Title: Modeling the evaporation of mini black holes

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Abstract: TeV-scale models of quantum gravity predict the formation of mini black holes at the Large Hadron Collider. If these black holes can be treated, at least for part of their evolution, as semi-classical objects, they will emit Hawking radiation. In this talk we review the modeling of this evaporation process, particularly for the case when the black hole is rotating. A detailed understanding of the Hawking radiation is necessary for accurate simulations of black hole events at the LHC.

Modelling the evolution of mini black holes

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School of Mathematics and Statistics
University of Sheffield
United Kingdom

Outline

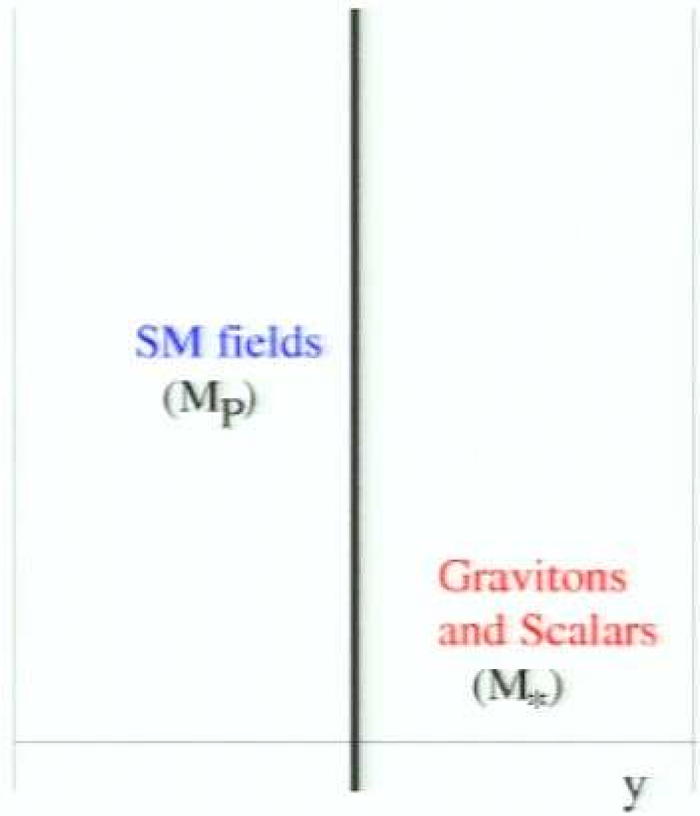
1. Introduction
   - Brane worlds
   - Formation of mini black holes
2. Evolution of mini black holes
   - Balding phase
3. Semi-classical evolution
   - Modelling mini black holes
   - Hawking radiation of black holes
   - Results for massless fields
   - More general effects
4. Simulations of black hole events
5. Conclusions

Brane worlds

Our universe is a brane living in a higher-dimensional bulk

- ADD model - flat compactified extra dimensions
- Standard model physics restricted to the brane
- Only gravity propagates in the bulk
- Fundamental higher-dimensional scale of quantum gravity, M_*, may be as low as the energy of the LHC:

$$M_P^2 \sim M_*^{n+2} R^n$$

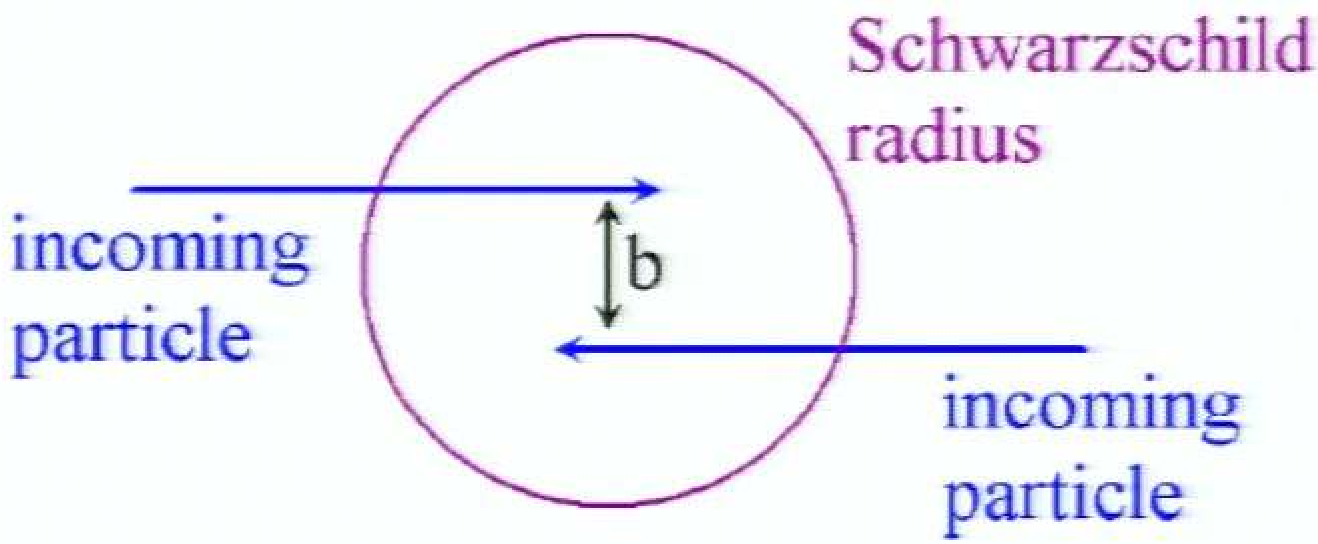


[Figure taken from Kanti, arXiv:0802.2218 [hep-th]]

Formation of mini black holes

If $M_* \sim$ few TeV, particle collisions at LHC may produce heavy, quantum gravitational objects

Two particles with centre-of-mass energies greater than M_*, and impact parameter b:

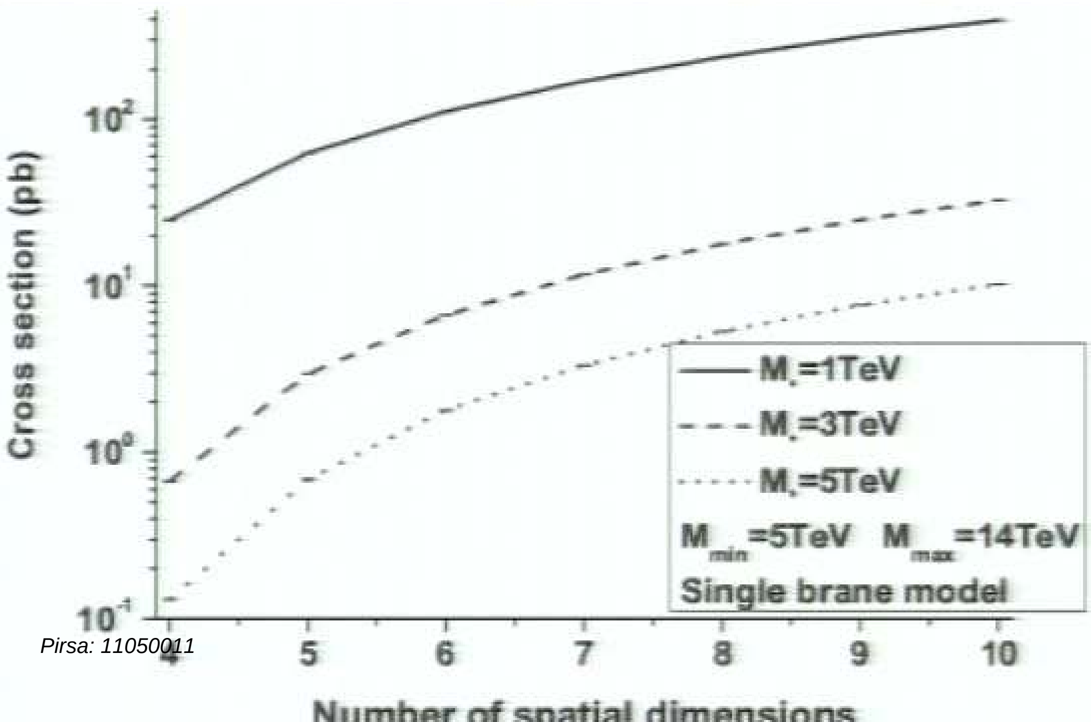


Black hole production cross-sections

Parton-level BH production cross-section

$$\sigma^{\text{ij} \to \text{BH}}_{\text{production}} \propto \pi r_H^2 \sim \frac{1}{M_*^2}\left(\frac{E}{M_*}\right)^{\frac{2}{n+1}}$$

[Giddings and Thomas, hep-ph/0106219 ;
Dimopoulos and Landsberg, hep-ph/0106295]



For $M_* = 1$ TeV and $M_{BH} = 5$ TeV with $n = 6$, $\sigma \sim 10^2$ pb : about one black hole per second!

[Figure taken from Dai et al, arXiv:0711.3012]

Can we expect semi-classical black holes to be formed?

Black hole formation at the LHC is not a classical process

Quantum gravity scattering processes are much more likely than semi-classical black hole formation

Compton wavelength [Meade and Randall, arXiv:0708.3017 [hep-ph]]

Compton wavelength of colliding particle of energy $E/2$ must lie within the Schwarzschild radius:

$$4\pi/E < r_h(E)$$

Therefore $E/M_* \gtrsim 10$ in order for black holes to form

"Quantum black holes"

Work on modelling genuinely quantum black holes:

[Calmet et al, arXiv:1005.1805 [hep-ph]]

[Gingrich, arXiv:0912.0826 [hep-ph]]

Recent ATLAS search for these types of events:

[arXiv:1103.3864 [hep-ex]]

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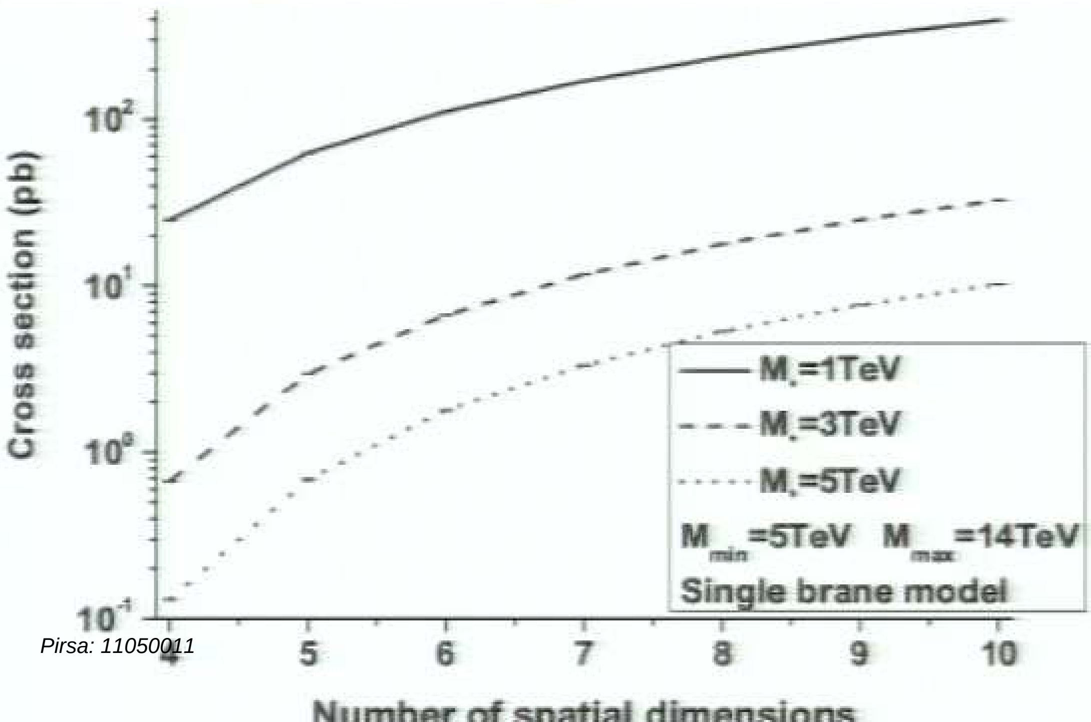

