The gravitational field at the shortest scales

Piero Nicolini

FIAS & ITP
Johann Wolfgang Goethe-Universität

nicolini@fias.uni-frankfurt.de

Institut für Theoretische Physik, Johann Wolfgang Goethe-Universität, Frankfurt a. M. - May 24, 2012

A physical quantity

- **Measurement of “X”**

  $$x \in M \longrightarrow \mathbf{X}(x) =$$
  $$= \left\{ X_1(x), \ldots, X_j(x), X^{j+1}(x), \ldots, X^n(x) \right\}$$

  x is a point (event) of the manifold (spacetime) M.
- $\{X_1(x), \ldots, X_n(x)\} \in \mathbb{R}^n$
- $||\mathbf{X}(x)|| \leq k < \infty$
- e.g. the **gravitational field**

A lunar gravimeter - Apollo 17 (1972)

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The gravitational field

- Newtonian gravity

$$\mathbf{g} = \frac{\mathbf{F}}{m} = -\frac{\mathrm{d}^2\mathbf{r}}{\mathrm{d}t^2} = -\frac{GM}{|\mathbf{r}|^2}\hat{\mathbf{r}} = -\nabla\Phi$$

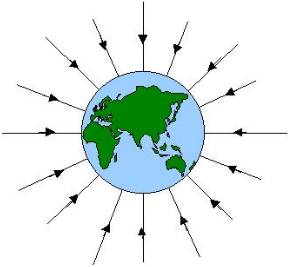
Gauss' law for gravity

$$-\nabla\cdot\mathbf{g} = \nabla^2\Phi = 4\pi G\rho$$

- Solution e.g. $\rho_{in} = \rho_0$ and $\rho_{out} = 0$

$$r > R \qquad \Phi(r) = -G\frac{M}{r}, \qquad g = -G\frac{M}{r^2}$$

$$r < R \qquad \Phi(r) = G\frac{M}{2R^3}\, r^2, \qquad g = -G\frac{M}{R^3}\, r$$



Earth's gravitational field

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Poisson/Laplace equation for gravity

- **Poisson**: point-like mass

$$-\nabla \cdot \mathbf{g}(\vec{x}) = \nabla^2 \Phi(\vec{x}) = 4\pi G M \delta(\vec{x})$$

Divergence theorem

$$\oiint_S (\mathbf{g} \cdot \mathbf{n})\, dS = \iiint_V (\nabla \cdot \mathbf{g})\, dV = -4\pi G M \iiint_V \delta(\vec{x}) dV.$$

$$\Rightarrow g(r) = -G\,\frac{M}{r^2}$$

- **Laplace**: homogeneous equation in $\mathbb{R}^3 \setminus \{0\}$

$$\text{div}\, \mathbf{g} = \nabla \cdot \mathbf{g} = \frac{1}{r^2}\frac{\partial}{\partial r}(r^2 g) = 0, \quad r^2 g = const.$$

$$\Rightarrow g(r) = \frac{const}{r^2}, \quad const = -GM \text{ (boundary conditions)}$$

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Einstein gravity

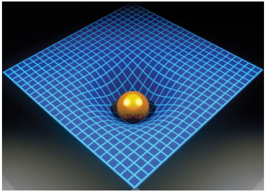
- Tensor field equations

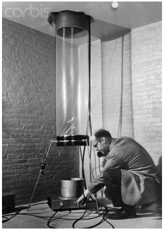
$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4} T_{\mu\nu}$$

- Curvature

$$R, \quad R_{\mu\nu}, \quad R^{\mu}{}_{\nu\rho\sigma}.$$

- Classical tests of GR
  1. the perihelion precession of Mercury's orbit
  2. the deflection of light by the Sun
  3. the gravitational redshift of light





The Pound-Rebka experiment (1959)

Static, spherically symmetric gravitational field

- Perfect fluid stress-energy tensor for the star

$$T^{\alpha\beta} = \left(\rho + \frac{p}{c^2}\right) u^\alpha u^\beta + p g^{\alpha\beta}, \quad \rho(r) = \begin{cases} \rho_0, & \text{if } r \leq R \\ 0, & \text{if } r > R \end{cases}$$

