BLACK HOLES IN EXTRA DIMENSIONS

Jonathan Feng
University of California, Irvine

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OVERVIEW

Black holes: semi-classical and thermodynamic description for $M_{BH} \lesssim M_D$.

$D = 4$ dimensions

- $M_D \simeq 10^{19}$ GeV

- BHs confined to astrophysics

$(4+n)$ dimensions

- $M_D \sim$ TeV

- BHs $\rightarrow$ experimental particle physics

(LHC: $\sqrt{s} = 14$ TeV)
Cosmic Rays: $E \gtrsim 10^{19}$ eV $\Rightarrow$ $\sqrt{s} \gtrsim 100$ TeV

BHs $\rightarrow$ particle astrophysics

No black holes seen $\Rightarrow$

- stringent bounds

$M_D \approx 1$ TeV $\Rightarrow$

- 100 BHs before LHC turns on
- 1st evidence for extra dimensions
- exp. study of Hawking evaporation

JF, Shapere (2001)
Anchordoqui, JF, Goldberg, Shapere (2001)
Low-scale gravity

Consider gravity in \((4+n)\) dimensions, SM in 4 dimensions.

Compactification in \(n\) flat dimensions with length \(L\) gives

\[
F \sim \begin{cases} 
\frac{m_1 m_2}{M_D^{2+n} r^{2+n}}, & r \ll L \\
G_N \frac{m_1 m_2}{r^2}, & r \gg L
\end{cases}
\]

Observed gravitational strength \(\Rightarrow\)

\[
M_D^{2+n} L^n \approx (10^{19} \text{ GeV})^2
\]

\(L\) big in Planck units \(\Rightarrow M_D \ll 10^{19} \text{ GeV}.

Arkani-Hamed, Dimopoulos, Dvali (1998)
Bounds on $M_D$

<table>
<thead>
<tr>
<th>$n$</th>
<th>$L$</th>
<th>SN/NS</th>
<th>Tevatron</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$10^{11}$ m</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>mm</td>
<td>1000 TeV</td>
<td>1 TeV</td>
</tr>
<tr>
<td>4</td>
<td>nm</td>
<td>1 TeV</td>
<td>1 TeV</td>
</tr>
<tr>
<td>6</td>
<td>$10^3$ fm</td>
<td>100 GeV</td>
<td>1 TeV</td>
</tr>
</tbody>
</table>

Giudice, Rattazzi, Wells (1998)
Hewett (1998)
Han, Lykken, Zhang (1998)
Cullen, Perelstein (1998)
Hall, Smith (1999)
Hanhart, Pons, Phillips, Reddy (2001)
Hannestad, Raffelt (2001)

... 

For warped compactifications,
$M_D \sim M_P e^{-kr} \lesssim \text{TeV}$ possible, even for $n = 1$.
Randall, Sundrum (1999)

Here, just require black hole small compared to size of extra dimensions.
BHs in extra dimensions

For a Schwarzschild BH \((Q = J = 0)\),

\[
rs(M_{BH}^2) = \frac{1}{MD} \left[ \frac{MBH}{MD} \right]^{\frac{1}{1+n}} \left[ \frac{2n\pi^{\frac{n-3}{2}} \Gamma \left( \frac{3+n}{2} \right)}{2 + n} \right]^{\frac{1}{1+n}}
\]

Myers, Perry (1986)

In classical GR, expect a BH to form when two partons pass within \(r_s(\hat{s})\) of each other:

\[
\hat{\sigma}(ij \rightarrow BH)(\hat{s}) \approx \pi r_s^2(\hat{s})
\]


Numerical evidence from 4D axisymmetric collisions: \(M_{BH} \approx 0.8\sqrt{\hat{s}}\).

D'Eath, Payne (1992)
BH formation

\[ \tilde{\sigma}(ij \rightarrow \text{BH}) \sim e^{-I_E \pi r_s^2(\tilde{s})}, \quad I_E \propto \left[ \frac{M_{\text{BH}}}{M_D} \right]^{\frac{2+n}{1+n}} \]

Voloshin (2001)

Argument 1:

\[ P(\text{few} \rightarrow \text{BH}) = \sum_i |A(\text{few} \rightarrow \text{BH}_i)|^2 \]
\[ \sim N|A(\text{BH}_i \rightarrow \text{few})|^2 \text{ (CPT)} \]
\[ \sim e^S e^{-\sum_j \frac{E_j}{T}} = e^{S - \frac{M}{T}} = e^{-S} \]

But this ignores back-reaction: \( T \) grows.

Including this, get \( e^{S - \frac{M}{2T}} = 1 \).

Intuitively: BH formation is classical.

