Probing Large Extra Dimensions with Large Neutrino Telescopes

Aaron C. Vincent — TeVPA 2019, Sydney NSW — December 5 2019
Based on work with

Ningqiang Song

Katie Mack

1912.XXXX
(Mack, Song & ACV)

See also 1907.08628
(Song & ACV)
1. Large Extra Dimensions
Large Extra Dimensions (LEDs)

Arkani-Hamed, Dimopoulos, Dvali

If the SM (us) is confined to a 3-dimensional brane
Large Extra Dimensions (LEDs)

Arkani-Hamed, Dimopoulos, Dvali

If the SM (us) is confined to a 3-dimensional brane

\[ V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2}} \frac{1}{r^{n+1}}, \quad (r \ll R) \]

\[ V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2}} \frac{1}{R^n r}, \quad (r \gg R) \]
ADD Large extra dimensions

\[ M_{Pl}^2 \sim M_{Pl(4+n)}^{2+n} R^n \]

\[ R \sim 10^{30 \frac{n}{n-17} \text{cm}} \times \left( \frac{1 \text{TeV}}{m_{EW}} \right)^{1+\frac{2}{n}} \]

-> Solution (ish) to the Hierarchy problem

n = 1: too large: mess up gravity on solar system scales
n > 1: still works
Hoop conjecture (Thorne)

If the impact parameter of two colliding particles is less than 2 times the gravitational radius, \(r_h\), corresponding to their center-of-mass energy (\(E_{\text{CM}}\)), a black hole with a mass of the order of \(E_{\text{CM}}\) and horizon radius, \(r_h\), will form.

\[ r_s = 2G \times \text{TeV} \sim 10^{-35} \text{GeV}^{-1} \]

Contrast with regular 3+1 dim BH
Black hole evaporation

These things do not live very long: \( T_H = \frac{d-2}{r_h} \)

TeV black hole has a \( \sim \) TeV Hawking Temperature

So a small BH

1) Evaporates very fast
2) Evaporates to a few \( (~5-20) \) particles, because they each carry away an \( O(1) \) fraction of the BH mass.
Black hole evaporation

Evaporation spectrum is *thermal*: evaporation products drawn from every degree of freedom in the SM

Leptons
Neutrinos (invisible)
Gravitons (invisible, can escape into extra dimensions)
Photon, W, Z
Quarks
Gluons
Black hole evaporation

Evaporation spectrum is *thermal*: evaporation products drawn from every degree of freedom in the SM

- Leptons
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  - 3 generations, 3 colors, 2 polarizations: strong particle emission very likely!
- Gluons
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= 118 d.o.f. + $D(D - 3)/2$ gravitons
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\[ = 118 \text{ d.o.f.} + \frac{D(D - 3)}{2} \text{ gravitons} \]

Distinct signature at colliders: high-multiplicity state, with many hadronic jets + some missing momentum
Collider searches

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Limited by CM energy
Collider searches

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Limited by CM energy

We could wait for a 100 TeV collider…
or let the cosmos do it for us!
2. Black holes at IceCube (and beyond)
The main idea

Black hole evaporation:
Mostly hadronic

Electroweak event:
Mostly *not* hadronic
FROZENWATERHEXAGON
CONTINENTAL NEUTRINO OBSERVATORY
Pacific Ocean Neutrino Explorer (PONE)

Ocean Networks Canada
Discover the ocean. Understand the planet.

- NEPTUNE Observatory
- Clayoquot Slope
- Middle Valley (2400 m)
- Barkley Canyon (1000 m)
- Endeavour (2300 m)
- Cascadia Basin (2660 m)
- Juan de Fuca Plate

Water properties
- Antares

Volume available and (partly) cabled

- ~500 strings
- Volume: ~50 km³

Illustration
“plum pudding” configuration: PMTs inside the transparent detector

80 strings with 60 PMT ‘DOMs’ each

Cherenkov light

IceCube Collaboration
“plum pudding” configuration: PMTs inside the transparent detector

- 80 strings with 60 PMT ‘DOMs’ each
- Cherenkov light

IceCube Collaboration

Frozen Water Hexagon
Continental Neutrino Observatory
Black holes from neutrinos

\[
\sigma^{\nu N \rightarrow BH} = \int \frac{1}{M_\ast^2/s} \, du \pi b_{\text{max}}^2 \sum_i f_i(u, Q),
\]

\[
E_{CM} = \sqrt{2E_\nu m_p}
\]

TeV CM energy requires PeV neutrinos

6 LEDs

1 LED
Event rates

IceCube has seen \( \sim 120 \) HE events (30 TeV — 3 PeV) in 8 years. Flux decreases as \( E^{-2.5} \). We need to go to higher energies.