- The outer geometry

  [Schwarzschild, Sitzungsber. Preuss. Akad. Wiss. 189 (1916)]

$$ds^2 = \left(1 - \frac{2GM}{c^2 r}\right) c^2 dt^2 - \left(1 - \frac{2GM}{c^2 r}\right)^{-1} dr^2 - r^2 \left(d\theta^2 + \sin^2\theta \, d\varphi^2\right)$$

- The inner geometry

  [Schwarzschild, Sitzungsber. Preuss. Akad. Wiss. 424 (1916)]

$$ds^2 = e^{2\Phi} c^2 dt^2 - \left(1 - \frac{2Gm(r)}{c^2 r}\right)^{-1} dr^2 - r^2 \left(d\theta^2 + \sin^2\theta \, d\varphi^2\right)$$

$$m(r) = 4\pi \int_0^r \rho(r') {r'}^2 dr' = \frac{4}{3}\pi r^3 \rho_0$$

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The Schwarzschild black hole

- **Laplace**: vacuum solution *i.e.*

$$R_{\mu\nu} = 0$$

- Curvature singularity

> *"The mathematically rigorous solution may not be physically rigorous"* - R.P. Feynman

in Feynman & Hibbs, *Quantum mechanics and path integrals* p. 94 (McGraw-Hill, 1965)

$$R^{\alpha\beta\gamma\delta}R_{\alpha\beta\gamma\delta} = \frac{48G^2M^2}{c^4 r^6}\,.$$

Karl Schwarzschild (1873-1916)

- **Poisson**:

[Balasin & Nachbagauer, CQG **10**, 2271 (1993)]

$$T(x) = M\delta^{(3)}(x)\left(dt\otimes\partial_t + dr\otimes\partial_r - \frac{1}{2}d\theta\otimes\partial_\theta - \frac{1}{2}d\varphi\otimes\partial_\varphi\right)$$

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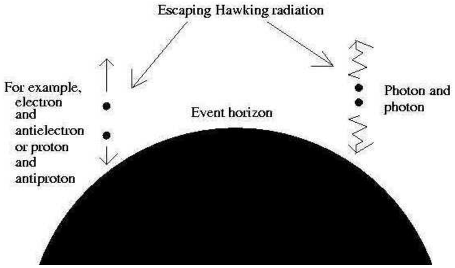
The Hawking radiation

- The vacuum state $|0\rangle$ is ill defined in curved space
  $\Longrightarrow$ Black hole thermal emission

$$\frac{d^2N}{dtd\omega} = \frac{1}{2\pi}\frac{1}{e^{\frac{\hbar\omega}{k_B T}} \pm 1} \quad \Rightarrow T = \frac{\hbar c^3}{Gk_B}\frac{1}{8\pi M}$$

- how important are quantum effects for black holes

$$r_H \lesssim 10^{-15}\ \mathrm{m} \Longrightarrow M \lesssim 10^{12}\ \mathrm{kg}$$



Hawking emission

The case of mini black holes

- Particle

$$\lambda \simeq \frac{\hbar}{Mc}$$

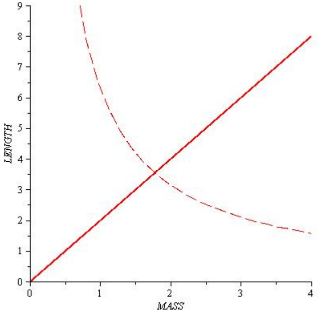
- Black hole

$$r_H \simeq \frac{GM}{c^2}$$

- "Particle black hole" $\lambda \approx r_H$

$$\Rightarrow M \simeq M_P \equiv \sqrt{\frac{\hbar c}{G}}$$

$$\Rightarrow r_H \simeq L_P \equiv \sqrt{\frac{\hbar G}{c^3}}$$

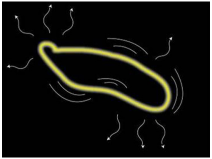


Gravity self completeness

- Evaporating black holes

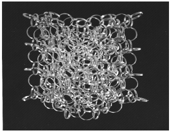
$$L_P \approx 10^{-35}\ \mathrm{m} < r_H < 10^{-15}\ \mathrm{m}$$
$$M_P \approx 10^{-8}\ \mathrm{kg} < M < 10^{12}\ \mathrm{kg}$$

