Black holes, TeV-scale gravity and the LHC

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Outline

1. Black holes in classical and semi-classical gravity
    - Black holes in classical gravity
    - Black holes in semi-classical gravity

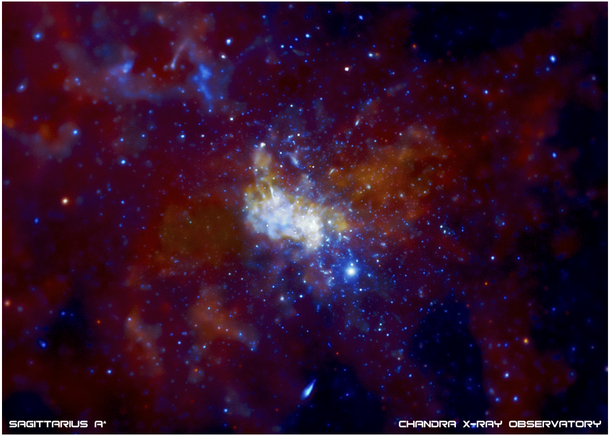
2. Large extra dimensions

3. Mini black hole production and decay
    - Balding phase
    - Spin-down and Schwarzschild phases

4. Experimental searches

5. Quantum black holes

Black holes in classical and semi-classical gravity



Black holes in four-dimensional general relativity

The simplest black hole: vacuum, static and spherically symmetric

Schwarzschild black hole

$$ds^2 = -\left(1 - \frac{2M}{r}\right) dt^2 + \left(1 - \frac{2M}{r}\right)^{-1} dr^2 + r^2 d\Omega_2^2$$

Metric becomes singular at

- Curvature singularity $r \to 0$
- Co-ordinate singularity $r = r_H = 2M$
- Schwarzschild radius $r_H = 2M$
- Black hole has mass M

Four-dimensional rotating black holes

Vacuum, axisymmetric

Kerr black hole

$$ds^2 = -\frac{\Delta}{\Sigma}\left[dt - a\sin^2\theta\, d\phi\right]^2 + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2 + \frac{\sin^2\theta}{\Sigma}\left[\left(r^2+a^2\right)d\phi - a\,dt\right]^2$$

$$\Delta = r^2 - 2Mr + a^2 \qquad \Sigma = r^2 + a^2\cos^2\theta$$

- Event horizon at $\Delta = 0$

$$r_H = M + \sqrt{M^2 - a^2}$$

- Event horizon rotates with angular velocity

$$\Omega_H = \frac{a}{r_H^2 + a^2}$$

- Black hole has mass M and angular momentum $J = aM$

Higher-dimensional black holes $d = 4 + n$

Myers-Perry black hole [Myers and Perry, *Annals Phys.* **172**, 304 (1986)]

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

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:

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

Black holes in semi-classical gravity

Quantum field theory in curved space-time

- Keep geometry fixed and classical (but not necessarily static)
- Quantum fields propagating on this background
- Semi-classical approximation to quantum gravity
- Semi-classical Einstein equations

$$R_{\mu\nu} - \frac{1}{2} R g_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi \langle T_{\mu\nu} \rangle$$

- $\langle T_{\mu\nu} \rangle$ - renormalized expectation value of the quantum stress-energy tensor

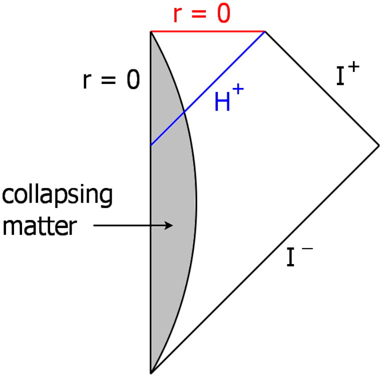
“Black holes ain’t so black”

Hawking radiation [Hawking 1975]

- Black hole formed by gravitational collapse
- Quantum state empty of particles at I^-
- A static observer at I^+ sees an outgoing flux of thermal particles

Hawking temperature

$$T = \frac{\kappa}{2\pi}$$



Black hole evaporation

Black hole temperature of a Schwarzschild black hole

$$T_{BH} = \frac{\kappa}{2\pi} = \frac{1}{8\pi M}$$

As the black hole radiates

- The black hole shrinks and its mass decreases
- The temperature T_{BH} increases
- Black holes have negative specific heat
- Rate of energy loss
$$\frac{dM}{dt} \propto \frac{1}{M^2}$$
- Lifetime of a Schwarzschild black hole of initial mass M_0
$$t_{BH} \propto M_0^3$$