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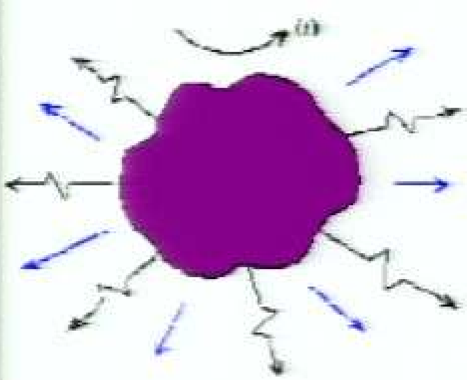
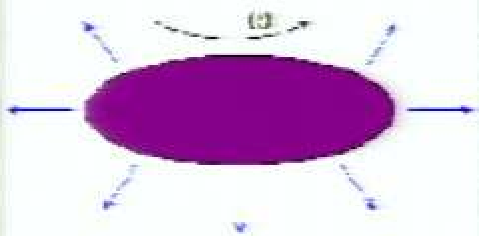
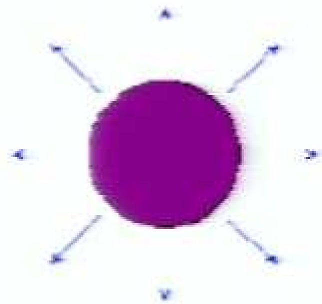
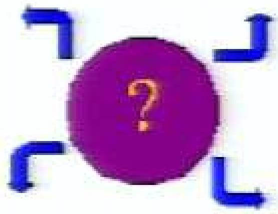
Stages in the evolution of mini black holes

Black holes formed will be rapidly rotating, highly asymmetric, and have gauge field hair

Four stages of subsequent evolution:

"Balding" stage	"Spin-down" stage	"Schwarzschild" stage	"Quantum gravity" stage
			

[Giddings and Thomas, hep-ph/0106219]

Balding phase

Shedding of mass and angular momentum through gravitational radiation modeled as part of formation process

Limits on amount of energy lost in gravitational radiation

- Colliding shock waves: $\leq 30\%$ $(n=0)$, $\leq 40\%$ $(n=7)$
  [Yoshino and Rychkov, hep-th/0503171]
- Four-dimensional numerical relativity: $\leq 35\%$ $(n=0)$
  [Sperhake et al, arXiv:0907.1252 [gr-qc]]

Angular momentum of formed black hole

- Angular momentum of black holes with $n>1$ potentially unbounded
- Limited by maximum impact parameter
- Colliding shock waves: $j \sim 0.93$ $(n=1)$
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Balding phase

Very little work done on shedding charges or gauge field hair

QCD effects

Likely to be significant, but little work on this

[Calmet et al, arXiv:0806.4605 [hep-ph]]

[Gingrich, arXiv:0912.0826 [hep-ph]]

Electromagnetic effects

- Classical Maxwell field on the brane only - modifies the "slice" of the Myers-Perry black hole
- Loss of black hole charge is not rapid in TeV gravity models

[Sampaio, arXiv:0907.5107 [hep-th]] ;

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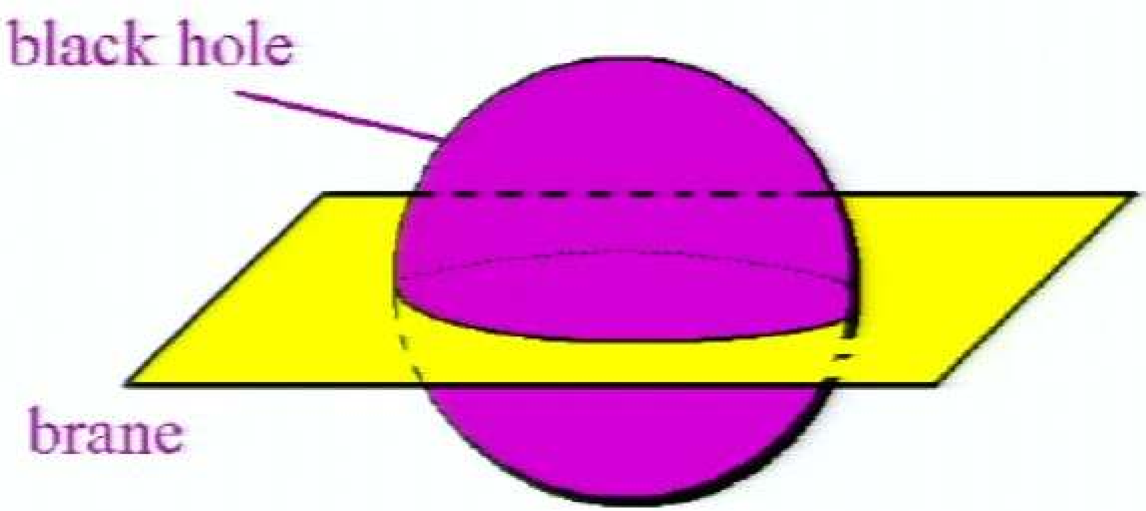
Modelling mini black holes at the end of the balding stage

Small black holes in ADD

- Metric of higher-dimensional black holes in general relativity is known [Myers and Perry, *Annals Phys.* **172**, 304 (1986)]
- Take a 'slice' through a higher-dimensional black hole to give a brane black hole



Modelling mini black holes in ADD

Myers-Perry higher-dimensional black hole

$$
\begin{aligned}
ds^2 &= \left(1 - \frac{\mu}{\Sigma r^{n-1}}\right) dt^2 + \frac{2a\mu \sin^2\theta}{\Sigma r^{n-1}} dt\, d\varphi - \frac{\Sigma}{\Delta_n} dr^2 - \Sigma\, d\theta^2 \\
&\quad - \left(r^2 + a^2 + \frac{a^2 \mu \sin^2\theta}{\Sigma r^{n-1}}\right) \sin^2\theta\, d\varphi^2 - r^2 \cos^2\theta\, d\Omega_n^2
\end{aligned}
$$

where

$$
\Delta_n = r^2 + a^2 - \frac{\mu}{r^{n-1}}, \qquad \Sigma = r^2 + a^2 \cos^2\theta
$$

Black hole mass M and angular momentum J:

$$
M = \frac{(n+2)\, A_{n+2}\mu}{16\pi G_{4+n}}, \qquad J = \frac{2aM}{n+2}
$$

Modelling mini black holes in ADD

Slice of Myers-Perry black hole

$$ds^2 = \left(1 - \frac{\mu}{\Sigma r^{n-1}}\right) dt^2 + \frac{2a\mu \sin^2\theta}{\Sigma r^{n-1}} dt\, d\varphi - \frac{\Sigma}{\Delta_n} dr^2 - \Sigma\, d\theta^2$$
$$- \left(r^2 + a^2 + \frac{a^2 \mu \sin^2\theta}{\Sigma r^{n-1}}\right) \sin^2\theta\, d\varphi^2$$

where

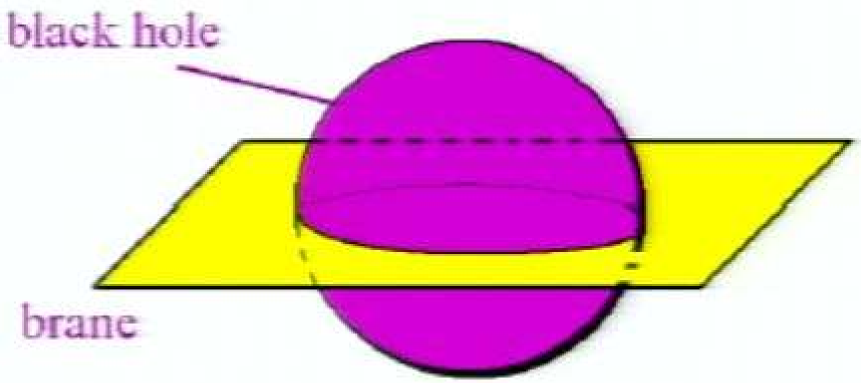
$$\Delta_n = r^2 + a^2 - \frac{\mu}{r^{n-1}}, \qquad \Sigma = r^2 + a^2 \cos^2\theta$$

and n is the number of extra dimensions.

Usual Kerr black hole

Set $n = 0$ in the above metric

Hawking radiation on the brane and in the bulk



Hawking temperature

$$T_H = \frac{(n+1)r_h^2 + (n-1)a^2}{4\pi(r_h^2 + a^2)r_h}$$

Particles on the brane

- Standard model particles: fermions, gauge bosons, Higgs
- Also gravitons and scalars
- Live on the brane "slice" of the black hole geometry

Particles in the bulk

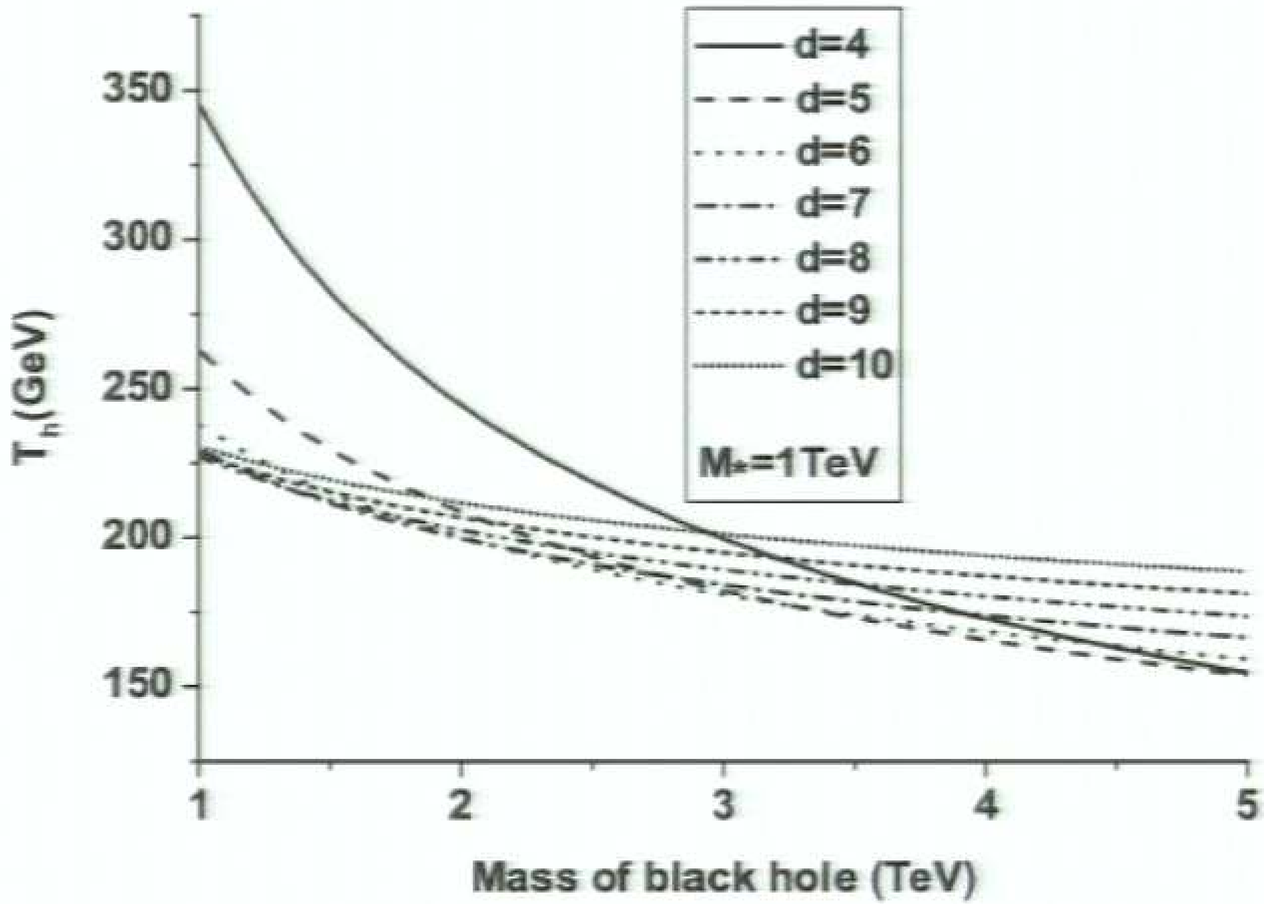
- Gravitons and scalars
- Will be invisible
- Live on the higher-dimensional black hole geometry

