Microscopic black holes in neutrino telescopes, colliders and cosmology

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Sep 14th 2020

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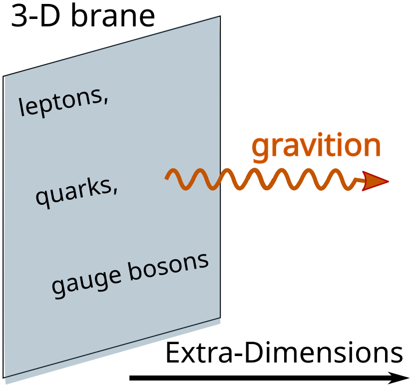
Overview

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

Overview

Large Extra Dimensions (LEDs)

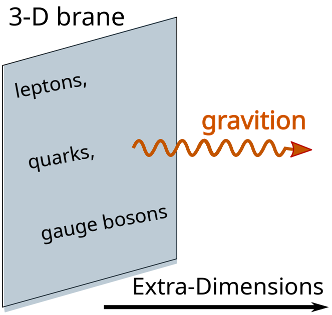


ADD, PLB429(1998), PRD59(1999)086004

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

- SM particles confined to the *3*-D "brane"
- Gravitions can propagate in the $3+n$-D bulk "bulk"

Large Extra Dimensions (LEDs)



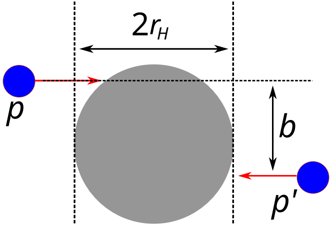
- $M_\star \sim \mathrm{TeV} \ll M_{pl}$
- Solve the hierarchy problem

Gravitational potential

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

$\Longrightarrow$ In $4D$ $\boxed{M_{pl}^2 \sim M_\star^{2+n} R^n}$

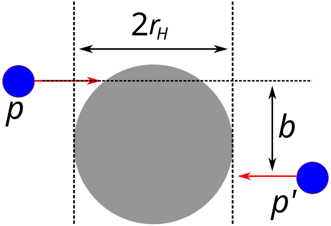
Microscopic Black Holes and Hoop conjecture



BH production only allowed if the impact parameter

$$b \leq b_{\max} = 2r_H(E_{\rm CM}, n, M_\star)$$

Microscopic Black Holes and Hoop conjecture

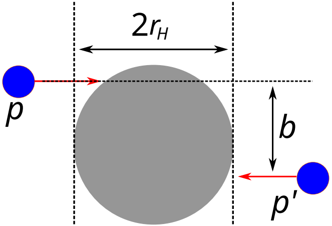


Equivalently, BH production is allowed if $E_{cm} \gtrsim M_\star$

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
- ...

Microscopic Black Holes and Hoop conjecture



BH production allowed if the impact parameter $b \leq b_{\max}$

For pp collision the cross section

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

D. Dai et al. Phys.Rev. D77 (2008)

Current Limits

n=1 killed

extra dimensions

bulk Planck scale

Method	Reference	n	$\log_{10}(E_*/\text{eV})$	$\log_{10}(L/\text{m})$
Grav force	[26]	2	12.5	−4.36
SN1987A	[27]	2	13.4	−6.18
		3	12.4	−9.10
NS cooling	[28]	1		−4.35
		2		−9.81
		3		−11.6
		4		−12.5
		5		−13.0
		6		−13.4
CMS	[29]	2	13.0	
		3	12.9	
		4	12.8	
		5	12.8	
		6	12.7	

$M_\star > 5 \sim 10$ TeV

Mack, McNees PRD 2019/1809.05089

Current Limits

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

Some energy scales:

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

n=1 killed

extra dimensions

bulk Planck scale

Method	Reference	n	$\log_{10}(E_*/\mathrm{eV})$	$\log_{10}(L/\mathrm{m})$
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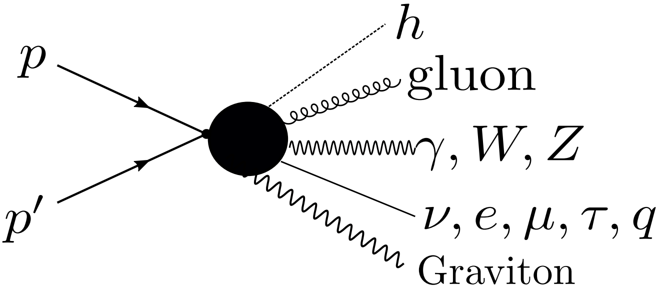
$M_\star > 5 \sim 10$ TeV

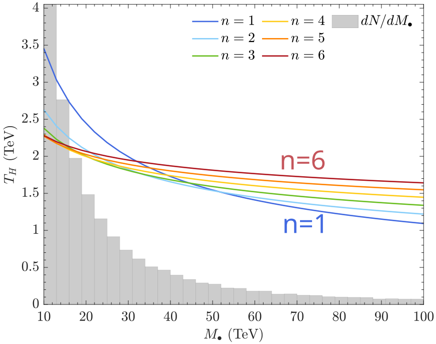
Hawking Radiation



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

Hawking Radiation

Song, Vincent PRL 2020/arXiv:1907.08628



- Hawking temperature

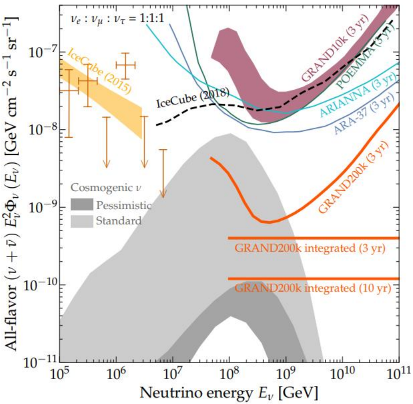
$$T_H = \frac{n+1}{4\pi r_H(M_{BH}, n, M_\star)}$$

- Graybody distribution spectrum

$$\frac{dE}{dt} \propto \frac{\omega}{\exp(\omega/T_{BH}) \mp 1} \frac{d\omega}{2\pi}$$

