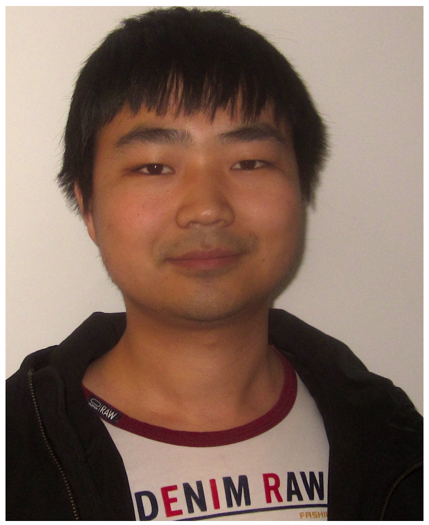
Queen's University

Probing Large Extra Dimensions with Large Neutrino Telescopes

Aaron C. Vincent — TeVPA 2019, Sydney NSW — December 5 2019

Institut Canadien de Recherche en Physique des Astroparticules
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

Based on work with



Ningqiang Song

Katie Mack

1912.XXXX

(Mack, Song & ACV)

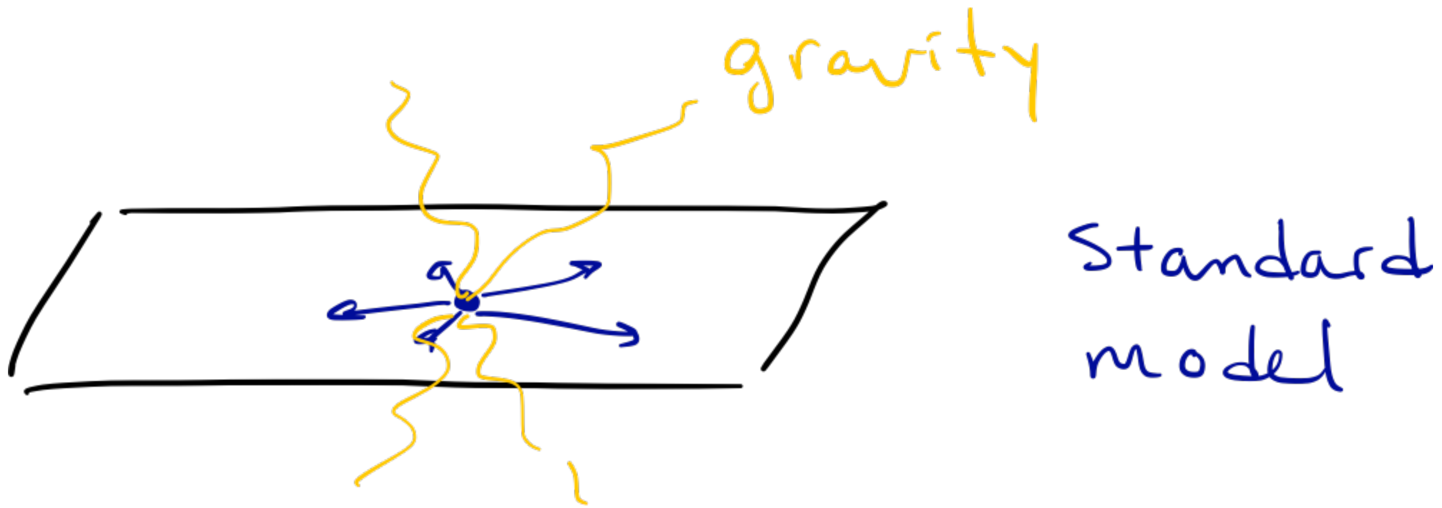
See also 1907.08628

(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

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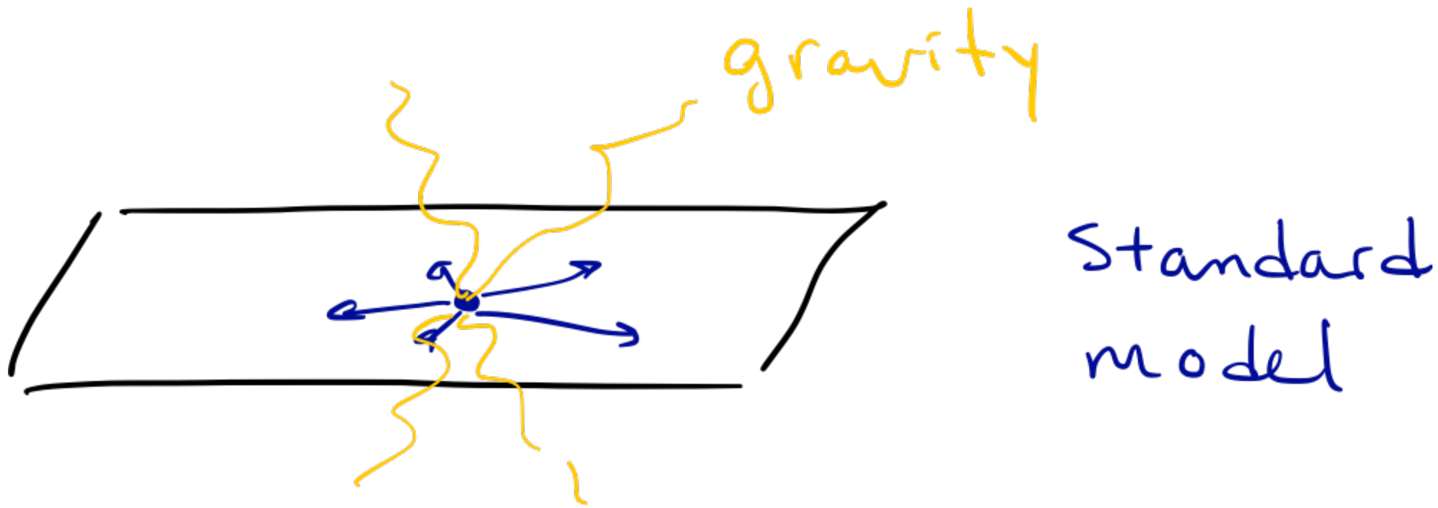

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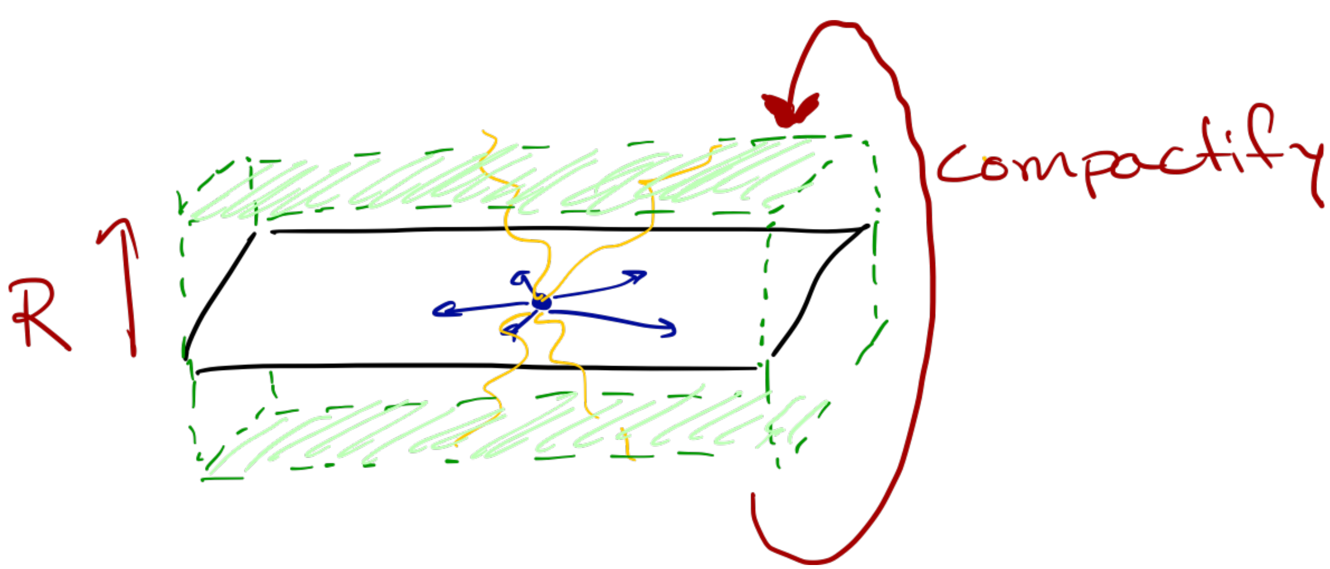


$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2}} \frac{1}{r^{n+1}}, \; (r \ll R).$$

$$V(r) \sim \frac{m_1 m_2}{M_{Pl(4+n)}^{n+2} R^n} \frac{1}{r}, \; (r \gg R)$$

ADD Large extra dimensions

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

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

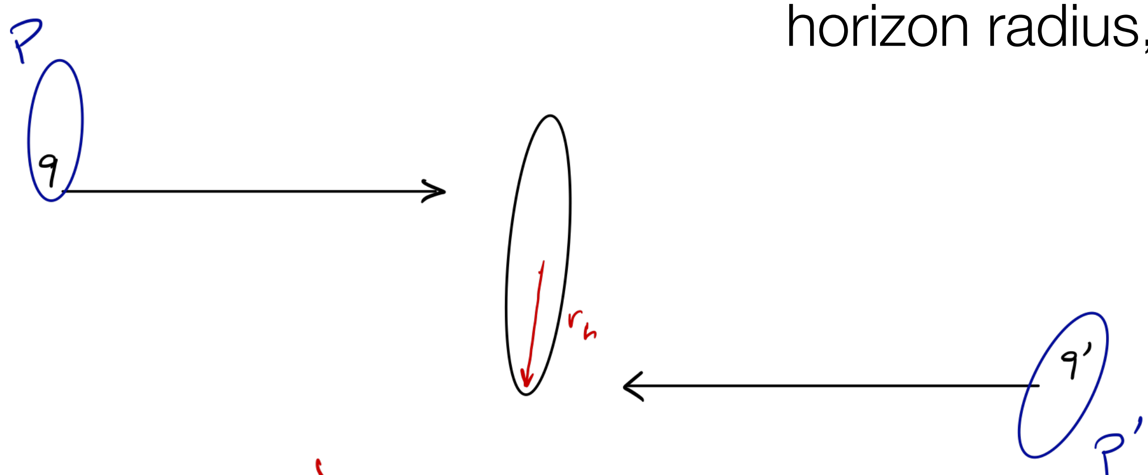
-> Solution (ish) to the Hierarchy problem

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_{CM}), a black hole with a mass of the order of E_{CM} and horizon radius, r_h, will form.

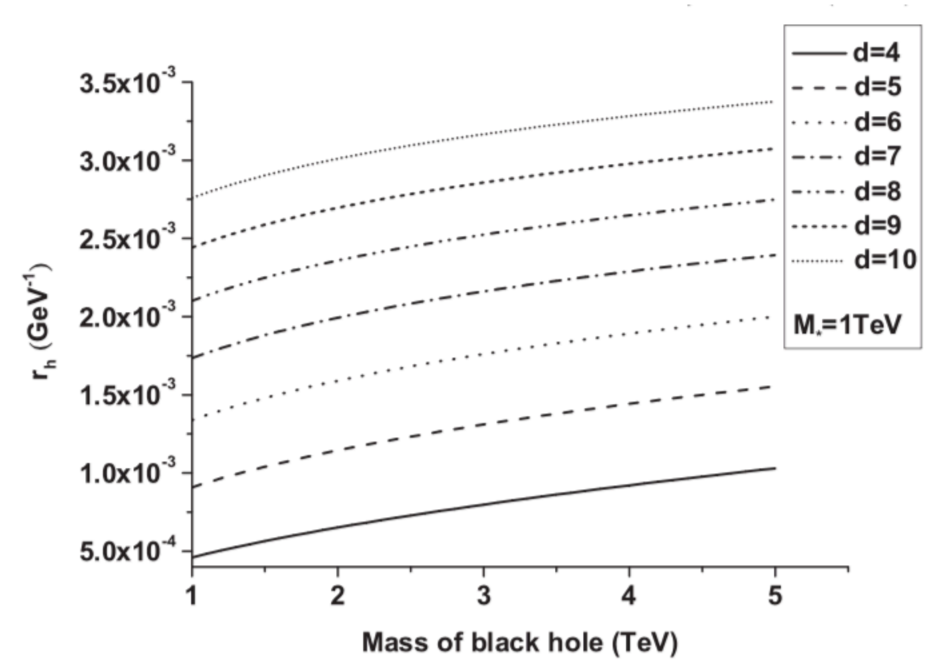


$$r_s^{(d)} = \frac{k(d)}{M_*}\left[\frac{E_{CM}}{M_*}\right]^{1/(d-2)}.$$

(d): # spatial dims = 3+n

k(d): some number

M_*: real Planck scale



Contrast with regular 3+1 dim BH

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

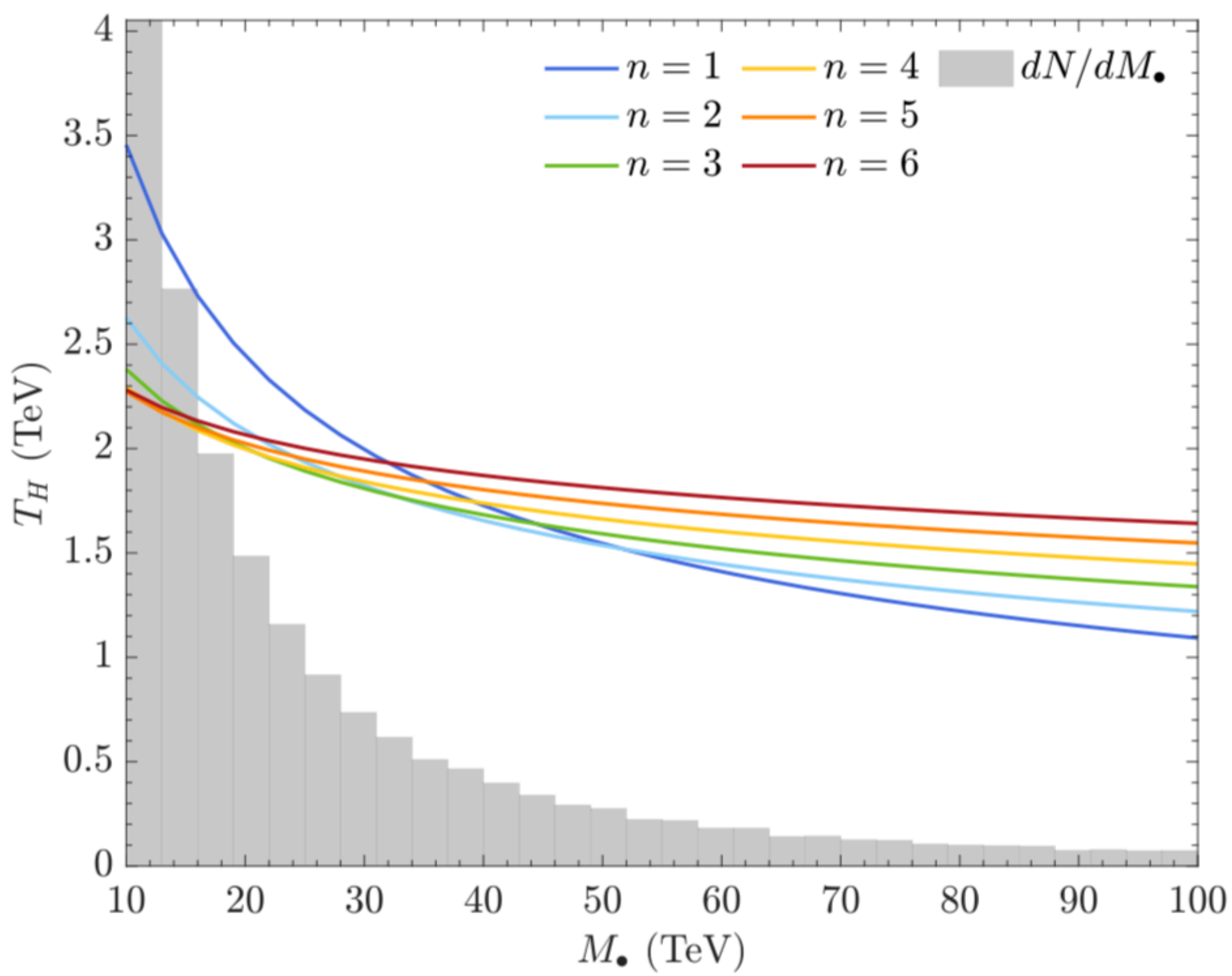
PDFs

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

Black hole evaporation

These things do not live very long: $T_H = \dfrac{d-2}{r_h}$

TeV black hole has a ~ TeV Hawking Temperature

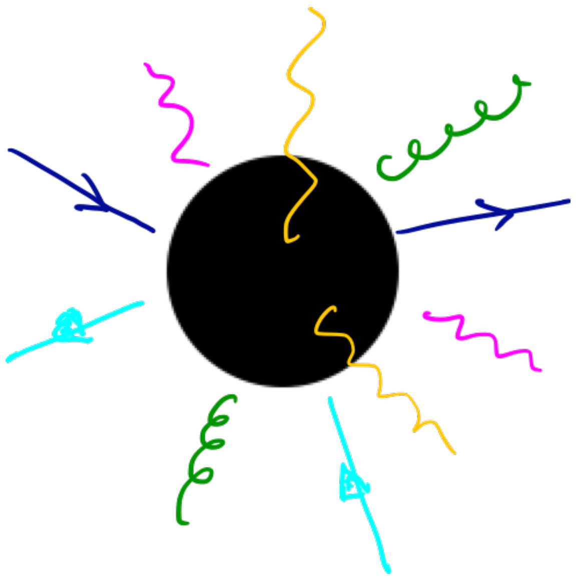


So a small BH

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

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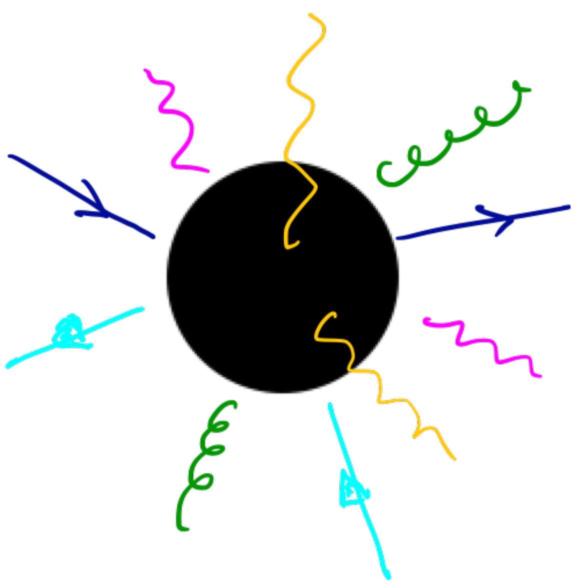