Shapere (2001)
Solodukhin (2002)
Argument 2: Classical study was for $b = 0$.

- D’Eath and Payne now generalized to $b \neq 0$.
  
  Eardley, Giddings (2001)

Argument 3: Angular momentum ignored.

- $b \neq 0 \Rightarrow J \neq 0 \Rightarrow r_s \rightarrow r_{Kerr}$.

  No evidence for large reduction.

  Anchordoqui, JF, Goldberg, Shapere (2001)
Semi-classical Validity

Requirements:

- Small statistical fluctuations in number of degrees of freedom.
- Little back reaction from radiation.

Preskill, Schwarz, Shapere, Trivedi, Wilczek (1991)

Both require large entropy $S \propto r_s^{2+n}$.

- BH lifetime $\tau \gg M_{\text{BH}}^{-1}$.

For $n = 6$,

$S(5M_D) = 27, \quad S(10M_D) = 59$

$\tau(5M_D) = 10M_{\text{BH}}^{-1}, \quad \tau(10M_D) = 12M_{\text{BH}}^{-1}$

Giddings, Thomas (2001)

Semi-classical analysis valid for $M_{\text{BH}}^{\text{min}} \approx \text{few } M_D$. 
Colliders

Convolute $\hat{\sigma}(ij \rightarrow \text{BH}) = \pi r_s^2$ with parton distribution functions.

Events at LHC with 100 fb$^{-1}$:

“BH factory” in 2008 if $M_D = M_{\text{BH}}^{\text{min}} = 1$ TeV. BH decays thermally to all SM particles.

*Extreme* sensitivity to $M_{\text{BH}}^{\text{min}}$ (see below).
Cosmic Rays

Kampert, Swordy (2001)

- The energy frontier: \( \sqrt{s} = \sqrt{2m_NE} \)

\[
E \sim 10^{19} \text{ eV} \Rightarrow \sqrt{s} \sim 100 \text{ TeV}
\]
Cosmic Neutrinos

\[ \sigma(\nu N \rightarrow BH) = \sum_i \int_{(M_{BH}^{\text{min}})^2/s}^{1} dx \tilde{\sigma}_i(xs) f_i(x, Q) \]

For \( M_D = M_{BH}^{\text{min}} = 1 \) TeV and \( n = 1, \ldots, 7 \) from below.

JF, Shapere (2001)

\( \sigma \) large:
- Sum over partons, including gluon
- No small couplings
- \( \nu \) has \( x = 1 \)

Relatively insensitive to \( M_{BH}^{\text{min}} \) (see below).
Length scales

Vertical atm. depth: 10 mwe
Horizontal atm. depth: 360 mwe

- \( pN \rightarrow BH: \) Hopeless

- \( \nu N \rightarrow BH: \) uniform at all atm. depths

Best signal is quasi-horizontal, deep showers: maximizes signal, uses atmosphere to remove proton, nucleus background.
Far inclined showers (thousands per year)

- Flat and thin shower front
- Narrow signals
- Time alignment

Deep inclined showers (~few per year?)

- Curved and thick shower front
- Broad signals

FIG. 6. Schematic representation of a UHE air shower, and of its placement with respect to the ground and the Auger array. A "far inclined" shower is likely to be due to a hadronic cosmic ray, whereas a "deep inclined" shower can only be caused by a neutrino.

Coutu, Bertou, Billoir (1999)
Rates

\[ N = \int dE_\nu N_A \frac{d\phi}{dE_\nu} \sigma(E_\nu) A(E_\nu) T \]

where

\[ N_A = 6.022 \times 10^{23} \]

\[ \frac{d\phi}{dE_\nu} = \text{source flux of neutrinos} \]

\[ A = \text{acceptance in cm}^3\text{we} \]

\[ T = \text{running time of experiment} \]
Fluxes

Guaranteed: $\pi$ photoproduction

$$p + \gamma_{\text{CMB}} \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu$$

Choose most conservative: Protheroe, Johnson.
Other sources

Additional $\nu$ sources may exist (for example, to solve the GZK problem):

Below consider only $\pi$ photoproduction; other sources may increase rates by 2 orders of magnitude.
Apertures

Showers may be detected by ground arrays and air fluorescence.

Current: AGASA, Hires
Future: Pierre Auger Observatory

Quasi-horizontal shower acceptance for Auger ground array (solid), AGASA (dashed), Hires (dotted).

Capelle, Cronin, Parente, Zas (1998)
Díaz, Shellard, Amaral (2001)
Anchordoqui, JF, Goldberg, Shapere (2001)
Hires Collaboration (1994)
Lower bounds on $M_D$ from absence of black holes at AGASA and Hires. $M_{\text{BH}}^{\text{min}} = M_D$.