Overview

High Energy Neutrino Flux



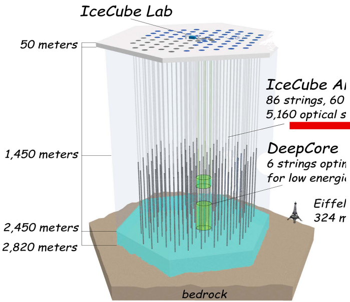
GRAND Collaboration/1810.09994

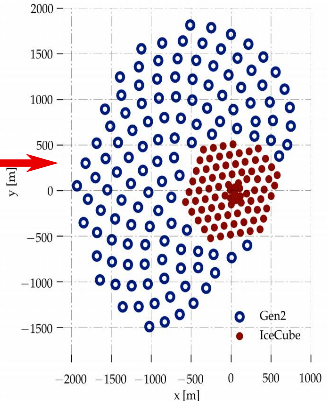
- Atmospheric neutrinos already detected in IceCube
- Need larger detector for ultra high energy cosmogenic neutrinos

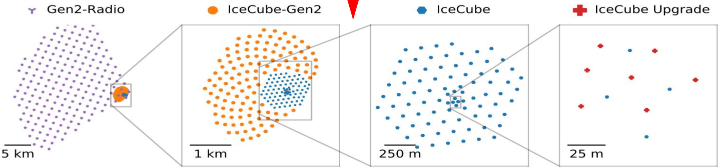
ID	Dep. Energy (TeV)	Time (MJD)	Decl. (deg.)	R.A. (deg.)	Med. Angular Error (deg.)	Event Type
1	$47.6^{+6.5}_{-5.4}$	55351	−1.8	35.2	16.3	Shower
2	117^{+15}_{-15}	55351	−28.0	282.6	25.4	Shower
3	$78.7^{+10.8}_{-8.7}$	55451	−31.2	127.9	$\lesssim 1.4$	Track
4	165^{+20}_{-15}	55477	−51.2	169.5	7.1	Shower
5	$71.4^{+9.0}_{-9.0}$	55513	−0.4	110.6	$\lesssim 1.2$	Track
6	$28.4^{+2.7}_{-2.5}$	55568	−27.2	133.9	9.8	Shower
7	$34.3^{+3.5}_{-4.3}$	55571	−45.1	15.6	24.1	Shower
8	$32.6^{+10.3}_{-11.1}$	55609	−21.2	182.4	$\lesssim 1.3$	Track
9	$63.2^{+7.1}_{-8.0}$	55686	33.6	151.3	16.5	Shower
10	$97.2^{+10.4}_{-12.4}$	55695	−29.4	5.0	8.1	Shower
11	$88.4^{+12.5}_{-10.7}$	55715	−8.9	155.3	16.7	Shower
12	104^{+13}_{-13}	55739	−52.8	296.1	9.8	Shower
13	253^{+26}_{-22}	55756	40.3	67.9	$\lesssim 1.2$	Track
14	1041^{+132}_{-144}	55783	−27.9	265.6	13.2	Shower
15	$57.5^{+8.3}_{-7.8}$	55783	−49.7	287.3	19.7	Shower
16	$30.6^{+3.6}_{-3.5}$	55799	−22.6	192.1	19.4	Shower
17	200^{+27}_{-27}	55800	14.5	247.4	11.6	Shower
18	$31.5^{+4.6}_{-3.3}$	55924	−24.8	345.6	$\lesssim 1.3$	Track
19	$71.5^{+7.0}_{-7.2}$	55926	−59.7	76.9	9.7	Shower
20	1141^{+143}_{-133}	55929	−67.2	38.3	10.7	Shower
21	$30.2^{+3.5}_{-3.3}$	55937	−24.0	9.0	20.9	Shower
22	220^{+21}_{-24}	55942	−22.1	293.7	12.1	Shower
23	$82.2^{+8.6}_{-8.4}$	55950	−13.2	208.7	$\lesssim 1.9$	Track
24	$30.5^{+3.2}_{-2.6}$	55951	−15.1	282.2	15.5	Shower
25	$33.5^{+4.9}_{-5.0}$	55967	−14.5	286.0	46.3	Shower
26	210^{+29}_{-26}	55979	22.7	143.4	11.8	Shower
27	$60.2^{+5.6}_{-5.6}$	56009	−12.6	121.7	6.6	Shower
28	$46.1^{+5.7}_{-4.4}$	56049	−71.5	164.8	$\lesssim 1.3$	Track

IceCube Collaboration/1311.5288

IceCube-Gen2

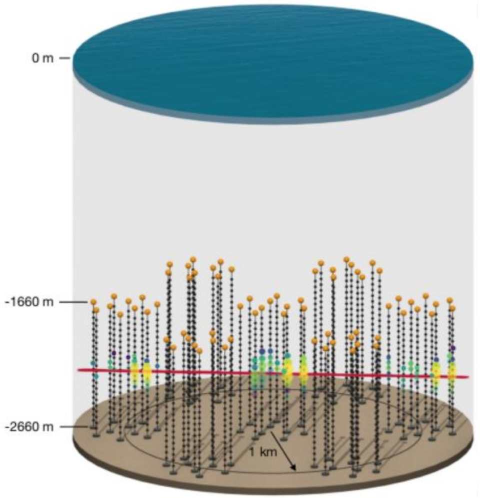






IceCube Collaboration

Pacific Ocean Neutrino Experiment (P-ONE)



P-ONE Collaboration/2005.09493

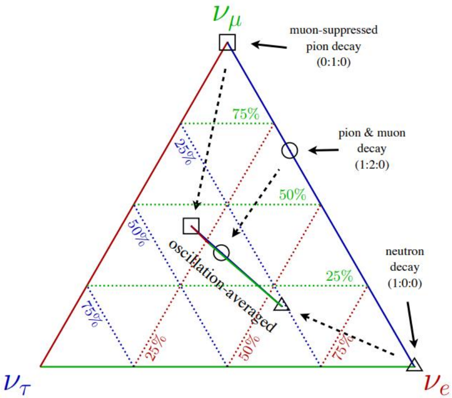
High Energy Neutrino Flavor Compositions