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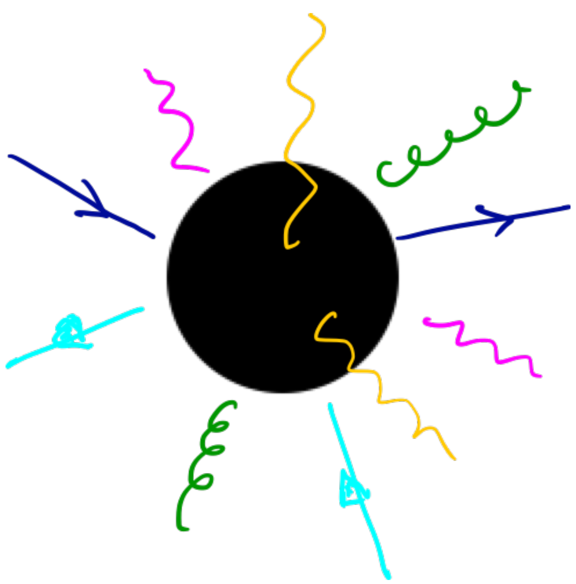

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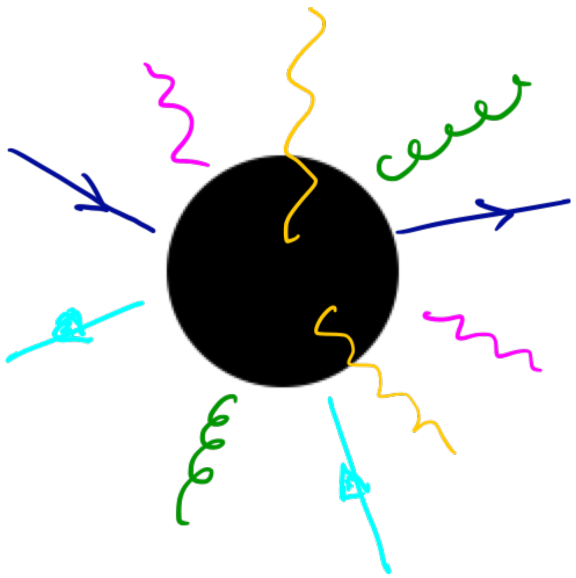

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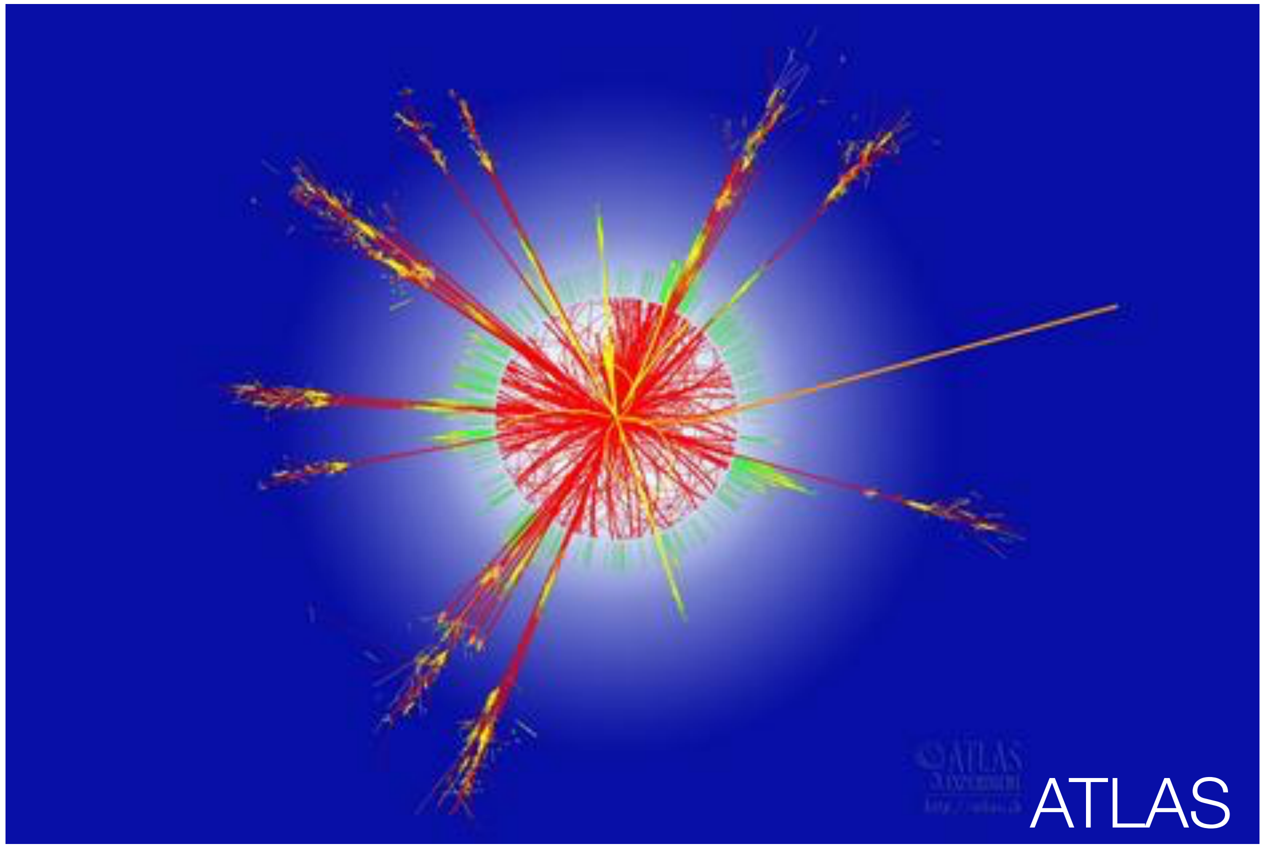
Distinct signature at colliders: high-multiplicity state, with many hadronic jets + some missing momentum

Collider searches

extra dimensions | 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	

Mack & McNees 1809.05089



Limited by CM energy

Collider searches

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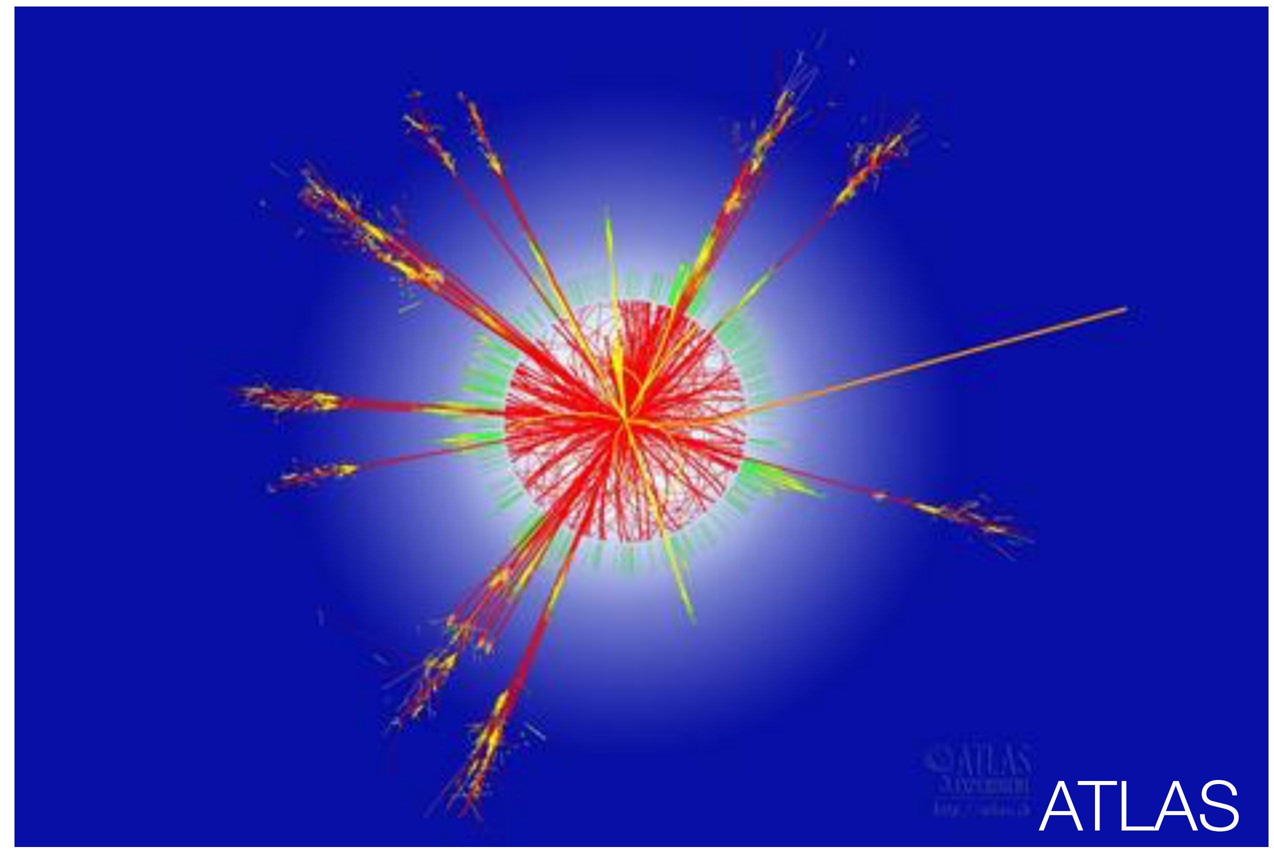
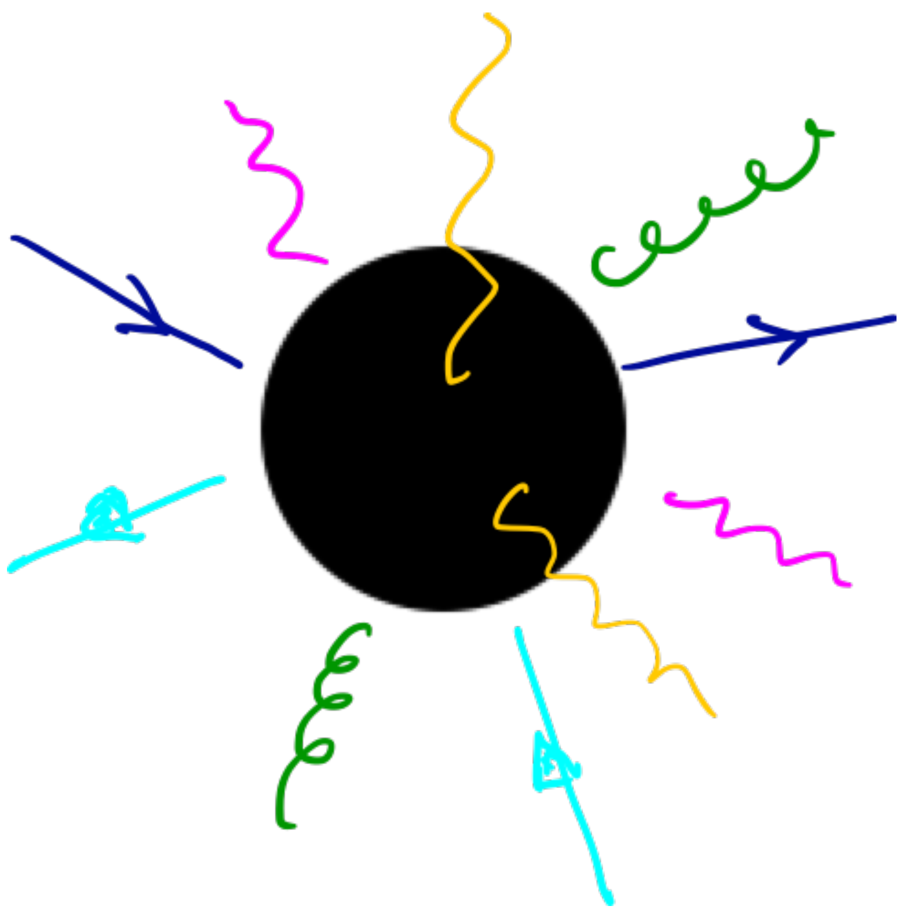


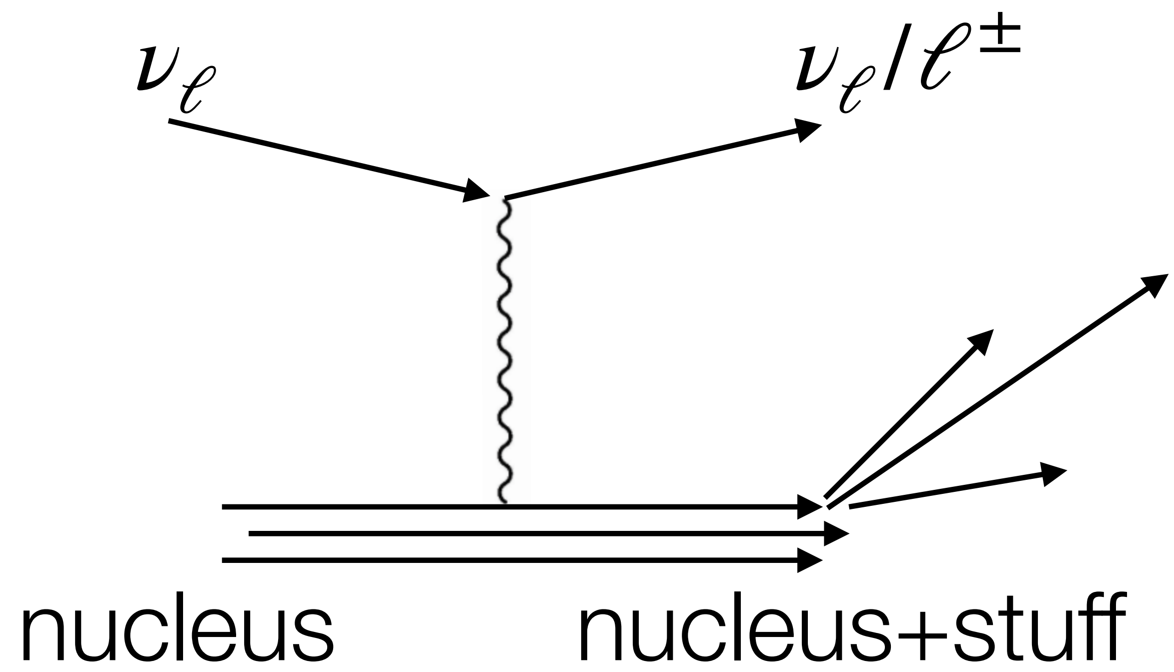
Limited by CM energy

We could wait for a 100 TeV collider…
or let the cosmos do it for us!

