Microscopic black holes in neutrino telescopes, colliders and cosmology

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McDonald Institute, Queen’s University & Perimeter Institute

Sep 14th 2020
Overview

1. Introduction

2. Discovery of Microscopic Black Holes at Neutrino Telescopes

3. A Black Hole Portal to Dark Matter at Colliders

4. Black Hole Imprints in the Early Universe

5. Conclusions
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Large Extra Dimensions (LEDs)

3-D brane

leptons, quarks, gauge bosons

Extra-Dimensions

gravitation

Arkani-Hamed, Dimopoulos and Dvali (ADD), 1998

- SM particles confined to the 3-D “brane”
- Gravitations can propagate in the 3+n-D bulk “bulk”
3-D brane

leptons, quarks, gauge bosons

Gravitational potential

\[ V(r) \sim \frac{m_1 m_2}{M_*^{n+2}} \frac{1}{r^{n+1}} (r \ll R) \Leftrightarrow V(r) \sim \frac{m_1 m_2}{M_*^{n+2} R^n} \frac{1}{r} (r \gg R) \]

\[ \Rightarrow \text{In} \ 4D \quad M_{pl}^2 \sim M_*^{2+n} R^n \]

• \( M_* \sim \text{TeV} \ll M_{pl} \)
• Solve the hierarchy problem
BH production only allowed if the impact parameter

\[ b \leq b_{\text{max}} = 2r_H(E_{\text{CM}}, n, M_*) \]
Equivalently, BH production is allowed if $E_{cm} \gtrsim M_\star$

BHS can be produced in high energy particle collisions:

- Cosmic neutrino-nucleon scattering
- High energy cosmic ray detection
- Cosmic ray-cosmic ray collision
- $pp$ collision in FCC
- Hot plasma in the early universe
- ...
BH production allowed if the impact parameter $b \leq b_{\text{max}}$

For $pp$ collision the cross section

$$\sigma^{pp \rightarrow BH} = \int_{M^2/s}^1 du \int_{u}^1 \frac{dv}{v} \pi b_{\text{max}}^2 \sum_{i,j} f_i(v, Q) f_j(u/v, Q)$$

## Current Limits

$n=1$ killed

<table>
<thead>
<tr>
<th>Method</th>
<th>Reference</th>
<th>$n$</th>
<th>$\log_{10}(E^*/\text{eV})$</th>
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<td>Grav force</td>
<td>[26]</td>
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<td>12.5</td>
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<td>SN1987A</td>
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<td>$M^*_\gamma &gt; 5 \sim 10$ $\text{TeV}$</td>
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**Current Limits**

$n = 1$ is excluded by gravity at the solar system scale

Some energy scales:

- $E_{CM} = 5 \ TeV = \sqrt{2m_p E_\nu}$
  \[ \Rightarrow E_\nu \approx 13 \ PeV \]
- $E_{CM} = 13 \ TeV$ at LHC
- $E_{CM} \approx 100 \ TeV$ at FCC
- $E_p \sim 50 \ EeV$ at GZK limit

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BHs may decay to all possible degree of freedom, including SM and possible BSM particles.
Hawking Radiation


- Hawking temperature
  \[ T_H = \frac{n + 1}{4\pi r_H(M_{BH}, n, M_*)} \]

- Graybody distribution spectrum
  \[ \frac{dE}{dt} \propto \frac{\omega}{\exp(\omega/T_{BH}) + 1} \frac{d\omega}{2\pi} \]
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High Energy Neutrino Flux

- Atmospheric neutrinos already detected in IceCube
- Need larger detector for ultra high energy cosmogenic neutrinos

GRAND Collaboration/1810.09994

IceCube Collaboration/1311.5288
IceCube-Gen2

IceCube Lab

IceCube A1
86 strings, 60
5,160 optical s

DeepCore
6 strings optin
for low energi

Eiffel
324 m

IceCube Collaboration
UC Davis Seminar
Ningqiang Song
Pacific Ocean Neutrino Experiment (P-ONE)
High Energy Neutrino Flavor Compositions

