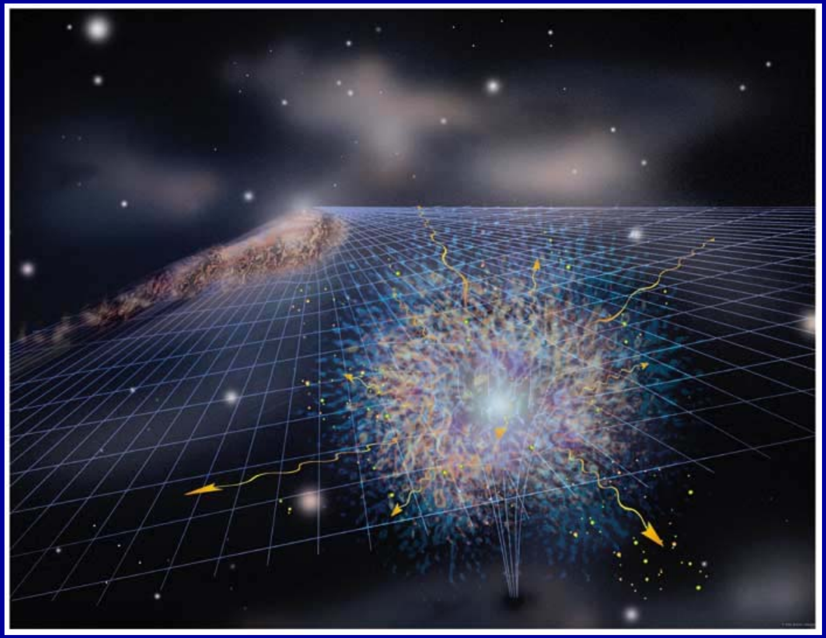
Quelques aspects de gravitation étendue



Aurélien Barrau

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Pourquoi chercher au-delà de la RG ?

Dark energy (and dark matter) / quantum gravity

- Observations : the Universe is accelerating while gravity is (most of the time) attractive. Dark matter could even be more dramatic for standard models.
- Consistence with quantum mechanics

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 and the early universe are probably the most promising places !

* thermodynamics (entropy)

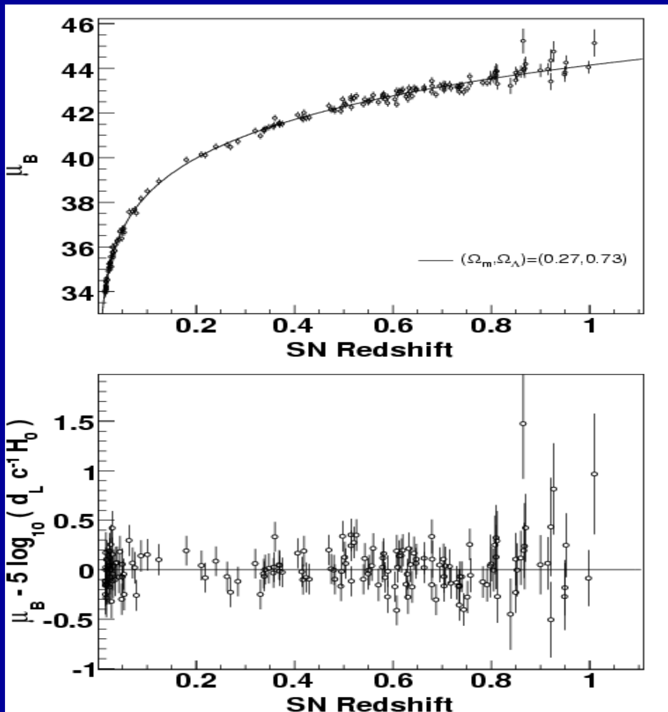
* violation of coherence

* IR/UV connection…

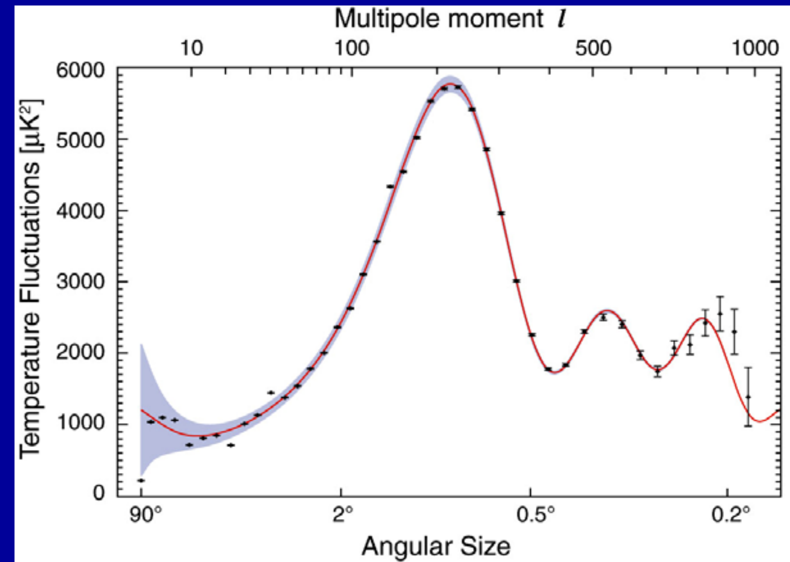
→ String theory ?

→ Loop quantum gravity ?

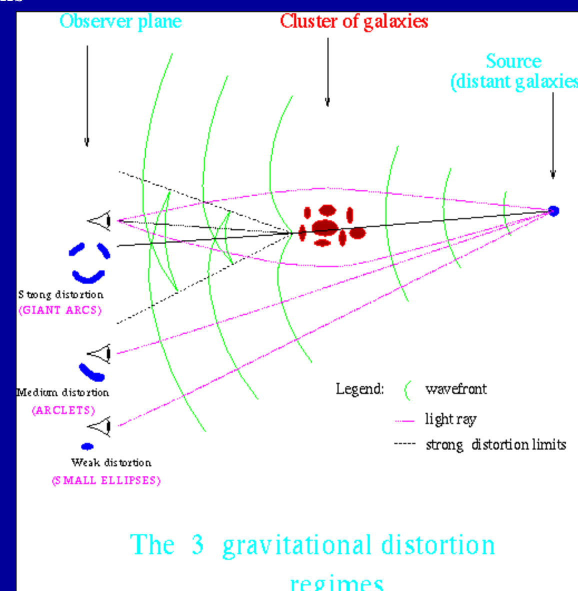
L'accélération observée

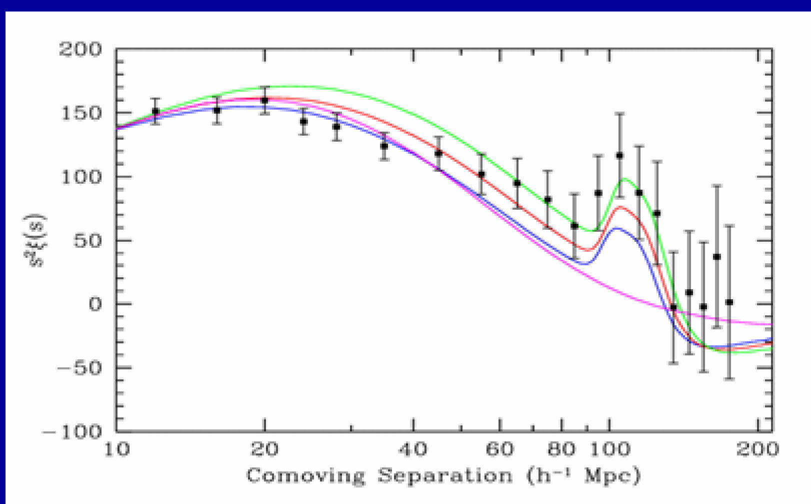


SNLS, Astier et al.



WMAP, 5 ans





SDSS, Eisenstein et al. 2005

Aurélien Barrau LPSC-Grenoble (CNRS / UJF)

Comment "reconstruire" l'énergie noire ?

$$\Lambda / 8\pi G \sim 10^{-47}\, GeV^4$$

← Nous dit ce que l'énergie noire n'est pas !

Deux classes: physique / géométrique

Pléthore de modèles (motivés par l'inflation « primitive ») :

- Quiessence
- Quintessence
- Chaplygin Gaz
- 'Phantom' DE
- Oscillating DE
- Scalaire-tenseur
- Gravité modifiée
- DE quantique
- Branes
- DE holographique
- Etc.

Sahni & Starobinsky, IJMP A (2006)

Définition effective de la DE. Conduit dans un fond FRW à:

$$H^2 = \frac{8\pi G}{3}\left(\sum_a \rho_a + \rho_{DE}\right) - \frac{k}{a^2}\ ,$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\sum_a (\rho_a + 3p_a) + \rho_{DE} + 3p_{DE}\right)$$

Attention, pour DGP par exemple w est <u>effectif</u>

$$H = \sqrt{\frac{8\pi G\rho_{\rm m}}{3} + \frac{1}{l_c^2}} + \frac{1}{l_c}\ ,$$

Trois quantités fondamentales : $r(z)$,$D_L(z)$,$D_A(z)$

→Reconstruction : age, décélaration, z(reionisation), dA*H, dA^2/H, A, R, etc.

→Attention aux ordres de différentiation

Avec w=p/ρ

$$w(x) = \frac{2q(x)-1}{3\,(1-\Omega_{\rm m}(x))} \equiv \frac{(2x/3)\ d\ \ln H\ /\ dx - 1}{1\ -\ (H_0/H)^2\Omega_{m0}\ x^3}$$

Face aux “véritables” données

H(z) et d’autres sondes importantes de la DE sont très clairement mathématiquement reconstructibles mais les données sont : disctrètes et bruitées. → Necessité d’un lissage

1) Reconstruction paramétrique : $D_L(z,a_i)$, $H(z,a_i)$, $w(z,a_i)$ comparées aux observations

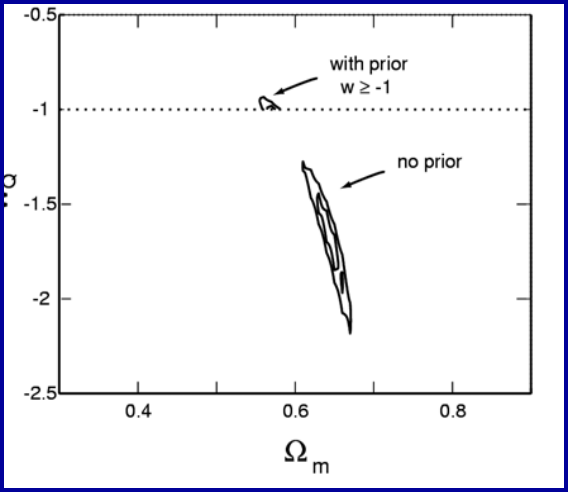
Attention au “critère d’information” ! Par exemple :

$$\delta = -\frac{1}{aHf}\nabla \cdot \mathbf{v}$$

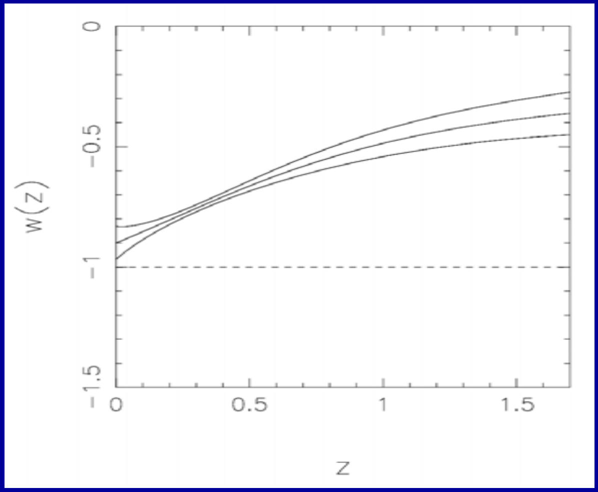
2) Reconstruction non-paramétrique. Différentes approches.