Pontecorvo–Maki–Nakagawa–Sakata matrix:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

From the source to the earth

$$P^{s\to\oplus}_{\alpha\beta} = \sum_{ij} U_{\beta i} U^*_{\beta j} U_{\alpha j} U^*_{\alpha i} \exp(-i \frac{\Delta m^2_{ij} L}{2E})$$
$$= \sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

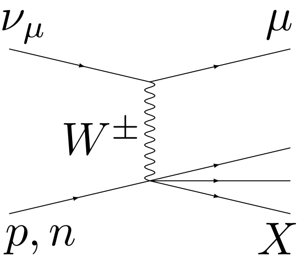


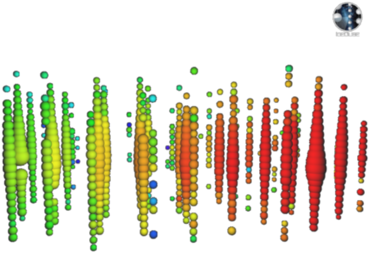
arXiv:1412.5106

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

Event Topologies at IceCube: Standard Model

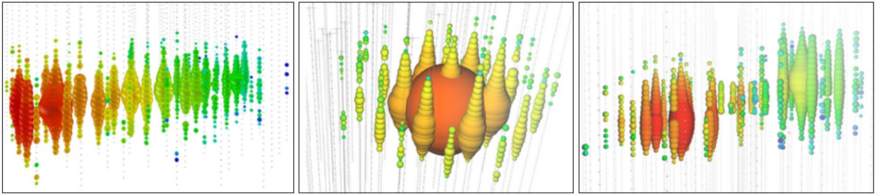
ν_μ Charged Current (CC)





icecube.wisc.edu

Event Topologies at IceCube: Standard Model



arXiv:2008.04323

SM tracks:

- ν_μ charged current
- ν_τ charged current with high energy τ track

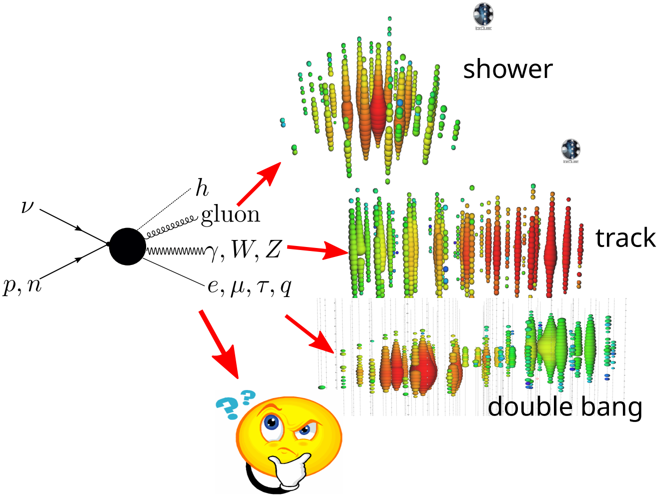
SM showers:

- ν_e charged current
- All ν neutral current
- ν_τ charged current with low energy τ decay

SM double-bangs:

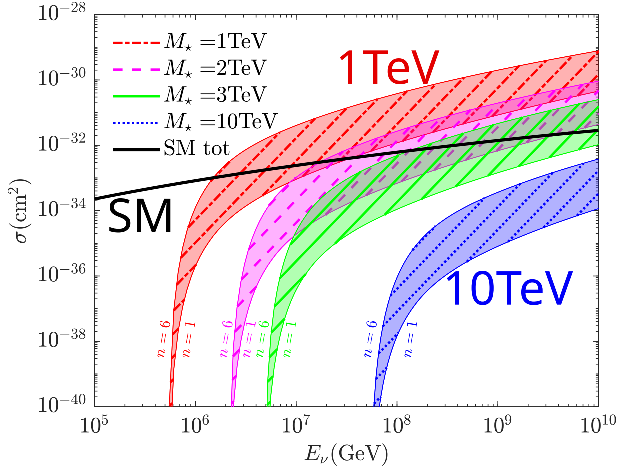
- ν_τ charged current with high energy τ decay

Event Topologies at IceCube: Black Holes



All Standard Model topologies are expected in black hole events

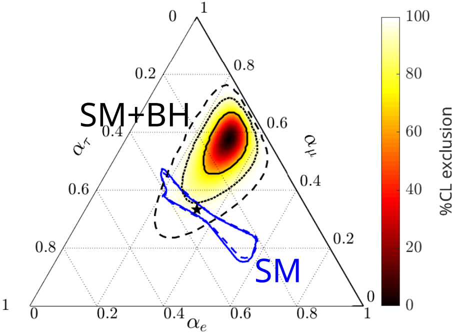
Black Hole Production Cross Section



The $\nu - N$ scattering cross section

$$\sigma^{\nu N \to BH} = \int_{M_\star^2/s}^{1} du \pi b_{\max}^2 \sum_i f_i(u, Q)$$

Reconstructed Flavor Composition From Black Holes

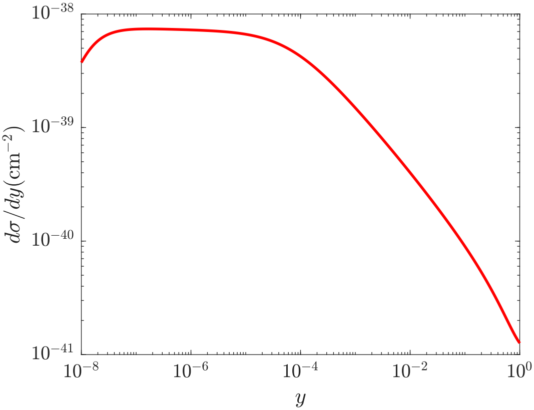


- more events expected from the same flux if $M_\star = 3$ TeV
- more tracks from μ, τ
- rarer double bang due to energy asymmetry condition