Quantum fields on black hole space-times

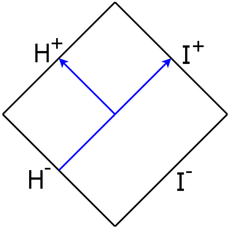
Quantum field modes

- "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:

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

"Up" modes

$$R_{s\omega\ell m} = \begin{cases} e^{i\tilde{\omega} r_*} + A^{\mathrm{up}}_{\omega\ell m} e^{-i\tilde{\omega} r_*}, & r_* \to -\infty \\ B^{\mathrm{up}}_{\omega\ell m} e^{i\omega r_*}, & r_* \to \infty \end{cases}$$



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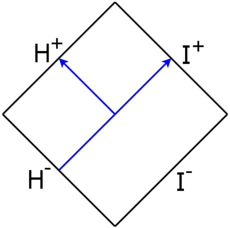


Computing Hawking radiation

Differential emission rates, integrated over all angles:

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

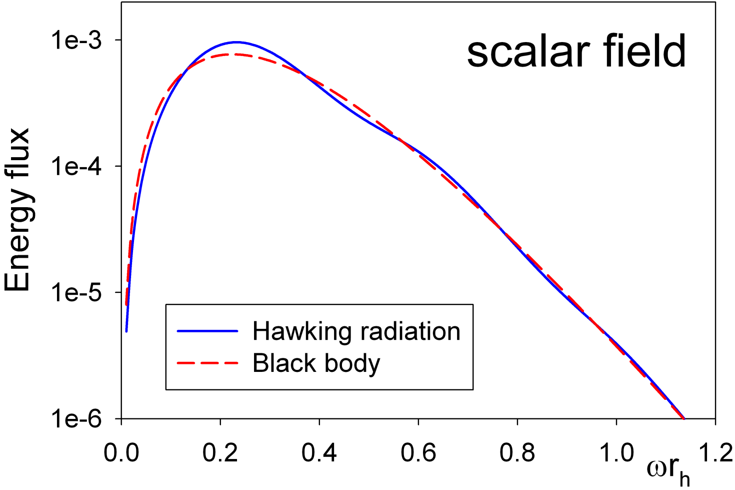
where $\tilde{\omega} = \omega - m\Omega_H$

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

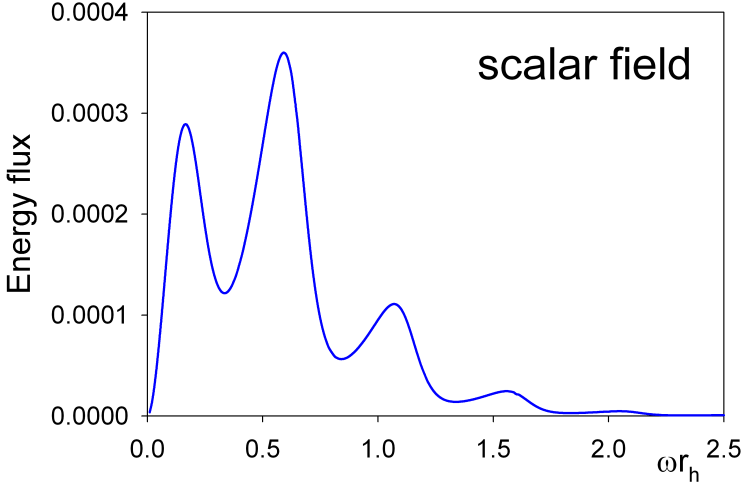
- Emitted radiation is not precisely thermal
- Interaction of emitted quanta with gravitational potential around the black hole
- For an outgoing wave from the event horizon of the black hole:

