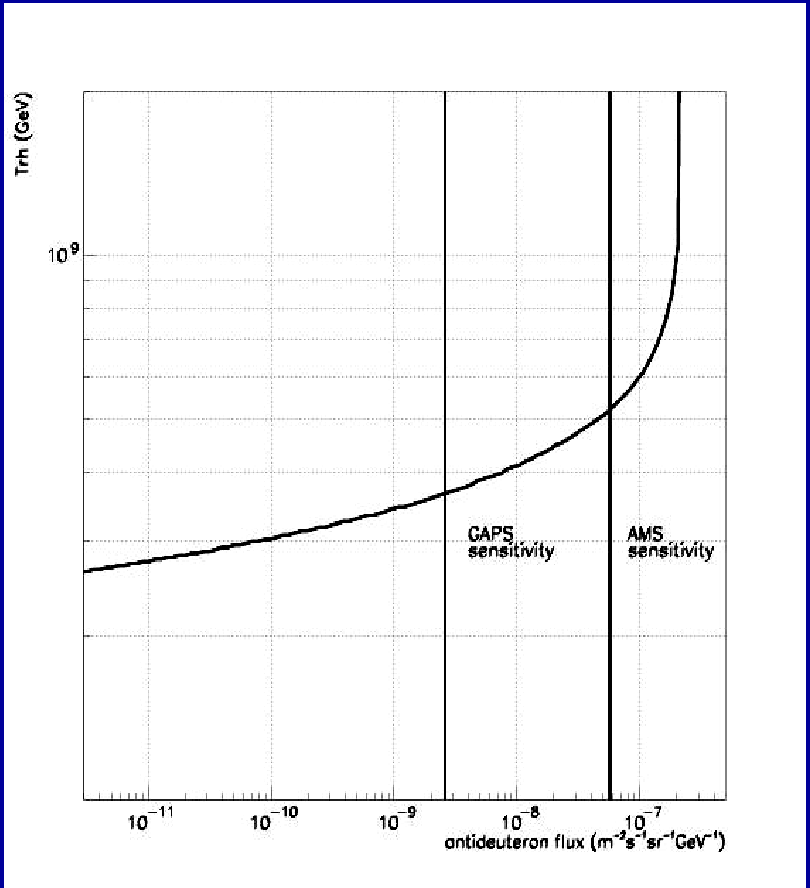
4He + gamma → p+T

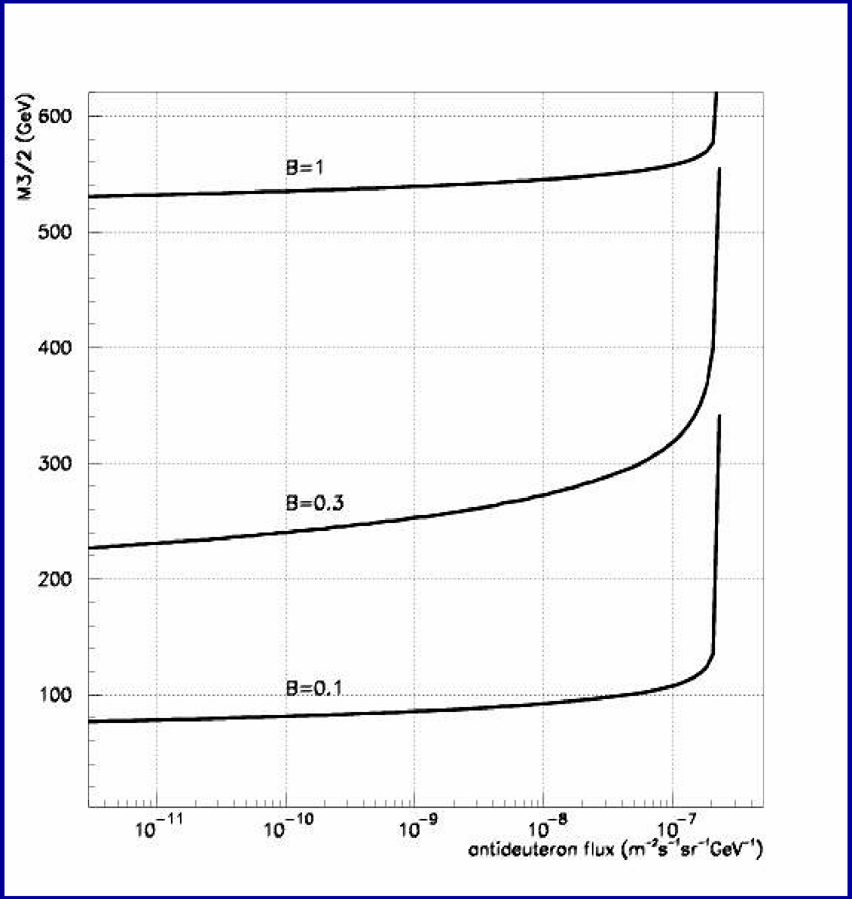
4He + gamma → n+3He

4He + gamma → p+n+D

……

Constraints on SUGRA

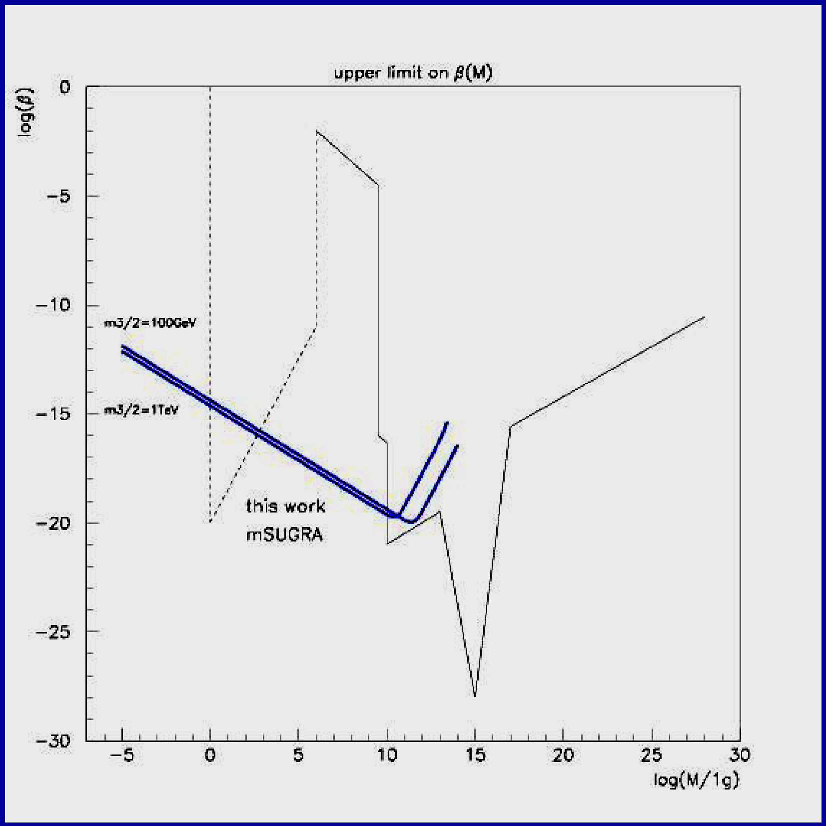


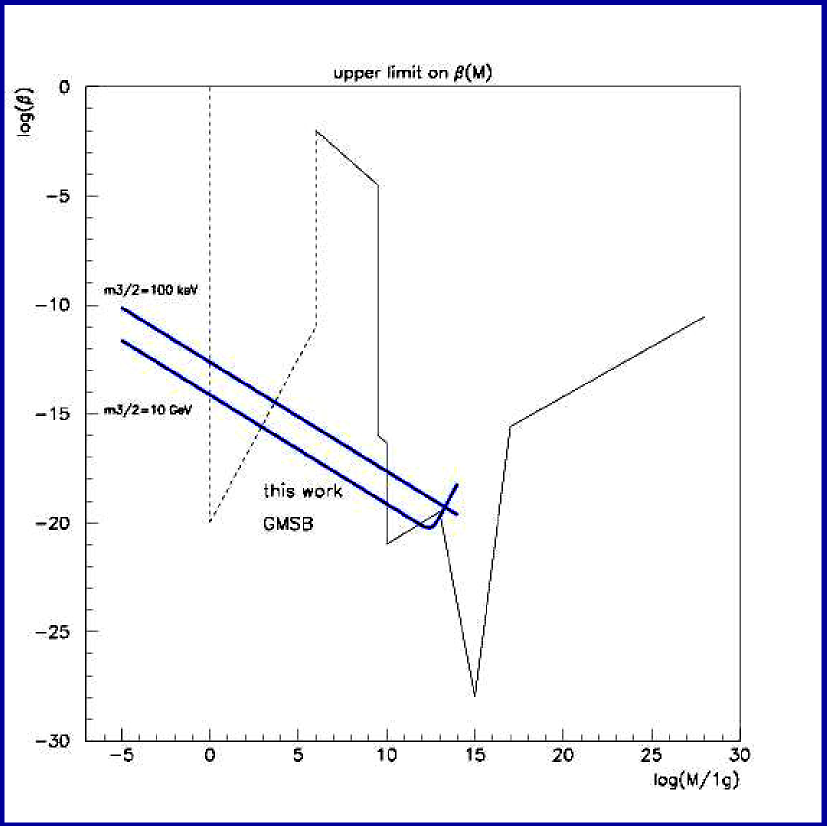


Lower limit on the reheating temperature as a function of the 100 MeV antideuteron flux

Barrau & Ponthieu, Phys. Rev. D 69 (2004) 105021

Gravitinos from PBHs





Khlopov & Barrau, Class. Quantum Grav. 23 (2006) 1875