Hawking temperature

- For a non-rotating black hole,

$$T_H = \frac{(n+1)}{4\pi r_h}$$

- Black hole evaporates away with a lifetime of about 10^{-26} s



[Figure taken from Dai et al, `arXiv:0711.3012`]

Quantum fields on black hole space-times

Quantum field theory in curved space-time

- Black hole geometry is fixed and classical
- Quantum fields (scalars, fermions, gauge bosons, gravitons) propagate on this background

Quantum field modes

- "Master" equation for fields of spin 0, $\frac{1}{2}$, 1 and 2 on Kerr [Teukolsky, *Phys. Rev. Lett.* **29** 1114 (1972); *Astrophys. J.* **185** 635 (1973)]
- Expand field Ψ in terms of modes of frequency ω:

$$\Psi = \sum_{\omega \ell m} R_{s\omega\ell m}(r) S_{s\omega\ell m}(\theta) e^{-i\omega t} e^{im\varphi}$$

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Computing Hawking radiation

Differential emission rates, integrated over all angles:

$$\frac{d^2}{dt\,d\omega}\begin{pmatrix} N \\ E \\ J \end{pmatrix} = \frac{1}{4\pi}\sum_{\text{modes}} \frac{|\mathcal{A}_{s\omega\ell m}|^2}{e^{\tilde{\omega}/T_H} \mp 1}\begin{pmatrix} 1 \\ \omega \\ m \end{pmatrix}$$

where $\tilde{\omega} = \omega - m\Omega_H$

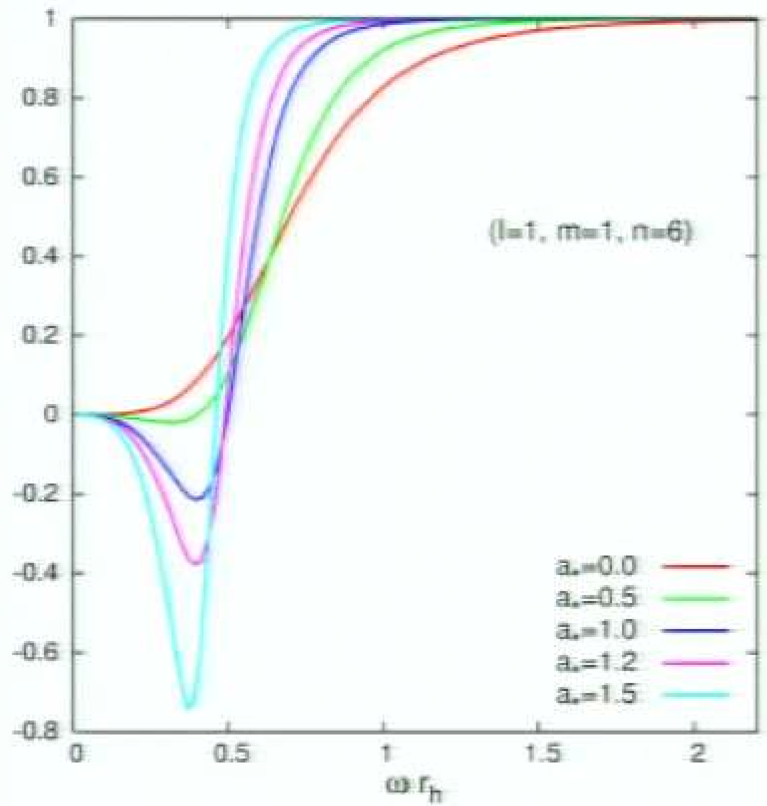
Grey-body factor $|\mathcal{A}_{s\omega\ell m}|^2$

- Emitted radiation is not precisely thermal
- Interaction of emitted quanta with gravitational potential around the black hole
- For an outgoing wave from the event horizon of the black hole:

$$|\mathcal{A}_{s\omega\ell m}|^2 = 1 - |\mathcal{R}_{s\omega\ell m}|^2 = \frac{\mathcal{F}_{\text{infinity}}}{\mathcal{F}_{\text{horizon}}}$$

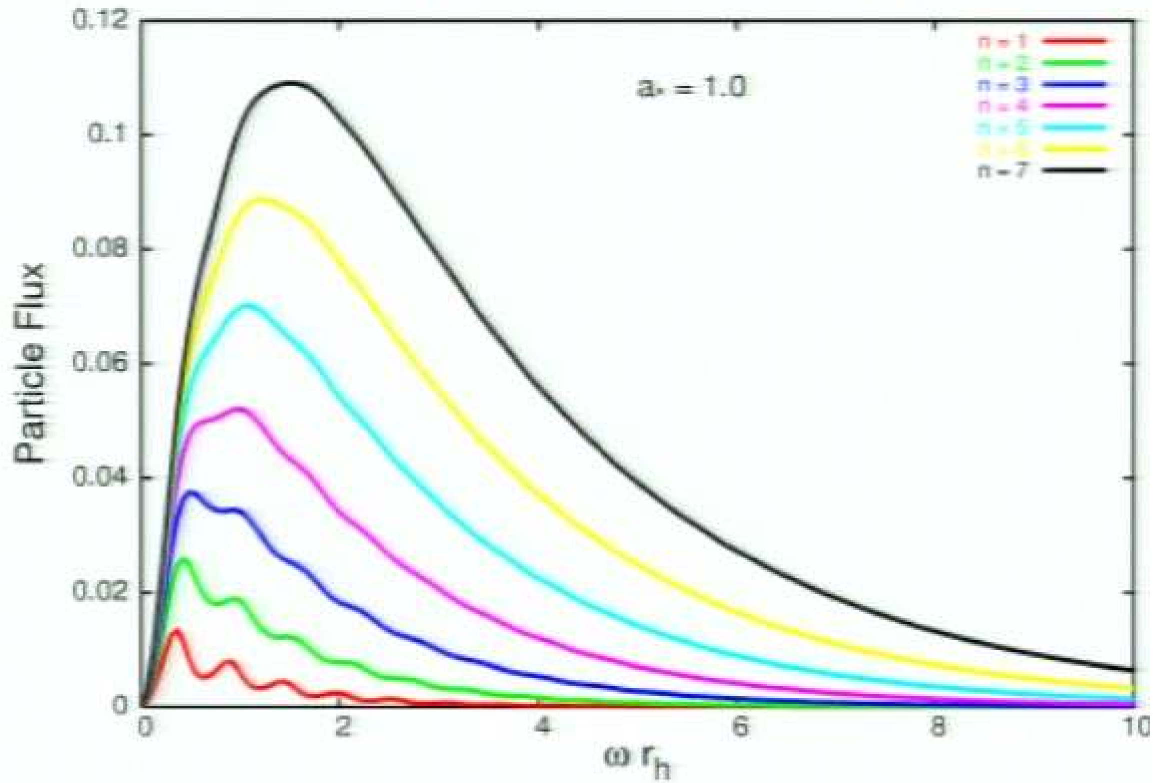
Grey-body factors and emission spectra

Grey-body factors for gauge boson emission and $n = 6$



[Figure taken from Casals et al, hep-th/0511163]

Fermion emission spectra for a rotating black hole, integrated over all angles



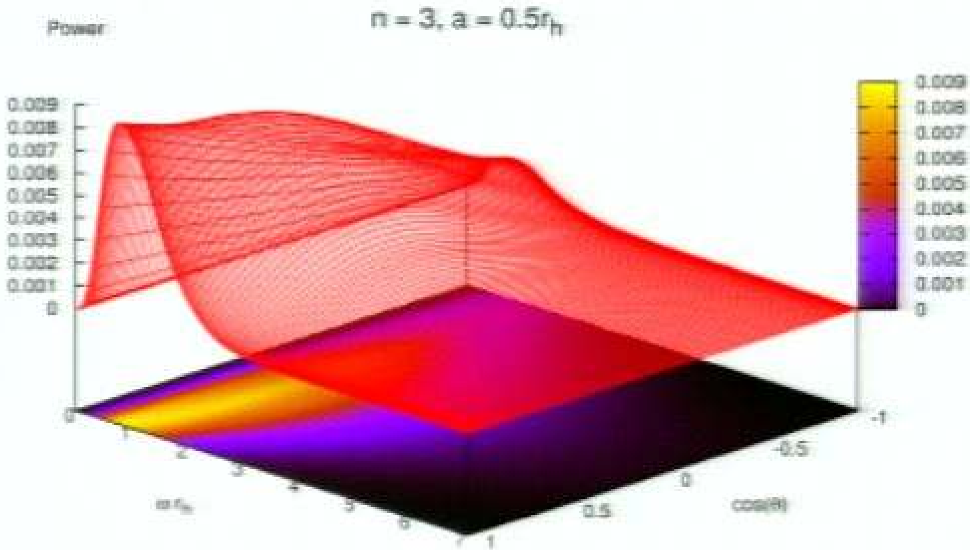
[Figure taken from Casals et al, hep-th/0608193]