Il faut choisir la taille caractéristique du lissage. $$\frac{\delta H}{H} \propto \frac{\sigma}{N^{1/2}\Delta^{3/2}}$$ **Pire pour w !**

Nombreuses erreurs Possibles :



Modèle fiduciel :
w=-0.7+0.8z
Omega_m=0.3
Reconstruction :
Bas : w=cte
Haut : w=cte>1



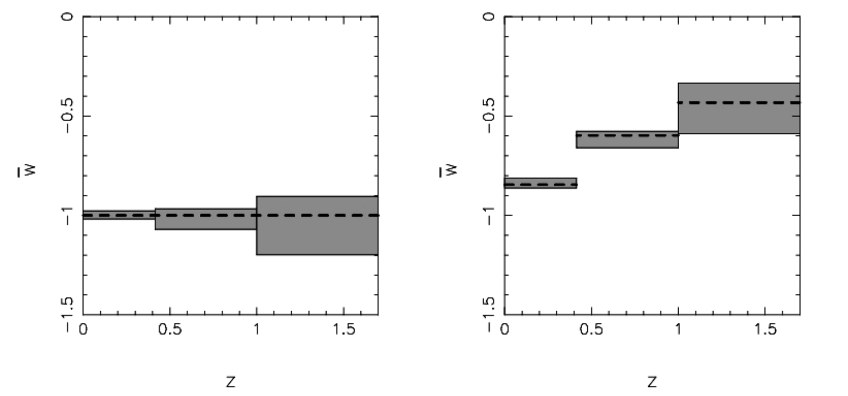
Modèle fiduciel :
w=-1
Omega_m=0.3
Recontrcution :
Omega_m=0.2

Shafieloo et al., MNRAS 366 (2006) 1081

Maor et al., Phys Rev D 65 (2002) 103512

Au-delà…

La “sonde w” : moyenne pondérée



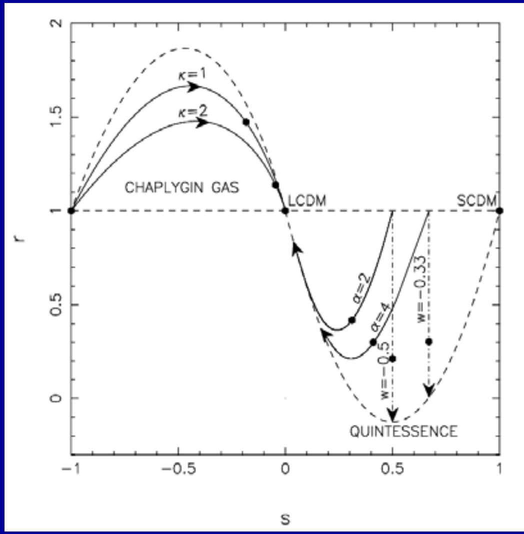
Gauche : w=-1, droite w=-1/(1+z)

Shafieloo et al., MNRAS 366 (2006) 1081

Géométrie “au troisième ordre”

$$a(t) = a(t_0) + \dot{a}\big|_0 (t - t_0) + \frac{\ddot{a}\big|_0}{2}(t - t_0)^2 + \frac{\dddot{a}\big|_0}{6}(t - t_0)^3 + \ldots .$$

Level	Geometrical Parameter	Physical Parameter
1	$H(z) \equiv \frac{\dot{a}}{a}$	$\rho_m(z) = \rho_{0m}(1+z)^3$, $\rho_{\rm DE} = \frac{3H^2}{8\pi G} - \rho_m$
2	$q(z) \equiv -\frac{\ddot{a}a}{\dot{a}^2} = -1 + \frac{d \log H}{d \log (1+z)}$, $q(z)\Big\vert_{\Lambda\rm CDM} = -1 + \frac{3}{2}\Omega_m(z)$	$V(z)$, $T(z) \equiv \frac{\dot{\phi}^2}{2}$, $w(z) = \frac{T-V}{T+V}$, $\Omega_V = \frac{8\pi G V}{3H^2}$, $\Omega_T = \frac{8\pi G T}{3H^2}$
3	$r(z) \equiv \frac{\dddot{a}a^2}{\dot{a}^3}$, $s \equiv \frac{r-1}{3(q-1/2)}$, $\{r,s\}\Big\vert_{\Lambda\rm CDM} = \{1,0\}$	$\Pi(z) \equiv \dot{V} = \dot{\phi}V'$, $\Omega_\Pi = \frac{8\pi G \dot{V}}{3H^3}$



Alam et al., MNRAS 344 (2003) 1057

Et surtout, de futures données : Planck, SNAP, ECLAIRS, JWST, EMIR, SKA, LSST ….

D'un peu plus près sur scalaire-tenseur

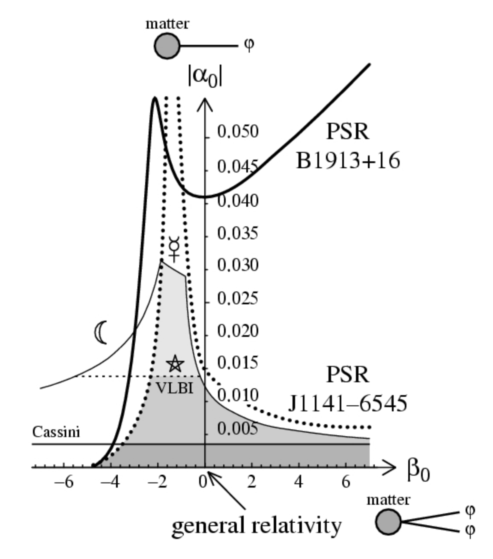
De nombreuses motivations théoriques

$$S = \frac{c^3}{4\pi G}\int \sqrt{-g}\left\{\frac{R}{4} - \frac{1}{2}(\partial_\mu\varphi)^2 - V(\varphi)\right\} + S_{\text{matter}}\left[\text{matter}; \tilde{g}_{\mu\nu} \equiv A^2(\varphi) g_{\mu\nu}\right]$$

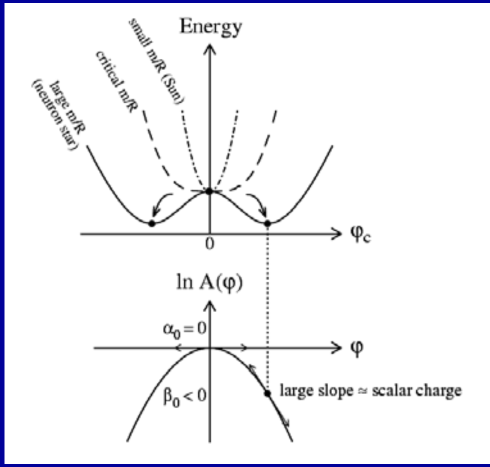
1) Tests "système solaire"

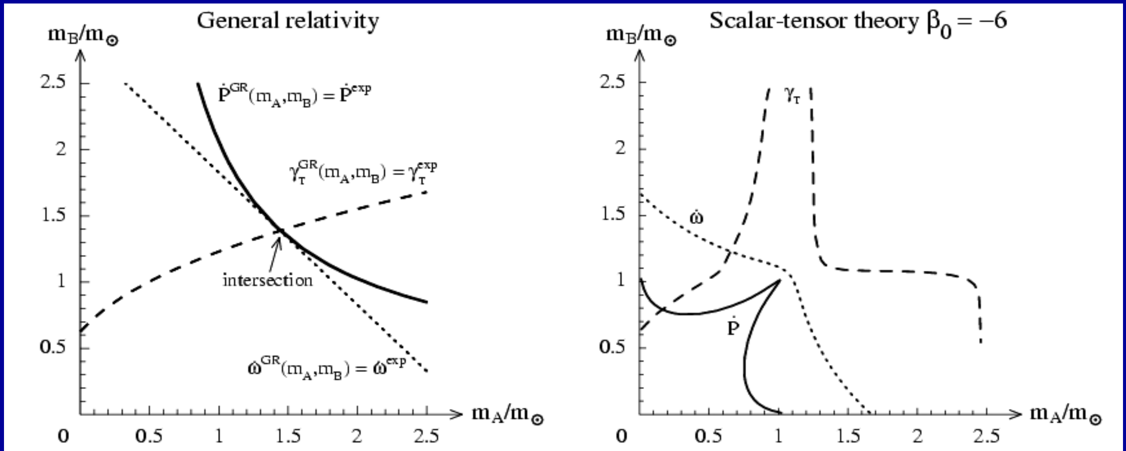
$$\ln A(\varphi) \equiv \alpha_0(\varphi - \varphi_0) + \frac{1}{2}\beta_0(\varphi - \varphi_0)^2 + \mathcal{O}(\varphi - \varphi_0)^3$$

Esposito-Farèse, gr-qc/0409081



2) Effets non perturbatifs en champ fort, pulsars binaires





Une reconstruction complète

H(z) peut être reconstruit à partir de $D_L(z)$

$$H(z) = \frac{da}{a^2 d\eta} = -(a_0\eta')^{-1} = \left[\left(\frac{D_L(z)}{1+z}\right)'\right]^{-1}$$

H(z) peut aussi être reconstruit à partir de δ(z)

$$H^2 = \frac{8\pi G}{3}\left(\rho_m + \frac{\dot\varphi^2}{2} + V\right) , \quad \rho_m = \frac{3\Omega_0 H_0^2 a_0^3}{8\pi G a^3}$$

$$\ddot\varphi + 3H\dot\varphi + \frac{dV}{d\varphi} = 0 ,$$

$$\dot H = -4\pi G(\rho_m + \dot\varphi^2) .$$

← Fond + perturbations (comme sans Λ)

$$\ddot\delta + 2H\dot\delta - 4\pi G\rho_m\delta = 0$$

→

$$\frac{H^2(z)}{H^2(0)} = \frac{(1+z)^2\delta'^2(0)}{\delta'^2(z)} - 3\Omega_0\frac{(1+z)^2}{\delta'^2(z)}\int_0^z \frac{\delta|\delta'|}{1+z}\,dz$$

On déduit immédiatement V(φ) de H(a) :

Starobinsky, astro-ph/9810431

$$8\pi G V(\varphi) = aH\frac{dH}{da} + 3H^2 - \frac{3}{2}\Omega_0 H_0^2\left(\frac{a_0}{a}\right)^3$$

$$4\pi G a^2 H^2\left(\frac{d\varphi}{da}\right)^2 = -aH\frac{dH}{da} - \frac{3}{2}\Omega_0 H_0^2\left(\frac{a_0}{a}\right)^3$$