Mack, **Song** & Vincent JHEP 2020/1912.06656

	shower	track	double bang
ν_e SM	28.58	0	0
ν_μ SM	2.31	8.31	0
ν_τ SM	5.07	5.39	2.83
All Flavor Total SM	35.96	13.70	2.83
All Flavor Total BH	62.96	36.36	0.20

Standard Model Events vs Black Holes

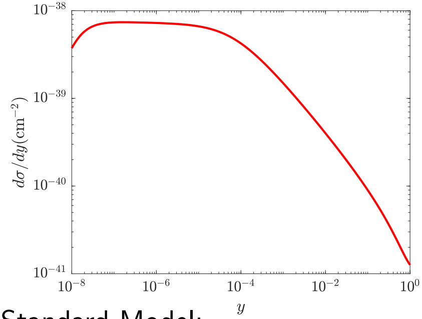


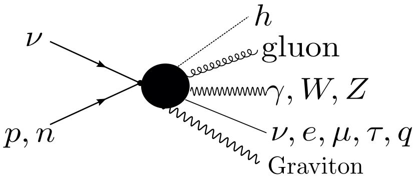
Standard Model:

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

Most neutrino energy is transferred to final state lepton/neutrino

Standard Model Events vs Black Holes





Standard Model:

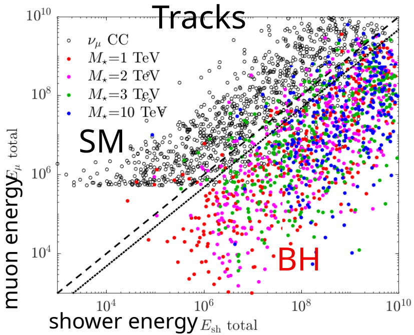
- $y = 1 - E_l/E_\nu$
- cross section peaks at large E_l

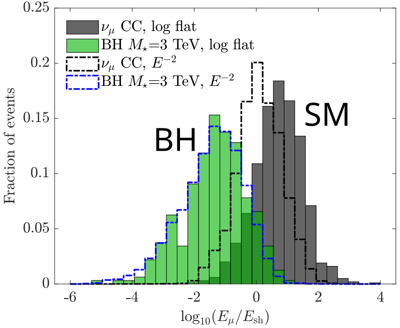
Black holes:

- BH produces $N \sim 6 \sim 20$ primary particles
- $E_l \sim E_\nu/N$

Lepton energy in black holes tends to be smaller than in SM!

Muon Energy Ratio in BH Tracks

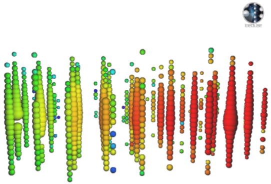




Tracks are produced in $\nu_{\mu,\tau}$ CC:

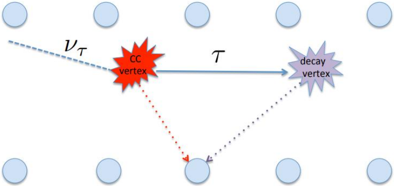
$\nu_{\mu,\tau} + n \to \mu(\tau) + X$

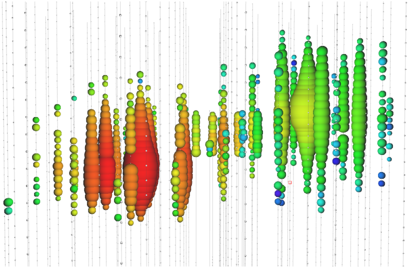
- SM: $E_\mu > E_{hadron}$
- Black holes: $E_{hadron} > E_\mu$



Lower track energy to shower energy ratio expected in BH events

Energy Asymmetry in BH Double Bangs



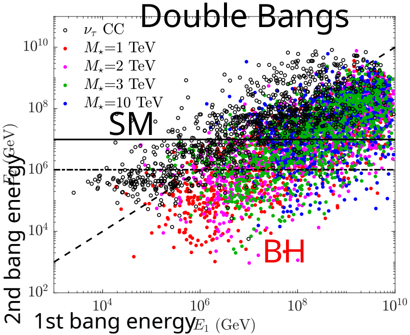


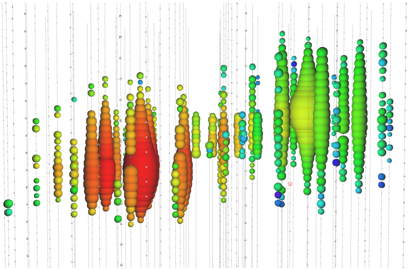
icecube.wisc.edu

Double bangs are produced in ν_τ CC: $\nu_\tau + n \to \tau + X$

τ travels certain distance before decay inside the detector

Energy Asymmetry in BH Double Bangs

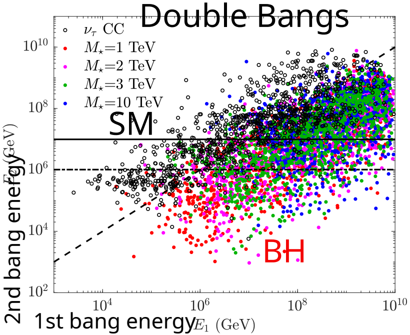




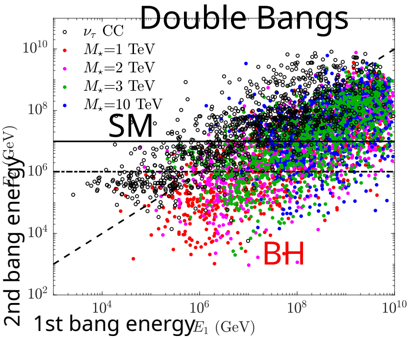
energy asymmetry: $E_A = \dfrac{E_1 - E_2}{E_1 + E_2}$