Quantum gravity



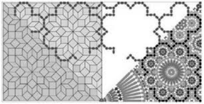
String theory

$$\mathcal{S} = -\frac{1}{2\pi\alpha'}\int \mathrm{d}^2\Sigma\sqrt{(\dot{X}\cdot X')^2-(\dot{X})^2(X')^2}.$$



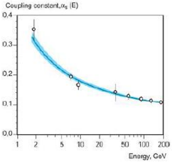
Loop quantum gravity

$$A_{\vec{j}}[\Sigma] = L_P^2\sum_i\sqrt{j_i(j_i+1)}$$



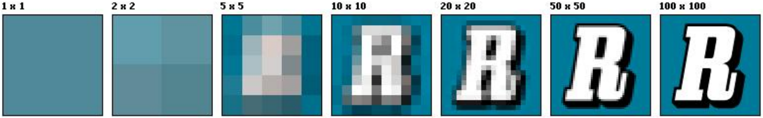
Noncommutative geometry

$$[\mathbf{x}^i,\mathbf{x}^j] = \Theta^{ij}$$



Asymptotically safe gravity

$$G_{AS}(p) = \frac{G_0}{1+\alpha G_0\, p^2}$$



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Effective quantum gravity equations

- A simple example

$$\textbf{GR:} \quad G_{\mu\,\nu} = 8\,\pi\,T_{\mu\,\nu} \quad \longrightarrow \quad T_0^0 = M\,\delta^{(3)}(\,\vec{x}\,)$$

$$\uparrow \ell \to 0 \qquad\qquad \ell \neq 0 \downarrow \uparrow \ell \to 0$$

$$\textbf{QG:} \quad G_{\mu\,\nu}\big|_\ell = 8\,\pi\,T_{\mu\,\nu}\big|_\ell \quad \longleftarrow \quad T_0^0\,\big|_\ell = \rho_\ell(\,\vec{x}\,)$$

- Energy density

$$\delta^{(3)}(\vec{x}) \to \rho_\ell(\vec{x}) = \begin{cases} \text{i)} & \dfrac{M}{(4\pi\ell^2)^{3/2}}\,\exp\left(-\frac{\vec{x}^2}{4\ell^2}\right) \\ \text{ii)} & \left(\dfrac{M}{\pi^2}\right)\dfrac{\ell}{(\vec{x}^2+\ell^2)^2} \\ \text{ii)} & \ldots \end{cases}$$

- Stress-energy tensor

$$T(x) = \{\rho_\ell(dt\otimes\partial_t) + P_r(dr\otimes\partial_r) + P_\perp(d\theta\otimes\partial_\theta + d\varphi\otimes\partial_\varphi)\}$$

The static, spherically symmetric case

- Line element

$$ds^2 = e^{2\Phi(r)}\left(1 - 2Gm(r)/r\right) dt^2 - \left(1 - 2Gm(r)/r\right)^{-1} dr^2 - r^2\, d\Omega^2$$

- Fluid-like gravity field equations

$$\frac{dm}{dr} = 4\pi\, r^2 \rho_\ell(r) \quad \Rightarrow m(r) = 4\pi \int_0^r \rho(r') r'^2 dr'$$

$$\frac{dP_r}{dr} = -G\, \frac{m(r) + 4\pi\, r^3 P_r}{r(r - 2Gm(r))}\left(\rho_\ell + P_r\right) + \frac{2}{r}\left(P_\perp - P_r\right)$$

- Equation of state

$$P_r = -\rho_\ell \Leftrightarrow \Phi(r) = 0$$

- **Gaussian profile solution**

[PN, Smailagic & Spallucci, PLB **632**, 547 (2006)], [Modesto, Moffat & PN, PLB **695**, 397 (2011)]

$$m(r) = M\, \frac{\gamma\left(3/2\,,\, r^2/4\ell^2\right)}{\Gamma\left(3/2\right)} = \begin{cases} M\left(1 - \frac{r}{\ell\sqrt{\pi}} \exp(-r^2/4\ell^2)\right) & r \gg \ell \\ \frac{1}{6\sqrt{\pi}}\left(\frac{r^3}{\ell^3}\right) M & r \sim \ell \end{cases}$$