A(φ) et V(φ) si $D_L(z)$ et δ(z)

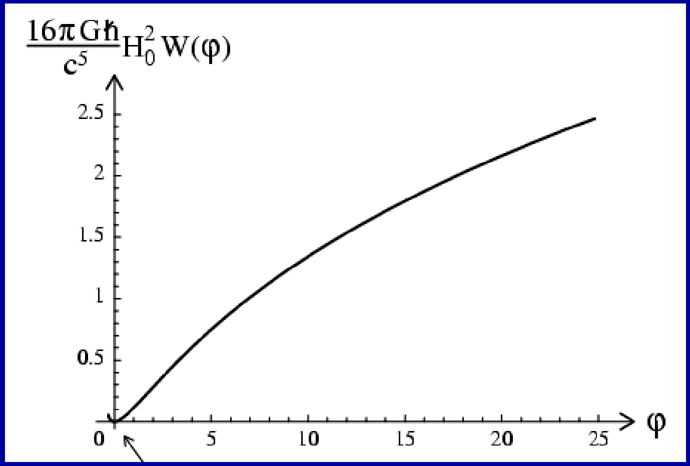
En écho à la recontruction de V(φ) pour l'inflation primitive

Lesgourgues et al., arXiv:0710.1630v2

Avec un terme de Gauss-Bonnet

Théorie la plus générale qui satisfait le principe d'équivalence faible et ne requiert qu'un degré de liberté de spin 0 au-delà des usuels spin-2 (gravitons) :

$$
\begin{aligned}
S = \; & S_{\text{matter}}[\text{matter}; \tilde{g}_{\mu\nu} \equiv A^2(\varphi) g_{\mu\nu}] \\
& + \frac{c^3}{4\pi G} \int \sqrt{-g} \left\{ \frac{R}{4} - \frac{1}{2}(\partial_\mu \varphi)^2 - V(\varphi) \right\} \\
& - \hbar \int \sqrt{-g}\, W(\varphi) \left(R^2_{\mu\nu\rho\sigma} - 4R^2_{\mu\nu} + R^2 \right)
\end{aligned}
$$



Esposito-Farèse, gr-qc/0409081

On peyt reconstruire W(φ) sans ambiguïté (au moins qd V=0) mais « hyper-fine » tunning.

+ analyse combinée avec les tests « système-solaire »

Pourquoi Lovelock (Gauss-Bonnet) ?
Cordes et inflation

Extra-dim en théorie des cordes: une pensée dynamique ?
(Analogie avec l'homogénéité avant l'inflation)

Ferrer & Rasanen, het-th/0707.0499 - CERN-TH/2007-113

$$
\begin{aligned}
L_{\mathrm{love}} &= \sum_{n=0}^{[d/2]} c_n L_n \\
&\equiv \sum_{n=0}^{[d/2]} c_n 2^{-n} \delta^{\alpha_1 \cdots \alpha_{2n}}_{\beta_1 \cdots \beta_{2n}} R_{\alpha_1 \alpha_2}{}^{\beta_1 \beta_2} \ldots R_{\alpha_{2n-1} \alpha_{2n}}{}^{\beta_{2n-1} \beta_{2n}}
\end{aligned}
$$

Généralise le tenseur d'Einstein à D dimensions

A l'ordre 2 :

$$
\begin{aligned}
S_{\mathrm{love}} &= \int \mathrm{d}^{10}x \sqrt{-g}\, (c_0 L_0 + c_1 L_1 + c_2 L_2) + S_{\mathrm{m}} \\
&= \frac{1}{2\kappa^2} \int \mathrm{d}^{10}x \sqrt{-g} \left[-2\Lambda + R + \alpha (R^2 - 4 R_{\alpha\beta} R^{\alpha\beta} + R_{\alpha\beta\gamma\delta} R^{\alpha\beta\gamma\delta}) \right] \\
&\quad + \int \mathrm{d}^{10}x \sqrt{-g} L_{\mathrm{m}} \ ,
\end{aligned}
$$

Stabilisation des 3 dimensions : SGC
GB assure une entrée et une sortie naturelle de l'inflation

Lovelock et trous noirs : contexte

Lovelock à nouveau

- 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.
- Gauss-Bonnet theory : 2nd order truncature

Lovelock, J. Math. Phys. 12 (1971) 498
Zwiebach, Phys. Lett. B 156 (1985) 316
Alexeyev, A.B. , Boudoul, Class. Quantum Grav. 19 (2002) 4444

Problème de la hérarchie

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

- Large extra dimensions

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

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

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

-

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

Hawking, Nature 248 (1974) 30

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

Black holes do evaporate

- Emission spectrum

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

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

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

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

- 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

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

A.B., Grain, Phys. Rev. D 76 (2007) 084009

- 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**

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

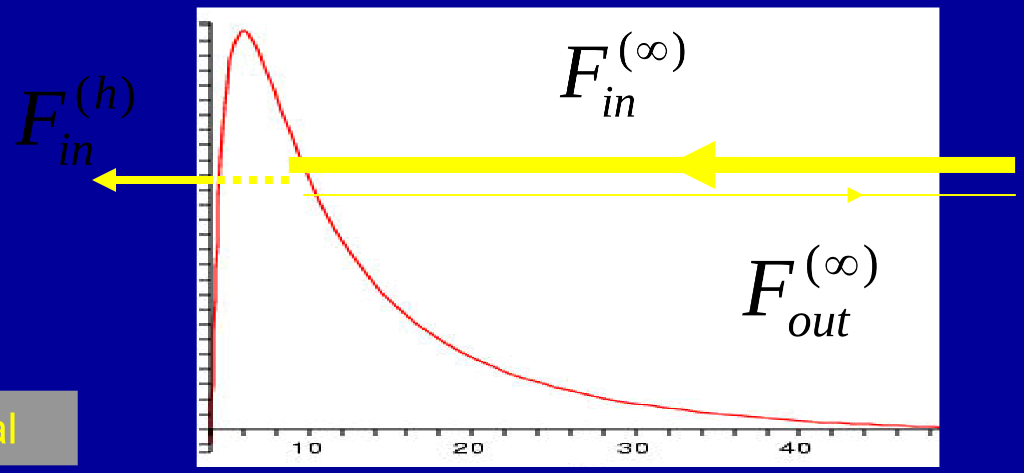
Centrifugal and gravitational potential

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

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

Vacuum fluctuations breaking

Diffusion on the gravitational potential



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

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

With a Spin :

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

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

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

For scalars in the bulk:

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

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

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

Greybody factors : computation

Exact results

UV regim

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

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

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

Numerical results

Asymptotic solutions, fits, determination of the coefficients, numerical errors under control

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

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

A.B., Grain, Phys. Rev. D 76 (2007) 084009

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

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

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

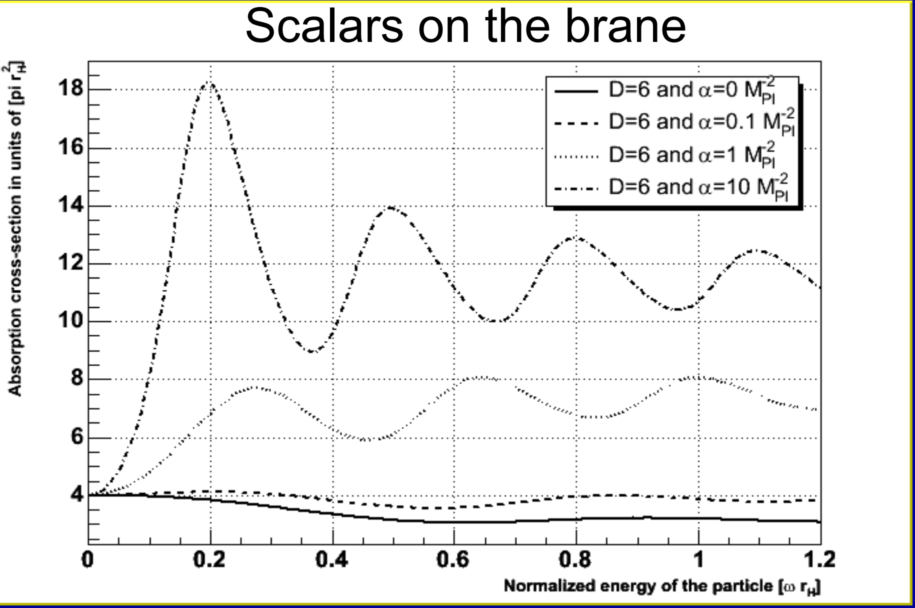
- Tunneling

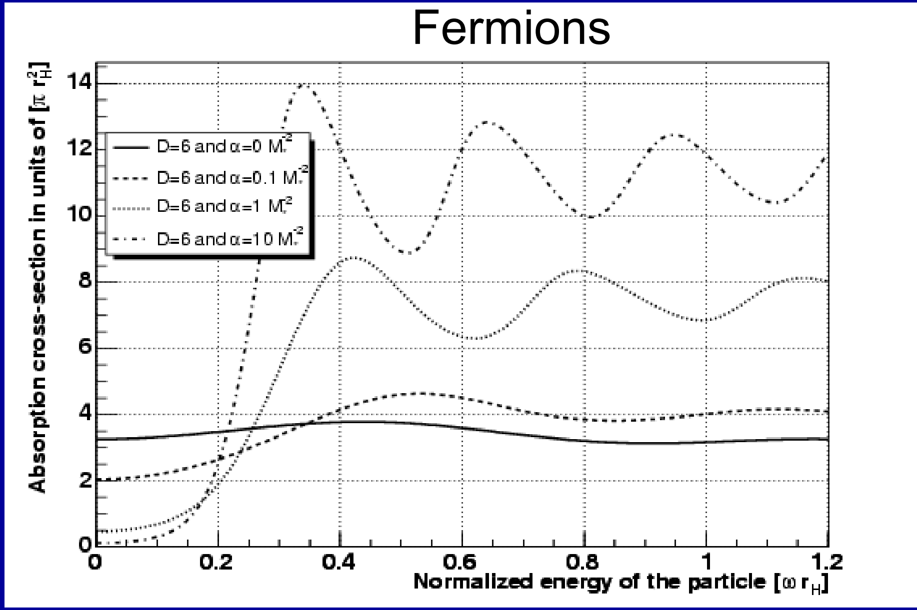
$$T = \exp\left(-2\int_{y_-}^{y_+} p_\omega(y)\,dy\right)$$

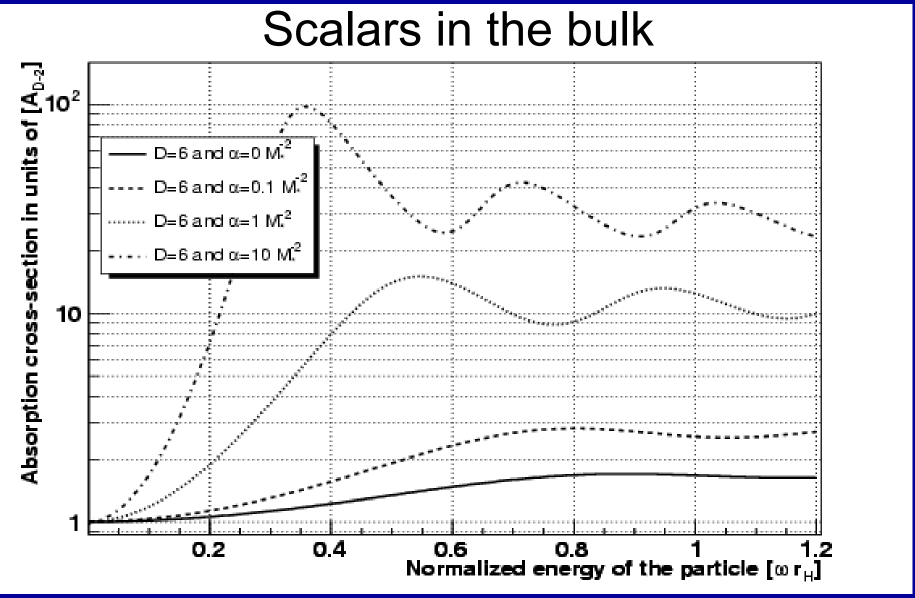
- fixed frequency propagator ←→ WKB wave function.