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

Hawking emission from a Schwarzschild black hole



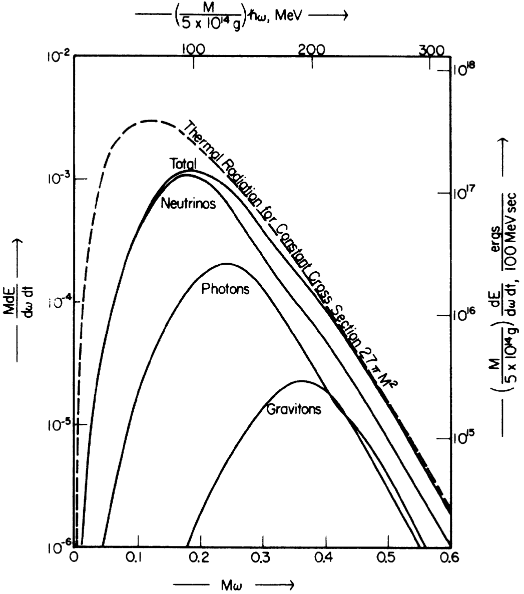
Hawking emission from a Kerr black hole



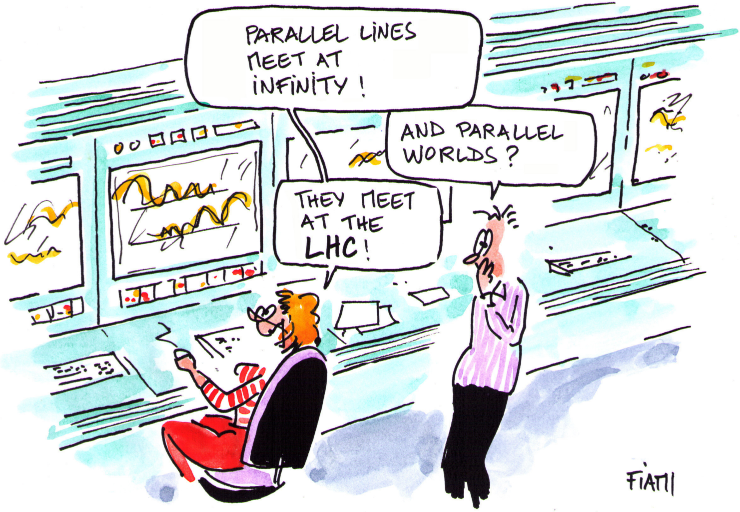
Properties of Hawking radiation from 4D black holes

- For a Schwarzschild black hole, the emission decreases significantly as the spin of the particle increases
- Kerr black hole sheds its angular momentum very rapidly

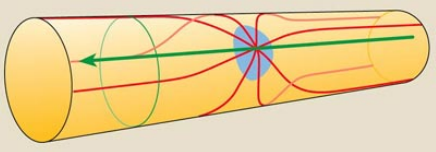
[Figure taken from Page, *Physical Review* **D 13** 198 (1976)]



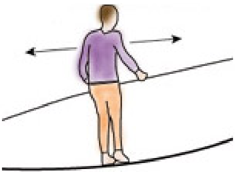
Large extra dimensions



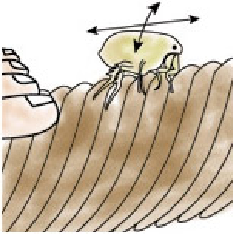
Theories with extra dimensions



Kaluza-Klein theory [1921/26] Additional, compact space-like dimension smaller than any observable length-scale

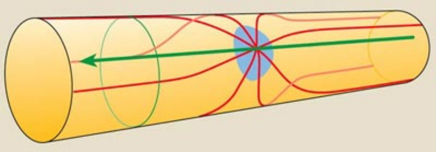


An acrobat can only move in one dimension along a rope..



...but a flea can move in two dimensions.

Theories with extra dimensions



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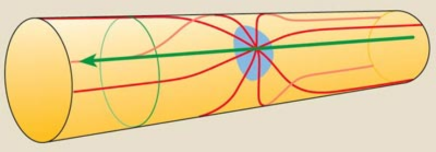
Superstring theory [1970's-80's] Unifies all forces in 10 space-time dimensions, 6 of which are compactified and roughly of the size of the Planck length L_P

Planck length

$$L_P = \sqrt{\frac{\hbar G}{c^3}} \sim 10^{-35} \text{ m}$$

Theories with extra dimensions



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M-theory [mid 1990's] Five different string theories are different limits of underlying 11-dimensional theory

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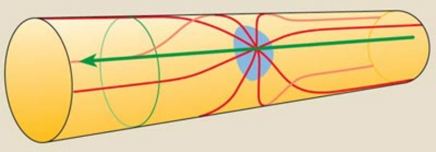

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M-theory [mid 1990's] Five different string theories are different limits of underlying 11-dimensional theory

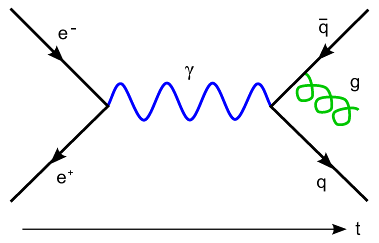
Horava-Witten theory [1996] Size of 11th dimension can be very much larger than L_P

The hierarchy problem

Two very different energy scales in fundamental physics

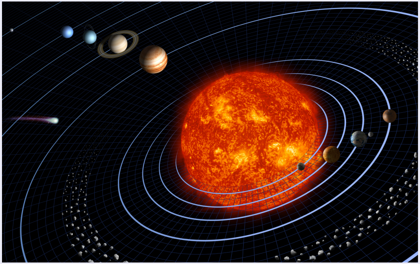
Electroweak scale

Higgs mass ~ 100 GeV



Planck mass

$$M_P = \sqrt{\frac{\hbar c}{G}} \sim 10^{19} \text{ GeV}$$



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The (A)ADD scenario

[Antoniadis, Arkani-Hamed, Dimopoulos and Dvali, `hep-ph/9803315` ; `hep-ph/9804398`]