Pontecorvo–Maki–Nakagawa–Sakata matrix:
\[
\begin{pmatrix}
\nu_e \\
\nu_\mu \\
\nu_\tau \\
\end{pmatrix} =
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \\
\end{pmatrix}
\begin{pmatrix}
\nu_1 \\
\nu_2 \\
\nu_3 \\
\end{pmatrix}
\]

From the source to the earth
\[
P_{\alpha\beta}^{s\rightarrow\oplus} = \sum_{ij} U_{\beta i} U_{j \beta}^* U_{\alpha j} U_{i \alpha}^* \exp(-i \frac{\Delta m_{ij}^2 L}{2E})
\]
\[
= \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2
\]

The flavor composition at the earth is **constrained** regardless of the flavor composition at the source

arXiv:1412.5106
Event Topologies at IceCube: Standard Model

$\nu_\mu$ Charged Current (CC)

\[ \nu_\mu \rightarrow \mu, W^{\pm}, p, n, X \]
Event Topologies at IceCube: Standard Model

SM tracks:
- $\nu_\mu$ charged current
- $\nu_\tau$ charged current with high energy $\tau$ track

SM showers:
- $\nu_e$ charged current
- All $\nu$ neutral current
- $\nu_\tau$ charged current with low energy $\tau$ decay

SM double-bangs:
- $\nu_\tau$ charged current with high energy $\tau$ decay
All Standard Model topologies are expected in black hole events
The $\nu - N$ scattering cross section

$$\sigma^{\nu N \rightarrow BH} = \int_{M^2/s}^{1} du \pi b_{\text{max}}^2 \sum_i f_i(u, Q)$$
Reconstructed Flavor Composition From Black Holes

- more events expected from the same flux if $M_\star = 3$ TeV
- more tracks from $\mu$, $\tau$
- rarer double bang due to energy asymmetry condition

Mack, Song & Vincent JHEP 2020/1912.06656

<table>
<thead>
<tr>
<th></th>
<th>shower</th>
<th>track</th>
<th>double bang</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu_e$ SM</td>
<td>28.58</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>$\nu_\mu$ SM</td>
<td>2.31</td>
<td>8.31</td>
<td>0</td>
</tr>
<tr>
<td>$\nu_\tau$ SM</td>
<td>5.07</td>
<td>5.39</td>
<td>2.83</td>
</tr>
<tr>
<td>All Flavor Total SM</td>
<td>35.96</td>
<td>13.70</td>
<td>2.83</td>
</tr>
<tr>
<td>All Flavor Total BH</td>
<td>62.96</td>
<td>36.36</td>
<td>0.20</td>
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</tbody>
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Standard Model Events vs Black Holes

Standard Model:

- $y = 1 - E_l/E_\nu$
- cross section peaks at large $E_l$

Most neutrino energy is transferred to final state lepton/neutrino

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Standard Model Events vs Black Holes

**Standard Model:**
- \( y = 1 - E_l / E_\nu \)
- Cross section peaks at large \( E_l \)

**Black holes:**
- BH produces \( N \sim 6 \sim 20 \) primary particles
- \( E_l \sim E_\nu / N \)

Leptons energy in black holes tends to be smaller than in SM!
Tracks are produced in $\nu_{\mu,\tau}$ CC:

$$\nu_{\mu,\tau} + n \rightarrow \mu(\tau) + X$$

- **SM**: $E_\mu > E_{\text{hadron}}$
- **Black holes**: $E_{\text{hadron}} > E_\mu$

Lower track energy to shower energy ratio expected in BH events
Double bangs are produced in $\nu_\tau$ CC: $\nu_\tau + n \rightarrow \tau + X$