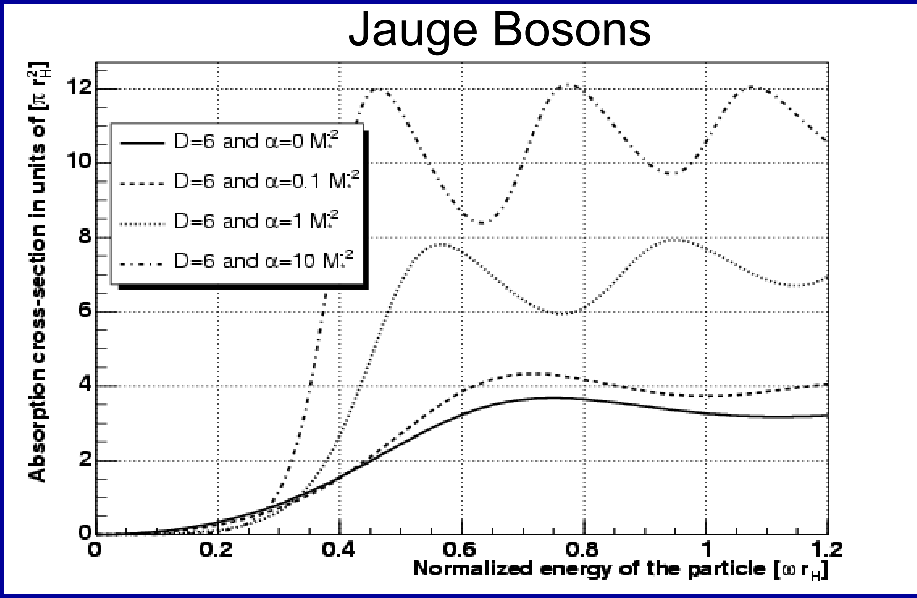
$$\tilde{G}(y,y',\omega) = \int e^{i\omega t}\tilde{K}(y,y';t,t') \equiv \sqrt{\frac{p(y')}{p(y)}}\, e^{i\int_{y'}^{y} p(x)dx}$$

First consequence : Gauss-Bonnet black holes (1)



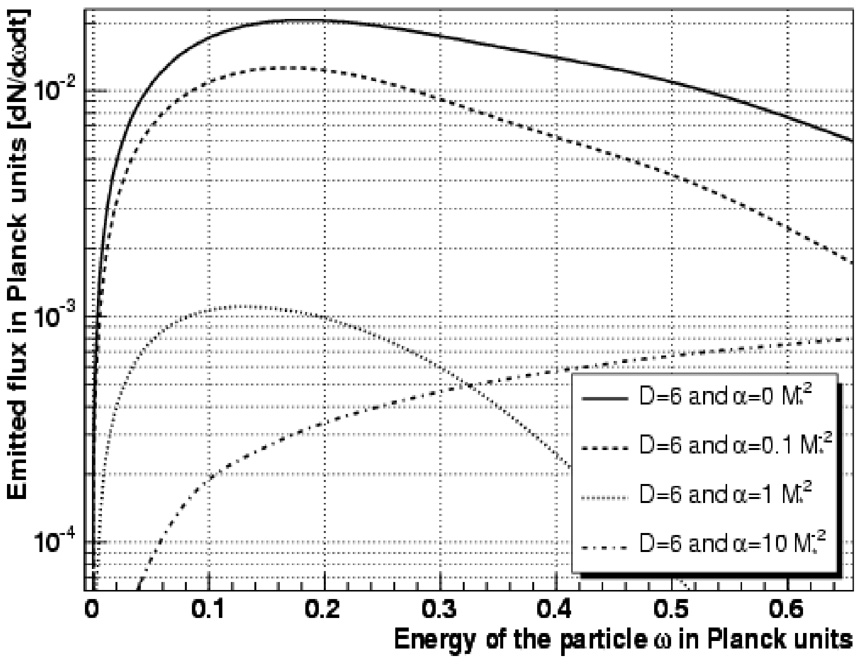


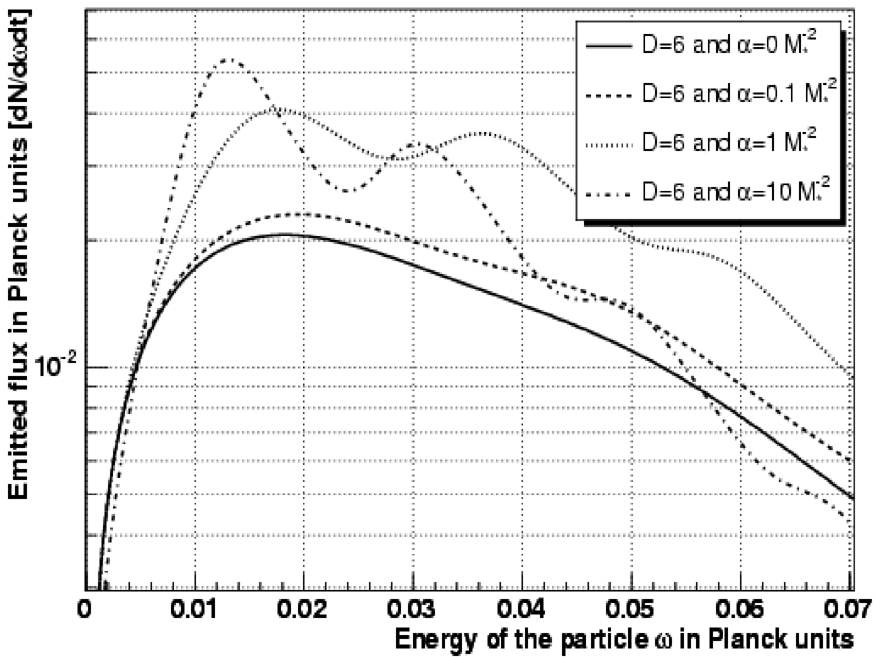




J. Grain, A. B. & P. Kanti, Phys. Rev. D 72 (2005) 104016

Gauss-Bonnet black holes (2)





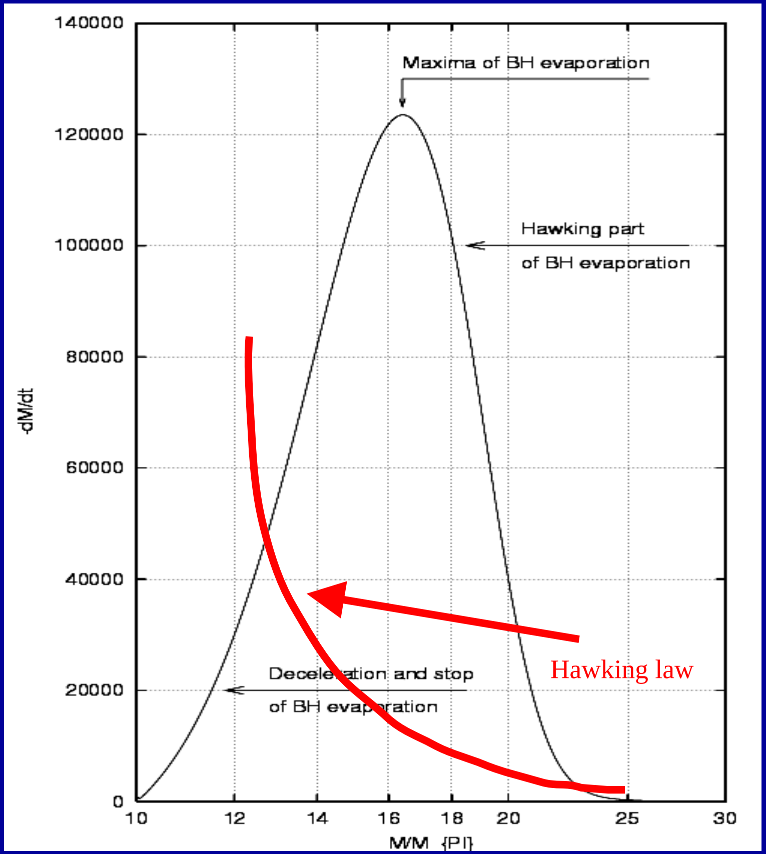
$$M_{BH} = 10 M_D$$

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

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

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

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



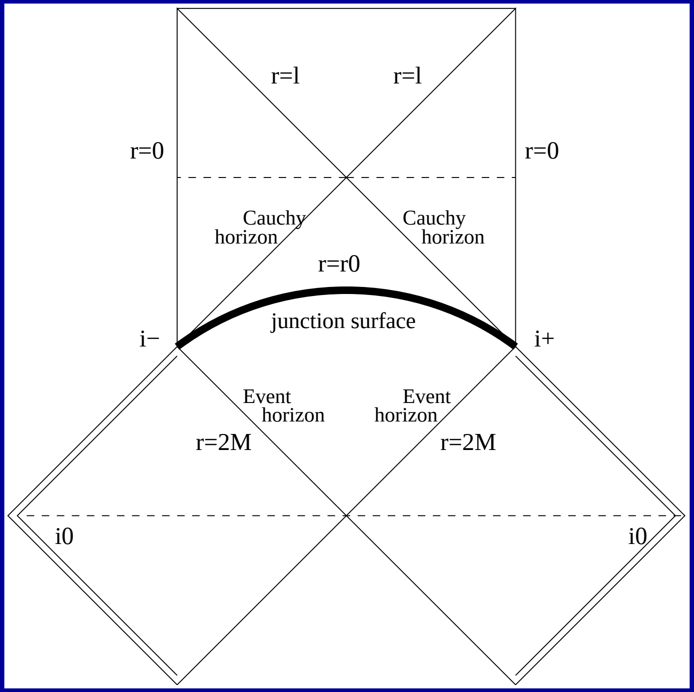
Alexeyev & Pomazonov, Phys. Rev. D 55 (1997) 2110
Alexeyev, Grav. Cosm. 3 (1997) 161

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

Stabilisation de la fin de vie des trous noirs

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

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



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

Cosmic natural selection (Smolin) associated with a Universe inside a black hole. What does Gauss-Bonnet gravity tells us about the Riemann invariant ?