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

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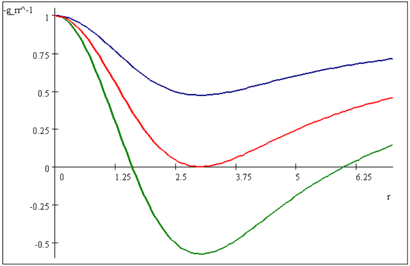
A regular static black hole



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

$M > M_0 \Rightarrow$ two horizons

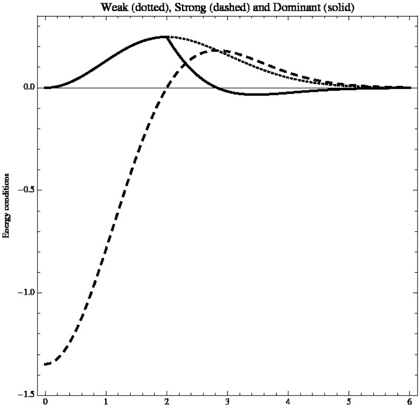
$M < M_0 \Rightarrow$ no horizon

$M = M_0 \approx 1.9\,\ell/G \Rightarrow$ one degenerate horizon

- The Ricci scalar near the origin is

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

- The curvature is constant and positive (deSitter geometry).



Energy conditions

- If $M < M_0 \Rightarrow$ no BH and no naked singularity (mini-gravastar?)
- If $M \gg M_0 \Rightarrow$
  - inner horizon $\rightarrow$ origin
  - outer horizon $\rightarrow 2M$

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Improved thermodynamics

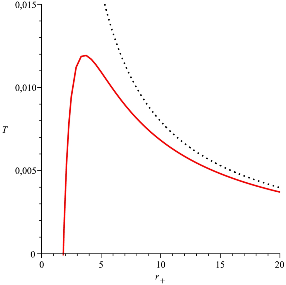
- new temperature profile

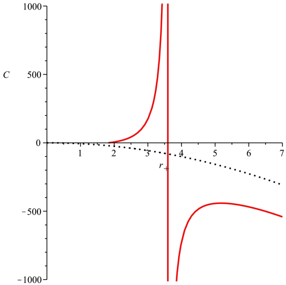
$$T_\ell = \frac{\hbar c}{4\pi k_B r_+}\left(1 - \frac{r_+^3}{4\ell^2}\frac{e^{-r_+^2/4\ell^2}}{\gamma(3/2; r_+^2/4\ell^2)}\right)$$

- transition to a positive heat capacity phase

$$C(r_+) = T_\ell\left(\frac{dS}{dr_+}\right)\left(\frac{dT_\ell}{dr_+}\right)^{-1}, \quad \frac{dS}{dr_+} = \frac{1}{T_\ell}\frac{\partial M}{\partial r_+}$$

- SCRAM phase (evaporation switching off)
- remnant formation
- ℓ for the BH is like $\hbar$ for the black body





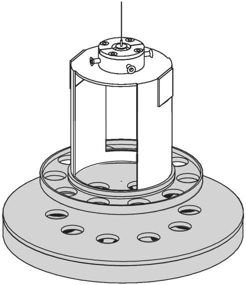
The measure of the gravitational field at short scales

- deviations of Newton's law

$$\Phi = -G\frac{M}{r}\left(1 + \alpha e^{-r/R_*}\right)$$

- torsion balance experiments
  [Hoyle *et al.*, PRL **86**, 1418 (2001)]

$$R_* < 44\ \mu\mathrm{m}$$



Scale drawing of the torsion pendulum and rotating attractor.

What if...

- Additional spatial dimensions (ADD scenario)
  [Arkani-Hamed, Dimopoulos, Dvali. Phys.Lett.B429:263-272,1998]
  - SM fields → brane
  - gravity → bulk
- R_* must be SMALL ...