Large volume for extra compact dimensions lowers the fundamental scale of quantum gravity to M_*

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

n - number of extra dimensions R - size of extra dimensions

If $M_* \sim 1$ TeV

$$R \sim 10^{\frac{30}{n}-19} \text{ m}$$

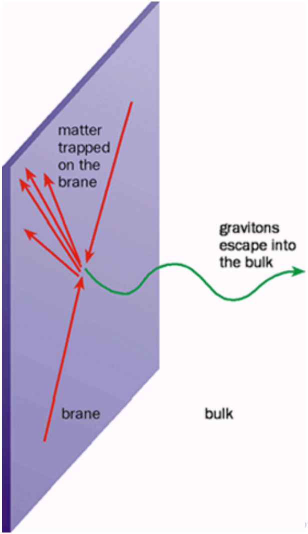
For $n = 5$, $R \sim 10^{-13}$ m

The (A)ADD scenario

[Antoniadis, Arkani-Hamed, Dimopoulos and Dvali, `hep-ph/9803315` ; `hep-ph/9804398`]

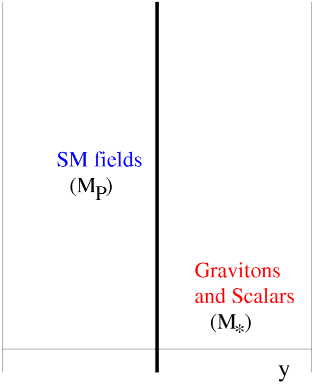
To avoid a contradiction with Standard Model physics:

- 4D brane where all Standard Model particles live
- Effective scale for gravity is M_P on the brane
- $(4 + n)$ D bulk
- Only gravitons propagate in the bulk
- Higher-dimensional fundamental scale for gravity is M_*



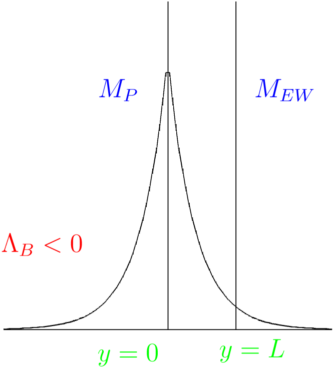
Brane worlds

ADD model



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

RS I model



$$M_P^2 = \frac{M_*^3}{k}\left(1 - e^{-2kL}\right)$$

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

Consequences of the ADD model

KK-modes

- A field in the higher-dimensional theory is seen by an observer on the brane as an infinite tower of massive modes with $m \sim 1/R$
- Produced at energies $E > 1/R$, modifying processes on the brane
- Modification of short-range gravitational potential

$$V(r) = -\frac{G_N M_1 M_2}{r}\left(1 + \alpha e^{-r/R}\right)$$

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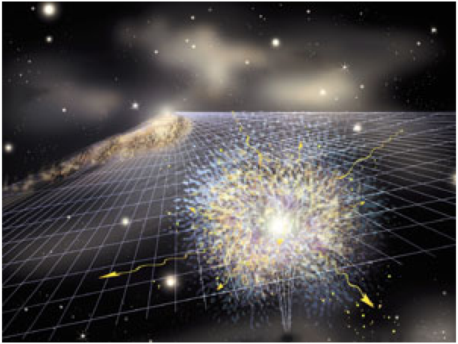
Probing quantum gravity at colliders

- Collider experiment with centre-of-mass energy $\sqrt{s} > M_*$ will probe strong-gravity regime
- Creation of heavy extended gravitational objects

[Banks and Fischler, `hep-th/9906038`]

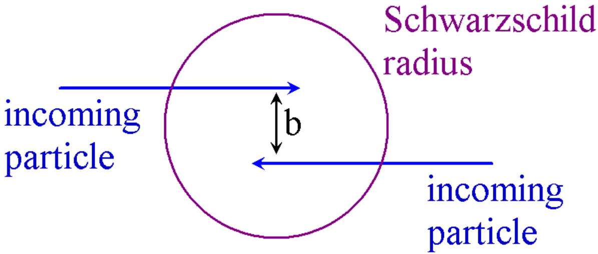
Mini black hole production and decay



[Image credit: Aurore Simonet]

Black hole production

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



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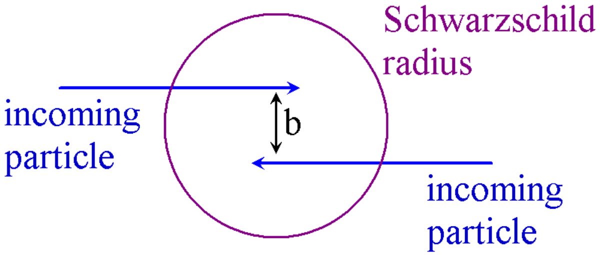