2. Black holes at IceCube (and beyond)

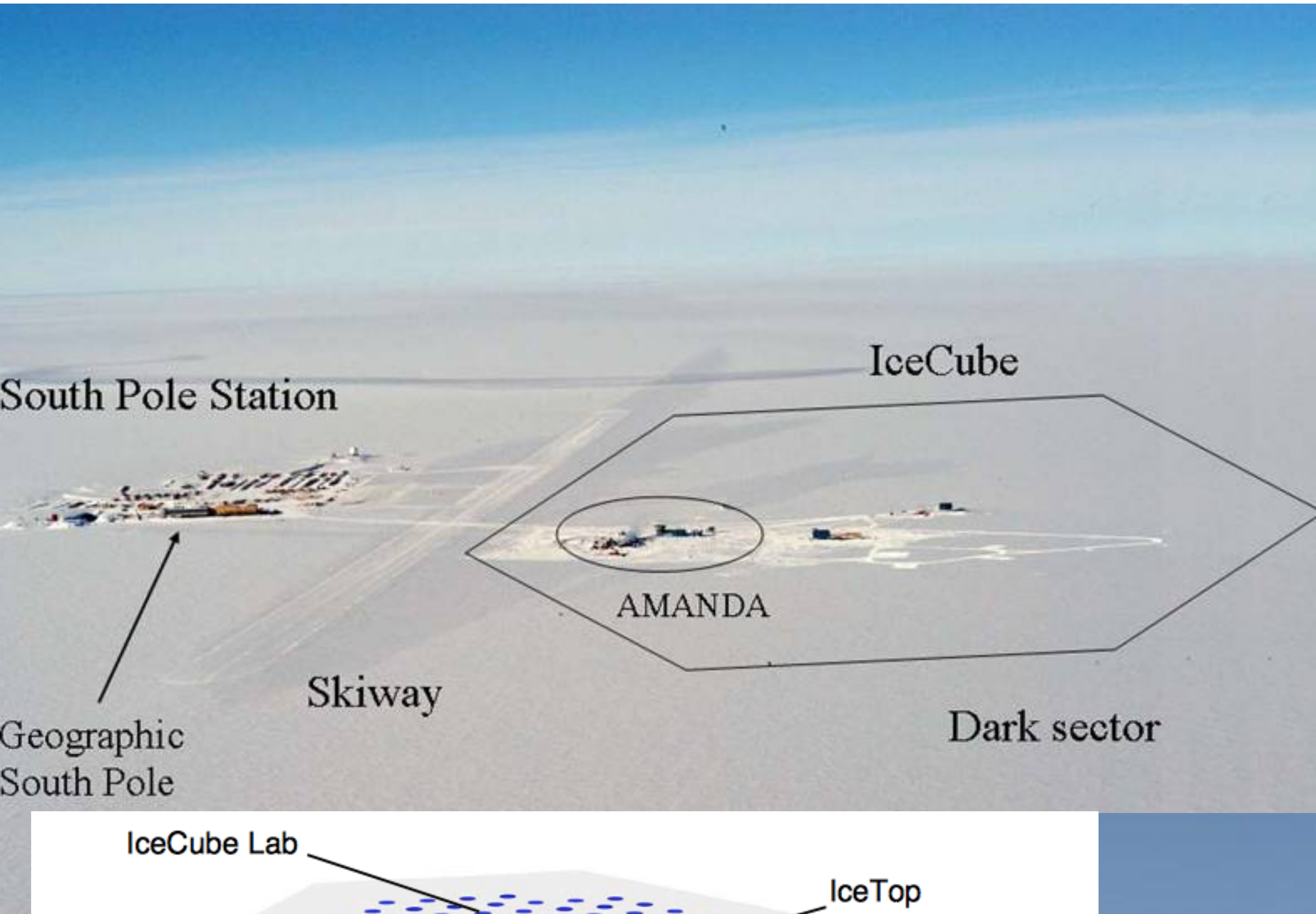
The main idea

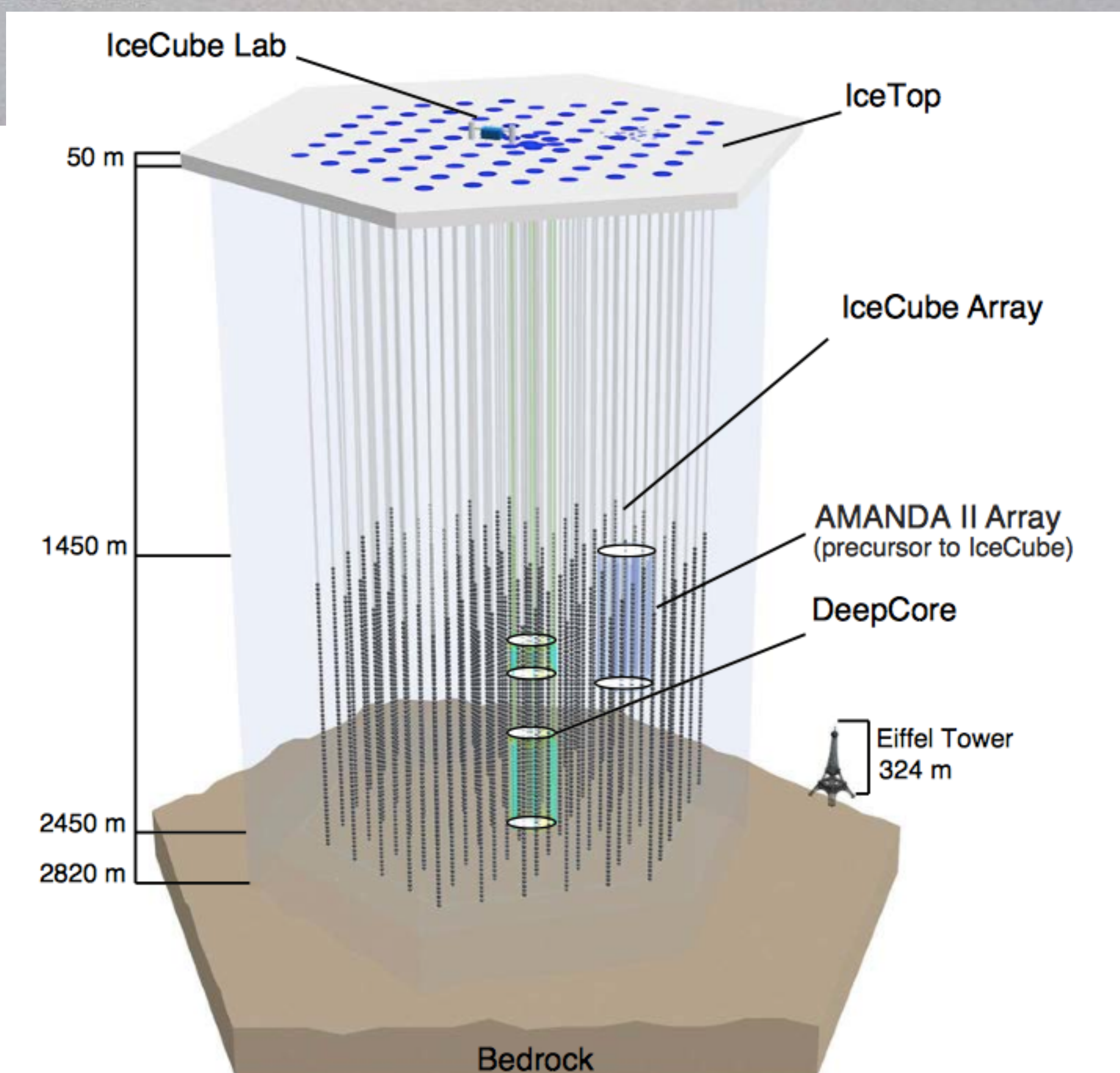


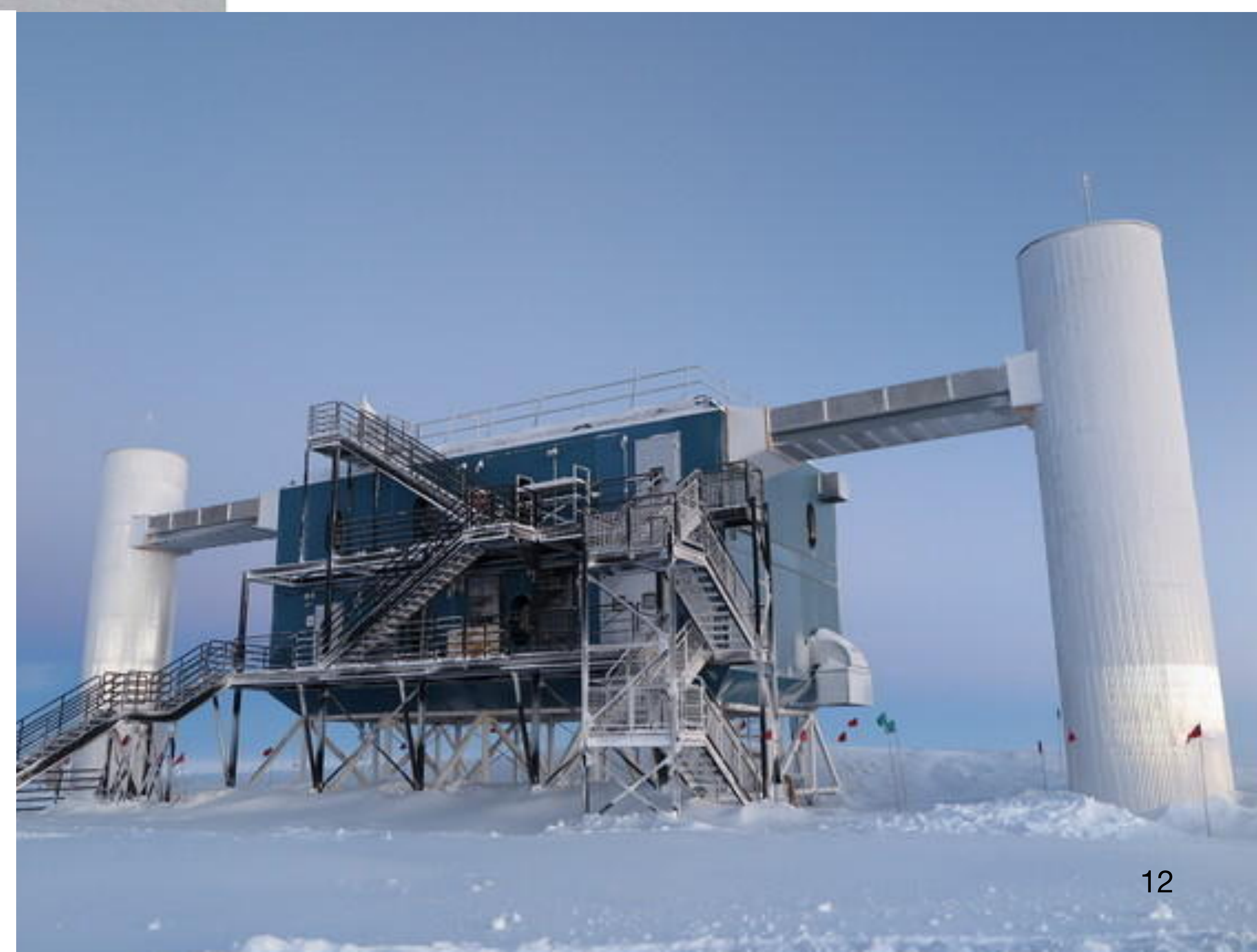


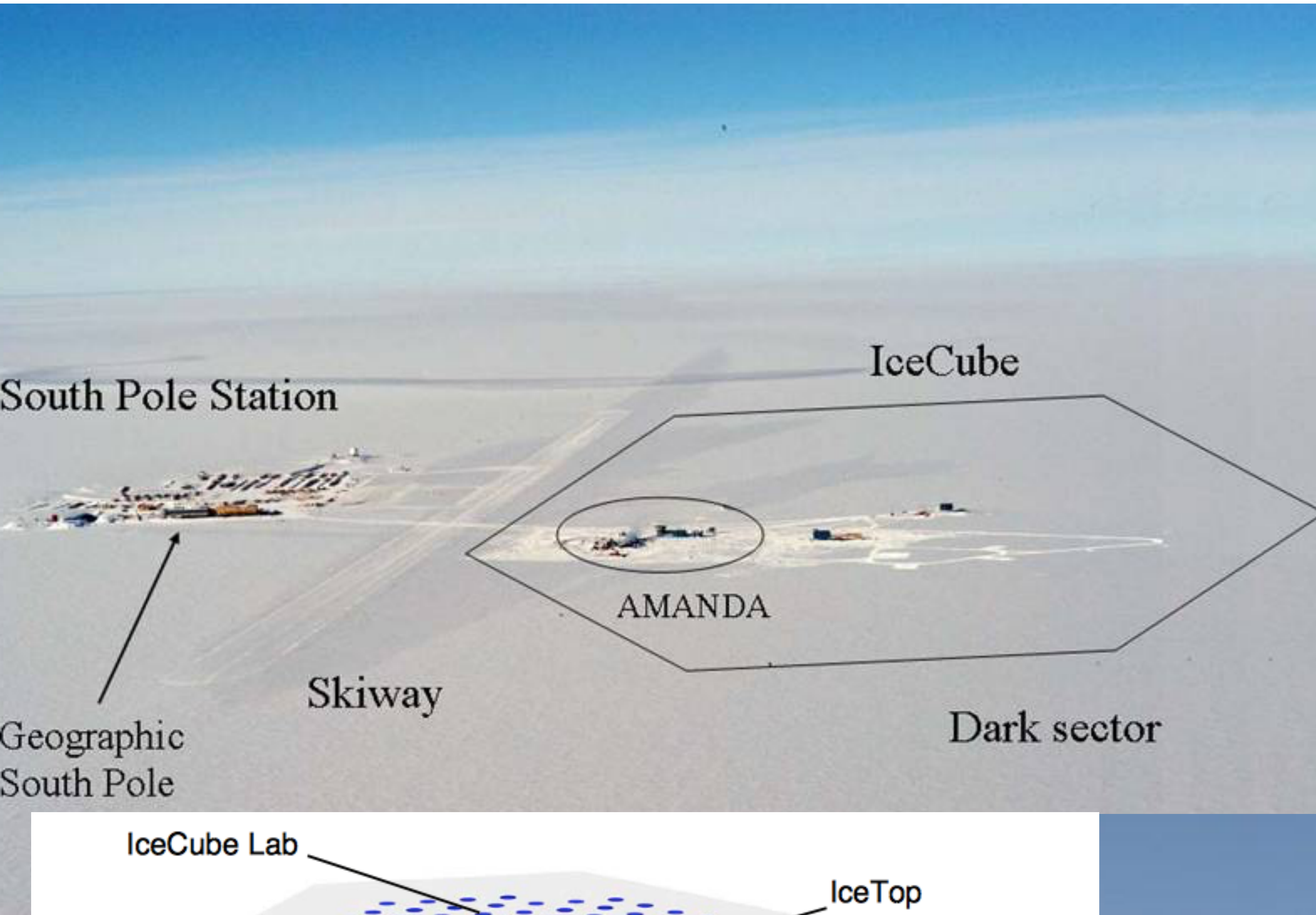
Black hole evaporation:
Mostly hadronic

Electroweak event:
Mostly *not* hadronic

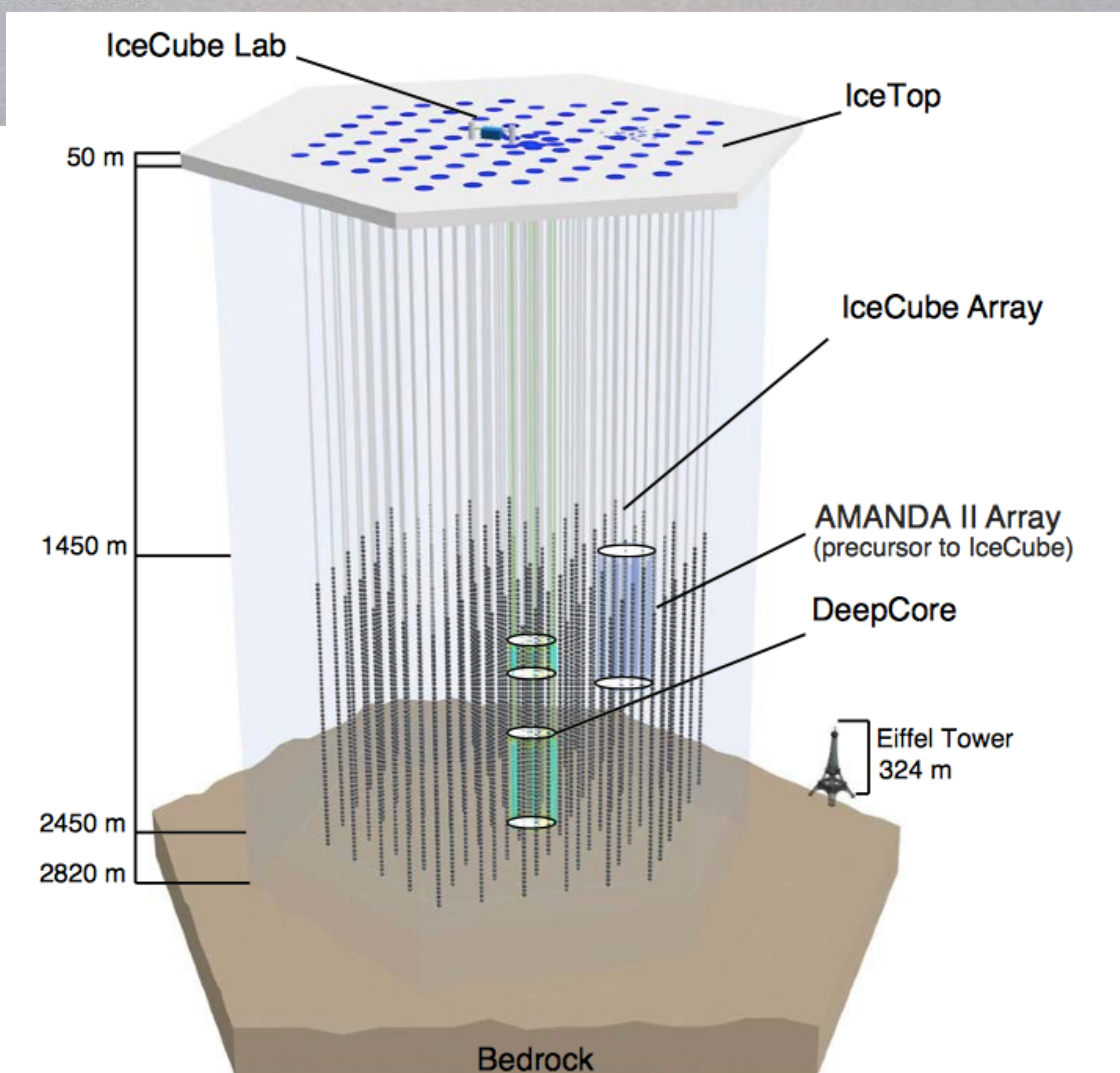

IceCube
South Pole Station
AMANDA
Skiway
Dark sector
Geographic
South Pole

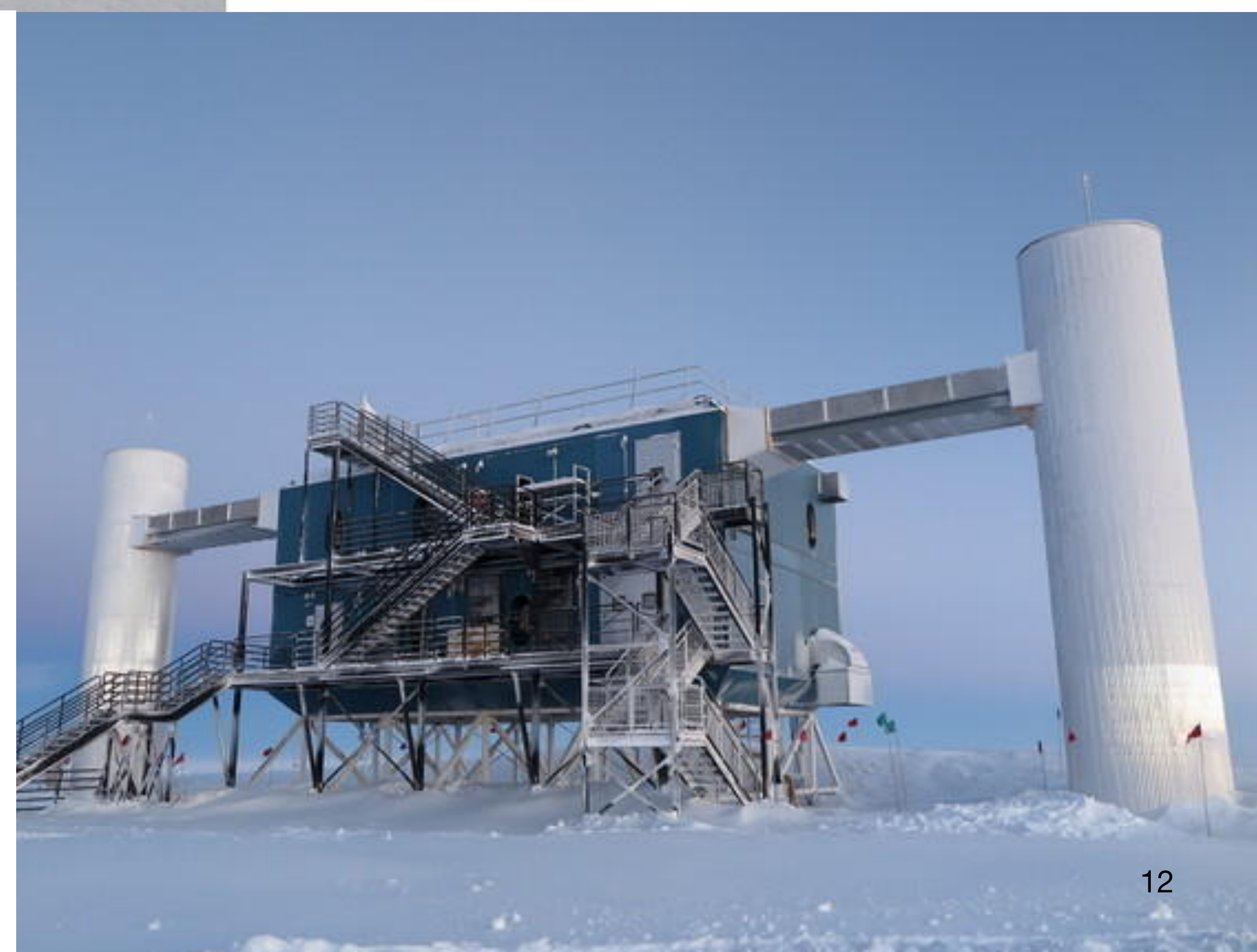

IceCube Lab
IceTop
50 m
IceCube Array
1450 m
AMANDA II Array
(precursor to IceCube)
DeepCore
Eiffel Tower
324 m
2450 m
2820 m
Bedrock