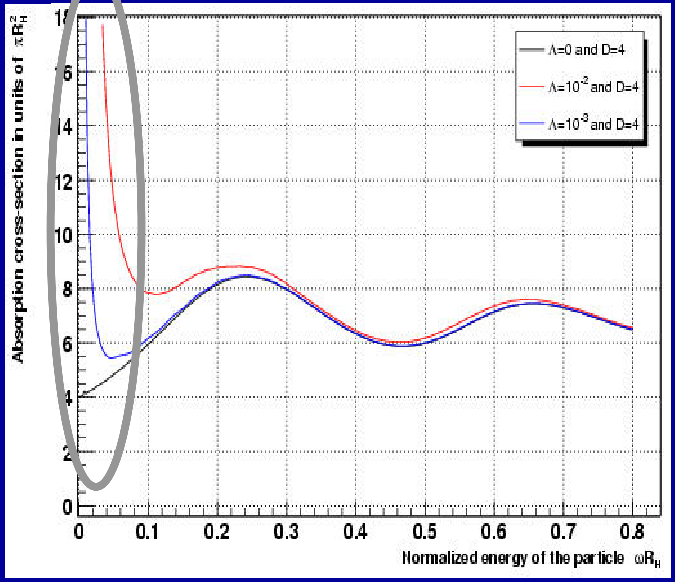
A. B., gr-qc/0612045

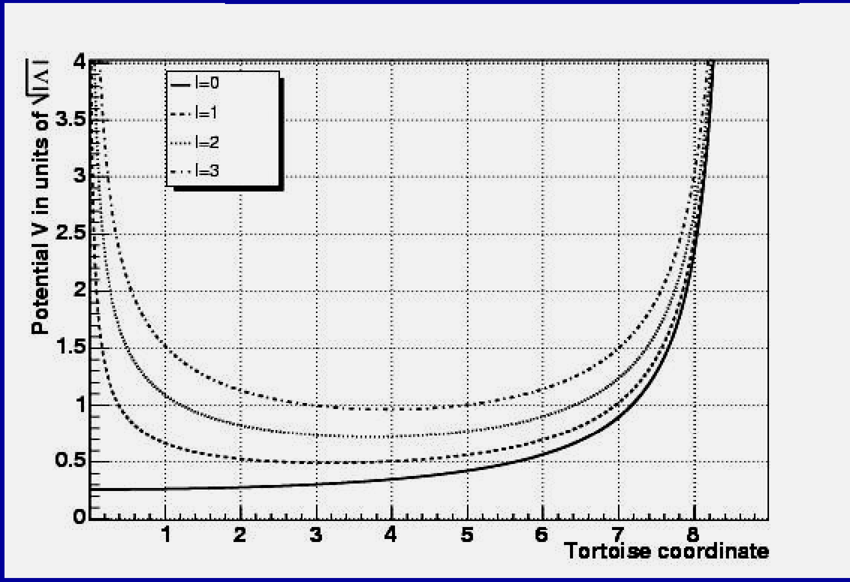
Other types of spaces

SdS space

AdS space

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





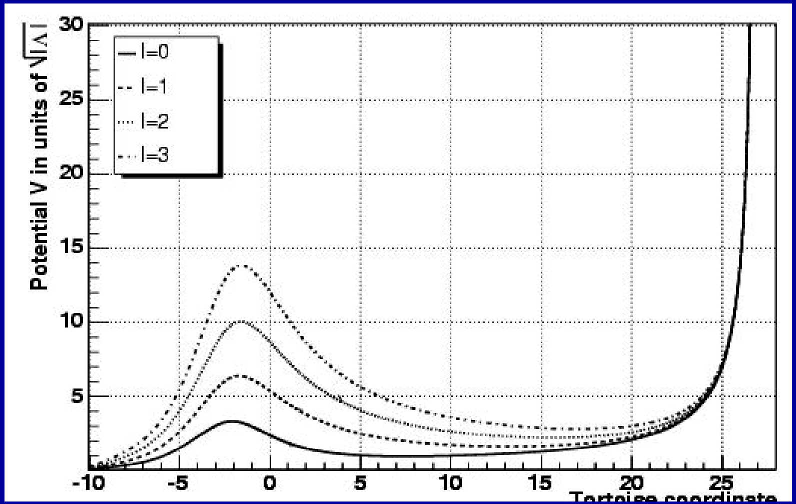
SAdS space

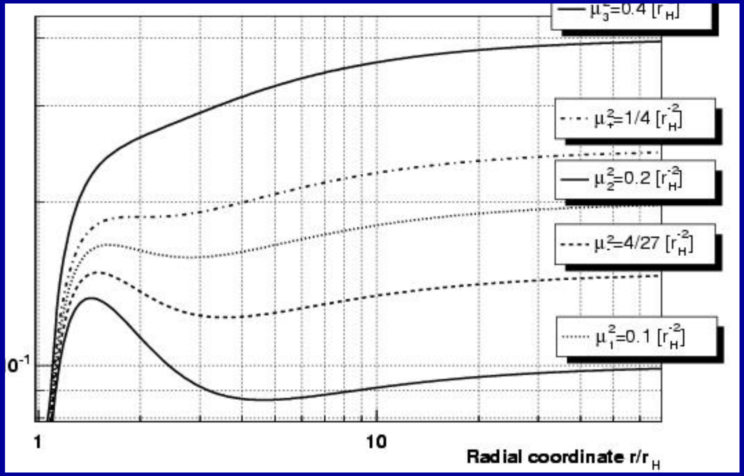
A. B., Grain, Nucl. Phys. B 742 (2006) 253

Schwarzschild space

Resonnances and singular transition SAdS → AdS

Quantum bound states





A.B., Eur. Phys. J. C 53 (2007) 641

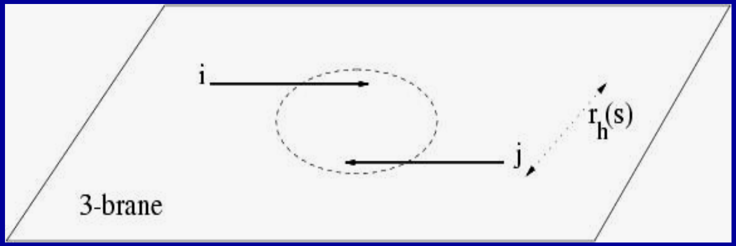
EXPERIMENTAL INVESTIGATIONS
BH @ the LHC if the Planck scale ~ TeV !

- Geometric cross section

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

$\sqrt{s} > M_D$

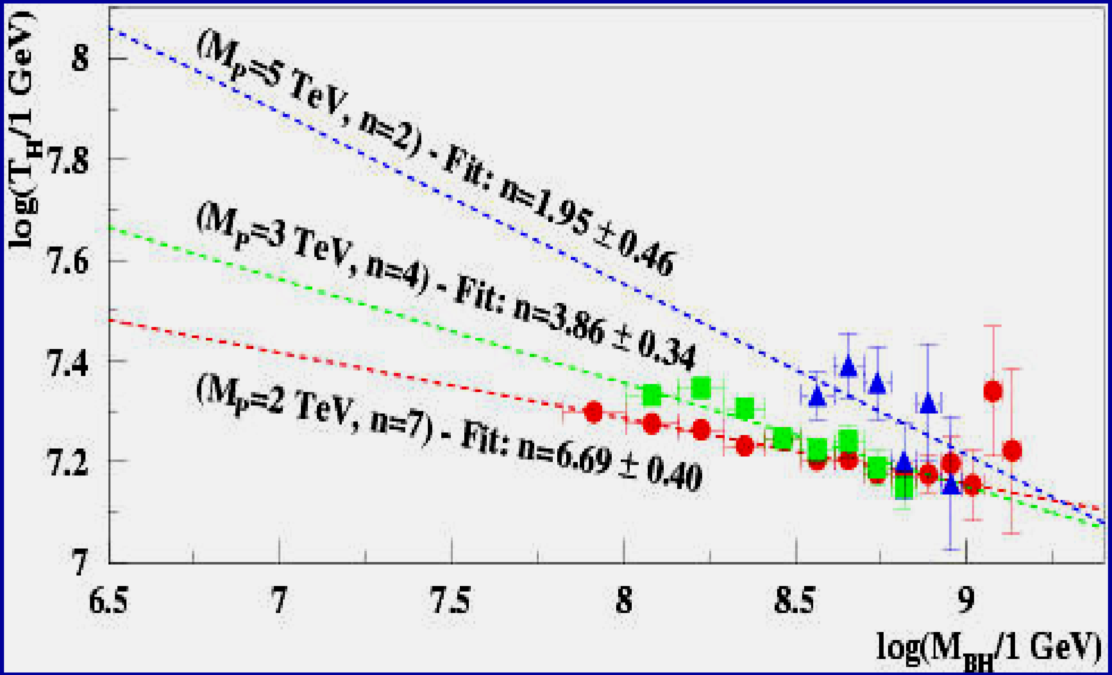
- Estimate of the number of produced black holes
- Reconstruction of the dimensionality

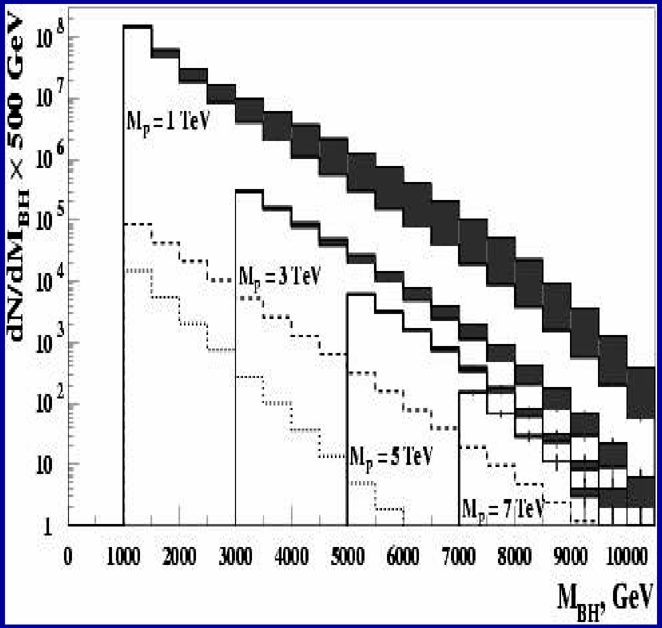


Banks, Fischler hep-th/9906038

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

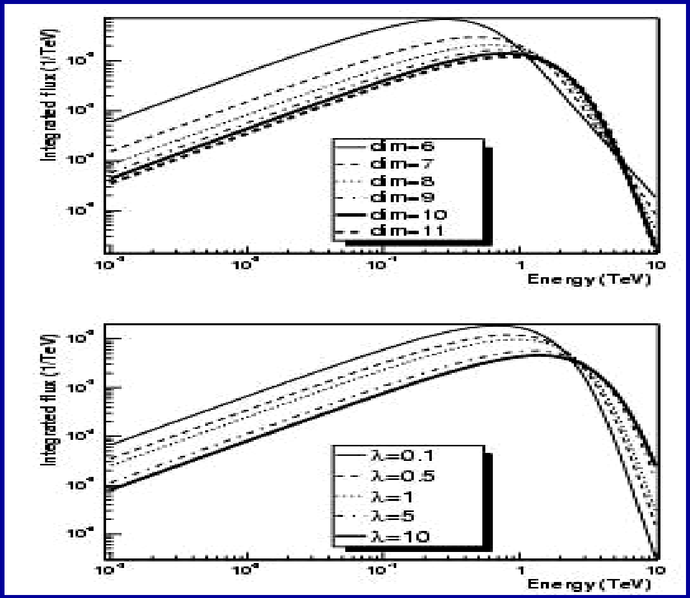
Dimopoulos, Landsberg Phys. Rev. Lett 87, 161602 (2001)