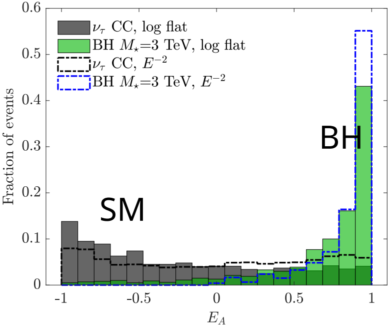
- SM: $E_1 < E_2$
- Black holes: $E_1 > E_2$

Energy Asymmetry in BH Double Bangs



Energy Asymmetry in BH Double Bangs



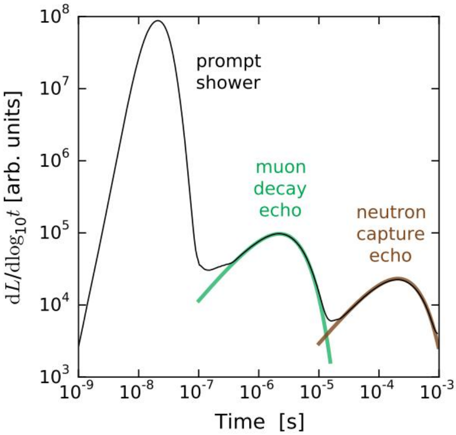


energy asymmetry: $E_A = \dfrac{E_1 - E_2}{E_1 + E_2}$

- SM: $E_A < 0$
- Black holes: $E_A > 0$

Mostly positive energy asymmetry expected in black hole events

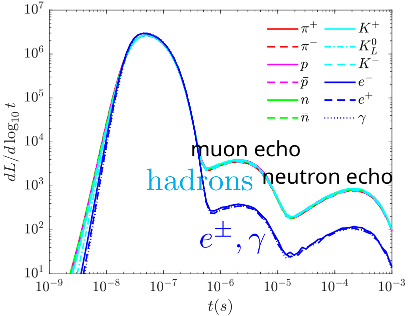
Cherenkov Light Echos



Li, Bustamante, Beacom PRL 2019/1606.06290

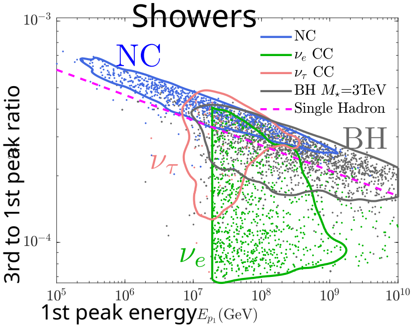
Particles from neutrino-nucleon interaction deposit their energy promptly within 10^{-7} s, secondary muons decay at $\sim 1 - 10\ \mu$s, and neutrons are captured at $\sim 200\ \mu$s

Cherenkov light echos



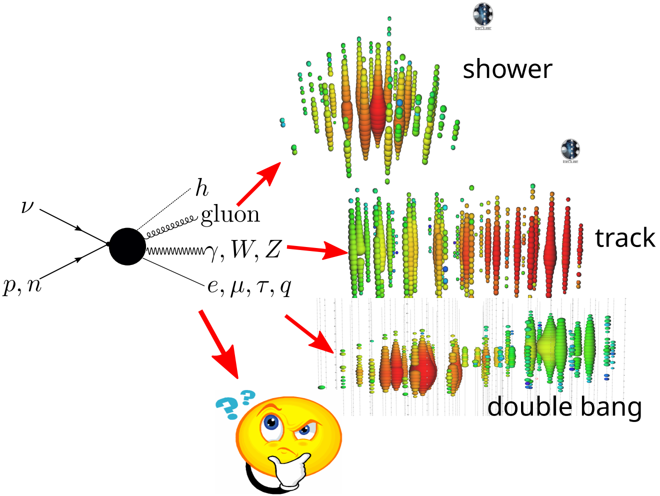
- Electromagnetic shower: electrons and gamma produce EM showers, featured with less muons and neutrons in the final states
- Hadronic shower: hadrons produce hadronic showers, featured with copious muons and neutrons in the final states
- Muon echo and neutron echo are closely correlated

Cherenkov light echos



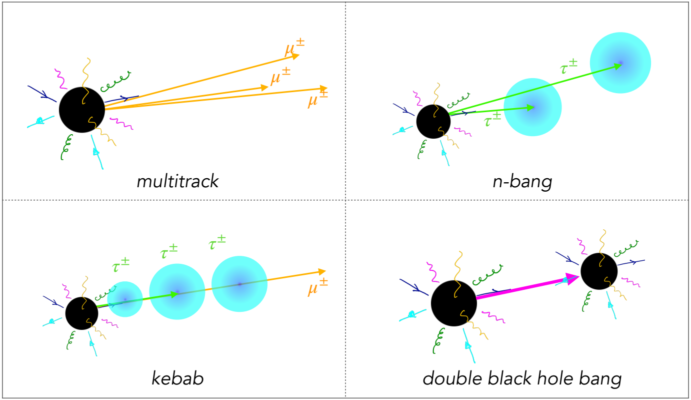
- ν_e CC: Energetic EM shower with less energetic hadronic shower
- ν_τ CC: EM shower or hadronic shower depending on decay product
- NC: Energetic hadronic shower
- Black holes: Energetic hadronic shower with less energetic EM shower

Event Topologies at IceCube: Black Holes



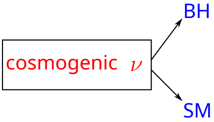
All Standard Model topologies are expected in black hole events

More Exciting Topologies!