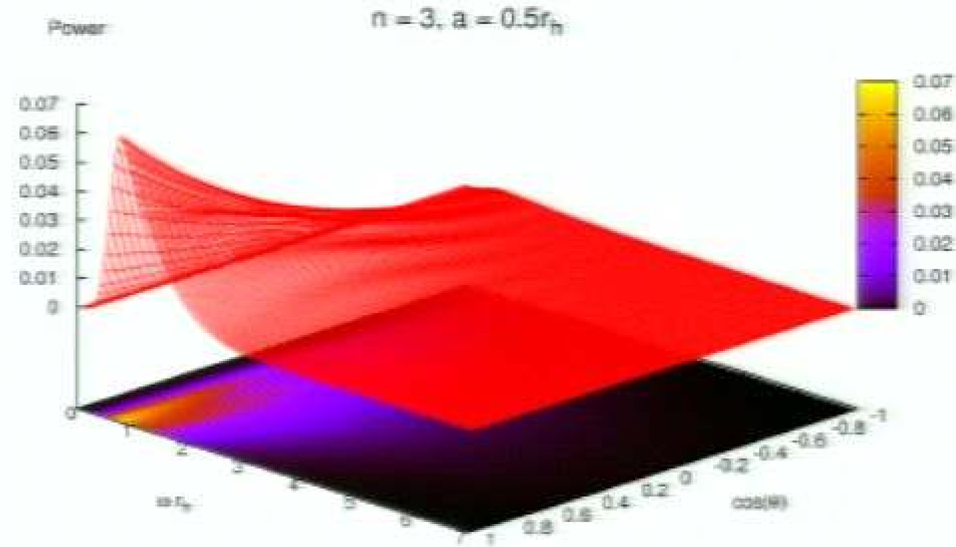
Angular distribution of energy flux

Differential energy emission rate:

$$\frac{d^3E}{dt\,d\omega\,d(\cos\theta)} = \frac{1}{4\pi}\sum_{\text{modes}} \frac{\omega\,|\mathcal{A}_{s\omega\ell m}|^2}{e^{\tilde{\omega}/T_H} \mp 1}\left[S_{|s|\omega\ell m}(\theta)^2 + S_{-|s|\omega\ell m}(\theta)^2\right]$$

Energy emission for positive helicity fermions and gauge bosons for $n = 3$ and $a_* = 0.5$

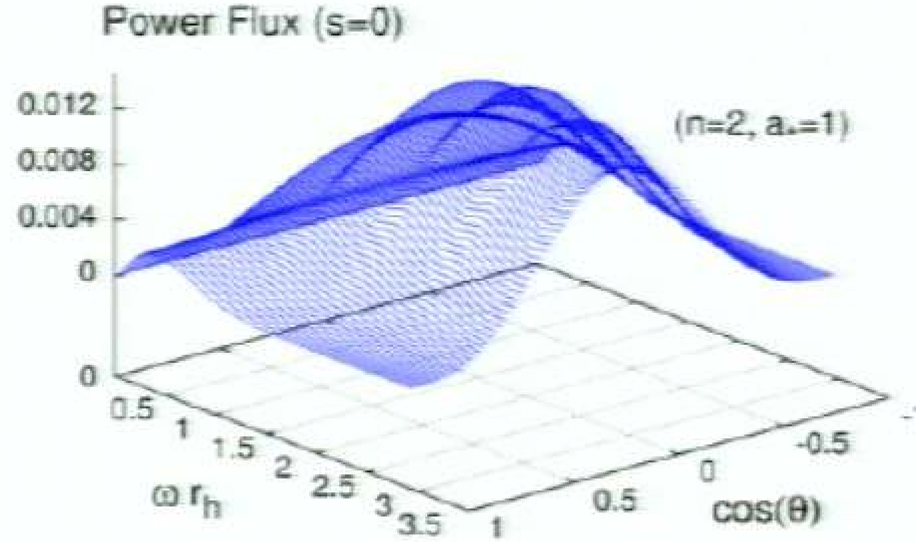


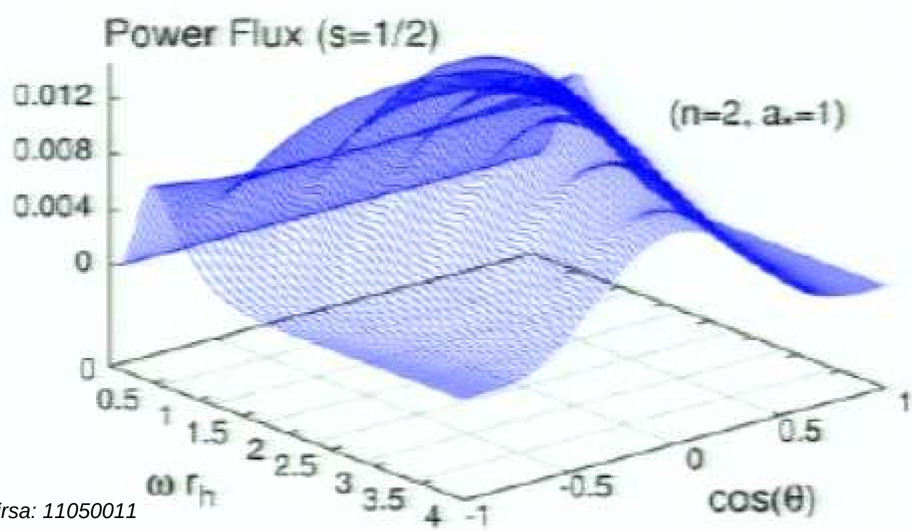


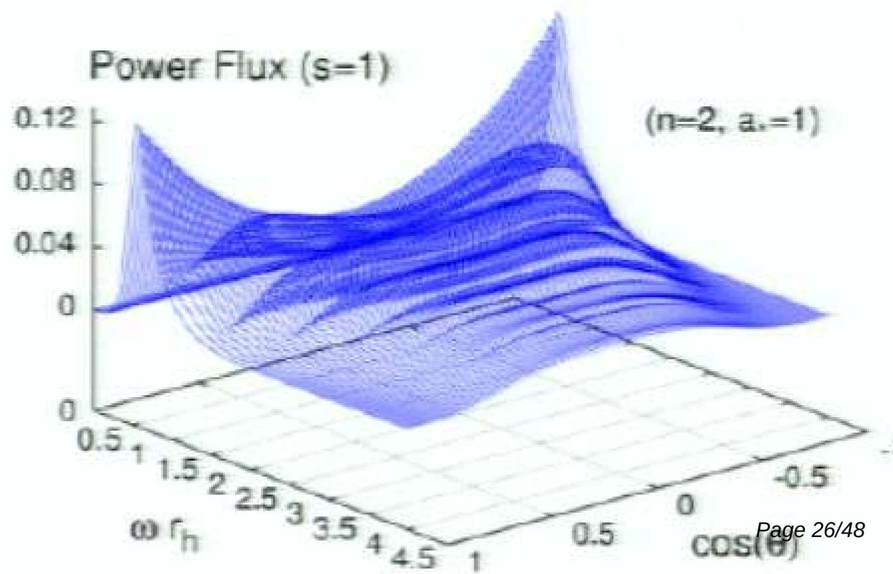
[Figures taken from Casals et al arXiv:0907.1511 [hep-th]]

Angular distribution of energy flux

Six-dimensional
black hole
$n=2$







What we know about the Hawking radiation phases

"Spin-down" phase

- Brane emission - scalars, fermions, gauge bosons done
- Bulk emission - scalars done
- Graviton emission - partial results only

"Schwarzschild" phase

- Brane emission - scalars, fermions, gauge bosons done
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"Black holes radiate mainly on the brane"

[Emparan, Horowitz and Myers, hep-th/0003118]

Ratio of bulk/brane emission for massless scalars, $n = 2$

$a_* = 0.0$	$a_* = 0.2$	$a_* = 0.4$	$a_* = 0.6$	$a_* = 0.8$	$a_* = 1.0$
19.9%	18.6%	15.3%	11.7%	9.0%	7.1%

[Casals et al, arXiv:0801.4910 [hep-th]]

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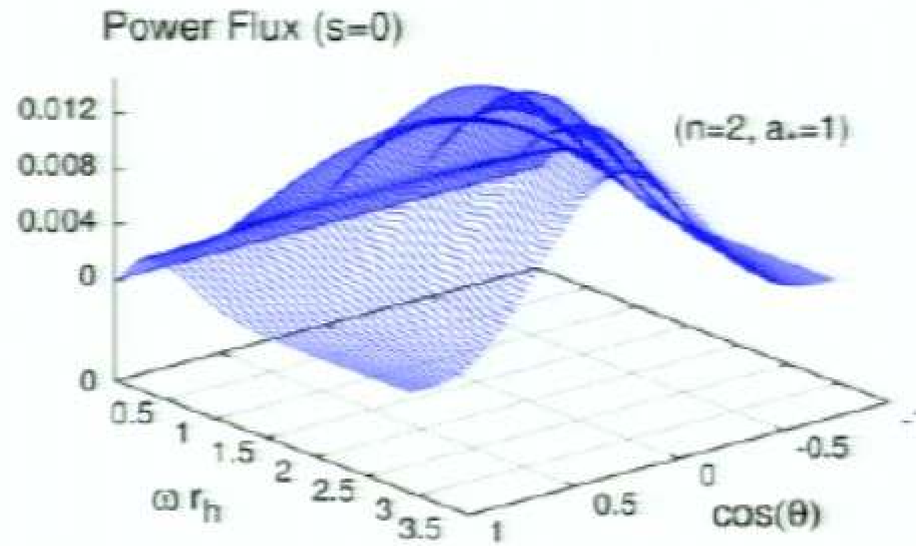