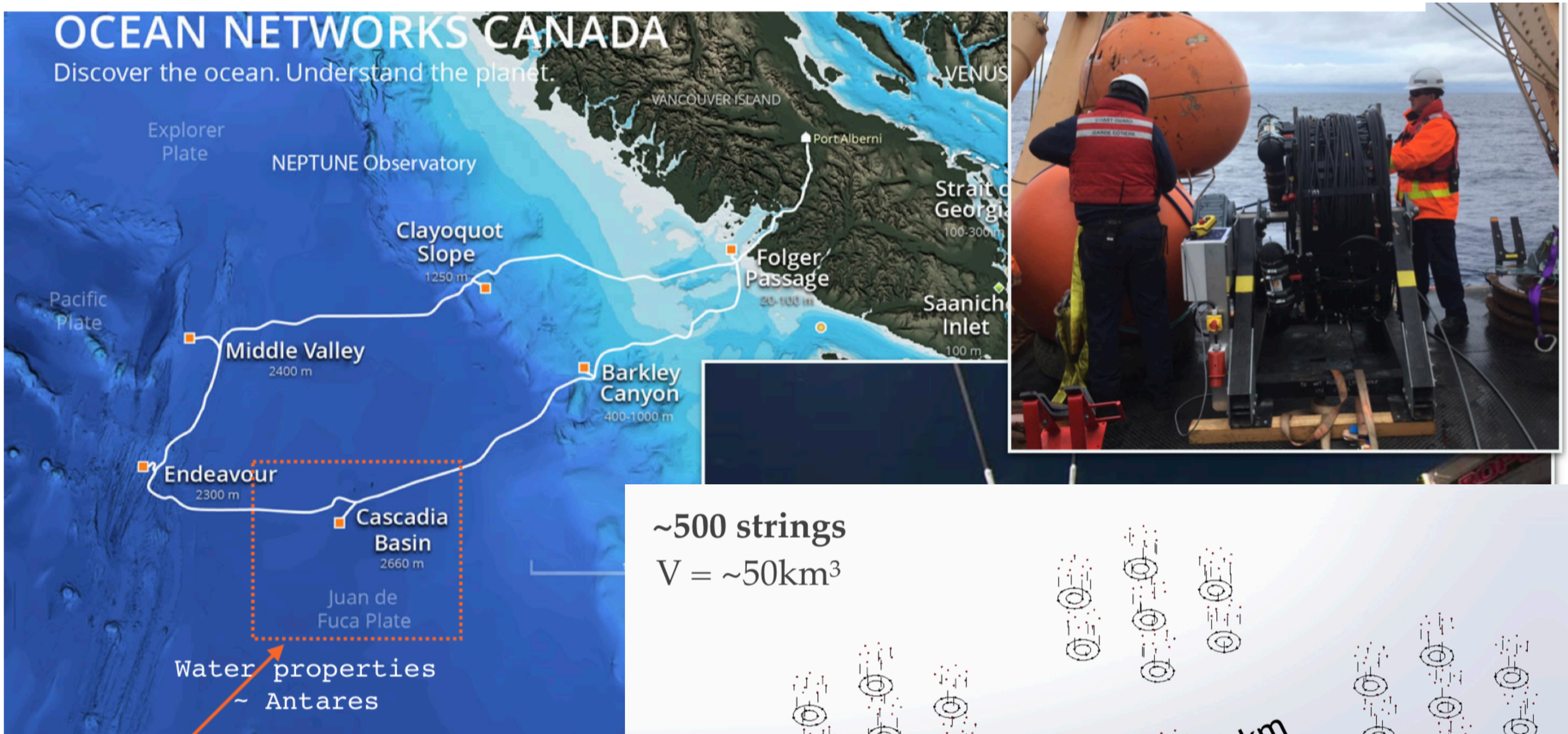


FrozenWaterHexagon
Continental Neutrino Observatory



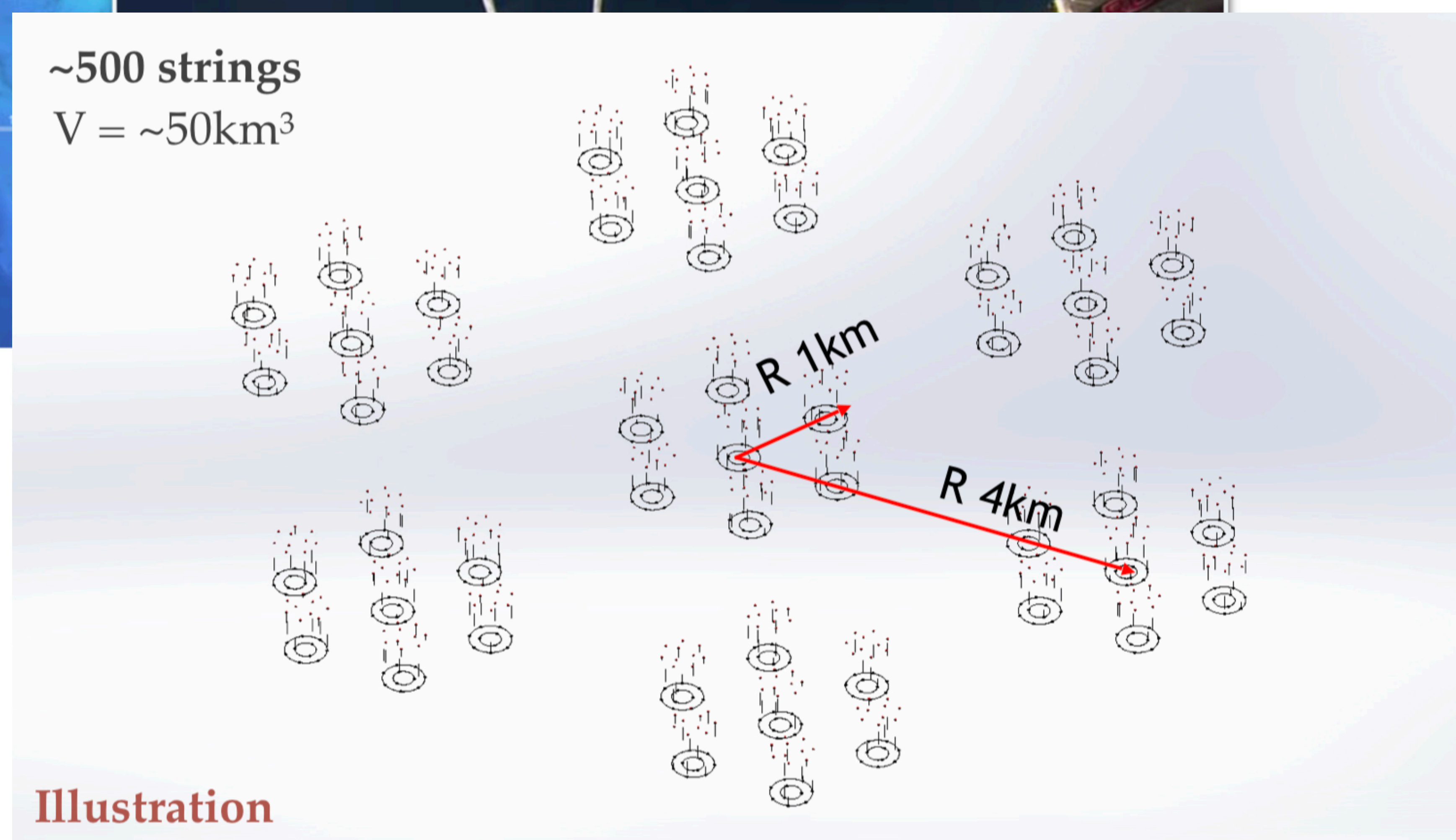


Pacific Ocean Neutrino Explorer (PONE)