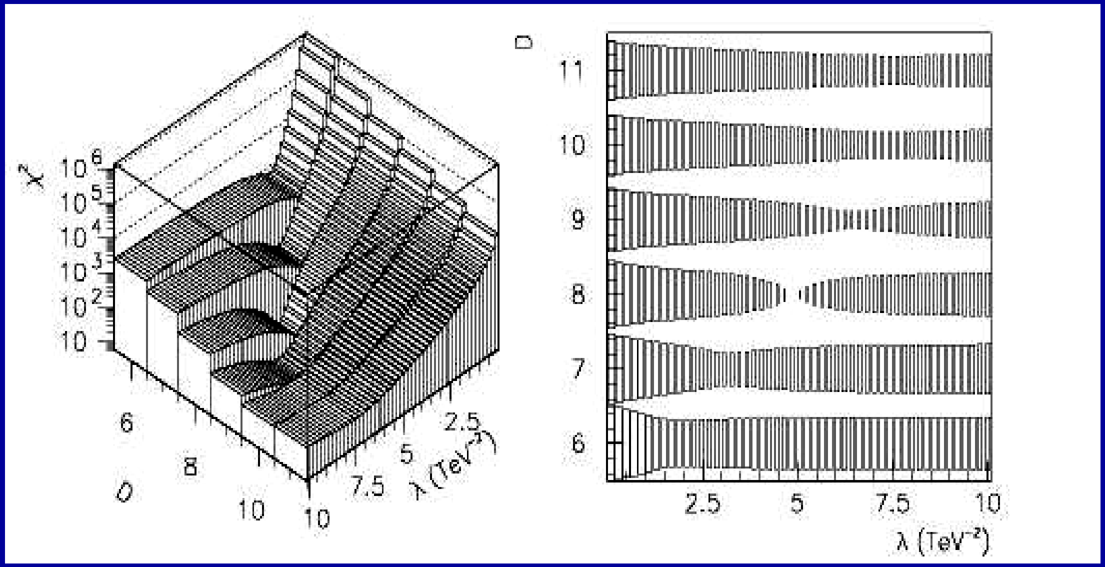




Extented gravity black holes at the LHC (2)

- Taking everything into account : Lovelock gravity can be probed !
- The statistical analysis allows to reconstruct both the dimensionality of space-time and the Gauss-Bonnet coupling constant.





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

Black holes at the LHC (3)

Prospects:

- Kerr-Gauss-Bonnet BH

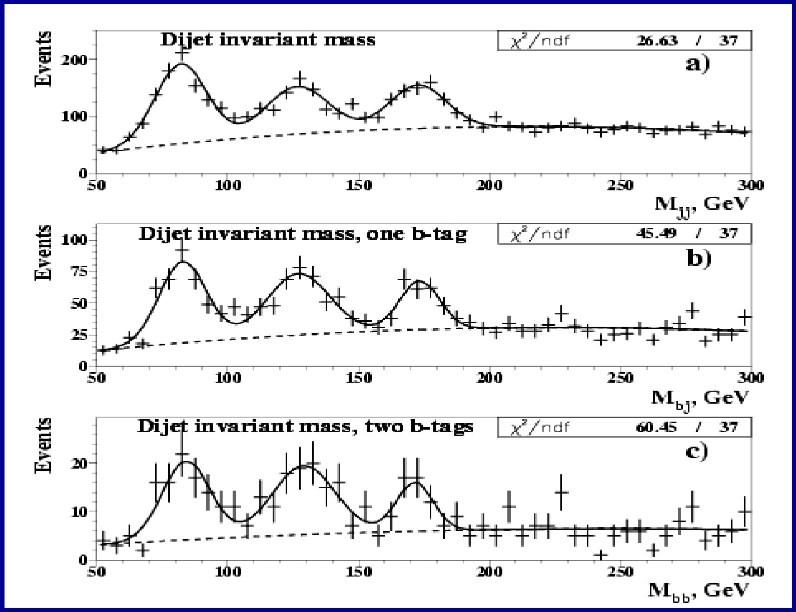
$$
\begin{aligned}
& R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \Lambda g_{\mu\nu} \\
+ & \ \alpha \left[\frac{1}{2} g_{\mu\nu} \left(R_{\mu\nu\alpha\beta} R^{\mu\nu\alpha\beta} - 4 R_{\alpha\beta} R^{\alpha\beta} + R^2 \right) \right. \\
- & \ 2 R R_{\mu\nu} + 4 R_{\mu\gamma} R^{\gamma}_{\nu} + 4 R_{\gamma\delta} R^{\gamma\delta}_{\mu\nu} \\
- & \left. \ 2 R_{\mu\gamma\delta\lambda} R^{\gamma\delta\lambda}_{\nu} \right],
\end{aligned}
$$

$$
\begin{aligned}
ds^2 = \ & dt^2 - dr^2 - (r^2 + a^2) \sin^2\theta d\phi_1^2 \\
& - (r^2 + b^2) \cos^2\theta d\phi_2^2 - \rho^2 d\theta^2 \\
& - 2dr \left(a \sin^2\theta d\phi_1 + b \cos^2\theta d\phi_2 \right) \\
& - \beta \left(dt - dr - a \sin^2\theta d\phi_1 \right. \\
& \left. - b \cos^2\theta d\phi_2 \right)^2,
\end{aligned}
$$

Alexeyev, A.B. et al., JETP 106 (2008) 710

$$
\beta = \frac{\rho^2 \pm \sqrt{\rho^4 - 4\alpha M - \frac{2}{3}\alpha\Lambda r^2 (2\rho^2 - r^2)}}{2\alpha}
$$

- Particle physics : resonances for light SUSY particles, etc.



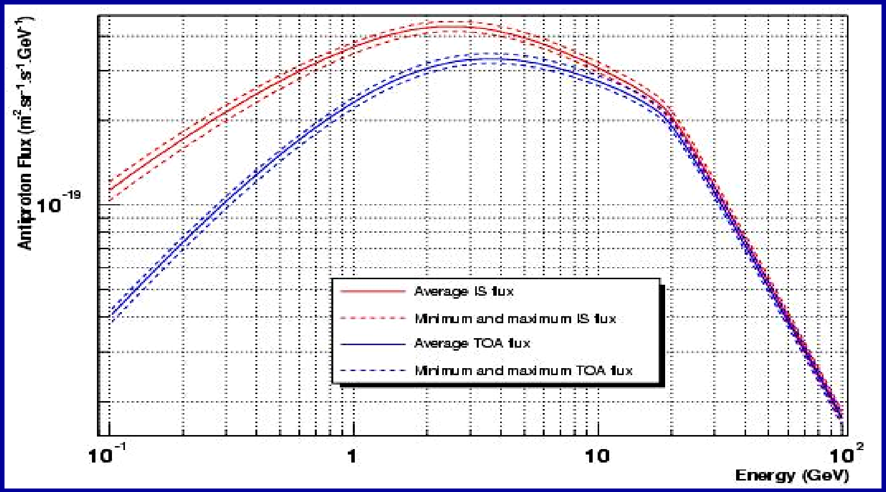
Landsberg, Phys. Rev. Lett. 88 (200é) 181801

Are μ-BHs viable from an astrophysical and cosmological viewpoint ?

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

- 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

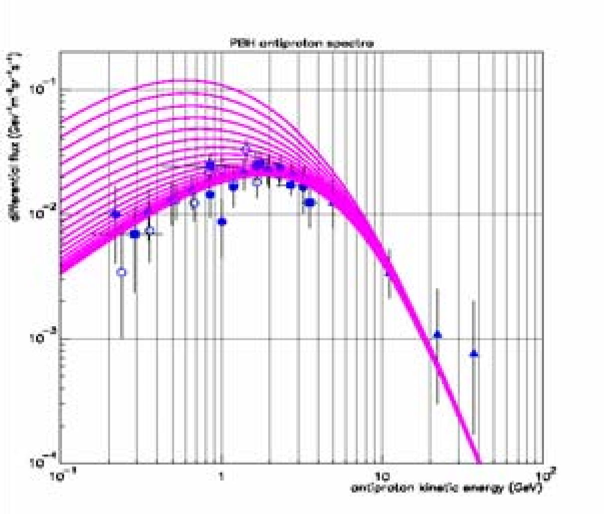
!! Quite generic !!

G. Dvali & M. Redi, hep-th : arXiv:0710/4344

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

What about primordial BHs as cosmological probes ?

Cosmic-ray emission → upper limit on the curent density

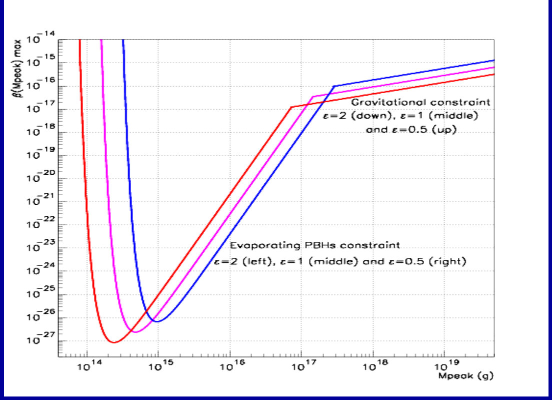


A. B. *et al.,* Astronom. Astrophys., 388, 767 (2002)

$$\Omega < 4 \times 10^{-9}$$

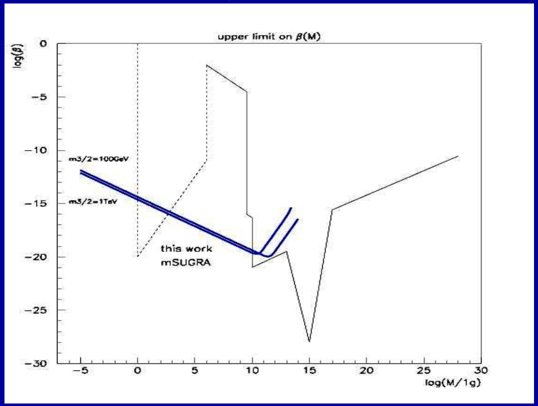
→ Constraints on BSI inflationary models on very small scales

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



Gravitino emission → constraints on the running and m3/2

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



→ Lovelock gravity provides dark matter candidates

A. B & Polarski, Ann. Phys. 13, 115 (2004)

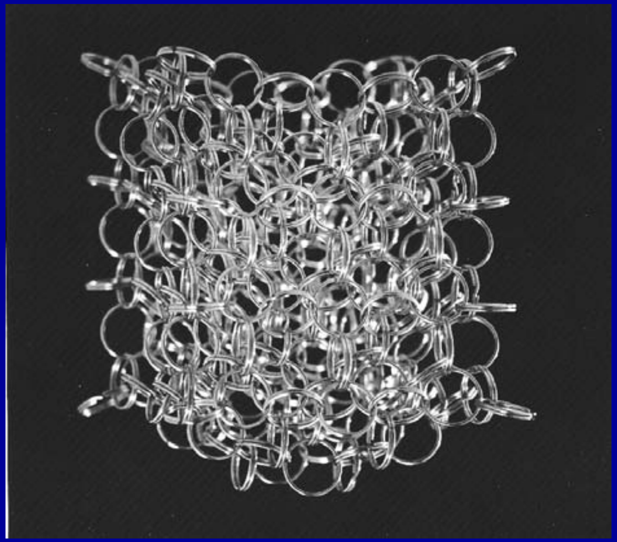
PRIMORDIAL BLACK HOLES ARE A UNIQUE COSMOLOGICAL PROBE

→Possible detection with antideuterons

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

Could loop quantum gravity corrections leave a footprint in the primordial tensor spectrum ?