4D hoop conjecture [Thorne, *Magic Without Magic* 231 (1972)]

A black hole is formed when a mass M gets compacted into a region whose circumference in every direction is less than $2\pi r_H(M)$

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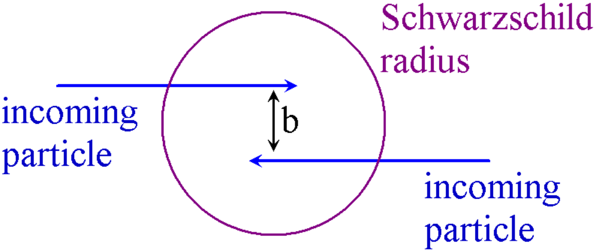


Hyperhoop conjecture [Ida and Nakao, `gr-qc/0204082`]

A black hole is formed when a mass M gets compacted into a region whose $D-3$-dimensional volume in every direction is less than $\alpha_D M$

Modified hyperhoop conjecture required when extra dimensions are compactified [Yoo et al, `arXiv:0906.0689 [gr-qc]`]

Modelling the formation of mini black holes

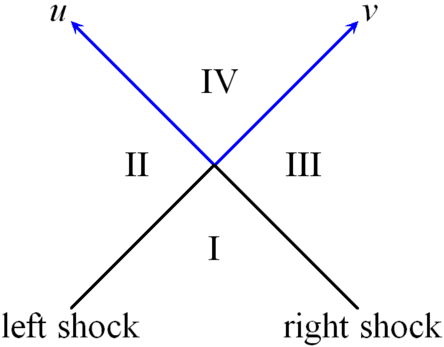
- Classical process
- Model particles as infinitely-boosted black holes
- Search for apparent horizon
- Maximum impact parameter b_{max}
- Parton-level production cross-section

$$\sigma \sim \pi b_{max}^2 \sim 3\pi r_h^2$$

[Yoshino and Rychkov, `hep-th/0503171`]

Aichelberg-Sexl shock waves

[Aichelberg and Sexl, GRG **2** 303 (1971)]



Classical high energy collisions in numerical relativity

Model particles as colliding boson stars, fluid particles or black holes

Key questions [Sperhake, `arXiv:1301.3772 [gr-qc]`]

- Validity of the hoop conjecture
- Scattering threshold for black hole formation
- Mass and spin of the formed black holes
- Effects of internal structure of colliding objects

Results to date

- Four-dimensional collisions best studied
- Higher-dimensional work in early days
  [Witek et al, `arXiv:1006.3081 [gr-qc]` ; `arXiv:1011.0742 [gr-qc]`]

  [Okawa et al, `arXiv:1105.3331 [gr-qc]`]

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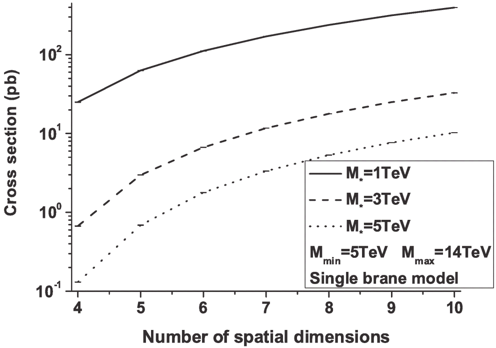
Black hole production cross-sections

Parton-level BH production cross-section

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

[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`]

Stages in the life of a mini black hole

[Giddings and Thomas, `hep-ph/0106219`]

Balding phase Shedding of hair and asymmetries

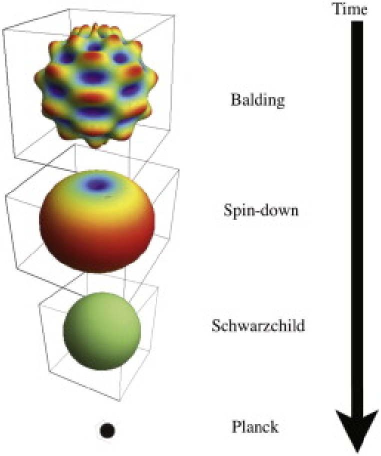
Spin-down phase Loss of angular momentum via Hawking radiation

Schwarzschild phase Loss of mass via Hawking radiation

Planck phase $M_{BH} \sim M_*$

Image credit:

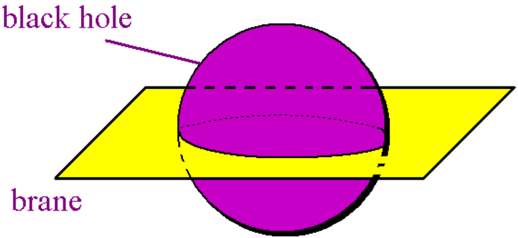
[Park, `arXiv:1203.4683 [hep-ph]`]



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

Slice of Myers-Perry black hole

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

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

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: $\leq 30\% \quad (n=0)$, $\leq 40\% \quad (n=7)$
  [Yoshino and Rychkov, `hep-th/0503171`]
- Four-dimensional numerical relativity: $\leq 50\% \quad (n=0)$
  [Sperhake et al, `arXiv:1211.6114 [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: $j \sim 0.93 \quad (n=1)$
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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

- Effect of charge on formation process

  [Zilhao et al, `arXiv:1205.1063 [gr-qc]`]
- 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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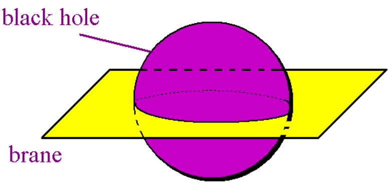
[Sampaio, `arXiv:0907.5107 [hep-th]`]

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

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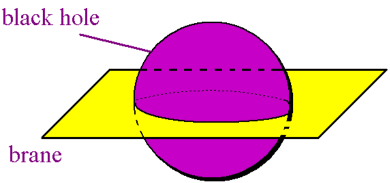

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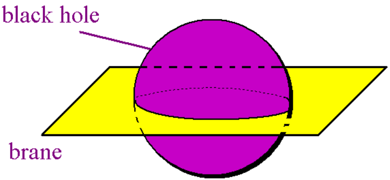

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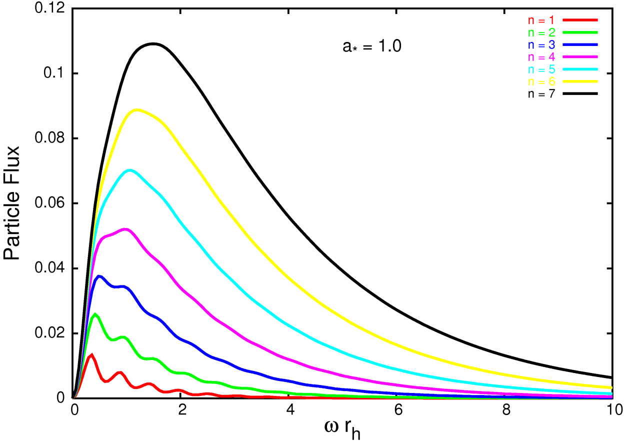
Emission spectra

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

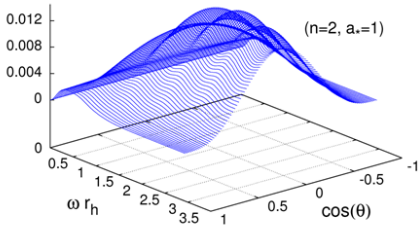


[Figure taken from Casals et al, `hep-th/0608193`]

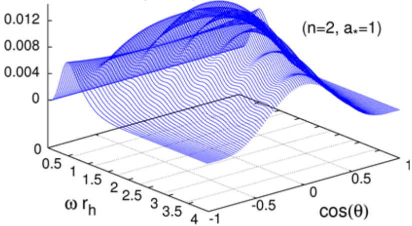
Angular distribution of energy flux

Six-dimensional
black hole
n=2

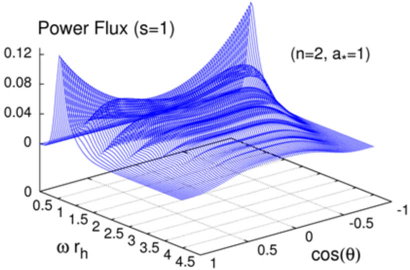
Power Flux (s=0)



Power Flux (s=1/2)



Power Flux (s=1)



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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- Graviton emission - bulk and brane done

"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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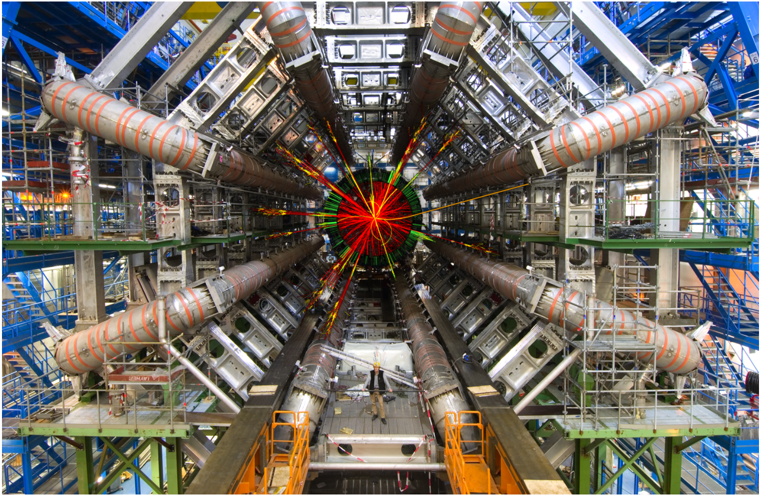
Experimental searches