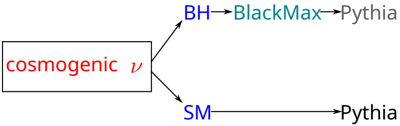


- Multitrack: BHs produce multiple muons or taus
- *n*-bang: BHs produce multiple taus decaying in the detector
- Kebab: Multiple taus decay in the detector along with a track
- Double BH bang: BH decay product produces another BH

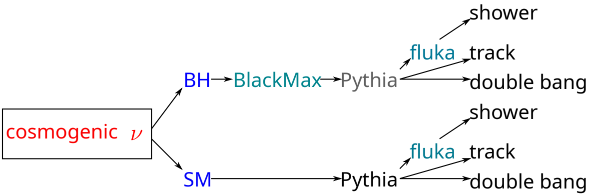
Analysis



Analysis

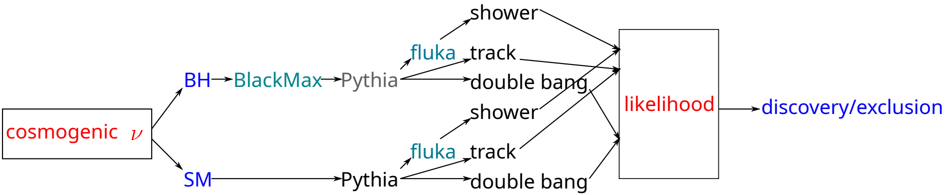


Analysis



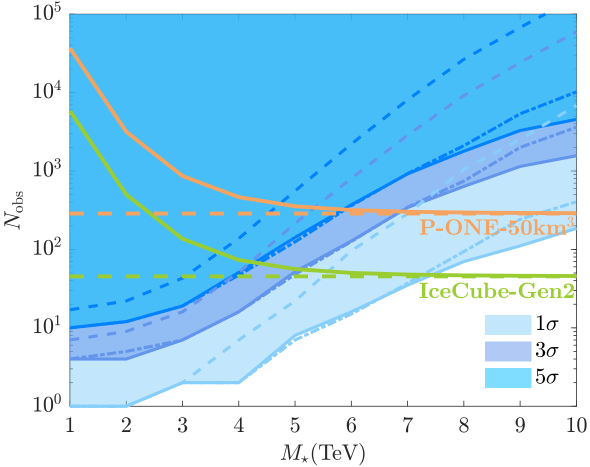
cosmogenic ν
BH
BlackMax
Pythia
fluka
shower
track
double bang
SM
Pythia
fluka
shower
track
double bang

Analysis



cosmogenic ν
BH
BlackMax
Pythia
fluka
shower
track
double bang
SM
Pythia
fluka
shower
track
double bang
likelihood
discovery/exclusion

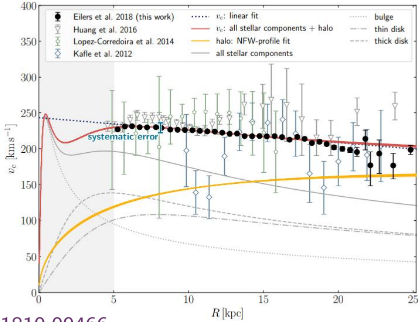
Black Hole Discovery Prospects



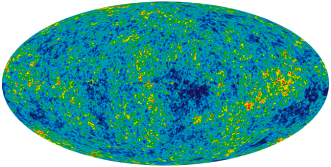
Mack, **Song**, Vincent JHEP 2020/arXiv:1912.06656

Overview

Dark Matter

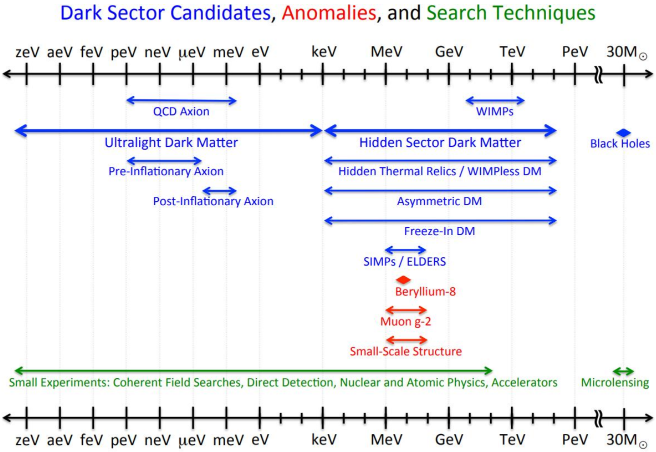


1810.09466



- 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 1903.01862
- Boson $M_{DM} \gtrsim 10^{-22} - 10^{-20}$ eV 2001.04403

Dark Matter Candidates



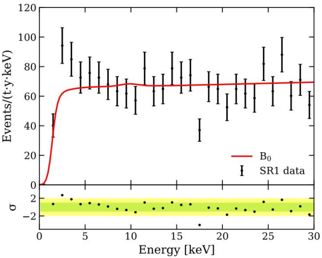
UC Cosmic Visions 2017/1707.04591

Dark Matter and XENONT1T Excess

Observation of Excess Electronic Recoil Events in XENON1T

E. Aprile, J. Aalbers, F. Agostini, M. Alfonsi, L. Althueser, F. D. Amaro, V. C. Antochi, E. Angelino, J. R. Ang
Baudis, B. Bauermeister, L. Bellagamba, M. L. Benabderrahmane, T. Berger, A. Brown, E. Brown, S. Bruer
M. R. Cardoso, D. Cichon, B. Cimmino, M. Clark, D. Coderre, A. P. Colijn, J. Conrad, J. P. Cussonneau, M.
A. Di Giovanni, R. Di Stefano, S. Diglio, A. Elykov, G. Eurin, A. D. Ferella, W. Fulgione, P. Gaemers, R. Ga
Hasterok, C. Hils, K. Hiraide, L. Hoetzsch, J. Howlett, M. Iacovacci, Y. Itow, F. Joerg, N. Kato, S. Kazama, M
Landsman, R. F. Lang, L. Levinson, Q. Lin, S. Lindemann, M. Lindner, F. Lombardi, J. Long, J. A. M. Lopes
Mahlstedt, A. Mancuso, L. Manenti, A. Manfredini, F. Marignetti, T. Marrodán Undagoitia, K. Martens, J. Ma
Messina, K. Miuchi, K. Mizukoshi, A. Molinario, K. Morå, S. Moriyama, Y. Mosbacher, M. Murra, J. Naganor
Palacio, B. Pelssers, R. Peres, J. Pienaar, V. Pizzella, G. Plante, J. Qin, H. Qiu, D. Ramírez García et al. (3