« Can we construct a quantum theory of spacetime based only on the experimentally well confirmed principles of general relativity and quantum mechanics ? » L. Smolin, hep-th/0408048

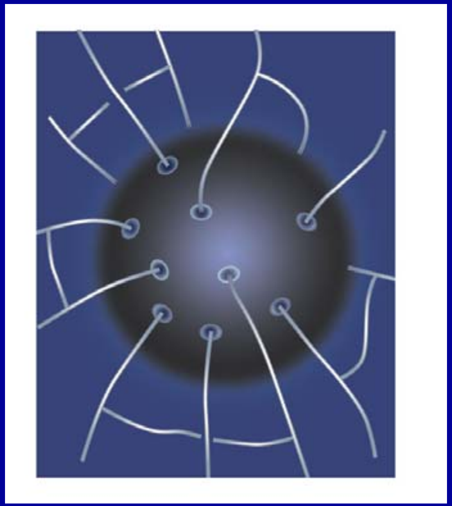


Four basic principles :

1) **Any theory which is to have general relativity as a low energy limit must be background independant.**
2) **Duality and diffeomorphism invariance may be consistently combined in a quantum theory.**
3) **General relativity and all related theories can be formulated as gauge theories.**
4) **Further, general relativity and related theories can be put in a special form in which they are constrained topological field theories.**

Basic results (nearly) randomly selected

- The area, volume and length operators have a discrete, finite spectra.
- The Wheeler deWitt equation is precisely recovered and can be solved exactly.
- The horizon entropy is completely explained in terms of the statistical mechanics of the state associated with the degrees of freedom on the horizon.
- Singularities are eliminated.
- The hawking radiation is recovered.
- Ultraviolet divergences of QFT are not present.
- There exist an exact physical state solution to the quatum constraint equation for any sign of Λ.
- Corrections to the energy-momentum relations.
- Loop quantum cosmology is on the way….



See *e.g.* the book « Quantum Gravity » by C. Rovelli

Holonomy corrections, basic picture

$$\left[\frac{\partial^2}{\partial\eta^2}+\left(\frac{\sin(2\gamma\bar{\mu}\bar{k})}{\gamma\bar{\mu}}\right)\frac{\partial}{\partial\eta}-\nabla^2-2\gamma^2\bar{\mu}^2\left(\frac{\bar{p}}{\bar{\mu}}\frac{\partial\bar{\mu}}{\partial\bar{p}}\right)\left(\frac{\sin(\gamma\bar{\mu}\bar{k})}{\gamma\bar{\mu}}\right)^4\right]h_a^i=16\pi GS_a^i$$

Bojowald & Hossain, Phys. Rev. D (2007) 023508

Which translates, in a cosmological framework, in:

$$\left[\frac{\partial^2}{\partial\eta^2}+\frac{2}{a}\frac{\partial a}{\partial\eta}\frac{\partial}{\partial\eta}-\nabla^2-\left(\frac{2n\gamma^2\alpha}{M_{\rm Pl}^2}\right)\left(\frac{8\pi G\rho}{3}\right)^2a^{4+4n}\right]h_a^i=16\pi GS_a^i,$$

$$-0.5\le n\le 0$$

Redifining the field:

$$\left[\frac{\partial^2}{\partial\eta^2}-\nabla^2-\frac{\ddot{a}}{a}-\left(\frac{2n\gamma^2\alpha}{M_{\rm Pl}^2}\right)\left(\frac{8\pi G\rho}{3}\right)^2a^{4+4n}\right]\Phi_a^i=16\pi Ga(\eta)S_a^i,$$

Which should be compared (pure general relativity) to:

$$\left[\frac{\partial^2}{\partial\eta^2}-\nabla^2-\frac{\ddot{a}}{a}\right]\Phi_a^i=16\pi Ga(\eta)\tilde{S}_a^i,$$

The n=-1/2 case

With

$$\Phi(\vec{x}) = \int \frac{d^3k}{(2\pi)^3} \phi_k \exp\left(i\vec{k}\cdot\vec{x}\right),$$

Which leads to a Schrödinger equation:

$$\frac{\partial^2 \phi_k}{\partial \eta^2} + \left(k^2 - \frac{\nu}{\eta^2}\right)\phi_k = 0,$$

$$\nu = 2 - \alpha\left(\frac{\gamma H}{M_{\mathrm{Pl}}}\right)^2,$$

$$\eta_{critical} = -\sqrt{\nu}/k$$

Which can be solved by a linear combination of Bessel functions, leading to the spectrum:

$$\mathcal{P}_{\mathrm{T}}(k) = A_{\mathrm{T}} k^{3-2\tilde{\nu}},$$

$$A_{\mathrm{T}} = \left(\frac{2^{1+\tilde{\nu}}\Gamma(\tilde{\nu})H}{\pi M_{\mathrm{Pl}}\cos(2\beta)}\right)^2 |\eta_f|^{3-2\tilde{\nu}}.$$

$$\tilde{\nu} = \sqrt{\nu + 1/4}$$

A more detailed computation of the spectral index leads to…

$$
\begin{aligned}
n_{\mathrm{T}} &= 3 - 2\sqrt{\nu + 1/4} \\
&\simeq \frac{2\alpha}{3}\left(\frac{\gamma H}{M_{\mathrm{Pl}}}\right)^2 + \mathcal{O}(H^4/M_{\mathrm{Pl}}^4).
\end{aligned}
$$

For a de-Sitter inflation

and

$$
\begin{aligned}
n_{\mathrm{T}} &\simeq \frac{-2\epsilon}{1-\epsilon} + \frac{2\alpha}{(1-\epsilon)(3-\epsilon)}\left(\frac{\gamma H}{M_{\mathrm{Pl}}}\right)^2 + \mathcal{O}(H^4/M_{\mathrm{Pl}}^4) \\
&\simeq -2\epsilon + \frac{2\alpha}{3}\left(\frac{\gamma H}{M_{\mathrm{Pl}}}\right)^2 + \mathcal{O}(\epsilon H^2/M_{\mathrm{Pl}}^2).
\end{aligned}
$$

for a more realistic slow roll inflation

In the general case (dS)

$$\frac{\partial^2 \phi_k}{\partial \eta^2} + \left(k^2 - \frac{2}{\eta^2} - \frac{2n\alpha\gamma^2 H^4}{M_{\rm Pl}^2(-H\eta)^{4+4n}}\right)\phi_k = 0.$$

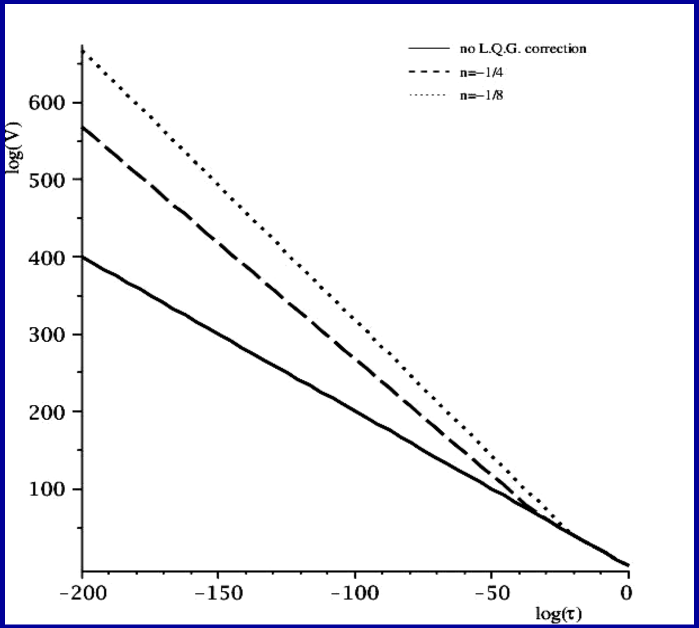
The potential is therefore

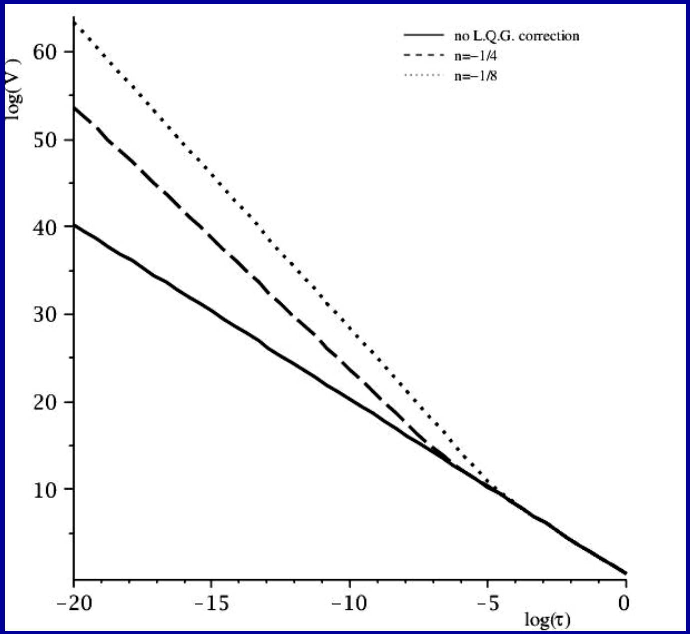
$$V(\tau) = \frac{2}{\tau^2} + 2n\alpha\gamma^2\left(\frac{H}{M_{\rm Pl}}\right)^2 \frac{1}{\tau^{4+4n}}$$