[Image credit: ATLAS experiment ©2012 CERN]

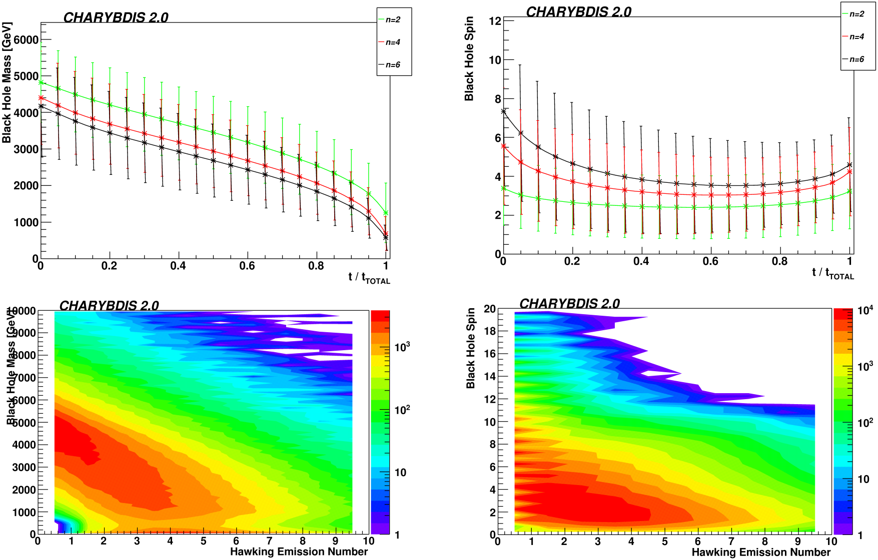
Simulations of black hole events at the LHC

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`
- `BlackMax` [Dai et al, `arXiv:0902.3577 [hep-ph]`]
  `http://projects.hepforge.org/blackmax/`
- `CHARYBDIS2` [Frost et al, `arXiv:0904.0979 [hep-ph]`]
  `http://projects.hepforge.org/charybdis2/`
- `QBH` [Gingrich, `arXiv:0911.5370 [hep-ph]`]
  `http://projects.hepforge.org/qbh/`

Evolution of black holes simulated by CHARYBDIS2

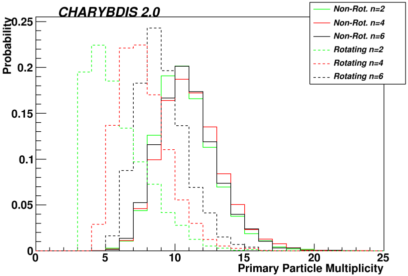


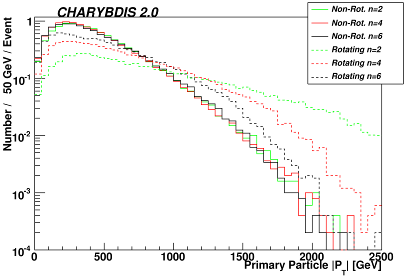
[Figures taken from Frost et al, `arXiv:0904.0979 [hep-ph]`]