Very high energies
Very high exposures

Planned experiments that we have in mind:

- IceCube Gen2: about 10x effective size of IceCube
- Pacific Ocean Neutrino Experiment (pONE? STRAW?): up to 50 km\(^3\)

Radio arrays (ARA, ARIANA) have the capacity to reach large effective volumes, but events are harder to characterize.
Travel to earth: flavour mixing

Source \((\alpha_e : \alpha_\mu : \alpha_\tau)_S\)

\[(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus\]
Standard neutrino-nucleus interactions

Neutral-current (NC)

\[ \nu \rightarrow \nu + Z \rightarrow \text{nucleus} + \text{nucleus+stuff} \]
Standard neutrino-nucleus interactions

**Neutral-current (NC)**
\[ \nu \rightarrow \nu + Z \rightarrow \nu + \text{nucleus} + \text{stuff} \]

**Charged-current (CC)**
\[ \nu_\ell \rightarrow \ell^\pm + W^\mp \rightarrow \ell^\pm + \text{nucleus} + \text{stuff} \]

Final-state lepton:
- **electron**: deposits E
- **muon**: can travel ~ km
- **tau**: If HE enough, can travel then decay
Standard neutrino-nucleus interactions

**Neutral-current (NC)**

$$\nu \rightarrow \nu$$

(nucleus) \rightarrow (nucleus+stuff)

\[\nu \rightarrow \nu\]

**Charged-current (CC)**

$$\nu \rightarrow \ell^{\pm}$$

(nucleus) \rightarrow (nucleus+stuff)

\[\nu \rightarrow \ell^{\pm}\]

**Final-state lepton:**
- **electron:** deposits E
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Event topology

**Shower** (electronic or hadronic)

**Muon track**

**Double bang:**
when tau lepton travels far enough and decays to $\pm$ or hadrons
(first db events reported 1908.05506)
We modify BlackMax (aimed at collider searches) to handle neutrino-nucleon collisions.
Showers

- Neutral-current (NC)
  \[ \nu \rightarrow \nu \]
  \[ \nu \rightarrow Z \rightarrow \text{nucleus + stuff} \]

- Charged-current (CC)
  \[ \nu_e \rightarrow e^\pm \]
  \[ \nu_e \rightarrow W^\pm \rightarrow \text{nucleus + stuff} \]

Black hole

- Plus mostly hadrons
- Some electrons

Tracks

- Charged-current (CC)
  \[ \nu_\mu \rightarrow \mu^\pm \]
  \[ \nu_\mu \rightarrow W^\pm \rightarrow \text{nucleus + stuff} \]

- Occasional muon

double-bangs

- Charged-current (CC)
  \[ \nu_\tau \rightarrow \tau^\pm \]
  \[ \nu_\tau \rightarrow W^\pm \rightarrow \text{nucleus + stuff} \]

mostly hadrons

or tau

mostly hadrons
BH vs SM

When BHs start being produced, they will dominate
What does the reconstructed flavor composition look like if I’m seeing black holes instead of electroweak events?
Reconstructed flavor composition (IC-Gen2 exposure)

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More tracks than SM
Fewer double-bangs
Reconstructed flavor composition (IC-Gen2 exposure)

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More tracks than SM
Fewer double-bangs
SM

Lepton carries away most of the momentum
\[
\frac{d\sigma}{dy} \text{ peaks at high } (1 - y) \equiv \frac{E_\ell}{E_\nu}
\]

Black hole

Lepton only carries \( \sim 1/N \) of the total energy, where \( N \) is the number of emitted particles.