with τ=-Hη

IF γ2<0

H=10^3 GeV





H=10^16 GeV

→ Blue spectrum

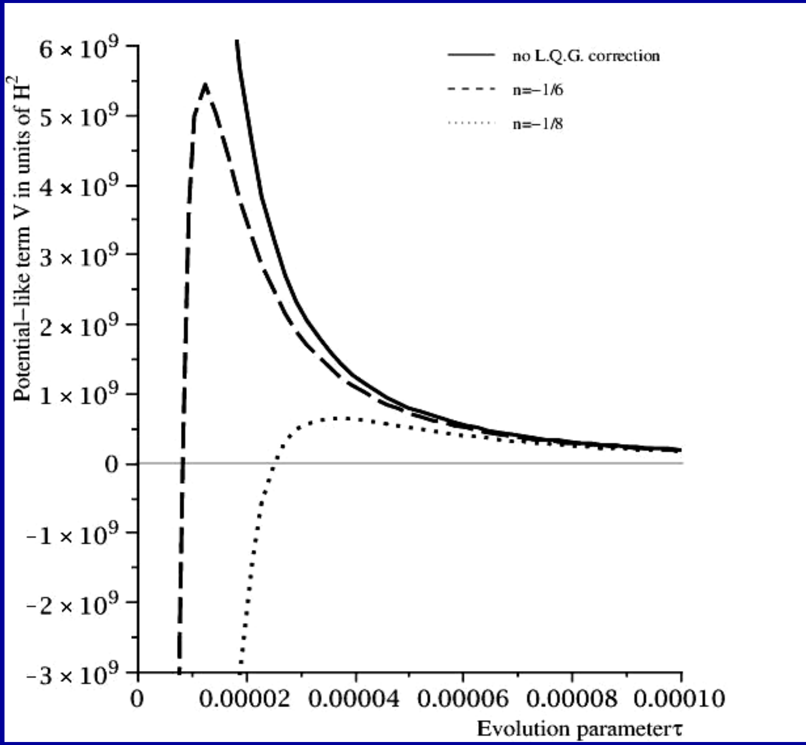
IF γ2>0

The potential becomes →

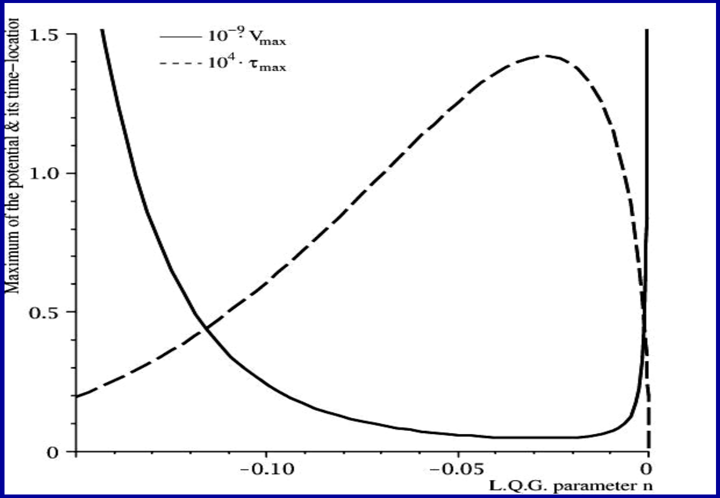
Keeping in mind that

$$V(\tau) = \frac{2}{\tau^2} + 2n\alpha\gamma^2 \left(\frac{H}{M_{\rm Pl}}\right)^2 \frac{1}{\tau^{4+4n}}$$

→ Red spectrum



The maximum of the potential and its location in time can be displayed with H ~ 10^16 GeV

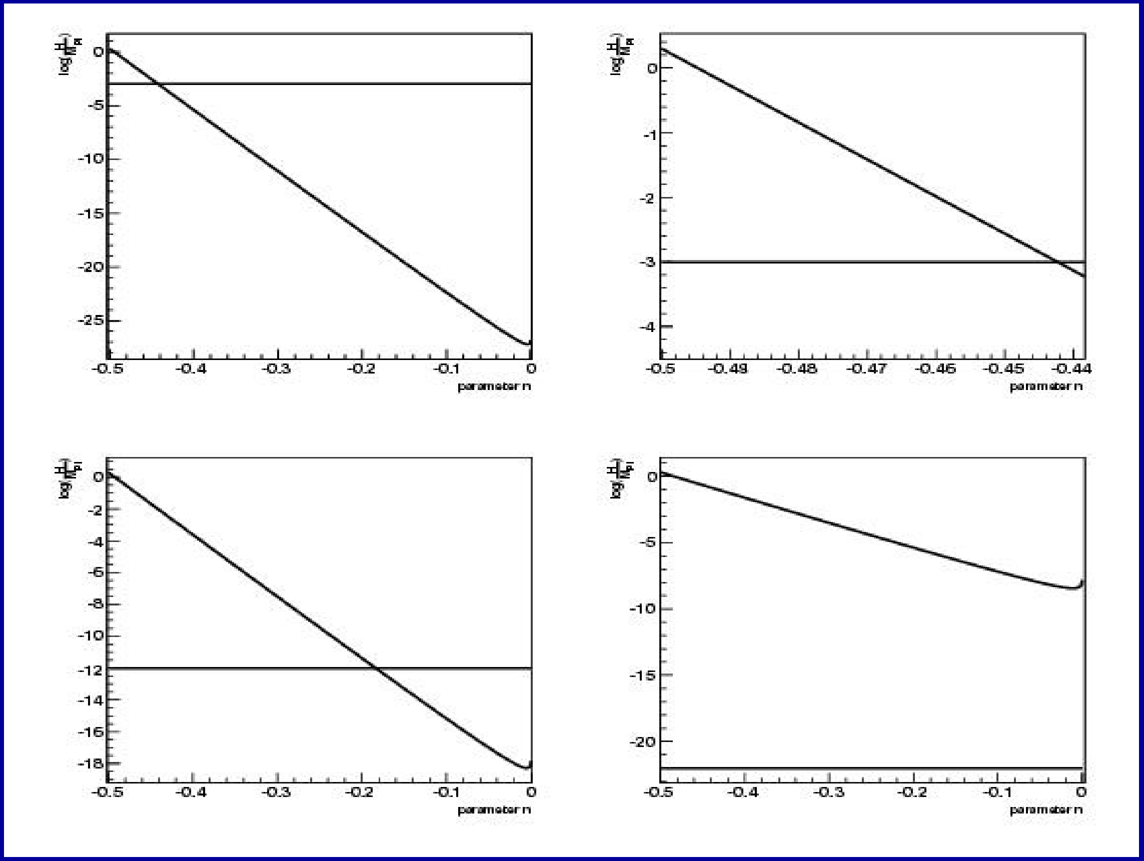


Aurélien Barrau LPSC-Grenoble (CNRS / UJF)

Combining all the constraints, the effect should be noticeable if:

$$\frac{H}{M_{\rm Pl}} > \frac{1}{\sqrt{|n(n+1)|}} \exp\left(\frac{-36 - \ln\left(T_{reh}/1~{\rm TeV}\right)}{\beta}\right).$$

Which translates in a wide parameter space →



Aurélien Barrau LPSC-Grenoble (CNRS / UJF)

In progress and… to do!

Infrared solution obtained:

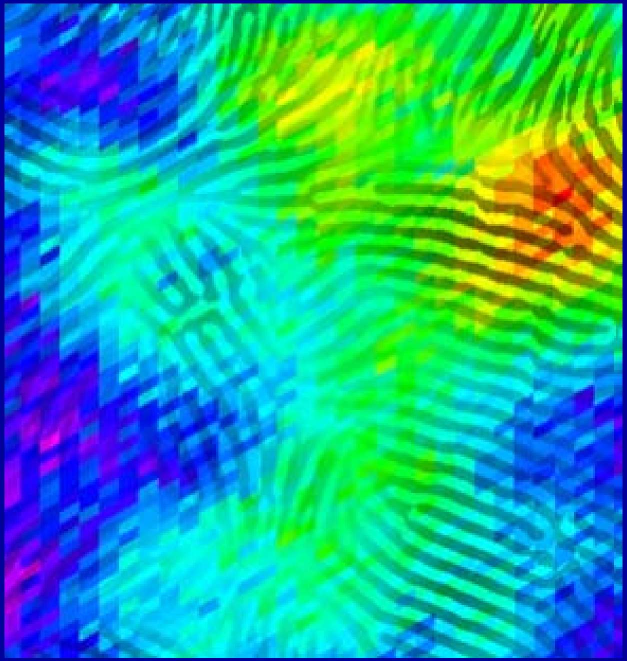
$$P(k \to 0) \simeq \frac{2A}{\pi H^2 |\eta_f|} \sqrt{\frac{2}{\pi z_f}} \left[\cos^2(z_f - \varphi) + B \left(\frac{k}{H} \right)^6 \sin^2(z_f - \varphi) \right]$$

WKB solutions…

Slow-roll inflation…

Inverse volume corrections…

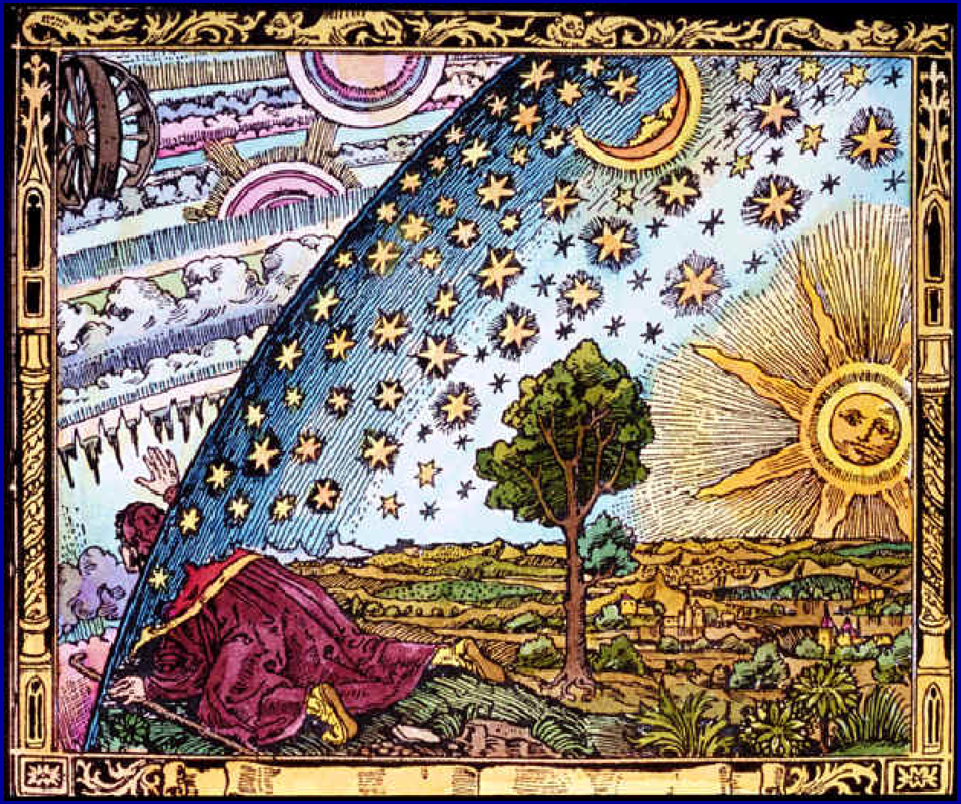
Scalar perturbations….



And mesurements !

LQG corrections could be probed by the next generation of cosmology experiments

Conclure ?



La cosmologie et la gravitation sont à un tournant. Le nouveau paradigme sera sans doute une révolution scientifique et conceptuelle.