Results from CHARYBDIS2

Primary particle multiplicity

Primary particle P_T





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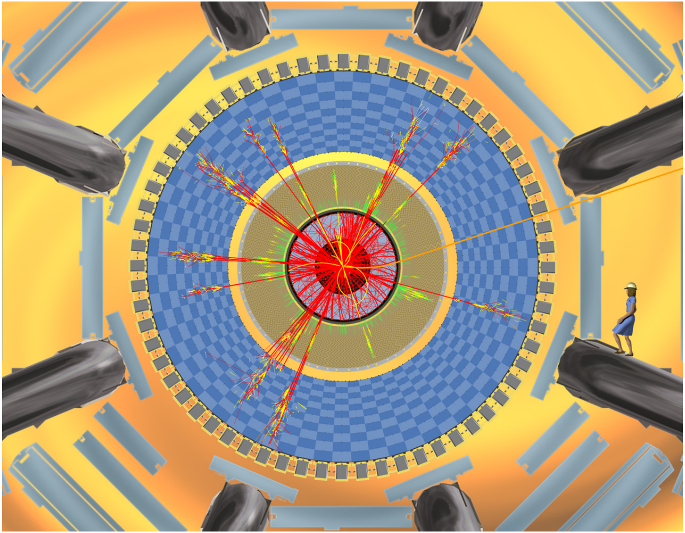
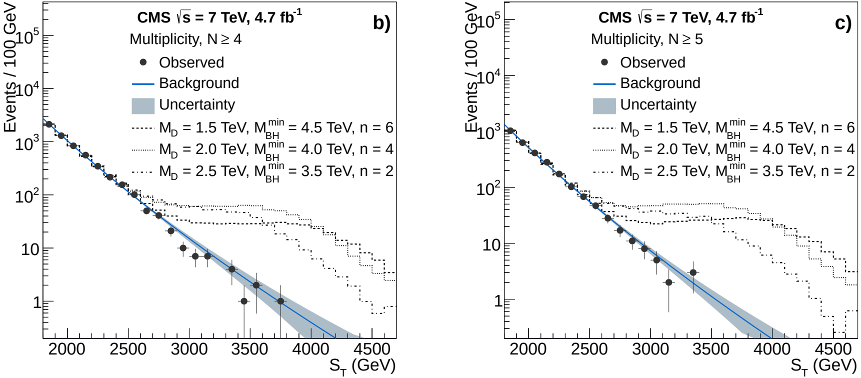
An example black hole event



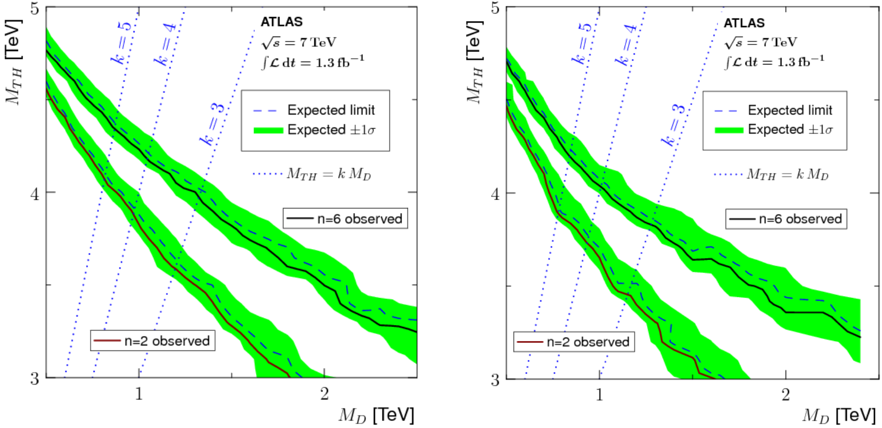
[Image credit: ATLAS experiment ©2012 CERN]

CMS search for black hole events



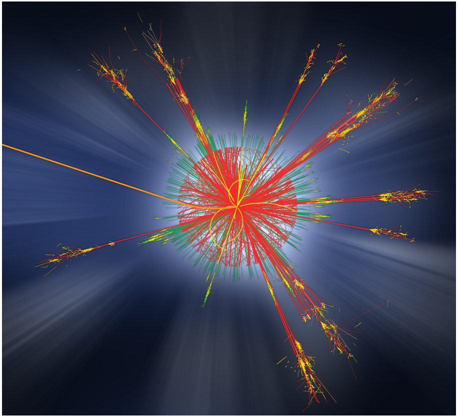
[CMS collaboration, `arXiv:1202.6396 [hep-ex]`]

ATLAS search for black hole events



[ATLAS collaboration, `arXiv:1111.0080 [hep-ex]`]

Quantum black holes



[Image credit: ATLAS experiment ©2012 CERN]

Drawbacks of the “standard” black hole model

Black hole formation

Classical approximation

- Colliding particles described by general relativity
- Difficult to include quantum fields, particularly QCD

Black hole evolution

Semi-classical approximation

- Black hole geometry described by general relativity
- Quantum fields on this background
- Semi-classical approximation breaks down for $M_{BH} \sim M_*$
- Details of quantum gravity unknown

Beyond the semi-classical approximation

Validity of semi-classical approximation

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 semi-classical black holes to form
[Meade and Randall, `arXiv:0708.3017 [hep-ph]`]

Planckian quantum black holes

Masses close to M_*

- Do not have thermal decay
- Particle physics symmetries used to constrain decay products

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

- Large-extra-dimension scenarios
- Scale of quantum gravity M_* could be as low as a few TeV
- Possibility of making microscopic black holes at the LHC
- Semi-classical model - decay by Hawking radiation
- Non-observation sets bound on M_*