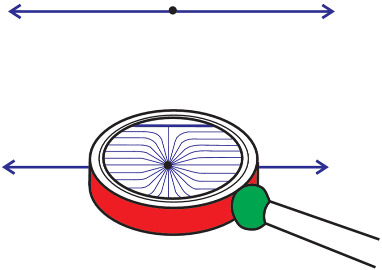
$$\Phi(r) = -\frac{\hbar^{k+1}}{M_*^{2+k}} \frac{c^{1-k}}{R_*^k} \frac{M}{r} \quad \to \quad -\frac{\hbar c}{M_P^2} \frac{M}{r}$$

$$\text{as} \quad r \gg R.$$

- R_* must be LARGE ...

$$M_* \sim \left(\frac{L_P}{R_*}\right)^{\frac{k}{k+2}} M_P \sim 1 \text{ TeV}$$

$$\Longrightarrow k \geq 2$$



Flux lines with one extradimension

Higher dimensional black holes

- Higher-dimensional Schwarzschild geometry

$$
\begin{aligned}
ds^2_{(k+4)} &= -F(r)dt^2 + F^{-1}(r)dr^2 + r^2 d\Omega^2_{3+k} \\
F(r) &= 1 - \left(\frac{r_H}{r}\right)^{k+1} \\
r_H &= \frac{1}{\sqrt{\pi}}\left(\frac{\hbar}{M_* c}\right)\left[\frac{8\Gamma(\frac{k+3}{2})}{(k+2)}\right]^{\frac{1}{k+1}}\left(\frac{M}{M_*}\right)^{\frac{1}{k+1}}
\end{aligned}
$$

- for $M \gtrsim M_* \sim 1\ \mathrm{TeV} \to r_H \sim 10^{-4}$ fermi
- validity of spherical symmetry $r_H \ll R_*$
- black hole formation $r_H \sim \lambda$
- black hole factory

$$
\sigma_{\mathrm{BH}} \sim \pi r_H^2 \sim 1\mathrm{nb} \Rightarrow N_{\mathrm{BH}}/\mathrm{s} = \sigma_{\mathrm{BH}} L_{\mathrm{LHC}} \sim 10
$$

- $T \sim 70 - 700\ \mathrm{GeV}$

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Data analysis

- at the 95 % CL they rule out BHs with

$$M = 3.5 - 4.5\ \mathrm{TeV}$$

for M_* up to 3 TeV.

[CMS collaboration, Phys.Lett.B697:434,2011]

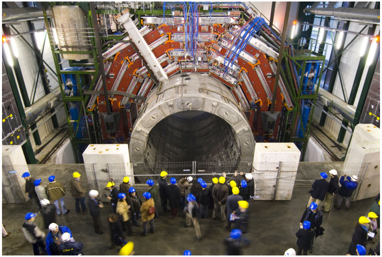
- Update, February 2012

$$M > 5.3\ \mathrm{TeV}$$

[CMS collaboration, arXiv:1202.6396 [hep-ex]]

- Results are questioned: semiclassical approximation not valid

[Park, Phys.Lett.B701:587,2011]



The CMS detector

The CMS control room

Beyond the semiclassical approximation

- Higher dimensional non-singular black hole

$$\begin{aligned} ds^2_{(4+k)} &= -F(r)dt^2 + F^{-1}(r)dr^2 + r^2 d\Omega^2_{3+k} \\ F(r) &= 1 - \left(\frac{r_h}{r}\right)^{k+1} \\ r_h &= \frac{1}{\sqrt{\pi}}\left(\frac{\hbar}{M_\star c}\right)\left[\frac{8\gamma(\frac{k+3}{2},\frac{r^2}{4\ell^2})}{(k+2)}\right]^{\frac{1}{k+1}}\left(\frac{M}{M_\star}\right)^{\frac{1}{k+1}} \end{aligned}$$

- Temperature

$$ds^2 = -F(r)\,dt^2 + F^{-1}(r)\,dr^2 + r^2 d\Omega^2_{3+k}$$
$$\longrightarrow \quad ds^2_E = F(r)\,d\tau^2 + F^{-1}(r)\,dr^2 + r^2 d\Omega^2_{3+k}.$$

$$\Rightarrow T_\ell = \frac{k+1}{4\pi r_h}\left[1 - \frac{2}{k+1}\left(\frac{r_h}{2\ell}\right)^{k+3}\frac{e^{-r_h^2/4\ell^2}}{\gamma\left(\frac{k+3}{2},\frac{r_h^2}{4\ell^2}\right)}\right].$$

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Evaporation and grey body factors

- Maximum temperatures

k	1	2	3	4	5	6	7
$T_\ell^{\max}$ [GeV]	30	43	56	67	78	89	98
T [GeV]	77	179	282	379	470	553	629