$\tau$ travels certain distance before decay inside the detector
Energy Asymmetry in BH Double Bangs

energy asymmetry: \[ E_A = \frac{E_1 - E_2}{E_1 + E_2} \]

- SM: \( E_1 < E_2 \)
- Black holes: \( E_1 > E_2 \)
Energy Asymmetry in BH Double Bangs

Double Bangs

$E_1$ (GeV) vs. $E_2$ (GeV)

- $\nu_e$ CC
- $M_s = 1$ TeV
- $M_s = 2$ TeV
- $M_s = 3$ TeV
- $M_s = 10$ TeV

SM

BH

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Energy Asymmetry in BH Double Bangs

Energy asymmetry: 

\[ E_A = \frac{E_1 - E_2}{E_1 + E_2} \]

- SM: \( E_A < 0 \)
- Black holes: \( E_A > 0 \)

Mostly positive energy asymmetry expected in black hole events
Particles from neutrino-nucleon interaction deposit their energy promptly within $10^{-7}$ s, secondary muons decay at $\sim 1 - 10\ \mu s$, and neutrons are captured at $\sim 200\ \mu s$
• **Electromagnetic shower**: electrons and gamma produce EM showers, featured with less muons and neutrons in the final states

• **Hadronic shower**: hadrons produce hadronic showers, featured with copious muons and neutrons in the final states

• **Muon echo and neutron echo** are closely correlated
Cherenkov light echos

- $\nu_e$ CC: Energetic EM shower with less energetic hadronic shower
- $\nu_\tau$ CC: EM shower or hadronic shower depending on decay product
- NC: Energetic hadronic shower
- Black holes: Energetic hadronic shower with less energetic EM shower
All Standard Model topologies are expected in black hole events.
More Exciting Topologies!

- **Multitrack**: BHs produce multiple muons or taus
- **n-bang**: BHs produce multiple taus decaying in the detector
- **Kebab**: Multiple taus decay in the detector along with a track
- **Double BH bang**: BH decay product produces another BH

![Diagram](multitrack, n-bang, kebab, double black hole bang)
Analysis

cosmogenic $\nu$

BH

SM
Analysis

cosmogenic $\nu$

BH → BlackMax → Pythia

SM → Pythia
Analysis

cosmogenic $\nu$

BH $\rightarrow$ BlackMax $\rightarrow$ Pythia $\rightarrow$ shower $\rightarrow$ fluka $\rightarrow$ track $\rightarrow$ double bang

SM $\rightarrow$ Pythia $\rightarrow$ shower $\rightarrow$ fluka $\rightarrow$ track $\rightarrow$ double bang
Analysis

cosmogenic $\nu$

BH $\rightarrow$ BlackMax $\rightarrow$ Pythia

SM $\rightarrow$ Pythia

likelyhood $\rightarrow$ discovery/exclusion

shower

double bang

fluka

track
Black Hole Discovery Prospects


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5. Conclusions
• Dark matter makes up $\sim 27\%$ of the universe, and $\sim 85\%$ of matter

• Dark matter is weakly interacting

• Fermion $M_{DM} \gtrsim 100 - 190$ eV

• Boson $M_{DM} \gtrsim 10^{-22} - 10^{-20}$ eV
Dark Matter Candidates

Dark Sector Candidates, Anomalies, and Search Techniques

UC Cosmic Visions 2017/1707.04591

UC Davis Seminar Ningqiang Song
Observation of Excess Electronic Recoil Events in XENON1T


We report results from searches for new physics with low-energy electronic recoil data recorded with the XENON1T detector in a unprecedentedly low background rate of $76 \pm 2_{	ext{stat}}$ events/(t \ y keV) between 1-30 keV. An excess over known background is observed towards lower energies and prominent between 2-3 keV. The solar axion model has a 3.5$\sigma$ significance, and a three-dimensional analysis for axion couplings to electrons, photons, and nucleons. This surface is inscribed in the cuboid defined by $g_{ae} \cdot g_{en} \cdot g_{en} \cdot g_{n}\cdot g_{n}\cdot g_{n} < 4.6 \times 10^{-18}$, and $g_{ae} < 7.6 \times 10^{-22}$ GeV$^{-1}$, and excludes either $g_{ae} = 0$ or $g_{ae} = 0$.