Anchordoqui, JF, Goldberg, Shapere (2001)

No events seen $\Rightarrow$ for $n \geq 4$, $M_D \gtrsim 1.5–2.0$ TeV, most stringent bounds to date.
Lower bounds for $n = 1, \ldots, 7$ from below.

For $M_{\text{BH}}^{\text{min}} \lesssim 10M_D$, bounds are comparable to or exceed best collider bounds.
Bounds from AMANDA flux

Lower bounds on $M_D$ from absence of black holes at AGASA and Hires. $M_{BH}^{min} = M_D$. 
Number of black holes expected at the Auger ground array for $n = 7$. $M_{\text{BH}}^{\text{min}} = M_D$. 
Comparison with LHC

Auger sensitivity (3 years) \( n = 7 \).

LHC events (100 fb\(^{-1}\))

- LHC predictions sensitive to \( M_{\text{BH}}^{\text{min}} \)
- No Auger BHs, \( x_{\text{min}} \gtrsim 5 \Rightarrow \) No LHC BHs

Of course, we could see events! ...
BH vs. SM

BH rates may be 1000 times SM rate. But

- large BH $\sigma \Rightarrow$ large rate, and
- $\phi$ large $\Rightarrow$ large rate.

However, consider Earth-skimming neutrinos:

[Diagram showing Earth-skimming neutrinos with angles and distances labeled]

Bertou et al. (2001)

For Earth-skimmers,

- $\phi$ large $\Rightarrow$ large rate, but
- large BH $\sigma \Rightarrow$ rate suppressed

Rates alone eliminate SM explanation (and almost all other non-SM explanations, too).
\[ N_{\text{QH}} \propto \phi^\nu (\sigma^\nu_{\text{CC}} + \sigma^\nu_{\text{BH}}) \quad N_{\text{ES}} \propto \phi^\nu \frac{\sigma^\nu_{\text{CC}}^2}{(\sigma^\nu_{\text{CC}} + \sigma^\nu_{\text{BH}})^2} \]

Quasi-horizontal shower (dashed) and Earth-skimming neutrinos (dotted) in 5 years.
**BH signatures**

BH rest lifetime is

\[ \tau \sim \frac{1}{M_D} \left[ \frac{M_{\text{BH}}}{M_D} \right]^{(3+n)/(1+n)} \sim 10^{-27} \text{ s} \]

Even with boost \( \gamma \sim 10^7 \), all BHs evaporate effectively instantaneously.

BH temperature is \( \sim 100 \text{ GeV} \).

Average multiplicity is

\[ \langle N \rangle \approx \frac{M_{\text{BH}}}{2T_H} \propto \left[ \frac{M_{\text{BH}}}{M_D} \right]^{2+n/(1+n)} \]

leptonic : hadronic \( \sim 1 : 5 \)

In contrast,

\[ \nu_e N \rightarrow eX \quad \Rightarrow \quad \text{EM (80\%) + hadronic (20\%)} \]

\[ \nu_\mu N \rightarrow \mu X \quad \Rightarrow \quad \text{nothing + hadronic (20\%)} \]
EM activity for $\nu N \rightarrow \text{BH}$ vs. $\nu e N \rightarrow eX$

Anchordoqui, Goldberg (2001)

Test of $M_{\text{BH}}$ vs. $\langle N \rangle$:

$$\langle N \rangle \approx \frac{M_{\text{BH}}}{2T_H} \propto \left[ \frac{M_{\text{BH}}}{M_D} \right]^{\frac{2+n}{1+n}}$$

Shower energy $\leftrightarrow M_{\text{BH}}$

$X_{\text{max}} \leftrightarrow \langle N \rangle$
Additional possibilities

Under-ice: AMANDA, IceCube

Radio: RICE, ANITA

Space-based: EUSO/OWL

These provide BH branching ratios, angular distributions, etc.

Emparan, Masip, Rattazzi (2001)
Uehara (2001)
Ringwald, Tu (2001)
Ahn, Cavaglia, Olinto (2002)
Kowalski, Ringwald, Tu (2002)
Jain, Kar, Panda, Ralston (2002)
Alvarez-Muniz, JF, Halzen, Han, Hooper (2002)
Anchordoqui, JF, Goldberg (2002)
Anchordoqui, Goldberg, Shapere (2002)
McKay, et al. (2002)

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CONCLUSIONS

- BHs: a rare opportunity to consider super-Planckian energies.

- Naturally probed at the energy frontier: UHE Cosmic Rays

- Constraints on TeV gravity:

\[ M_D \approx 1 \text{ TeV} \Rightarrow 100 \text{ BHs at Auger} \]