- negligible quantum back reaction
- longer decaying times

$$t \lesssim 10^{-16} \; (10^{-26}) \; \mathrm{s}$$

no Doomsday scenario

[Bleicher & PN, J.Phys.Conf.Ser. 237 (2010) 012008]

- Particle spectrum

$$\frac{dN^{(s)}}{dt} = \sum_j \mathrm{N}_j \int \frac{g_{jn}^{(s)}(\omega)}{\exp\left(\hbar\omega / k_{\mathrm{B}} T_\ell\right) \pm 1} \frac{d\omega}{(2\pi)}$$

where $g_{jk}^{(s)}$ is the grey body factor and N_j is the j-state multiplicity.

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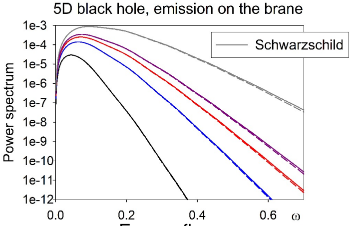
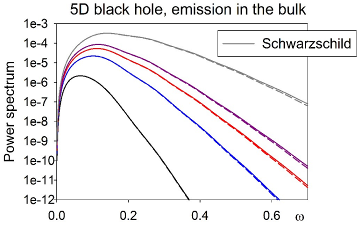
Scalar emission

- Brane emission with varying M



Energy fluxes

- Bulk emission with varying M

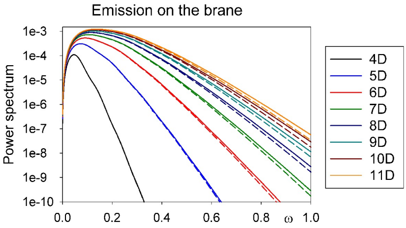


Energy fluxes

- Schwarzschild black hole (grey) with the same mass as the non-singular BH at $T_\ell^{\max}$ (purple).
- dashed curves correspond to additional quantum gravity corrections on matter fields
- the units are $\ell = 1$

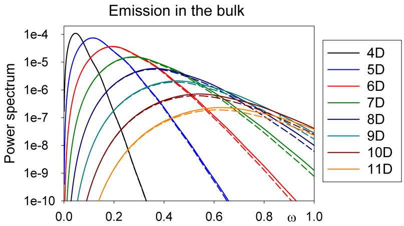
Scalar emission

- Brane emission with varying *k*



Energy fluxes

- Bulk emission with varying *k*



Energy fluxes

- Non-singular BHs with maximum temperature $T_\ell^{\max}$
- dashed curves correspond to additional quantum gravity corrections on matter fields
- the units are $\ell = 1$

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Bulk/brane emission

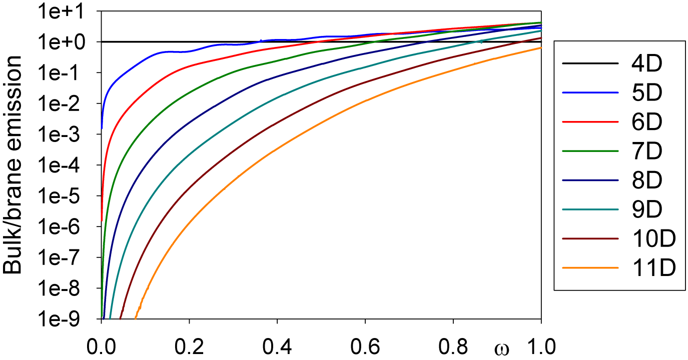

Figure: Bulk/brane emission

The units are $\ell = 1$.

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The signature

Total fluxes

	$k=1$	$k=2$	$k=3$	$k=4$	$k=5$	$k=6$	$k=7$
Particles	3.3	6.0	8.5	10.7	12.4	13.8	15.0
Power	5.5	13.1	21.8	30.2	37.6	44.0	49.3

brane emission (normalized to 4d)

	$k=1$	$k=2$	$k=3$	$k=4$	$k=5$	$k=6$	$k=7$
Particles	.56	.24	.091	.032	.011	.0033	.001
Power	1.46	1.08	.59	.27	.11	.042	.014

bulk emission (normalized to 4d)

- Bulk/brane emission decreases with increasing k.
- e.g. for $k=7$ bulk/brane 0.02% (in marked contrast to the usual result 93%)
- emission dominated by **soft particles mostly on the brane**.