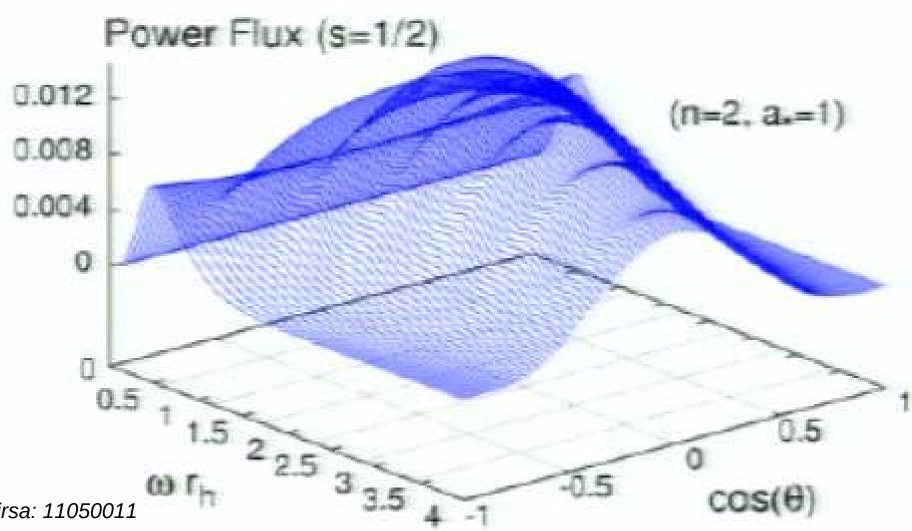

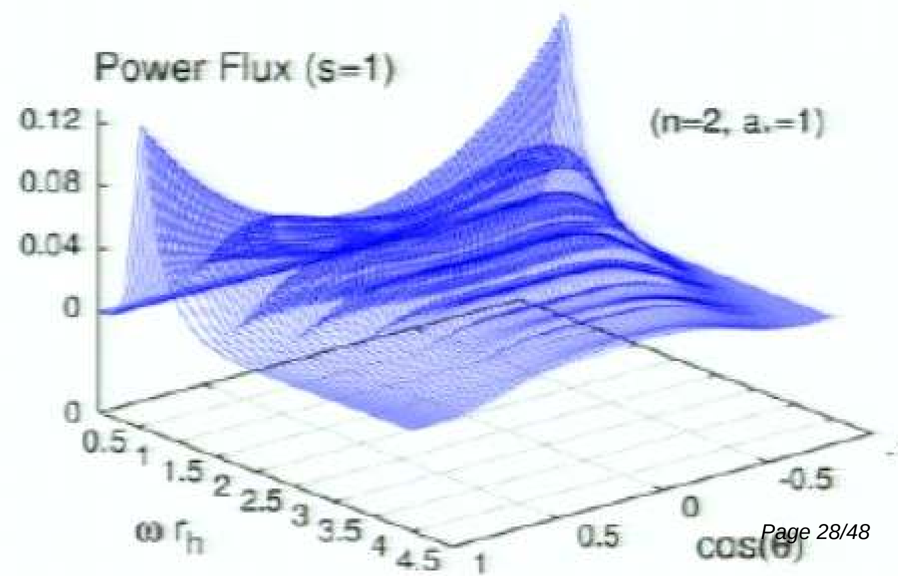

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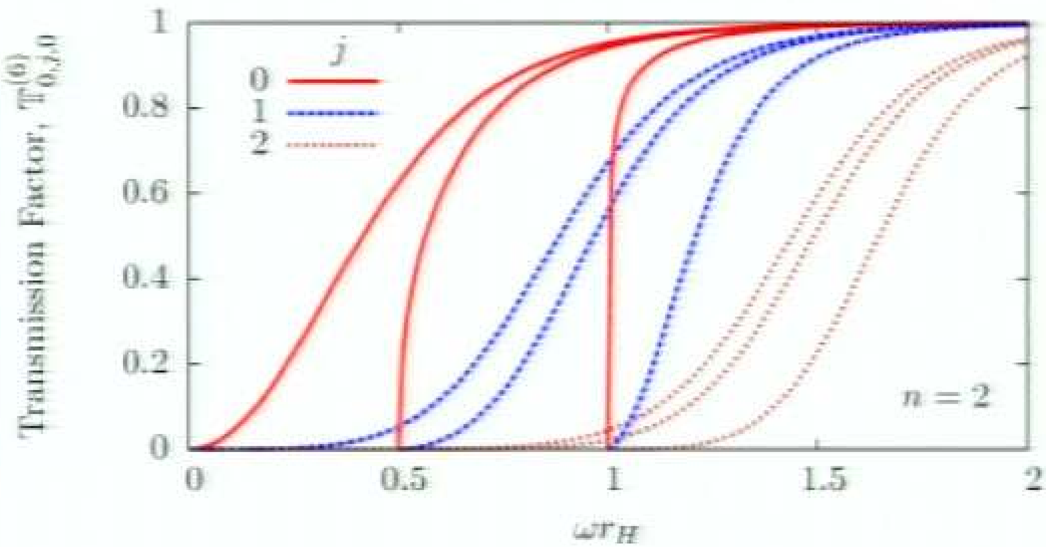
More complicated effects in Hawking radiation

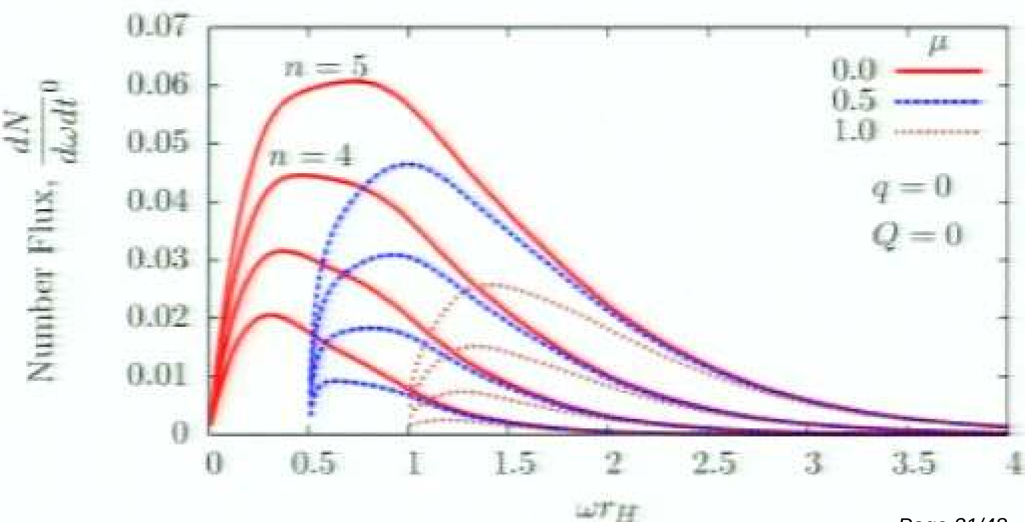
Massive particles

- Sharp cut-off in grey-body factor at particle mass
- Reduction in number of particles emitted

[Rogatko and Szyplowska, arXiv:0904.4544 [hep-th]]
[Kanti and Pappas, arXiv:1003.5125 [hep-th]]

[Figures taken from Sampaio, arXiv:0911.0688 [hep-th]]





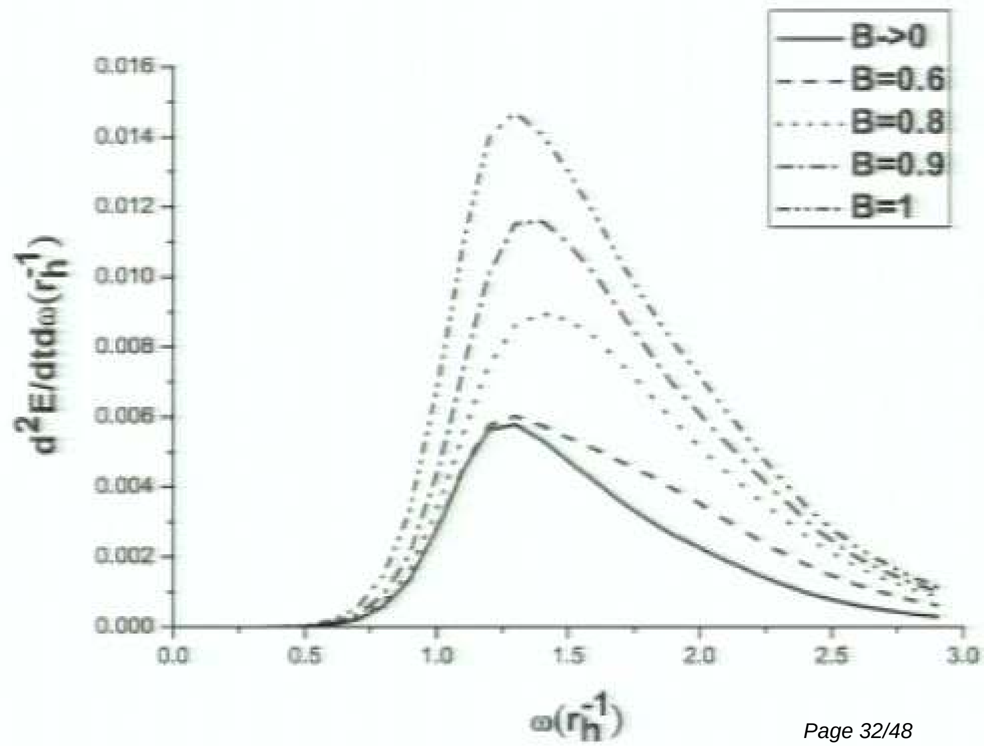
More complicated effects in Hawking radiation

Brane tension

Exact codimension-2 solutions for a black hole with a tense brane
[Kaloper and Kiley, hep-th/0601110]
[Kiley, arXiv:0708.1016 [hep-th]]

Bulk emission suppressed by brane tension

[Figure taken from Dai et al, hep-th/0611184]
[Kobayashi et al, arXiv:0711.1395 [hep-th]]
[Rogatko and Szyplowska, arXiv:0905.4342 [hep-th]]

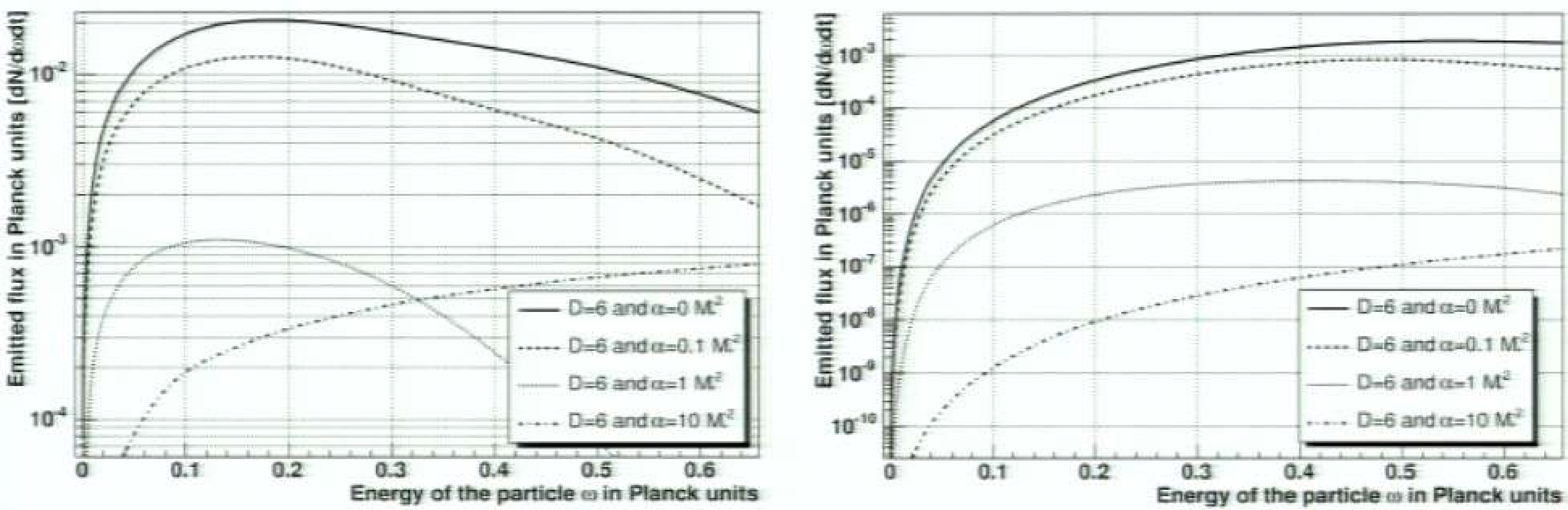


More complicated effects in Hawking radiation

Gauss-Bonnet gravity

Exact metric for spherically symmetric black hole with Gauss-Bonnet corrections [Boulware and Deser, *Phys. Rev. Lett.* **55**, 2656 (1985)]

Suppression of emission of both brane (left) and bulk (right) particles



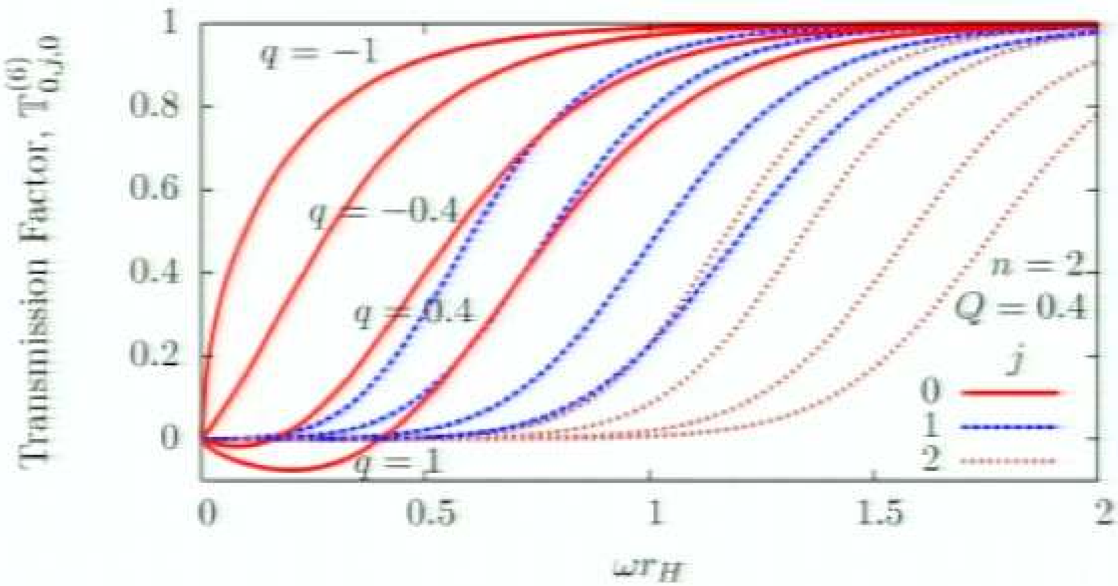
[Figures taken from Grain et al, `hep-th/0509128`]