- Neutrino magnetic moment/non-standard neutrino interaction?
- Solar axion/dark photon?
- Axion/dark photon dark matter?
- Boosted dark matter?
- Exothermic dark matter?

Bramante, Song/arXiv:2006.14089
There exists the possibility of the “Nightmare” scenario where DM and SM only interact via gravity. However, we can still probe particle dark matter if large extra dimensions exist.
Microscopic Black Holes at Colliders

BH production only allowed if the impact parameter

\[ b \leq b_{\text{max}} = 2r_H(E_{\text{CM}}, n, M_*) \]

The cross section

\[
\sigma^{pp\rightarrow BH} = \int_{M_*^2/s}^{1} du \int_{u}^{1} \frac{dv}{v} \pi b_{\text{max}}^2 \sum_{i,j} f_i(v, Q)f_j(u/v, Q)
\]
Invisible Decay

- Neutrinos, gravitons and dark matter may not be seen in future colliders
- Dark matter adds to the missing transverse momentum
Invisible Decay

- $N_{DM} = 1$: a scalar
- $N_{DM} = 4$: Dirac fermion
- $N_{DM} = 20$: simple dark sector
- $N_{DM} = 118$: a copy of SM
Invisible Decay

- $N_{DM} = 1$: a scalar
- $N_{DM} = 4$: Dirac fermion
- $N_{DM} = 20$: simple dark sector
- $N_{DM} = 118$: a copy of SM

Fraction of invisible decay $f_{inv} = \frac{N_{\nu} + N_G + N_{DM}}{N_{vis} + N_{\nu} + N_G + N_{DM}}$
Standard Model Background

$\gamma + \text{jets}$, $W/Z + \text{jets}$, $t\bar{t}$ production

CMS, arXiv:1303.5338
Results

$\rho_\perp$ from $10^3$ BH simulations (DM+SM) and $10^6$ BH simulations (SM)

As $N_{DM}$ increases, mean $\rho_\perp$ rises sharply
Sensitivity

Song, Vincent PRL 2020/1907.08628

Only $\mathcal{O}(100)$ to $\mathcal{O}(10000)$ BHs required to resolve the dark sector if $N_{DM} \geq 4$, well within the luminosity reach of FCC
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Microscopic BHs created in particle collisions in the plasma

BHs produced at $T_\gamma < M_\star$ due to Boltzmann distribution

BHs accrete instead of decay if $T_{BH} < T_\gamma$

BH mass after accretion only depends on $T_\gamma$ at production
The lifetime of LED black holes can be much longer than 4d black holes, depending on the number of extra dimensions.
Extragalactic Photon Background

$n = 0$

$n = 2$

$n = 3$

$n = 4$

$\rho_{\text{PBH}} / \rho_{\text{DM}}$

$M / g$


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• BHs inject energy into the plasma from Hawking radiation
• High-\(l\) anisotropies damped due to Thomson scattering
• Implement LED BHs with modified ExoClass (arXiv:1801.01871)
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Conclusions and Prospects

- Microscopic black holes @ neutrino telescopes
  - Unusual reconstructed flavor composition
  - Different event energy distribution
  - New event topologies
  - Radio/Cherenkov telescopes?

- Microscopic black holes @ colliders
  - Increased $p_\perp$ leads to discovery of dark matter DOF
  - Dark matter mass/spin?

- Microscopic black holes @ the early universe
  - Black holes accrete after microscopic production
  - Photon emission changes extragalactic photon background
  - EM emissions modify CMB anisotropies
  - BBN?
  - Constrain $M_\star$ from observations?
  - Evaporation products/Planckian remnants as dark matter?