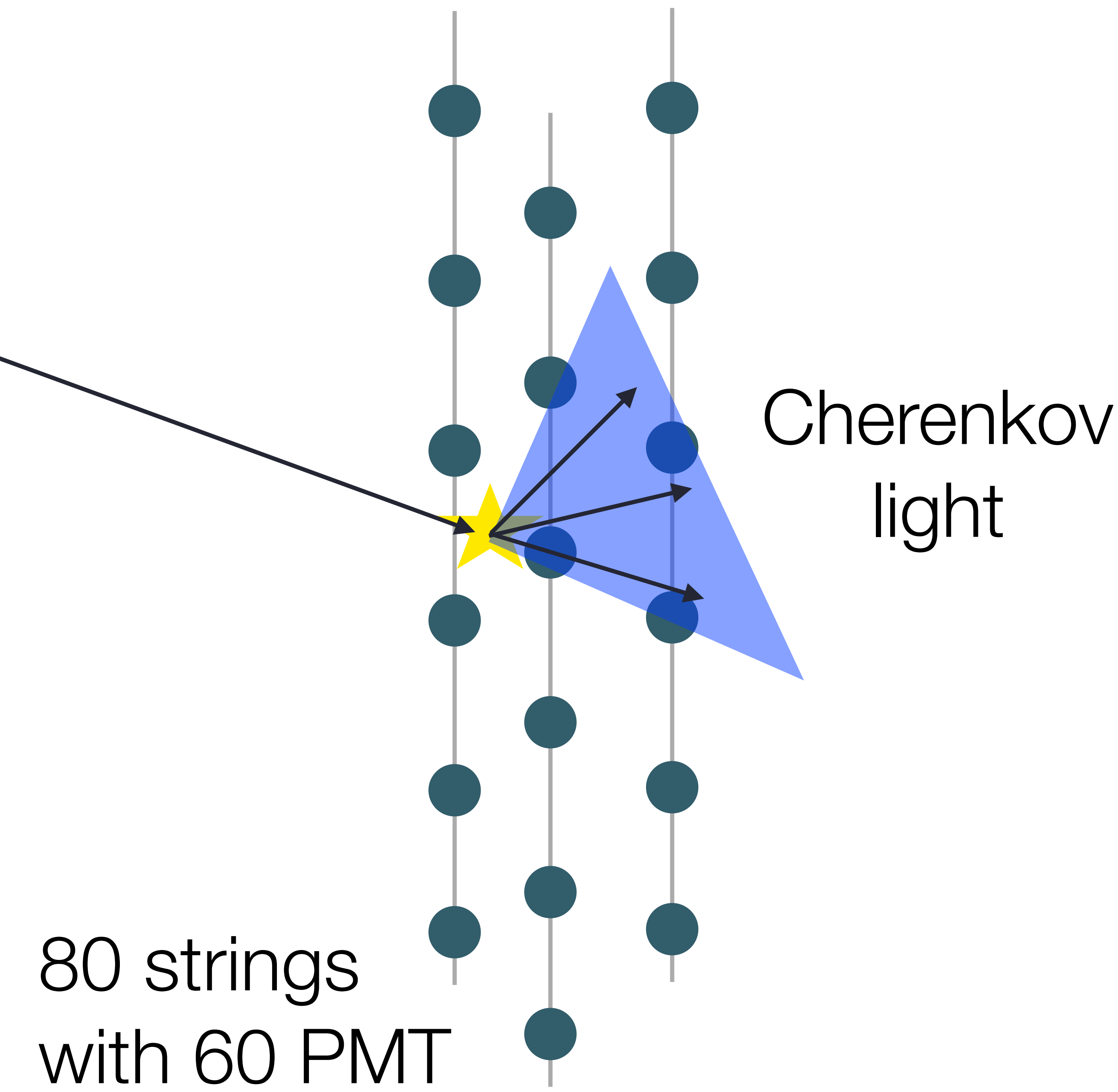
Water properties ~ Antares

volume available and (partly) cabled

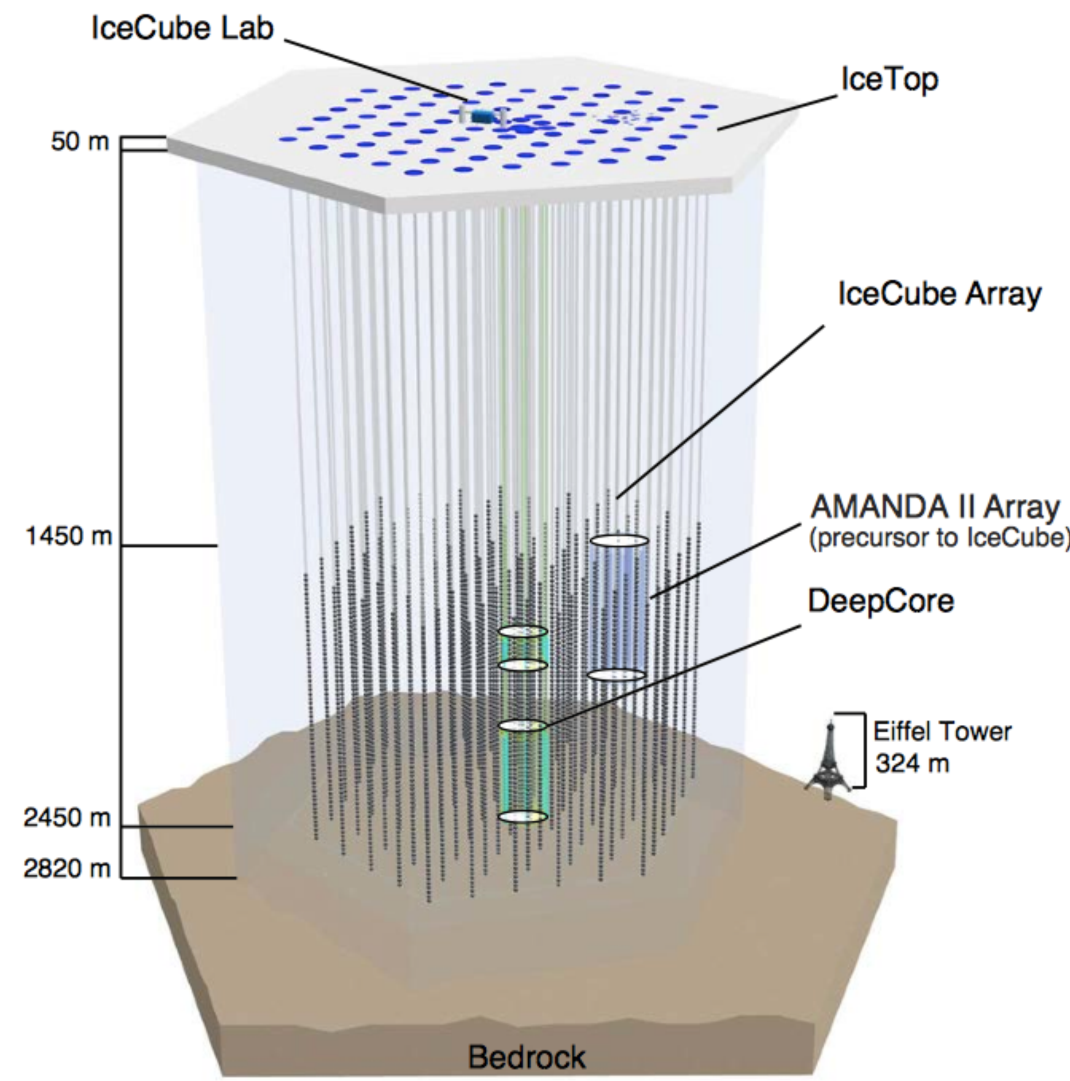


Resconi

“plum pudding” configuration: PMTs inside the transparent detector



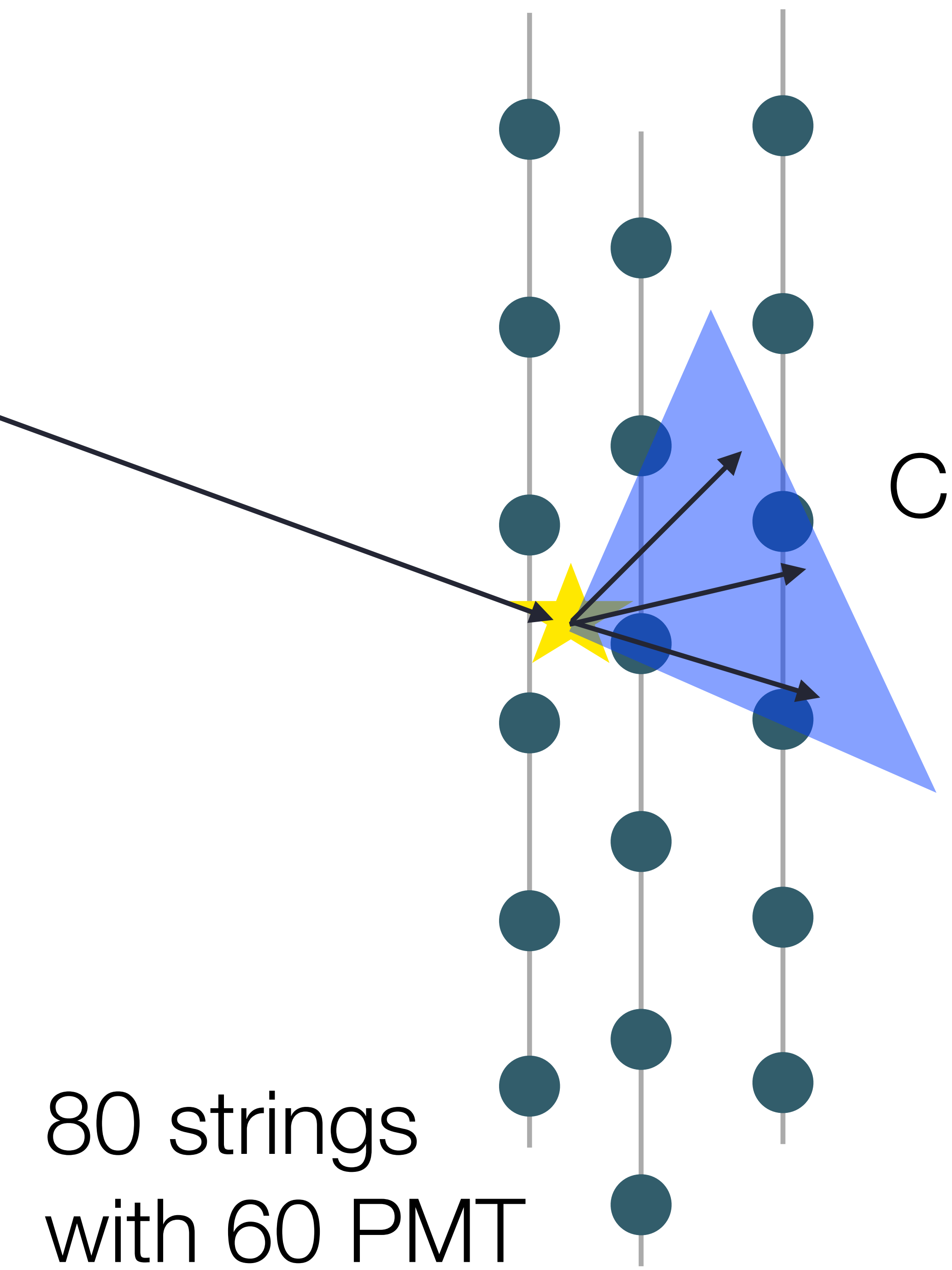
80 strings with 60 PMT ‘DOMs’ each



IceCube Collaboration

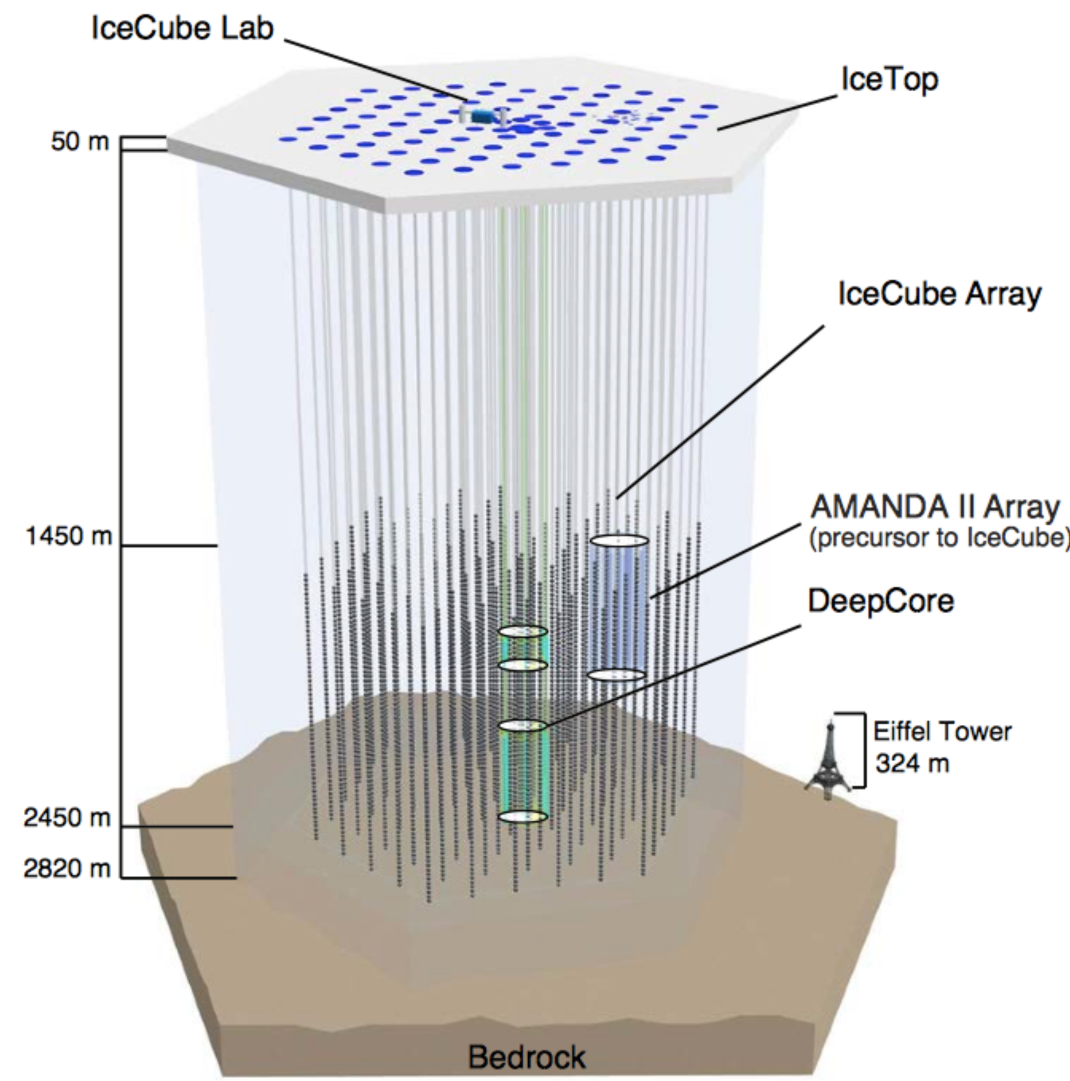
“plum pudding” configuration:
PMTs inside the transparent detector

FrozenWaterHexagon
Continental Neutrino Observatory



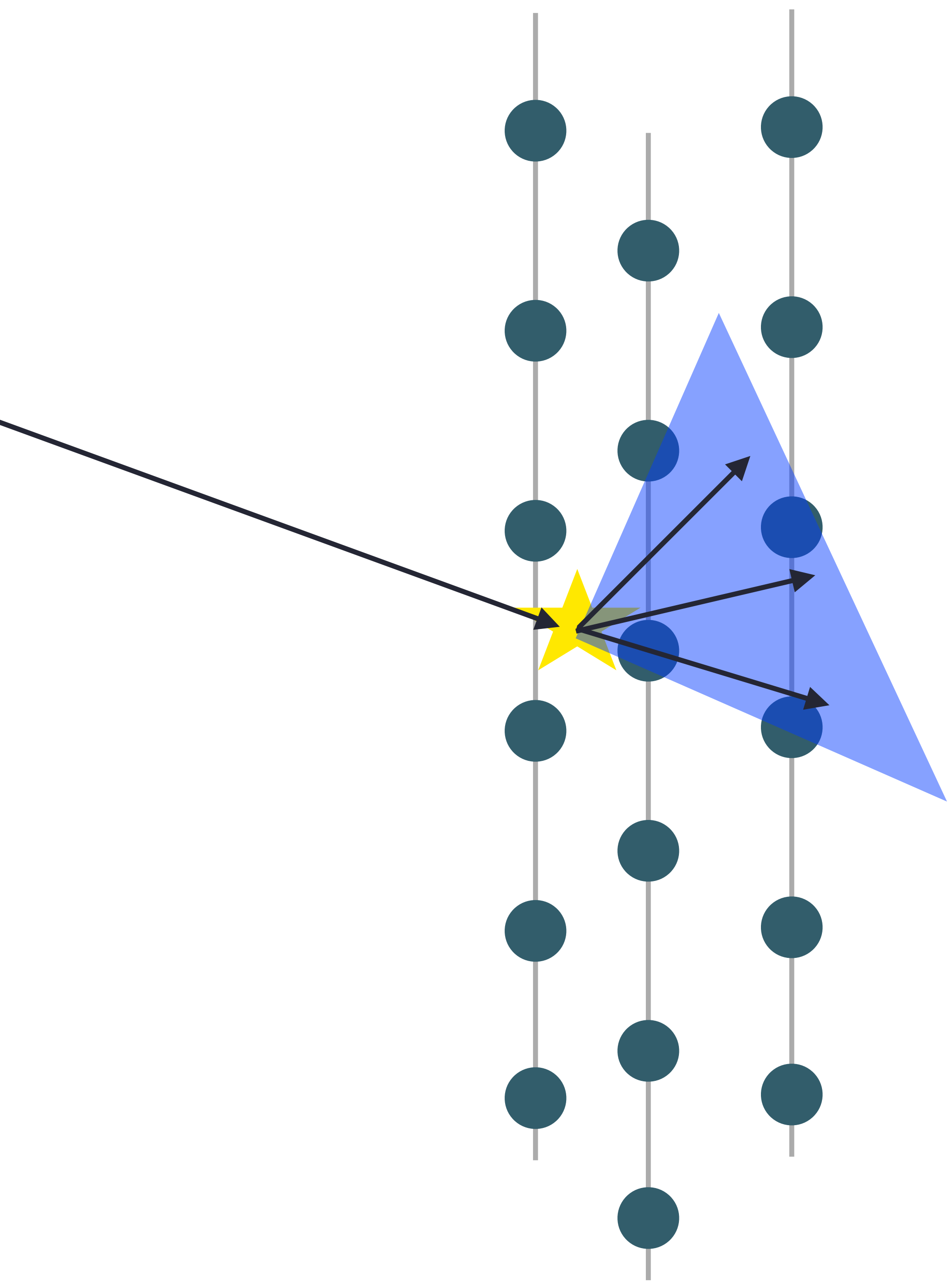
Cherenkov light

80 strings with 60 PMT ‘DOMs’ each



IceCube Collaboration

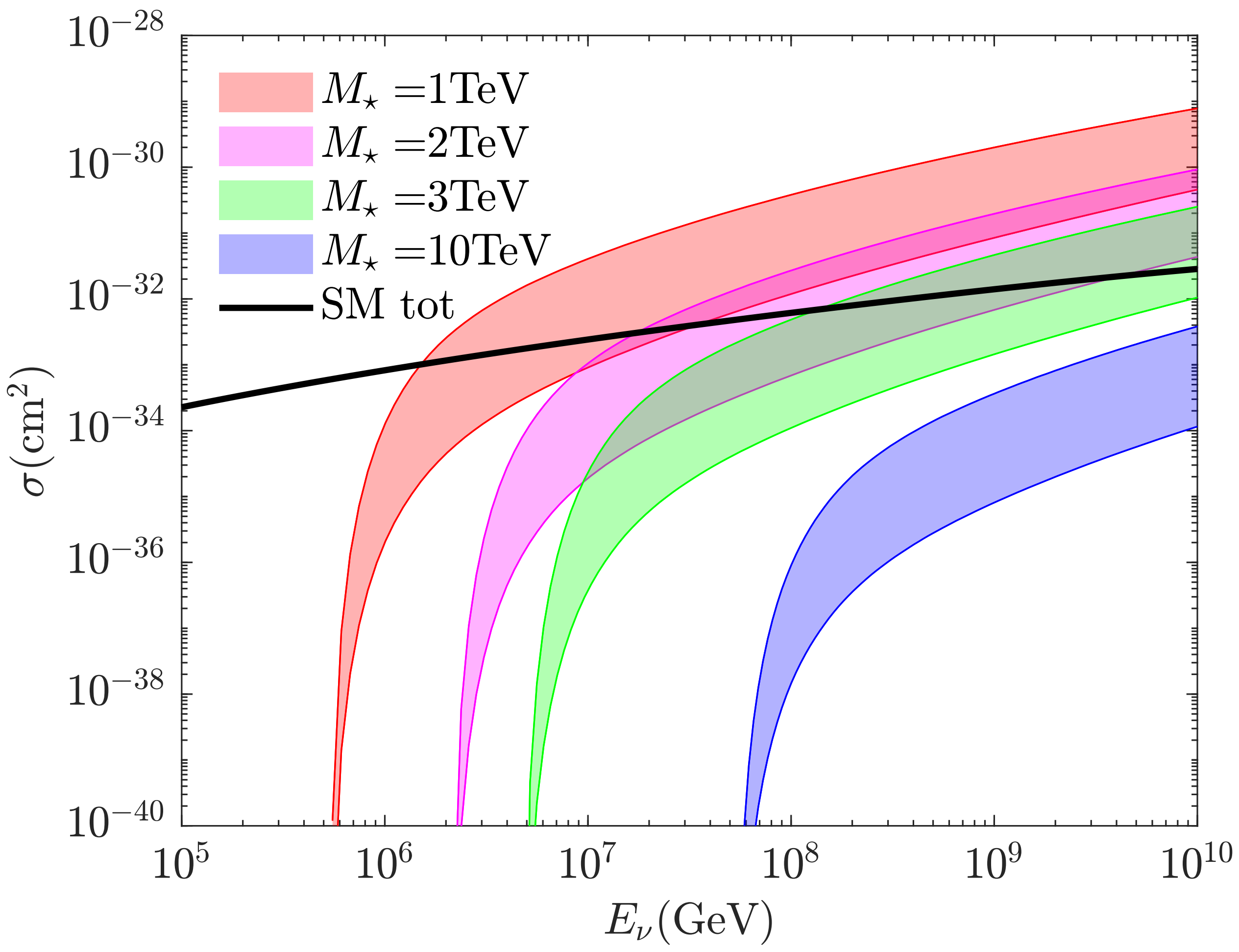
Black holes from neutrinos



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

$$E_{CM} = \sqrt{2E_\nu m_p}$$

TeV CM energy requires PeV neutrinos



6 LEDs

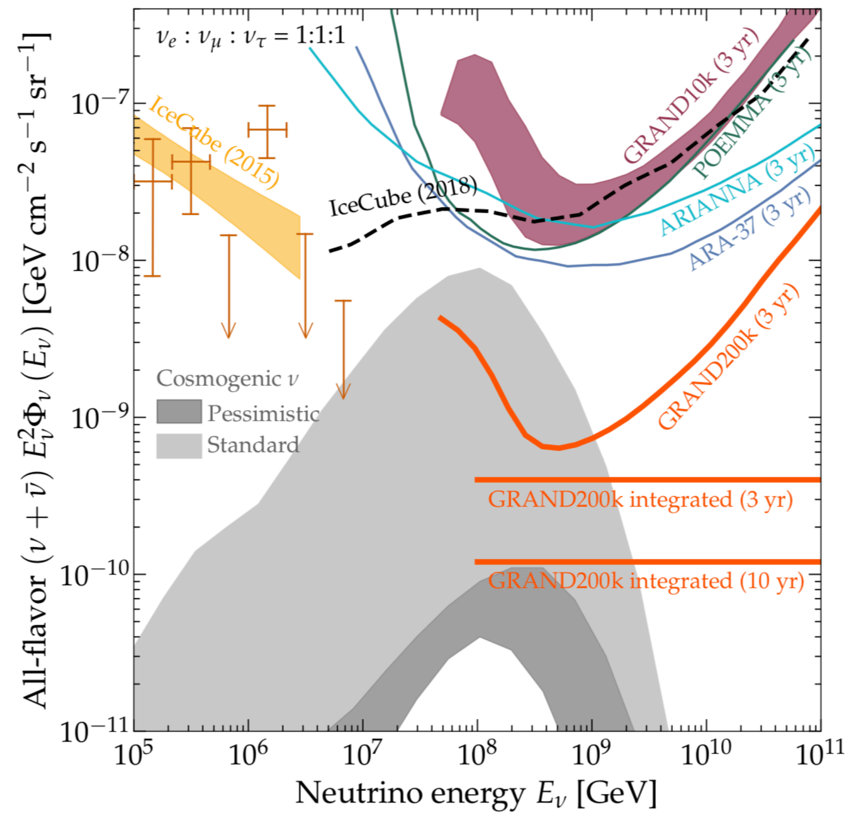
1 LED

Event rates

IceCube has seen ~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



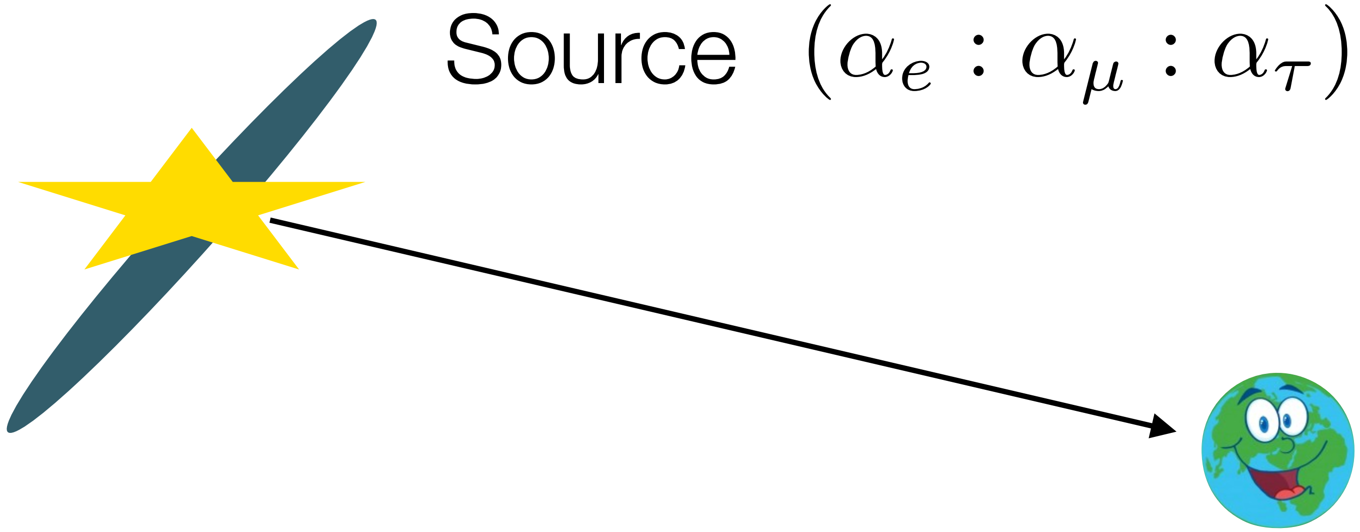
Planned experiments that we have in mind:

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

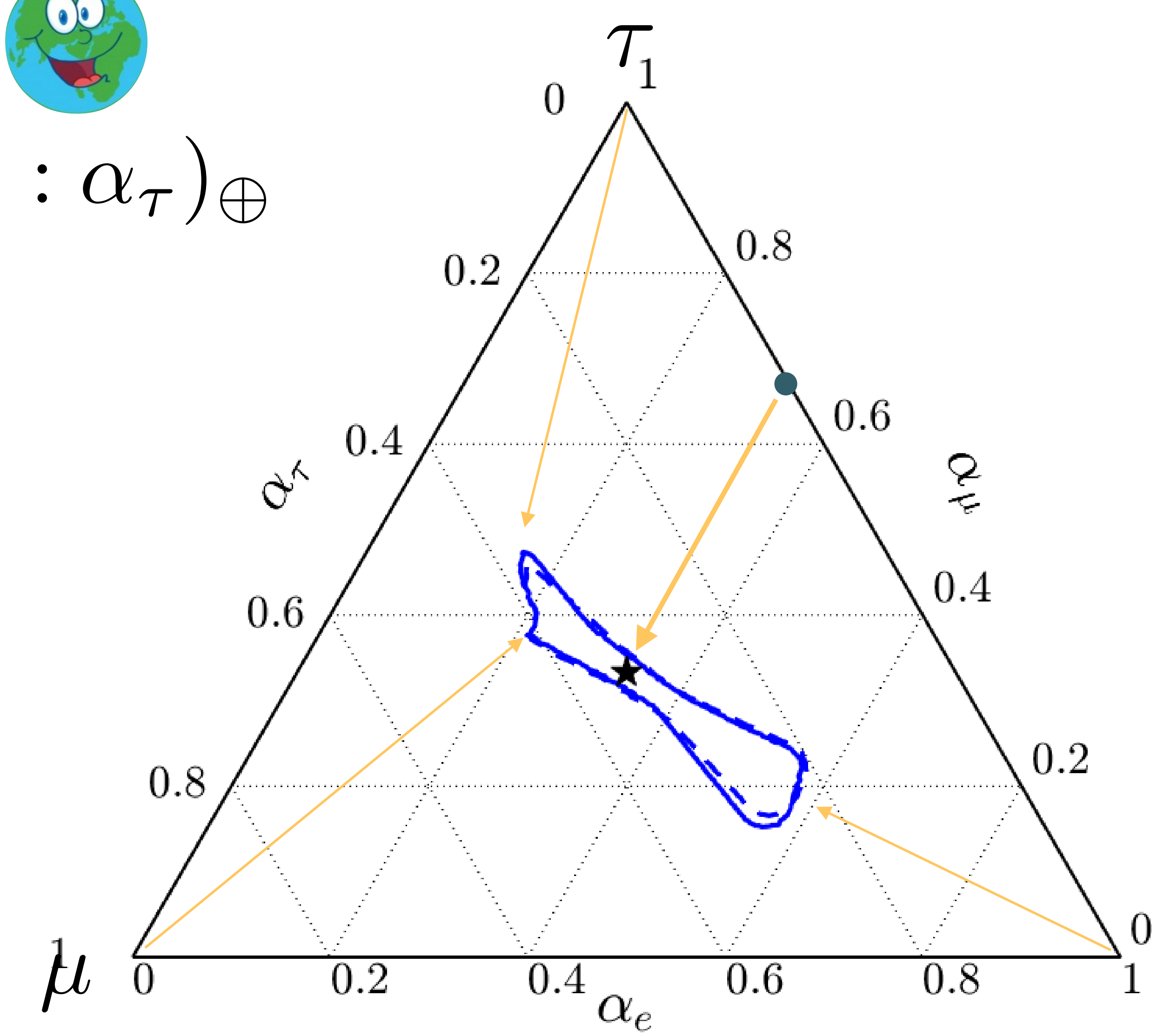
Radio arrays (ARA, ARIANA) have the capacity to reach large effective volumes, but events are harder to characterize

Travel to earth: flavour mixing

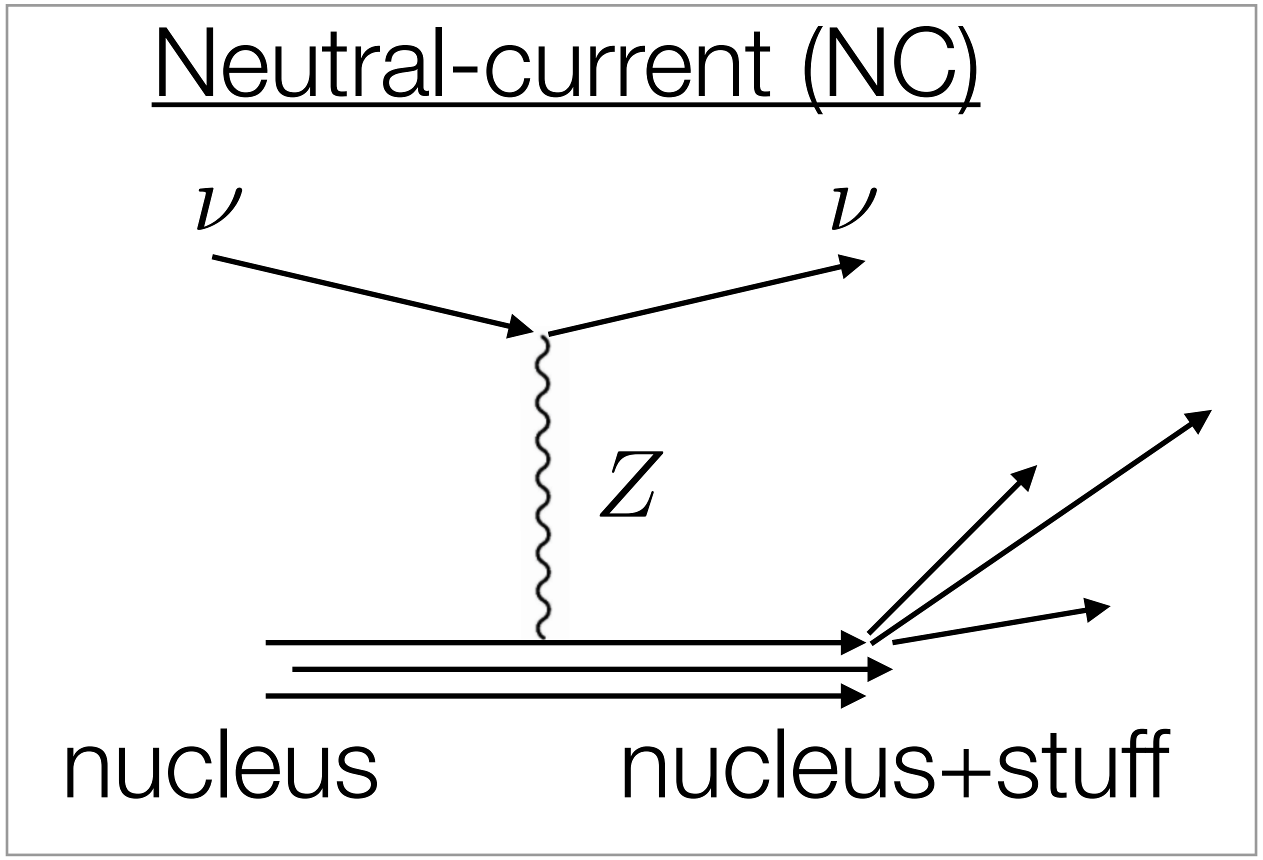
Source $(\alpha_e : \alpha_\mu : \alpha_\tau)_S$



$(\alpha_e : \alpha_\mu : \alpha_\tau)_\oplus$

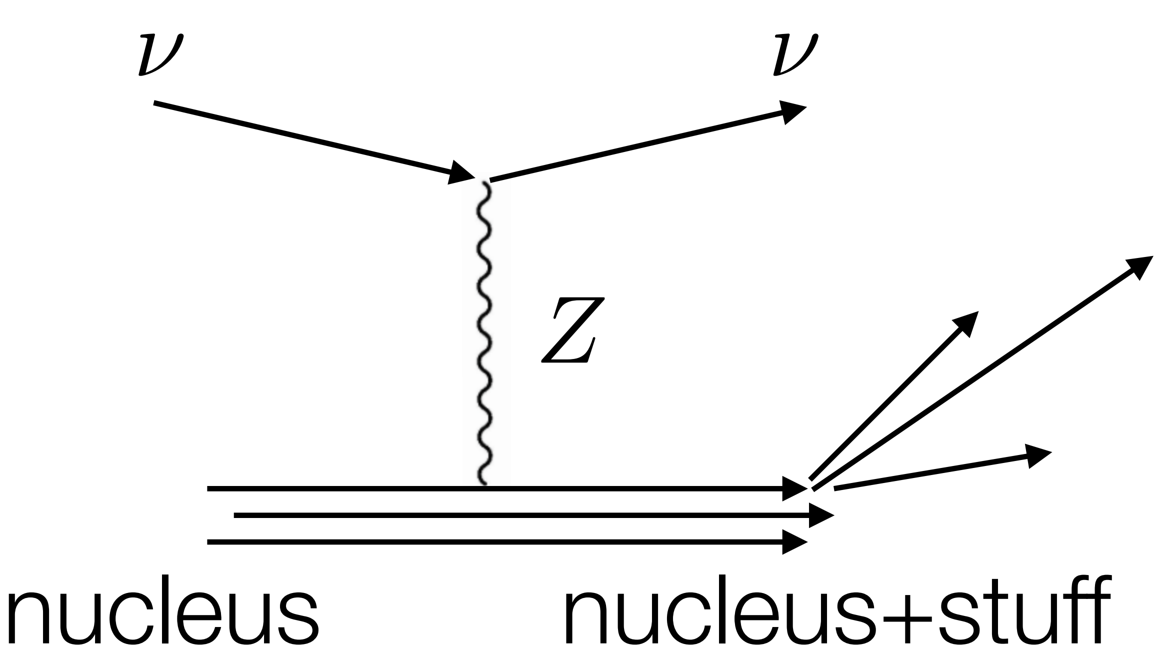


Standard neutrino-nucleus interactions

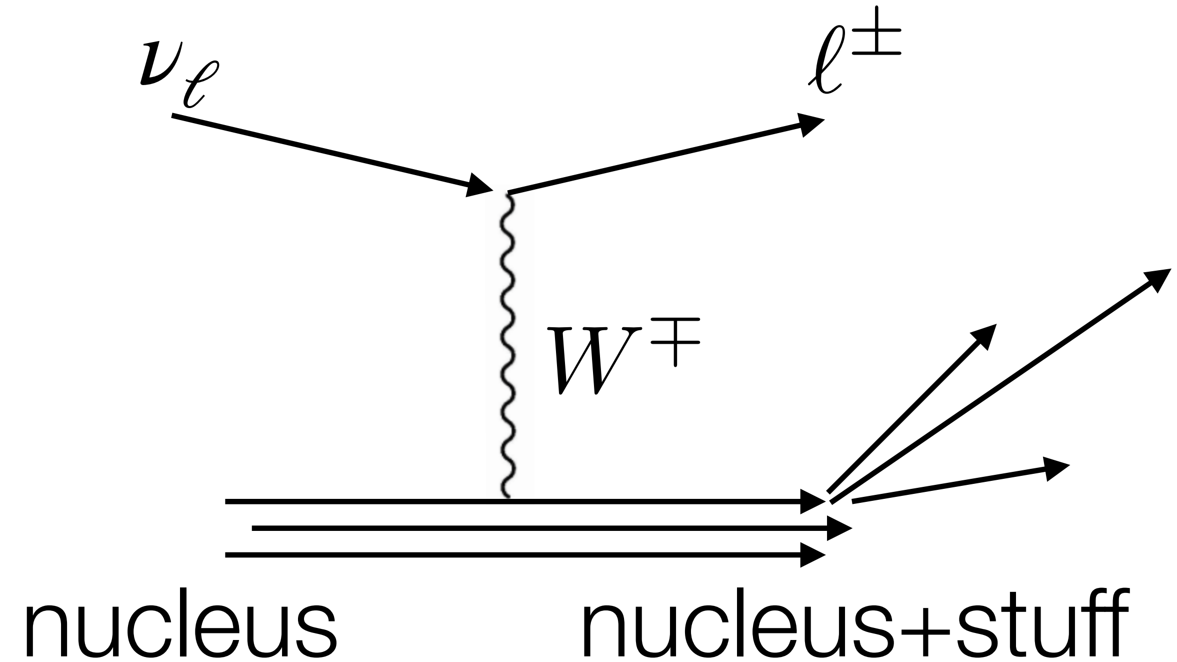


Standard neutrino-nucleus interactions

Neutral-current (NC)



Charged-current (CC)



Final-state lepton:

electron: deposits E

muon: can travel ~ km

tau : If HE enough, can travel then decay

Standard neutrino-nucleus interactions

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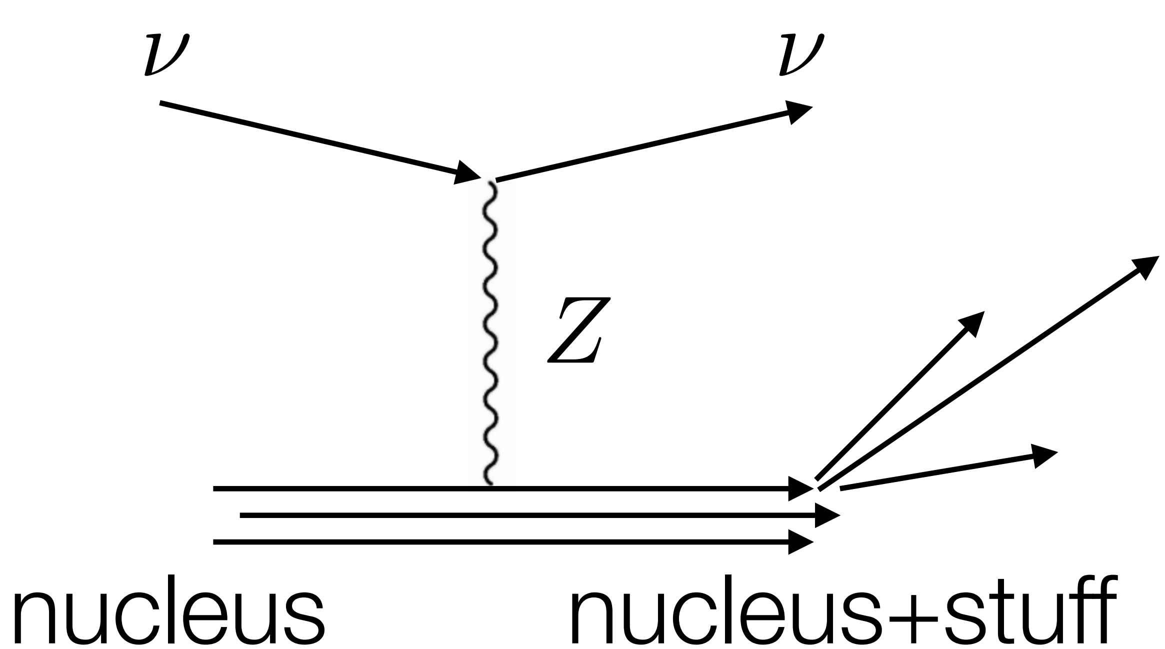
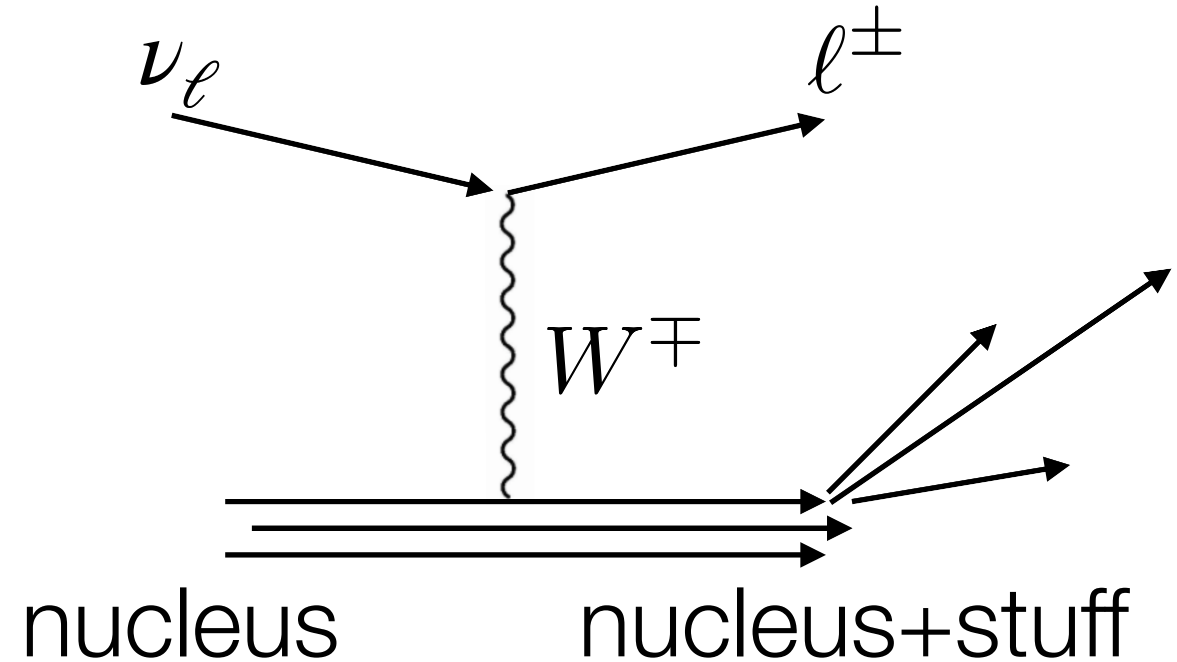


electron

Charged-current (CC)