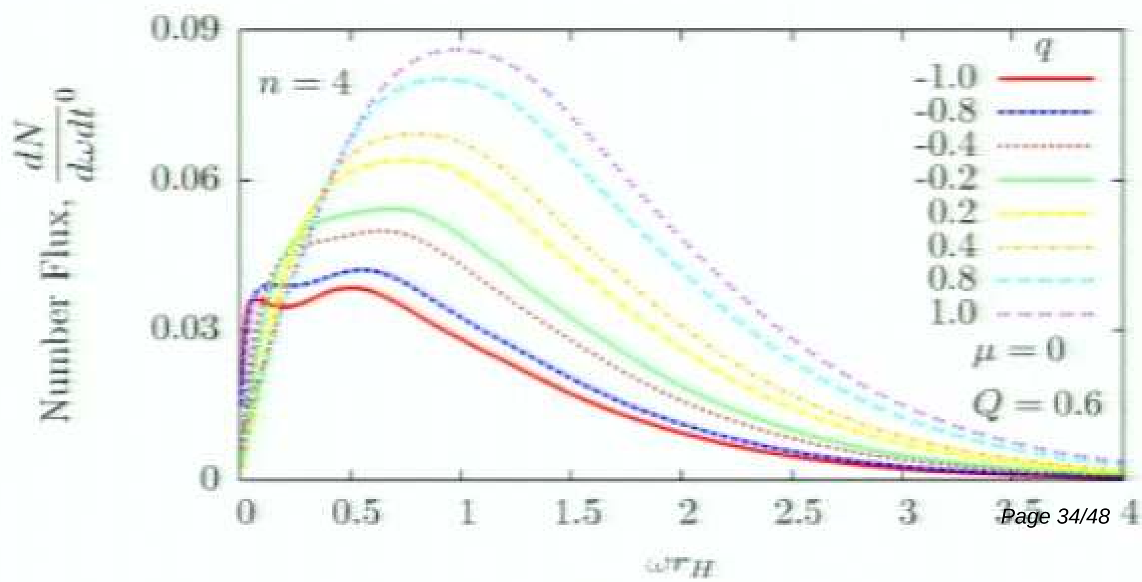
[Konoplya and Zhidenko, `arXiv:1004.3772 [hep-th]`]

More complicated effects in Hawking radiation

Charged particles

Modification of grey-body factor and emission spectrum for charged particles on the brane by a charged black hole





[Figures taken from Sampaio, `arXiv:0911.0688 [hep-th]`]

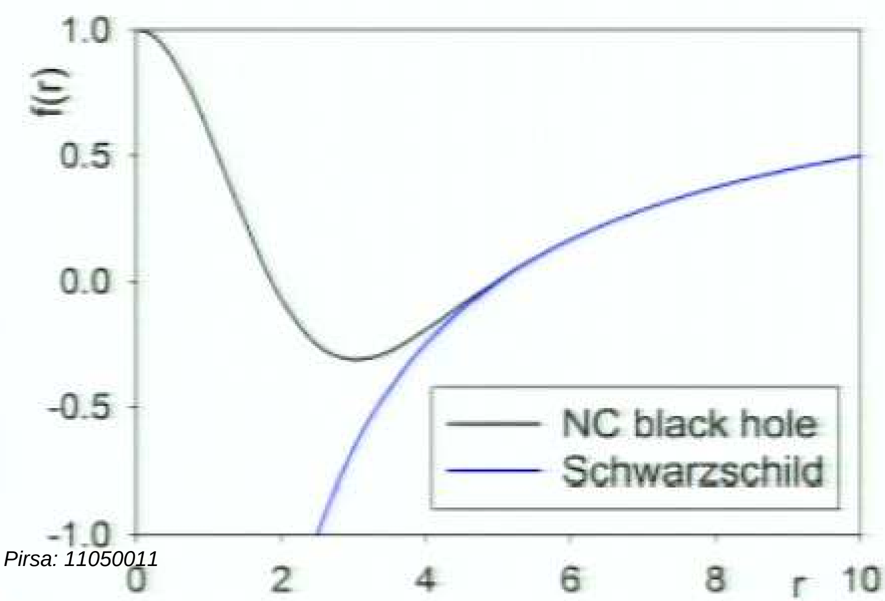
More complicated effects in Hawking radiation

Non-commutative-geometry-inspired black holes

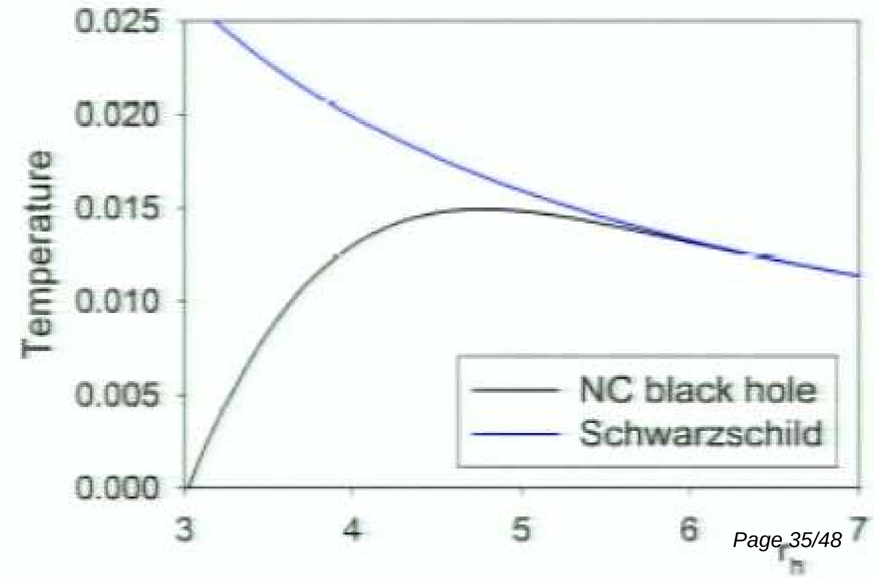
Use smeared mass density inspired by non-commutative geometry as source for classical metric

$$f(r) = 1 - \frac{2M}{r} \rightarrow 1 - \frac{4M}{r\sqrt{\pi}}\gamma\left(\frac{3}{2}, \frac{r^2}{4\vartheta}\right)$$

Metric



Temperature



[Nicolini et al. gr-qc/0510112]

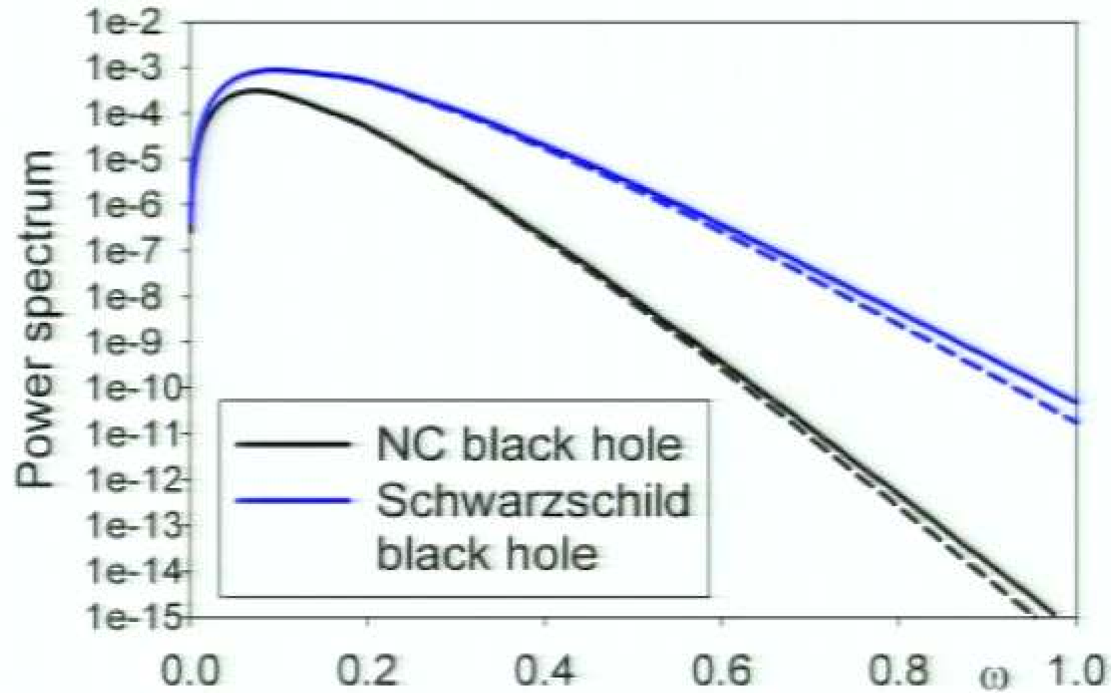
Effect of non-commutativity on Hawking radiation

Power spectrum modified by non-commutativity effects:

$$\frac{1}{4\pi}\sum_{\text{modes}}\frac{|\mathcal{A}_{s\omega\ell m}|^2}{e^{\omega/T_H}\mp 1}e^{-\omega^2}$$

[Casadio and Nicolini, `arXiv:0809.2471v1 [hep-th]`]

Scalar field emission on the brane, 5D black holes with the same mass



[Nicolini and EW, work in progress]

Open issues in modelling the evolution of mini black holes

- Complete computation of graviton radiation
  - Requires full gravitational perturbation equations for rotating higher-dimensional black holes
  - Work to date only for tensor-type gravitational perturbations with $n \geq 3$
    [Doukas et al, arXiv:0906.1515 [hep-th]]
    [Kanti et al, arXiv:0906.3845 [hep-th]]

- Realistic evolution will be a stochastic process
  - Individual quanta emitted rather than a continuum
  - Black hole will recoil, possibly even come off the brane
  - Black hole may not have time to approach thermal equilibrium between emissions

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Black hole events at the LHC

To discover black holes at the LHC, accurate event simulations are required

Black hole event generators [Gingrich, hep-ph/0610219]