• n<1.18 : the most stringent limit at small scale

• Positive running excluded

The only constrain of very small scale fluctuations

Dark Matter

In the BSI framework, PBHs can be reconsidered as CDM candidates
In two different scenarios

A. Barrau, D.Blais, G.Boudoul , D. Polarski
Ann. Phys. 13, 115 (2004)

- If M_{RH} is very large (greater than 10^{15} g) , PBHs become good candidates

$$p \approx \frac{\sigma_{H,COBE}}{\delta_{\min}} \sqrt{LW\left\{\frac{5.3\times 10^{-6}}{2\pi\Omega^2_{PBH}}\left[\frac{10^{15}}{M_{H,e}}\right]^3\right\}}$$

Pour $M_{H,e} = 10^{-15}$ g
$p \approx 6.5 \times 10^{-4}$

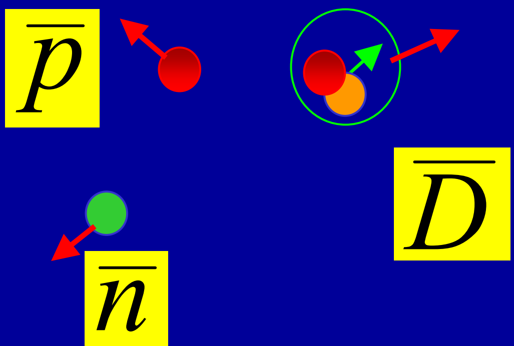
Experimental investigations possible above 10^{22} g by detection of gravitational waves

- If M_{RH} is small (smaller than 10^{9} g) , stable relics become good candidates

Very large parameter space (of masses) for PBH/relics dark matter. But fine tuning of the « jump » required (unnatural ? Caution in cosmology !)