[PN & Winstanley JHEP **1111**, 075 (2011)]

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Extragalactic neutrino oscillations

- Transition probability (two-flavour model)

$$P(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

- Modified transition probability

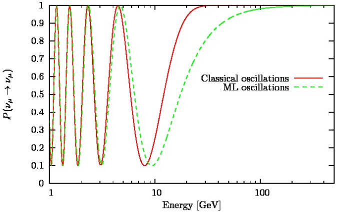
$$P_\ell(\nu_\alpha \to \nu_\beta) = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E} e^{-\ell^2 E^2}\right)$$

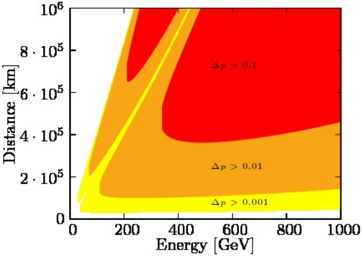
- Probability difference

$$\Delta p \equiv |P(\alpha \to \beta) - P_\ell(\alpha \to \beta)|$$

- **Extragalactic high energy neutrinos would not oscillate!**

[Sprenger, PN & Bleicher, CQG **28**, 235019 (2011)]





Δp for $\ell \sim 10^{-19}$ m.

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Back to 4d: an astronomical test

- Modified dispersion relation

$$p^2 = E^2\,[1 \pm a_0 (E/E_P)^{\alpha}]\,, \qquad \alpha = \begin{cases} \frac{1}{2} & \text{Random walk model} \\ & \text{[Amelino-Camelia, Lect.Not.Phys, } \mathbf{541}\text{, 1(2000)]} \\ \frac{2}{3} & \text{Holographic model} \\ & \text{[t'Hooft, in Salamfest p. 284(World Scientific 2003)]} \\ 1 & \text{Standard model [Smolin, hep-th/0303185]} \\ 2 & \textbf{Gaussian smearing model } (a_0 = 2/3) \end{cases}$$

- Farthest quasar image degradation
  [Tamburini *et al.*, A& A **533**, A71 (2011)]

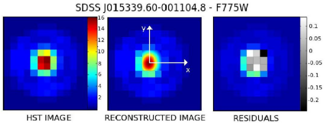

Fig. 1. *Left*: HST image of the QSO QSO 0153-0011, IAU name SDSS J015339.60-001104.8 located at $z = 4.205$. The field of view is 15×15 pixels. *Center*: we show the central region (3×3 pixels) reconstructed using the function F (Eq. (9)). We plot the cartesian axes centered on the maximum of the intensity pattern. Here $\epsilon = 0.23$ and $\alpha = 0.14$ rad. Each pixel of the analyzed area is divided into 15×15 sub-pixels. *Right*: we show the residuals of the central analyzed area (3×3 pixels).

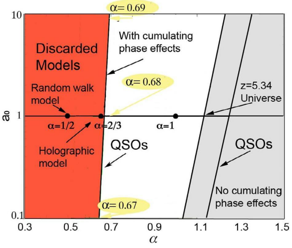

Fig. 5. Parameter space a_0 and α. The red region (colour online) in the left is the portion of the parameter space that is discarded by our observations with the most conservative approach that takes in consideration the cumulating effects of space-time fluctuations (see text). The white region in the middle is the additional portion of the parameter space that would be discarded if no compensation due to the cumulating effect of space-time occurs. The grey region in the right is the portion of the parameter space that cannot be excluded in any case. The data obtained with our analysis from the farthest QSOs exclude the random walk and the holographic models of space-time foam in the range of a_0, here reported. These results, indicated by the label QSOs, go far beyond the previous estimates reported in the literature (indicated by $z = 5.34$ Universe), obtained without considering the cumulating effects of space-time.