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



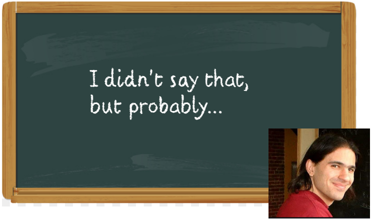
arXiv:2006.09721

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

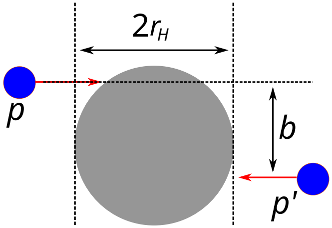
Bramante, **Song**/arXiv:2006.14089

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



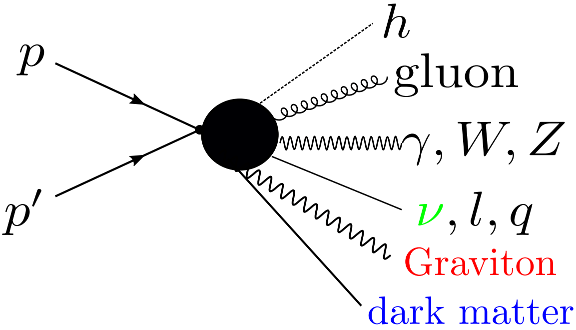
BH production only allowed if the impact parameter

$$\boxed{b \leq b_{\max} = 2r_H(E_{\mathrm{CM}}, n, M_\star)}$$

The cross section

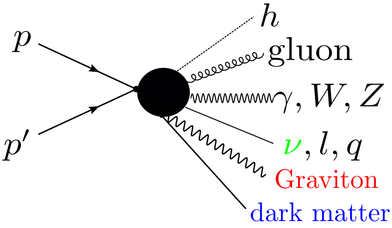
$$\sigma^{pp\to BH} = \int_{M_\star^2/s}^{1} du \int_u^1 \frac{dv}{v} \pi b_{\max}^2 \sum_{i,j} f_i(v, Q) f_j(u/v, Q)$$

Invisible Decay



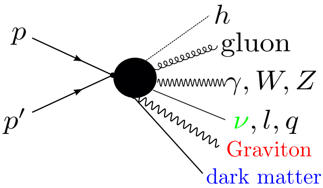
- Neutrinos, gravitons and dark matter may not be seen in future colliders
- Dark matter adds to the missing transverse momentum

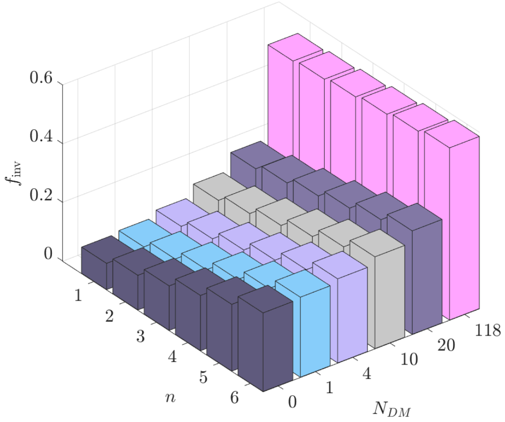
Invisible Decay



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

Invisible Decay



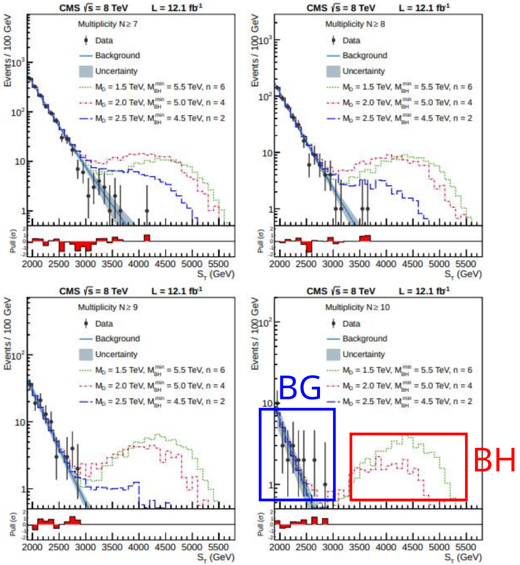


- $N_{DM} = 1$: a scalar
- $N_{DM} = 4$: Dirac fermion
- $N_{DM} = 20$: simple dark sector
- $N_{DM} = 118$: a copy of SM

Fraction of invisible decay $f_{\rm inv} = \dfrac{N_\nu + N_G + N_{DM}}{N_{vis} + N_\nu + N_G + N_{DM}}$

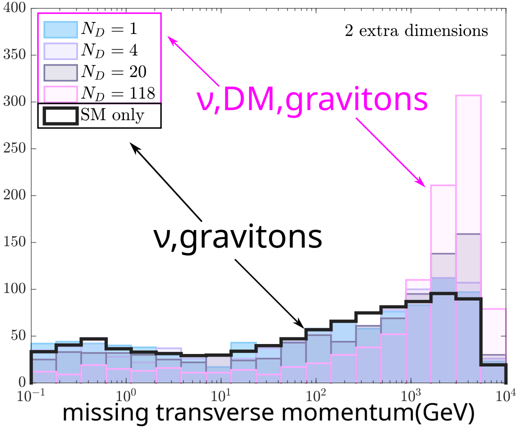
Standard Model Background

γ+jets, $W/Z + jets$, $t\bar{t}$ production CMS, arXiv:1303.5338



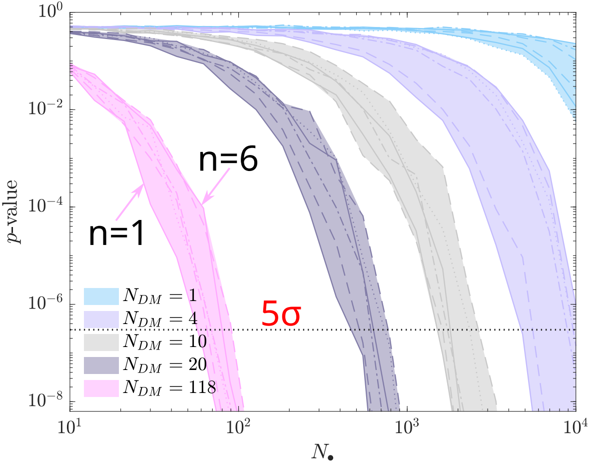
Results

$\not{p}_\perp$ from 10^3 BH simulations (DM+SM) and 10^6 BH simulations (SM)