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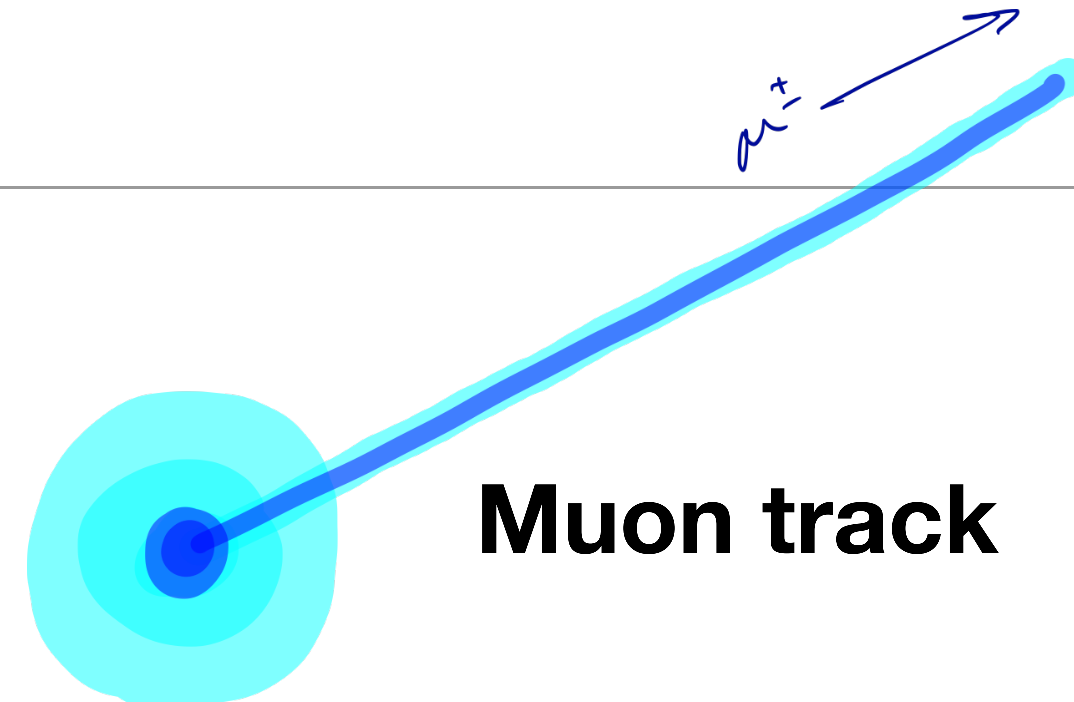
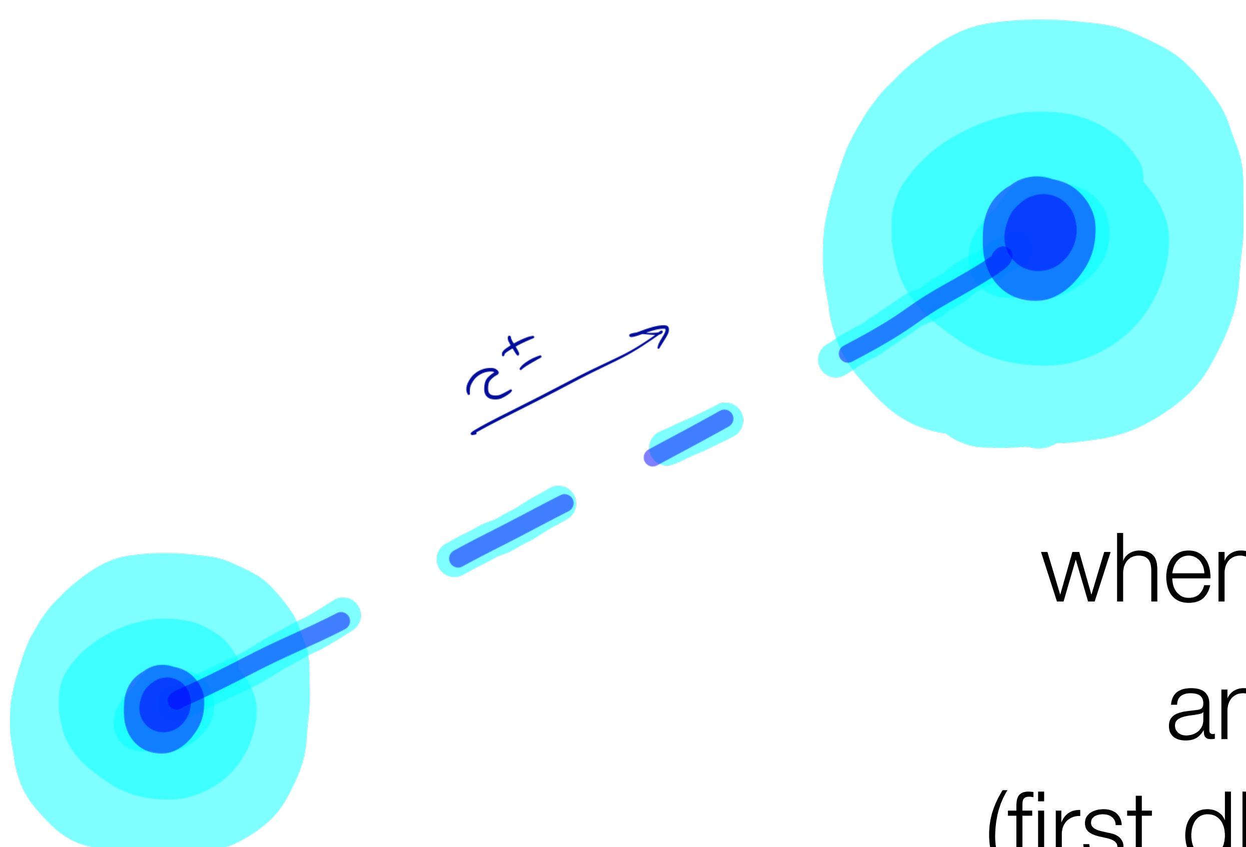
Event topology

Shower
(electronic
or hadronic)

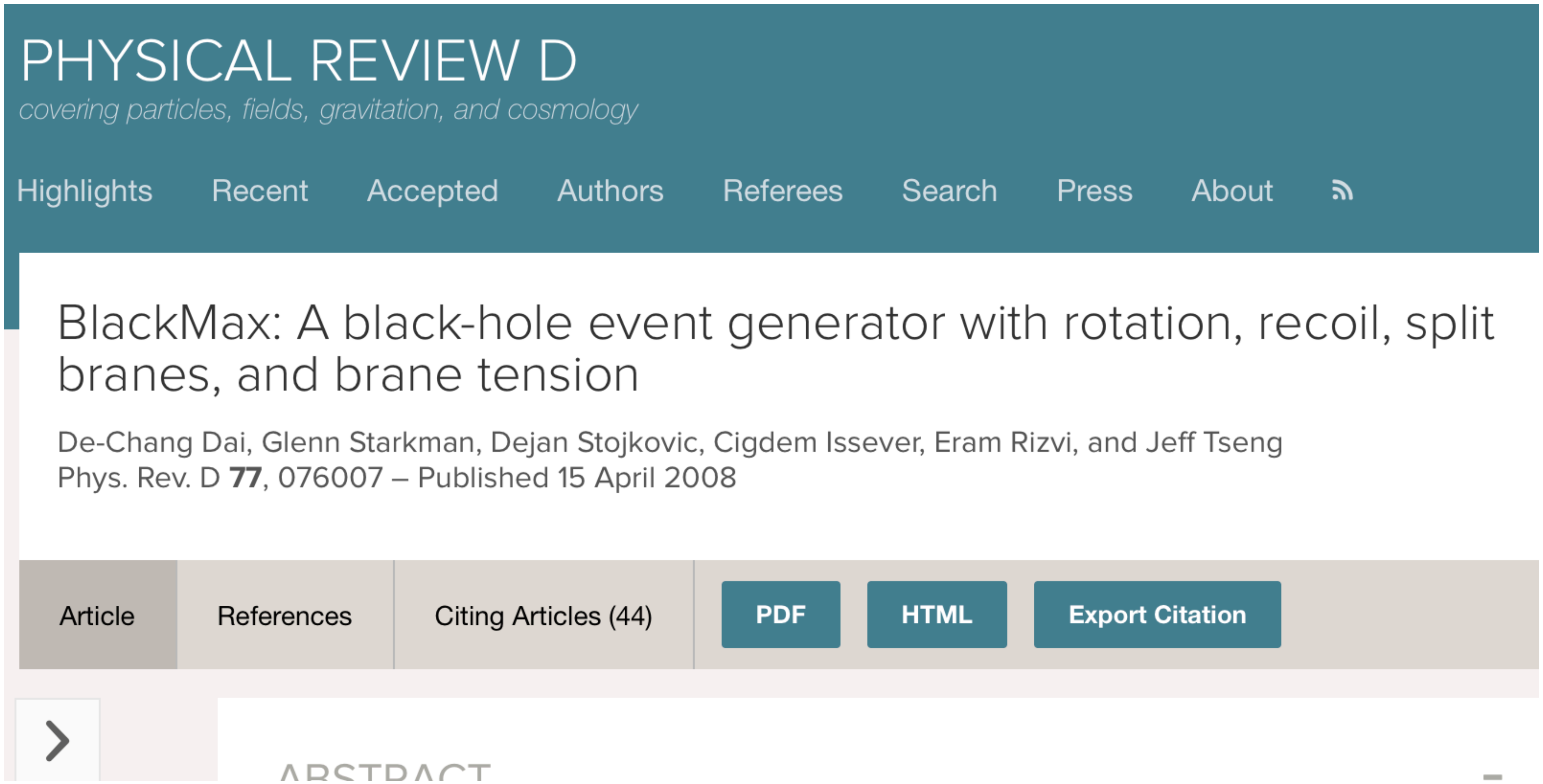


Muon track

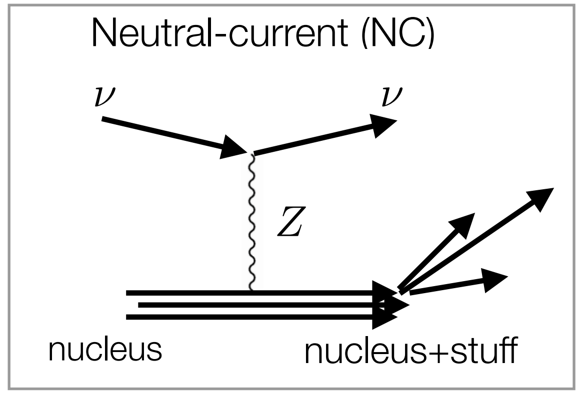
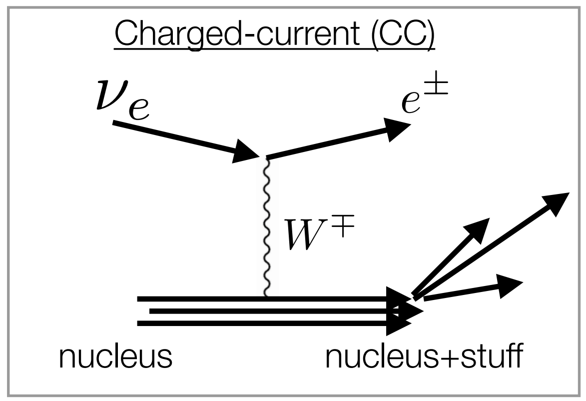
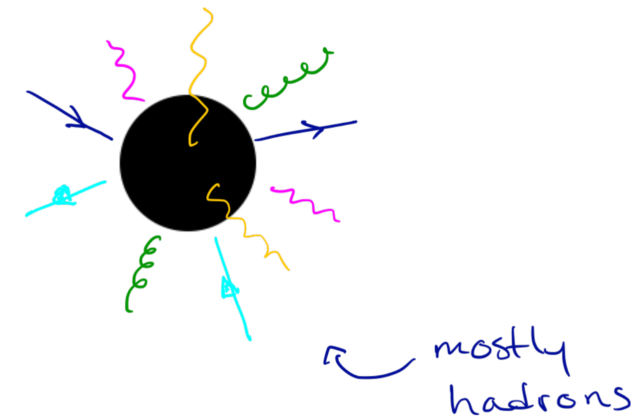
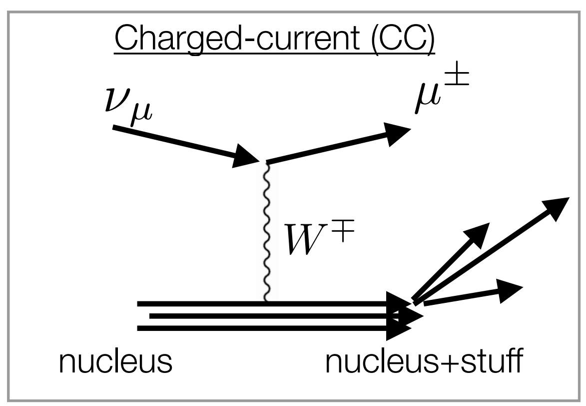
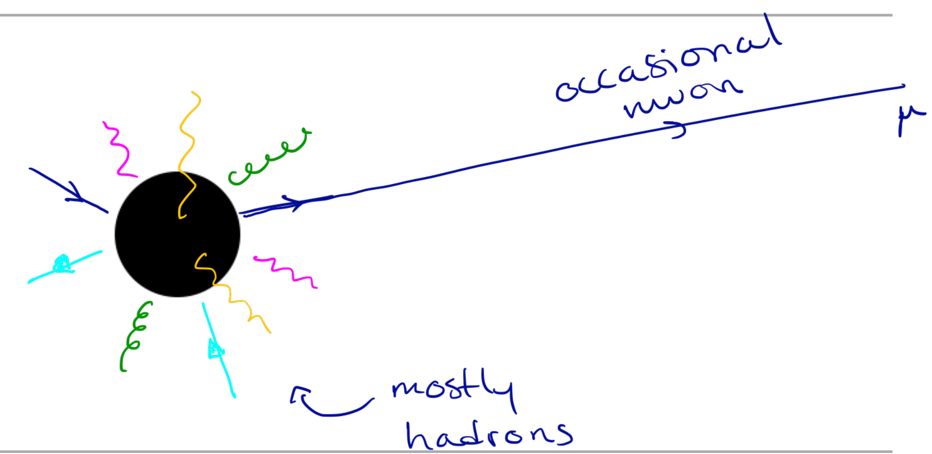
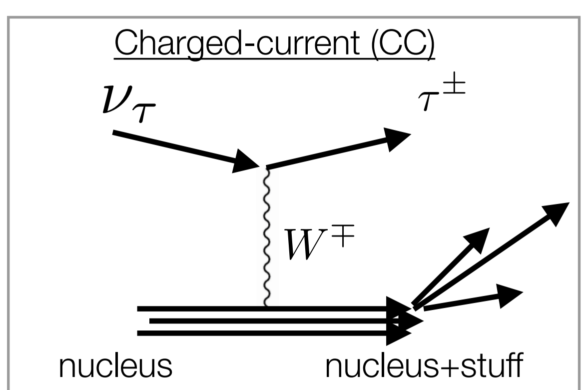
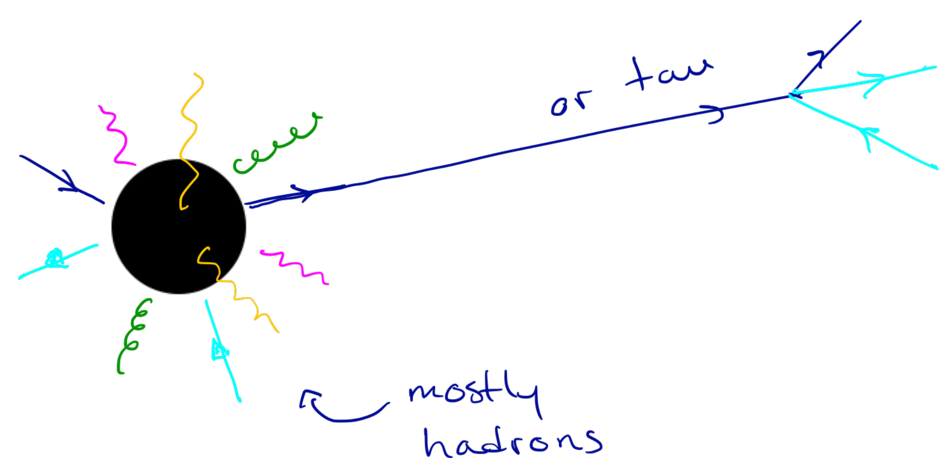


Double bang:
when tau lepton travels far enough
and decays to $e^{\pm}$ or hadrons
(first db events reported 1908.05506)