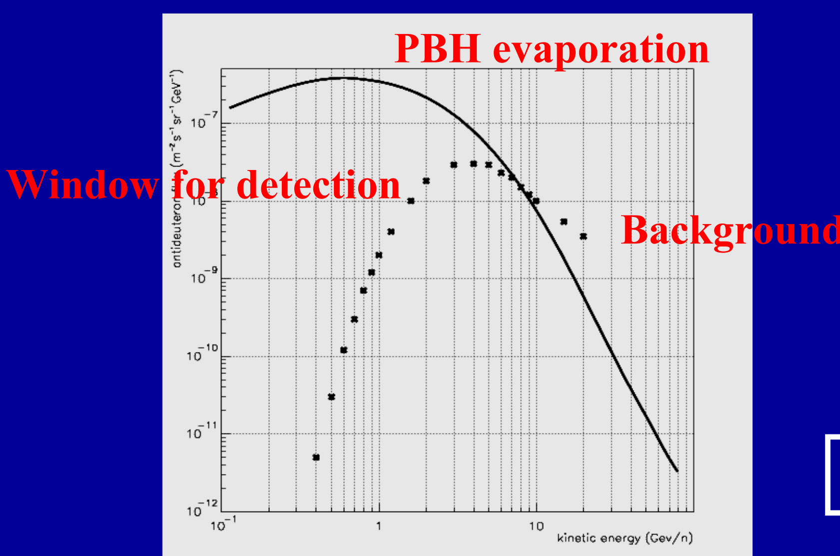
A new hope for detection ? Antideuterons !

➜ Secondary noise very small (kinematics)



$$\frac{d^2N_{\bar{D}}}{dEdt} = \sum_j \int_{Q=E}^{\infty} \alpha_j \frac{\Gamma_j(Q,T)}{h}\left(e^{Q/kT} - (-1)^{2s_j}\right)^{-1} \times \frac{dg_{j\bar{D}}(Q,E,P_0)}{dE} dQ$$