- TrueNoir [Landsberg, hep-ph/0607297]
  http://hep.brown.edu/users/Greg/TrueNoir/
- CATFISH [Cavaglia et al, hep-ph/0609001]
  http://www.phy.olemiss.edu/GR/catfish/introduction.html
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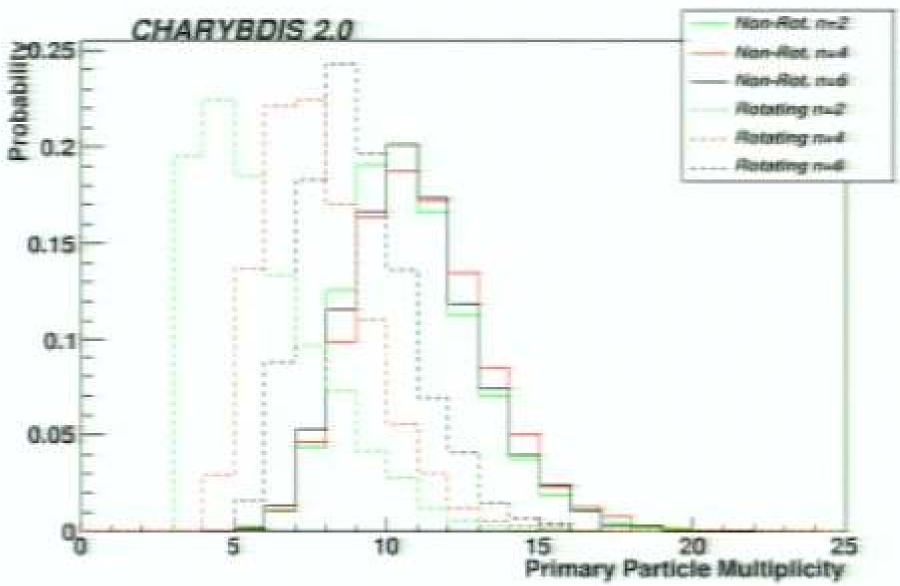
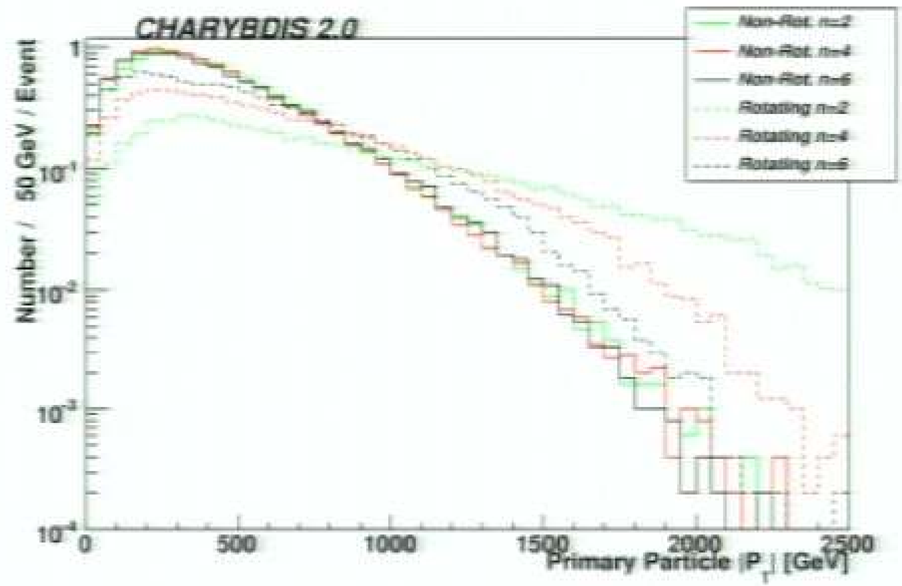
Results from CHARYBDIS2

Primary particle multiplicity

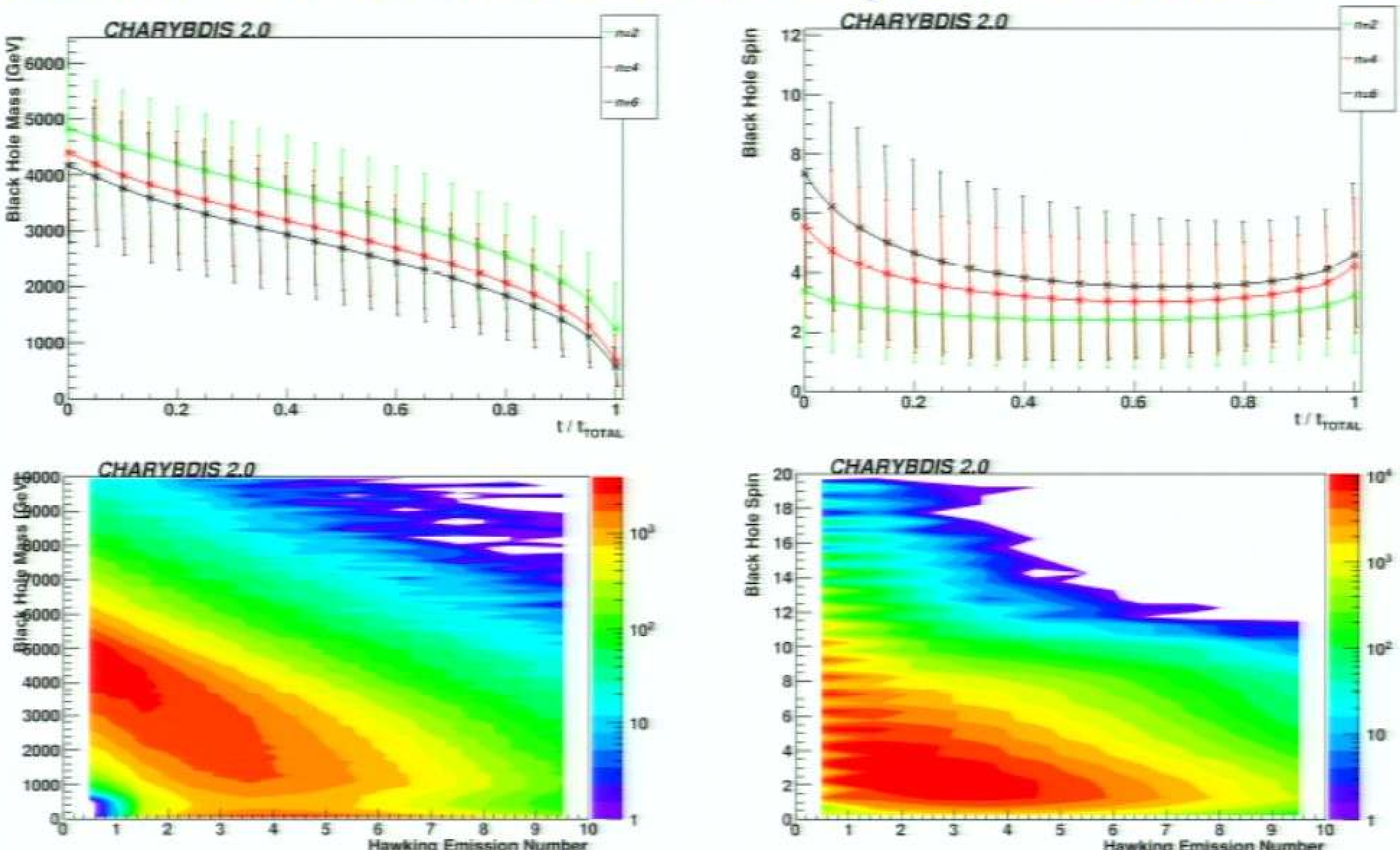


Primary particle P_T



[Figures taken from Frost et al, `arXiv:0904.0979 [hep-ph]`]

Evolution of black holes simulated by CHARYBDIS2



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Status of LHC searches for semi-classical black holes

CMS search for microscopic black holes

- Assumes semi-classical approximation valid
- Rules out black holes with masses 3.5–4.5 TeV for M_* up to 3 TeV

arXiv:1012.3375 [hep-ex]

Critical comment by Park:

Semi-classical model not valid at these energy ranges

arXiv:1104:5129 [hep-ph]

A simulated black hole event

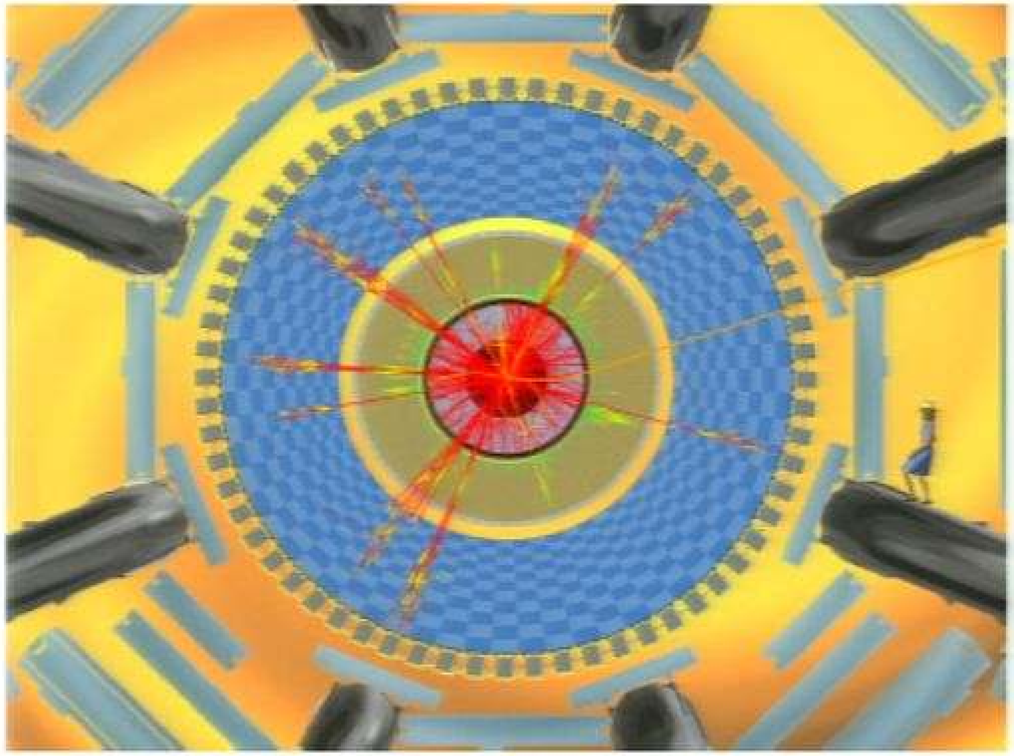

Figure: ATLAS/CERN

Conclusions

Four stages in the evolution of mini black holes

- Balding phase
- Spin-down phase
- Schwarzschild phase
- Quantum gravity phase

- Modelling of balding phase is very complicated due to matter coupling to the black hole and lack of symmetry
- Detailed analysis of semi-classical Hawking radiation apart from graviton modes for rotating black hole
- End-point of black hole evolution not fully understood
- Need to understand mini black holes as quantum rather than semi-classical objects