**Tracks**

Charged-current (CC)

- \( \nu_\mu \) to \( \mu^\pm \)
- \( W^\pm \)
- nucleus to nucleus+stuff

**double-bangs**

Charged-current (CC)

- \( \nu_\tau \) to \( \tau^\pm \)
- \( W^\pm \)
- nucleus to nucleus+stuff

Lepton carries away most of the momentum in SM, while in Black hole, lepton only carries \( \sim 1/N \) of the total energy, where \( N \) is the number of emitted particles.
Muon track energy ratio

SM events

BHs

Hadronic (shower) energy
Muon track energy ratio

SM events

BHs

Hadronic (shower) energy

Muons

SM

BH
Double bang energy ratio

![Graph showing the relationship between energy of the first bang and the energy of the second bang, with different markers for different scenarios, including SM events and BHs.](image)

- $E_1$ (GeV): Energy of the first bang
- $E_2$ (GeV): Energy of the second bang

Legend:
- $\nu_e$ CC
- $M_* = 1$ TeV
- $M_* = 2$ TeV
- $M_* = 3$ TeV
- $M_* = 10$ TeV
- BH $M_* = 3$ TeV, log flat
- BH $M_* = 3$ TeV, $E^{-2}$
Double bang energy ratio

Caveat: we only see this band:
- Lower limit: tau decays too close to first shower, and they are not distinguishable
- Upper limit: Tau escapes the detector: no second bang
Other crazy topologies that don’t occur in the SM

*Multitrack* events, when multiple muons are produced. Because these events are highly collimated, angular separation is too small to see 😞 (less than $0.01^\circ$ — IC can see at best $0.1^\circ$)
Other crazy topologies that don’t occur in the SM

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**n-bang:** multiple tau leptons decay hadronically, leaving a string of cascades separated by \( d = c \Delta t \). These occur in about 0.2% of black hole events.
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Double black hole bang: If one of the decay products is 1) energetic enough and 2) can travel far enough, it can collide and form a second black hole, again separated by $d = c\Delta t$

These are rare, but if we see even one we can suspect LEDs are involved!!
Showers

SM

Black hole

Neutral-current (NC)

\[ \nu \rightarrow \nu \]

Z

nucleus

nucleus + stuff

Charged-current (CC)

\[ \nu_e \rightarrow e^\pm \]

W^\pm

nucleus

nucleus + stuff

What about

these showers?

SM: hadronic shower have lower energies, electromagnetic showers have high energies

BH: shower should look like a very big hadronic shower

some electrons

mostly hadrons
Cherenkov light echoes

First interaction of neutrinos in ice produces a large prompt Cherenkov burst that lasts $\sim 10^{-7}$ s, proportional to the total event energy.
Cherenkov light echoes

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Muons produced during hadronization and propagation are low-energy, and therefore live \( \sim 10^{-6} \) s, leading to a second muon echo as they decay.
Cherenkov light echoes

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Muons produced during hadronization and propagation are low-energy, and therefore live $\sim 10^{-6}$ s, leading to a second muon echo as they decay.

Neutrons can live for up to .1 ms before being captured, leading to a third neutron capture echo.
Analysis

BlackMax:
- predict decay products

SM:
- electroweak cross sections

Pythia 8:
- Decay heavy stuff, hadronize

FLUKA:
- inject products into ice, count Čerenkov Photons
Cherenkov light echos

Cherenkov light generation for specific particles injected in the ice

Peaks 2 and 3 are exactly correlated, so we can use the peak ratio $E_3/E_1$ to determine how hadronic/electronic a shower is
Light echos seen with an astrophysical neutrino spectrum

Neutral current events: above the hadron line since hadronization yields mostly hadrons + a few $\gamma$. Low energy because neutrino takes away most of the $E$.

Charged current events: much lower muon/neutron light echo, because most energy injection is from an electron or positron

Black Holes: Most of the energy is hadronic: high energy and large Cherenkov echo.
Detection prospects (6 Large Extra Dimensions)

Combining **muon energy ratios**, (very few) **double bang energy ratios** and **light echos**
Exclusion prospects (6 Large Extra Dimensions)

Combining **muon energy ratios**, (very few) **double bang energy ratios** and **light echos**
If the Higgs potential actually puts us in a metastable vacuum, the extremely high curvature near a microscopic black hole can make tunnelling to true vacuum **much more probable**.
Stability of the Universe

If the Higgs potential actually puts us in a metastable vacuum, the extremely high curvature near a microscopic black hole can make tunnelling to true vacuum much more probable.

Discovery of a MBH at neutrino telescopes, combined with the fact that we are all not dead —> the Higgs vacuum is likely stable
Summary

• The next generation of large neutrino telescopes has the capacity to probe large extra dimensions.

• There are unique, interesting signatures in neutrino telescopes that have never been explored!

• Only tens to hundreds of events above ~5 PeV required

• Radio detectors (IC radio array, GRAND, etc) have potential for very large exposures, but it’s trickier to extract information

• If we see a MBH, we can infer some information about the Higgs vacuum at high energies
Thank You