Relativistic coalescence model in the MC

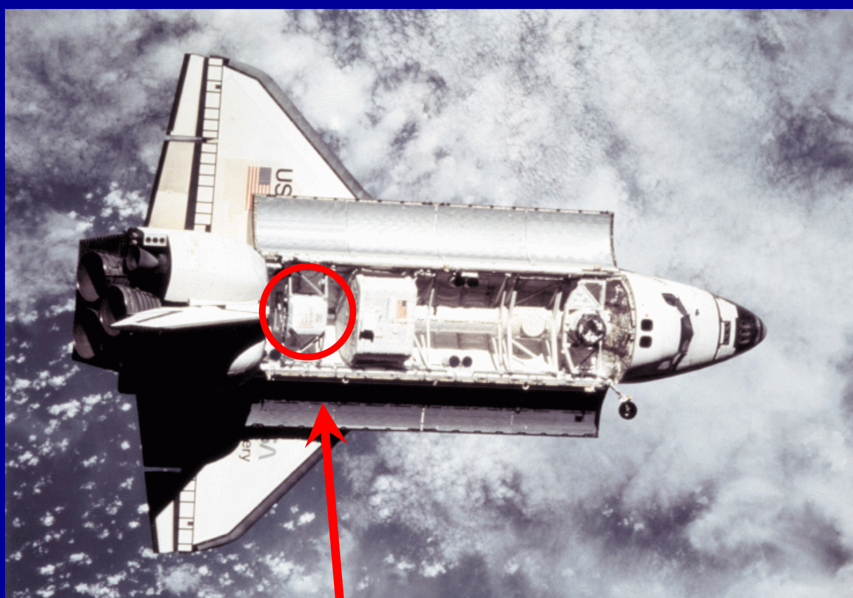


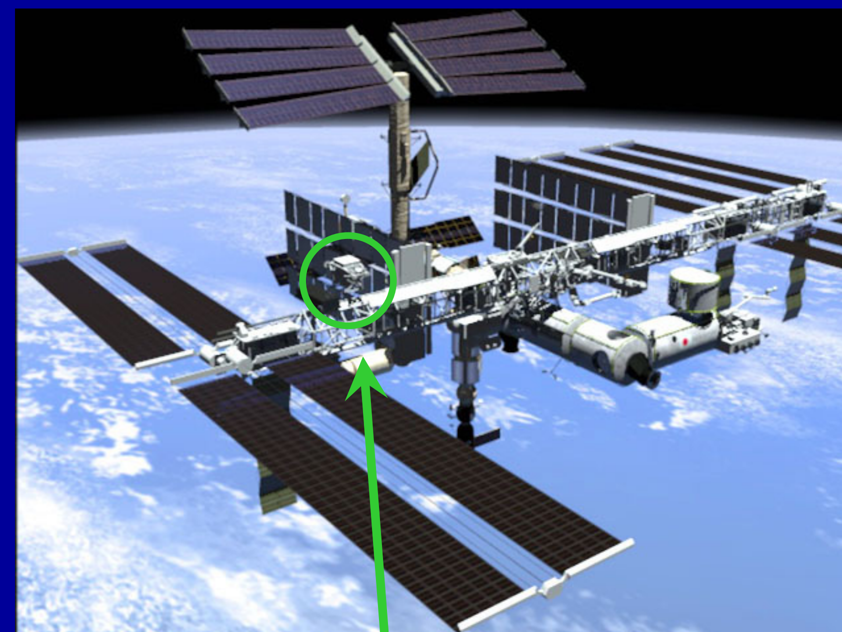
Improvement in sensitivity of 1-2 orders of magnitude

A. Barrau *et al.* Astronom. Astrophys. 398, 403 (2003)

The AMS experiment

- Antiproton sensitivity
- Antideuteron sensitivity
- Gamma-ray sensitivity





AMS-01: test fly in 1998 In 2010... AMS-02 on the ISS!

Aurélien Barrau LPSC-Grenoble (CNRS / UJF)

Back to the theory

Evaporating black holes encode an invaluable information on the underlying fundamental theories and on the intrinsic structure of spacetime.

Primordial black holes (whether they do exist or not) allow otherwise unreachable limits on the early universe.

Quantum effects near an event horizon exhibit an exceptionally rich physics.

Microscopic black holes *oblige* us to face unification

Toward a new paradigm ?

Unification and diversity : gauge fields and symmetry breaking

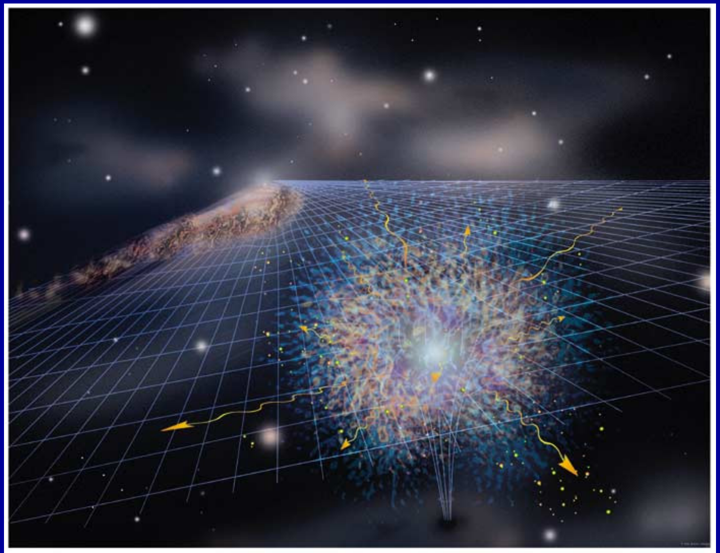
BUT… the story (of Newton and Maxwell) is changing : the number of parameters is inflating (maybe even more than the Universe did !!!) with supersymmetry and string theory.

The multiverse scenario (either through black holes or through chaotic inflation) is tantalizing … if anthropic devils (ID) do not take this opportunity to spoil the foundation of free thinking.

« Men are <u>within</u> the Universe. They are neither its reason to be –as Christian anthropocentrism has told us during centuries– nor its final cause –as contemporary atheistic anthropolatry tries, even more naïvely, to teach us today. »

M. Yourcenar (from the french Academy)
about the greak philosopher Empedocle d'Agrigente

A conclusion ?



Big black holes are fascinating
But… small black holes are much more fascinating!