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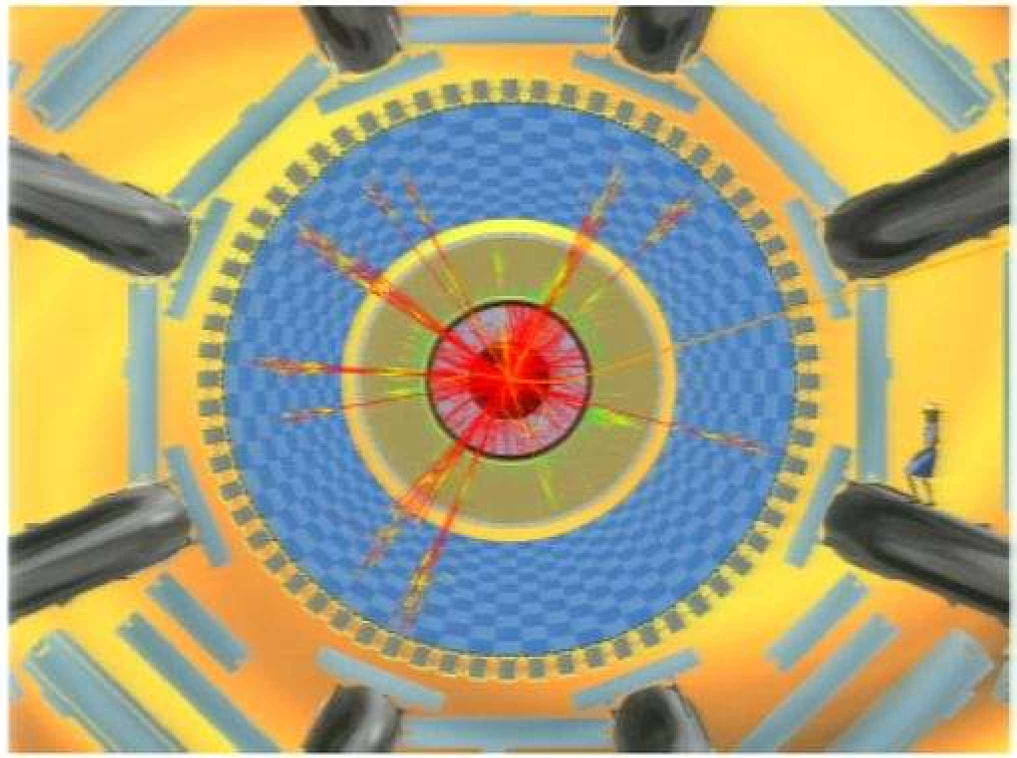


Figure: ATLAS/CERN

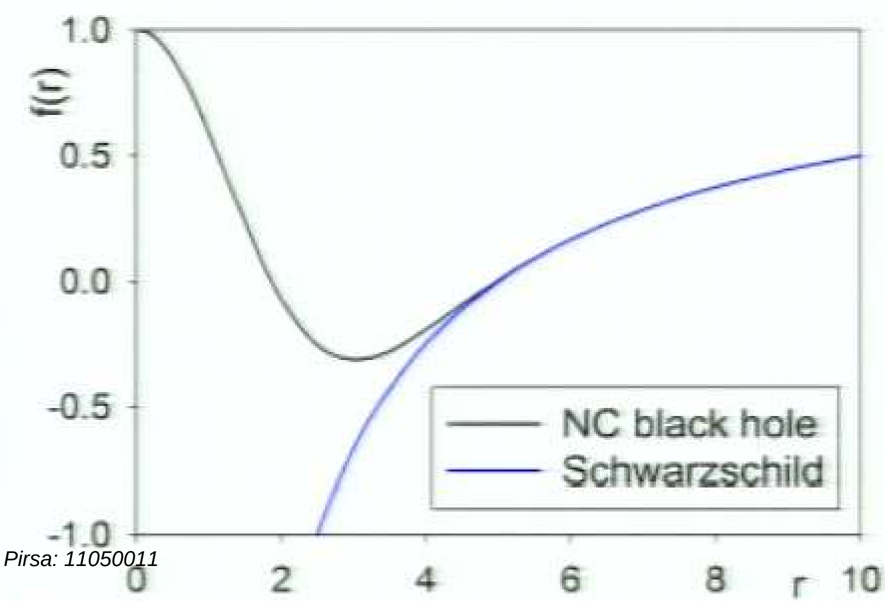
More complicated effects in Hawking radiation

Non-commutative-geometry-inspired black holes

Use smeared mass density inspired by non-commutative geometry as source for classical metric

$$f(r) = 1 - \frac{2M}{r} \to 1 - \frac{4M}{r\sqrt{\pi}}\gamma\left(\frac{3}{2}, \frac{r^2}{4\vartheta}\right)$$

Metric



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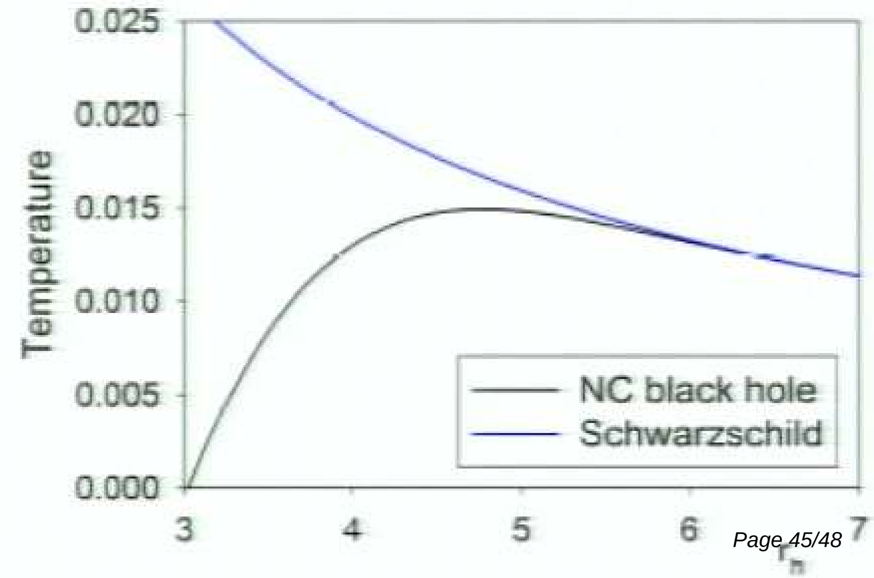

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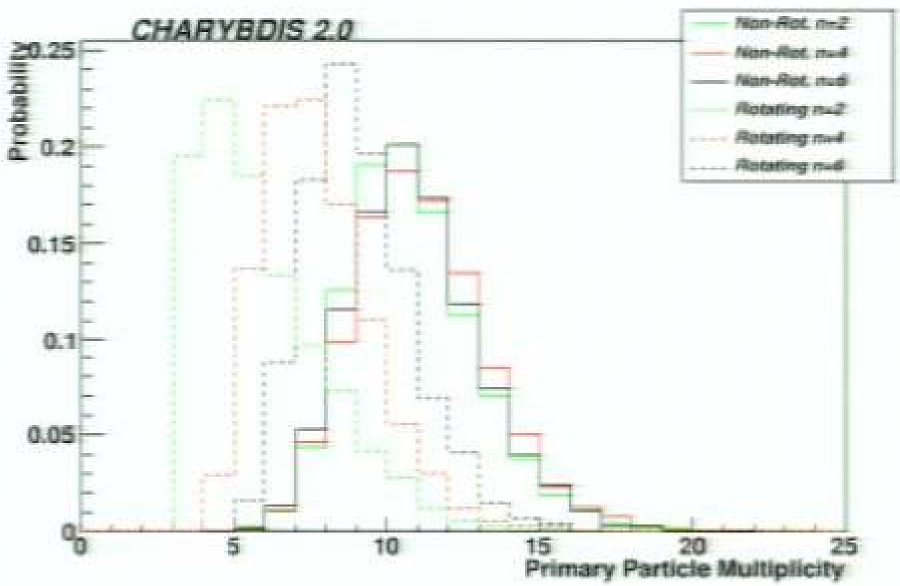

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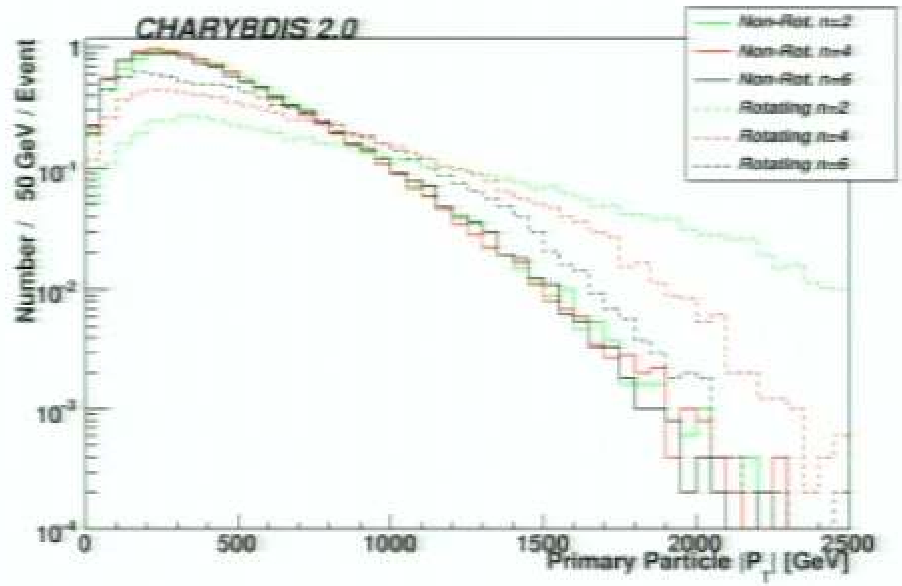

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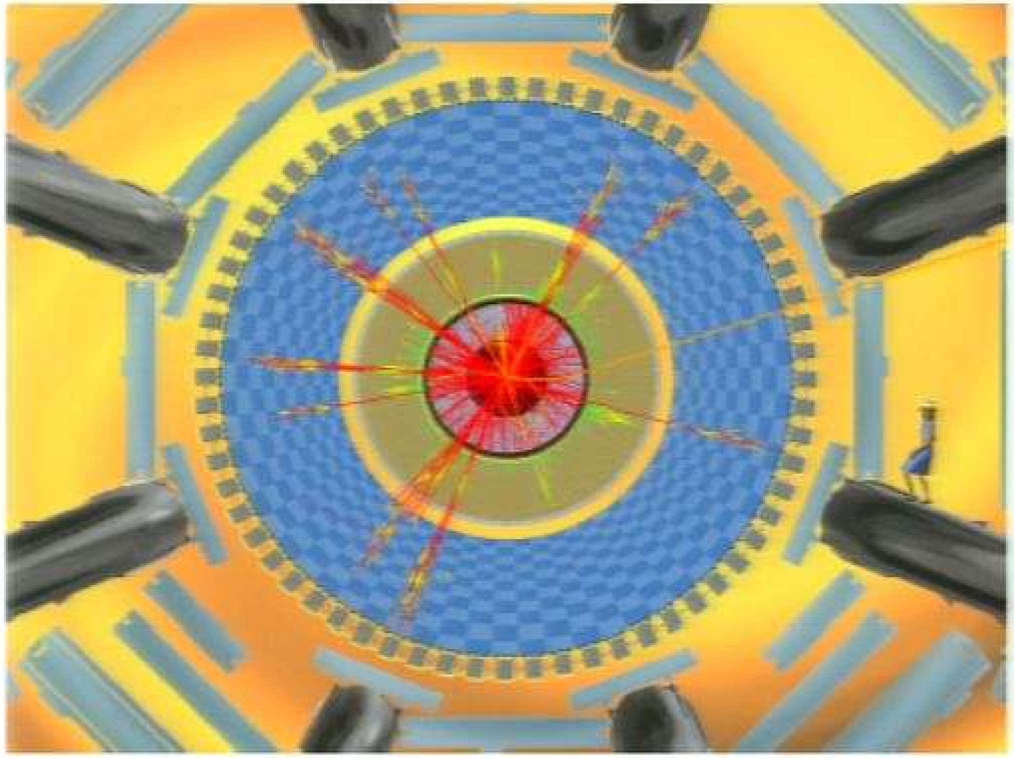

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