As N_{DM} increases, mean $\not{p}_\perp$ rises sharply

Sensitivity



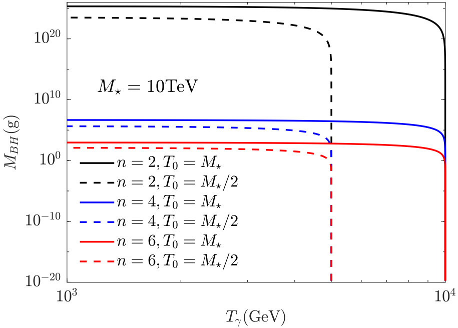
Song, Vincent PRL 2020/1907.08628

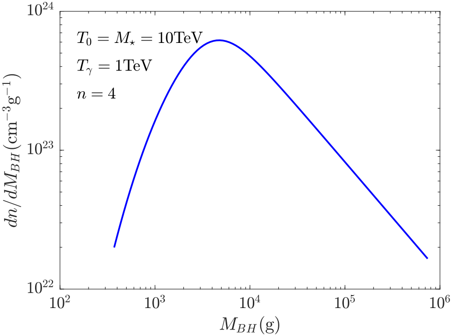
Only $\mathcal{O}(100)$ to $\mathcal{O}(10000)$ BHs required to resolve the dark sector if $N_{DM} \geq 4$, well within the luminosity reach of FCC

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

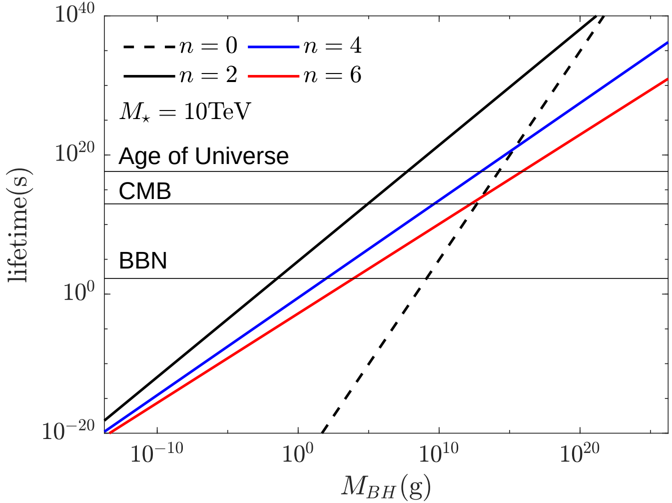
LED Black Holes in the Early Universe





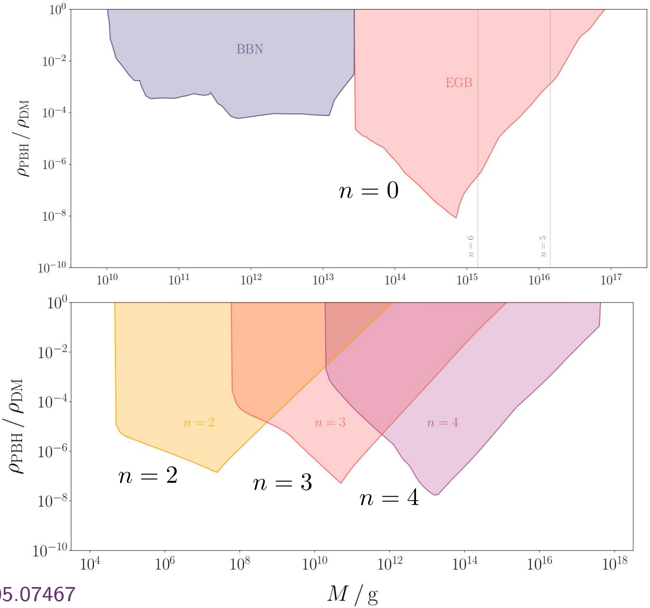
- Microscopic BHs created in particle collisions in the plasma
- BHs produced at $T_\gamma < M_\star$ due to Boltzmann distribution
- BHs accrete instead of decay if $T_{BH} < T_\gamma$
- BH mass after accretion only depends on T_γ at production

Lifetime of Black holes



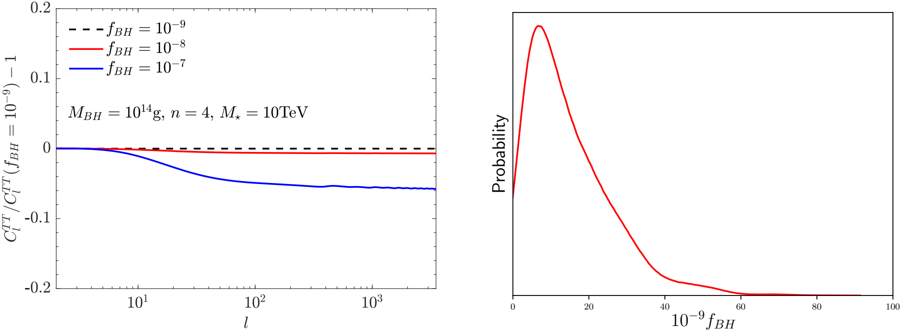
The lifetime of LED black holes can be much longer than 4d black holes, depending on the number of extra dimensions

Extragalatic Photon Background



arXiv:2005.07467

CMB Constraints



- 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)

Overview

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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 $\not{p}_\perp$ 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?