Back to 4d: detection of the Hawking radiation

- Schwarzschild

$$T = \frac{\hbar c^3}{G k_B}\frac{1}{8\pi M} \sim 10^{-7}\left(\frac{M_\odot}{M}\right)\mathrm{K}$$

$$t \sim 10^{58}\left(\frac{M}{M_\odot}\right)^3 \mathrm{Gyr}$$

- primordial BHs $\Leftrightarrow t \sim 13.75\ \mathrm{Gyr}$

$$\Rightarrow \quad M \gtrsim 10^{11}\ \mathrm{kg},\ r_h \lesssim 10^{-16}\mathrm{m},\ T \gtrsim 10^{12}\mathrm{K}$$

$$\Rightarrow \quad \mathrm{EMP} \sim 1\ \mathrm{GHz}$$

[Rees, Nature **266**, 333 (1977)] [Blandford, MNRAS **181**, 489 (1977)]

- **the scenario needs revision!**
  - quantum mechanical deSitter instability $\Rightarrow$ suppressed nucleation of Planck size regular BHs
    [Mann & PN, PRD **84**, 064014 (2011)]
  - new temperature profile

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Spontaneous dimensional reduction at short scales?

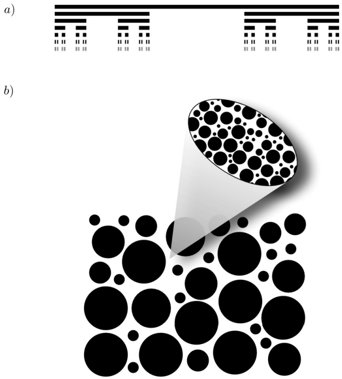
- **Dream**
  look for a mechanism of dimensional reduction to 2D to have gravity a power-counting renormalizable theory $[G_2] = (length)^0$
  [t'Hooft, in Salamfest p. 284 (World Scientific 1993)]
  [Carlip, in 25th Max Born Symposium (2009)]
- the quantum spacetime is like a fractal

$$D \to \mathbb{D}_\mathrm{s}$$

- **A dream come true**
  [Modesto & PN, PRD **81**, 104040 (2010)]

$$\mathbb{D}_\mathrm{s} = \frac{s}{s+\ell^2} D$$

for the here presented regular spacetimes

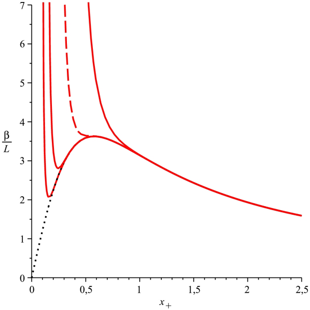


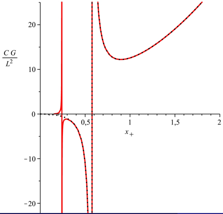
In a) a Cantor set
In b) holed structure with self-similarity.

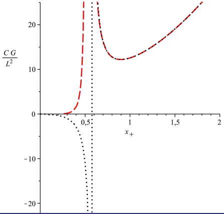
Phase transitions via gauge-gravity duality

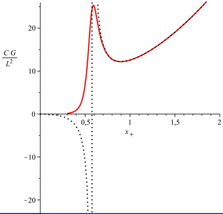
- **Witten:** Hawking-Page p.t. in $d+1$ dimension $\cong$ deconfinement in d dimensions for $N_c \to \infty$
- regular BHs with AdS background $\Lambda = -1/L^2$
- Hawking-Page $\underset{\ell\neq 0}{\longrightarrow}$ **Van der Waals**
- ℓ is the excluded volume b'
- “temperature” parameter $q \equiv 2\ell/L$
  - $q < q^* \Rightarrow$ 1st order p. t. small to large BHs
  - $q = q^* = 0.182 \Rightarrow$ critical point
  - $q > q^* \Rightarrow$ analytical cross over
- $q \cong N_f/N_c \Rightarrow$ **deconfinement/crossover**

[PN & Torrieri, JHEP **1108**, 097 (2011)]









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Conclusions

Summary: we easily passed all checks required by quantum gravity

- singularity avoidance
- black hole thermodynamics stability
- spontaneous dimensional reduction at the Planck scale to 2D.
- distinctive signatures

Theoretical developments

- new effective formulations of quantum gravity
- LHC phenomenology and quantum gravity at the terascale
- primordial and astrophysical black holes
- further developments about nuclear matter phase transition via gauge-gravity duality

  [Kaminski, Sprenger, Torrieri & PN, in progress] [Frassino & PN, in progress]
- ...

Observational tests

- Gravitational waves
- horizon imaging of black hole candidates
- black hole formation in particle detectors
- ...

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Dankeschön!