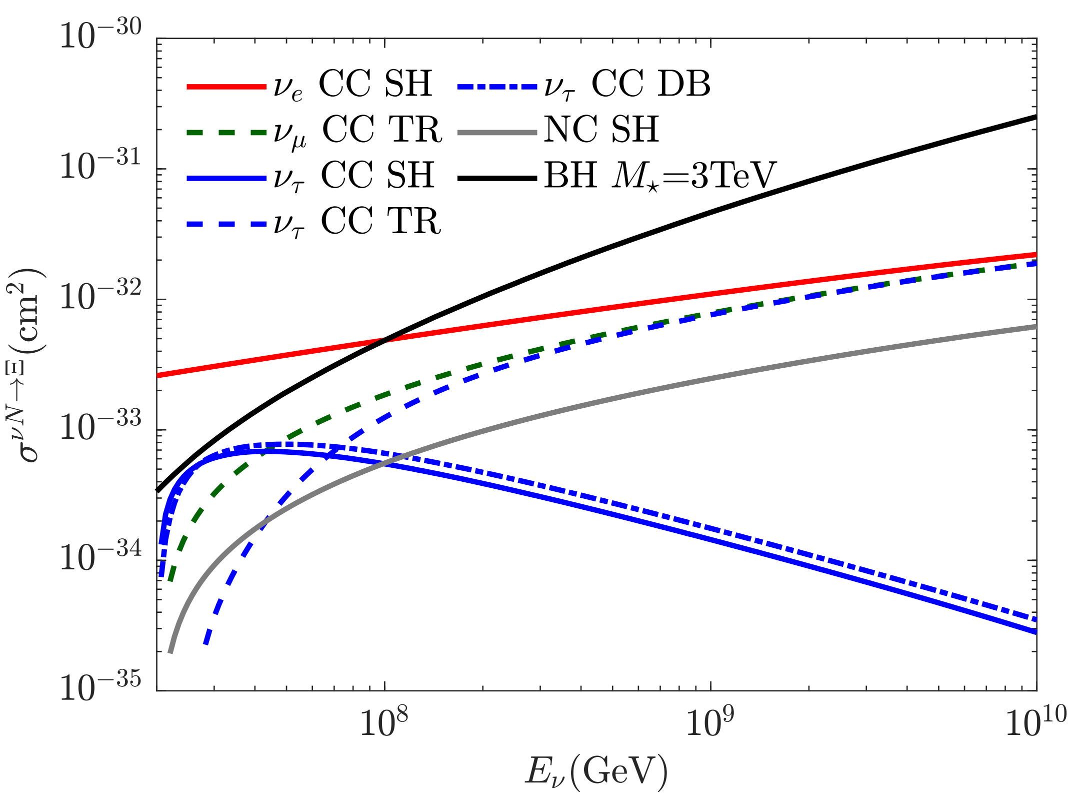
Black hole simulations



We modify BlackMax (aimed at collider searches) to handle neutrino-nucleon collisions

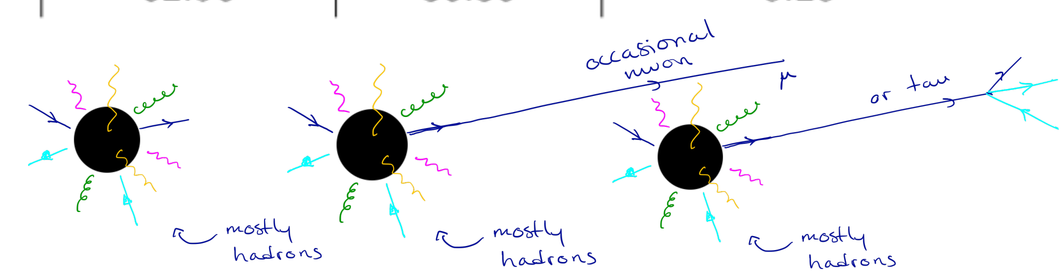
	SM	Black hole
Showers	 	 some electrons
Tracks		
double-bangs		

BH vs SM

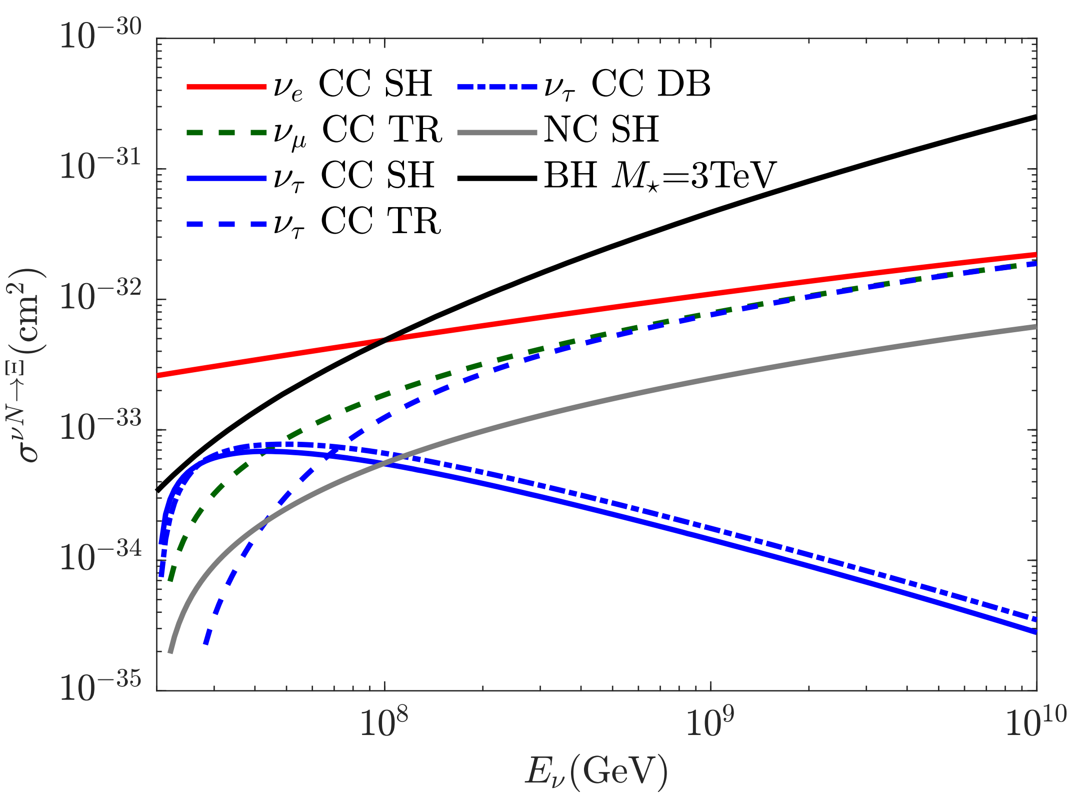


When BHs start being produced, they will dominate

	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



BH vs SM



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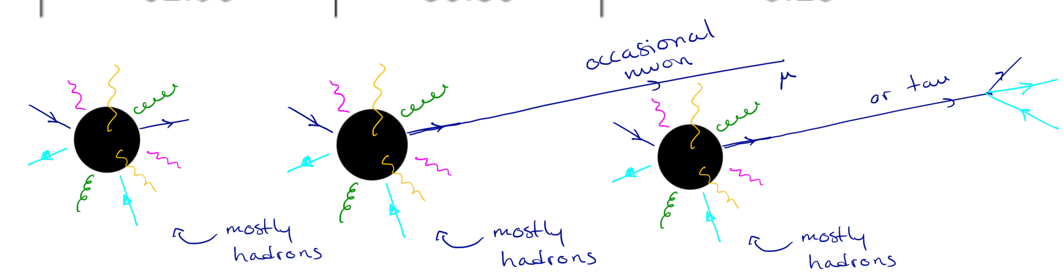

What does the reconstructed flavor composition look like if I'm seeing black holes instead of electroweak events?

Reconstructed flavor composition (IC-Gen2 exposure)

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More tracks than SM

Fewer double-bangs

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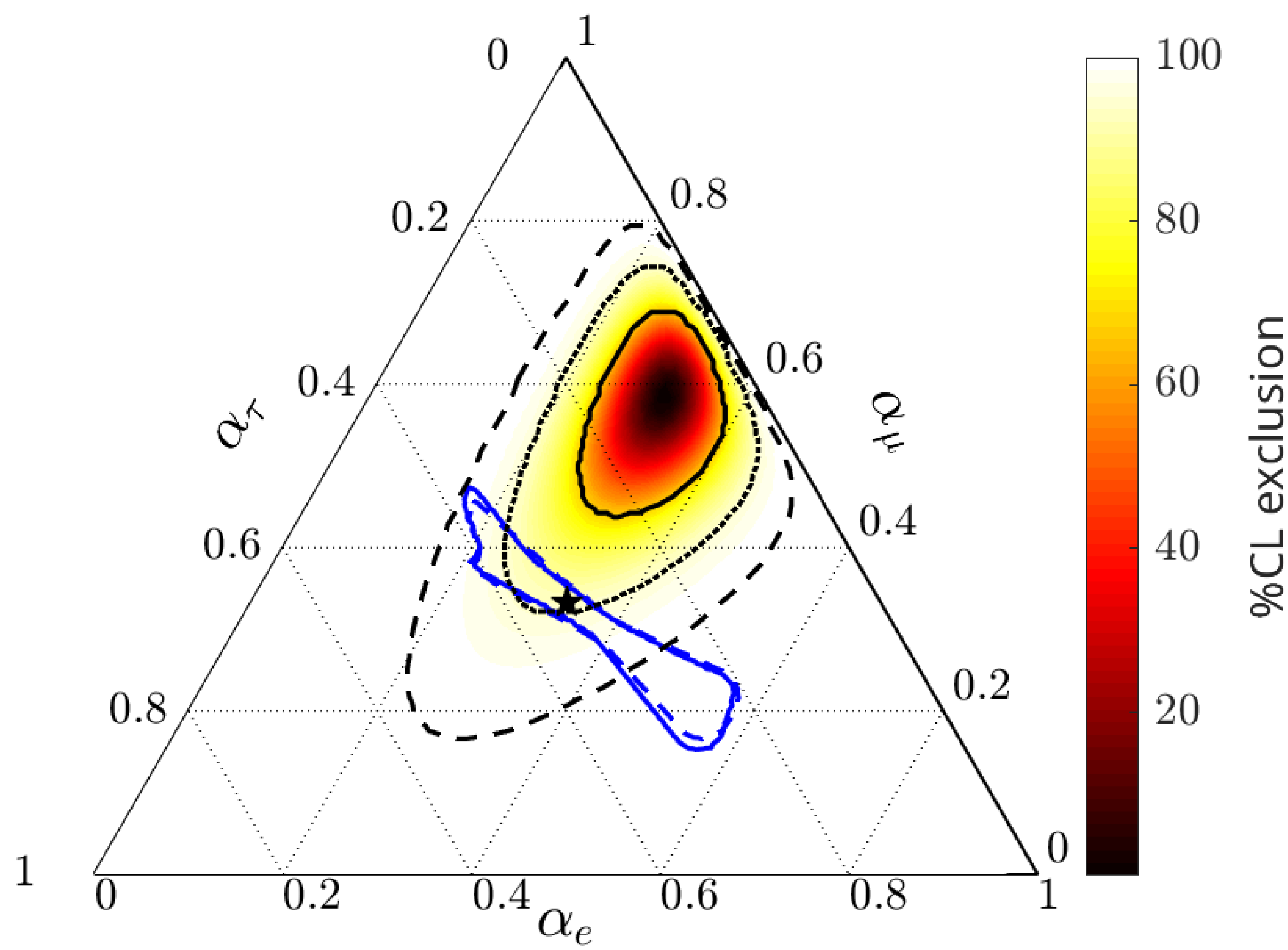
ν_e SM	28.58	0	0
ν_μ SM	2.31	8.31	0
ν_τ SM	5.07	5.39	2.83
All Flavor Total SM	35.96	13.70	2.83
All Flavor Total BH	62.96	36.36	0.20

More tracks than SM

Fewer double-bangs



Reconstructed flavor composition (IC-Gen2 exposure)

	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

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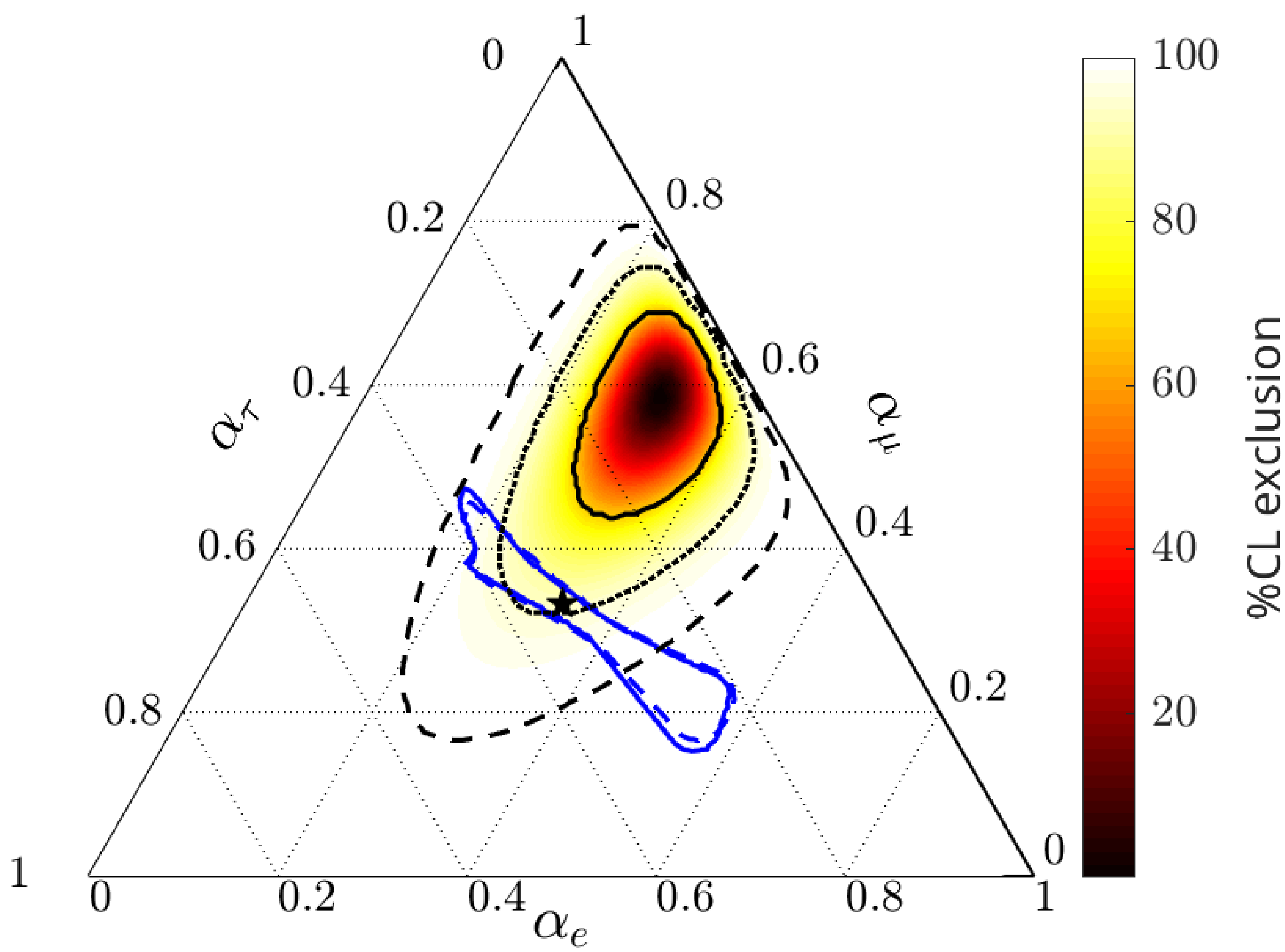
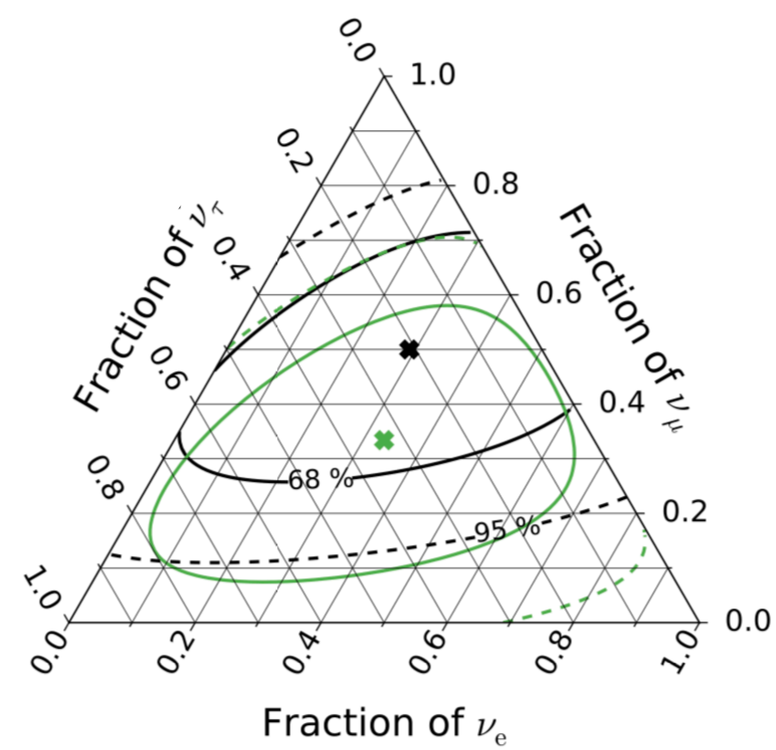
Fewer double-bangs





SM

Lepton carries away most of the momentum

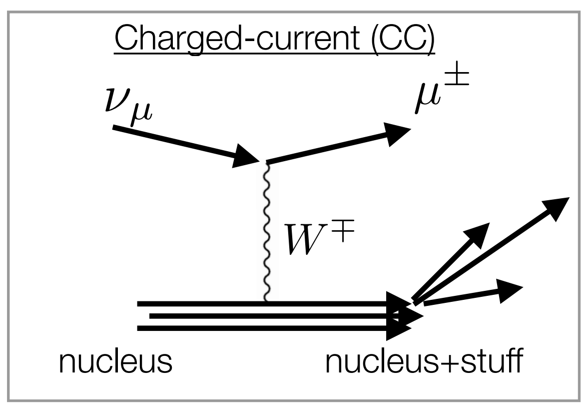
$\frac{d\sigma}{dy}$ peaks at

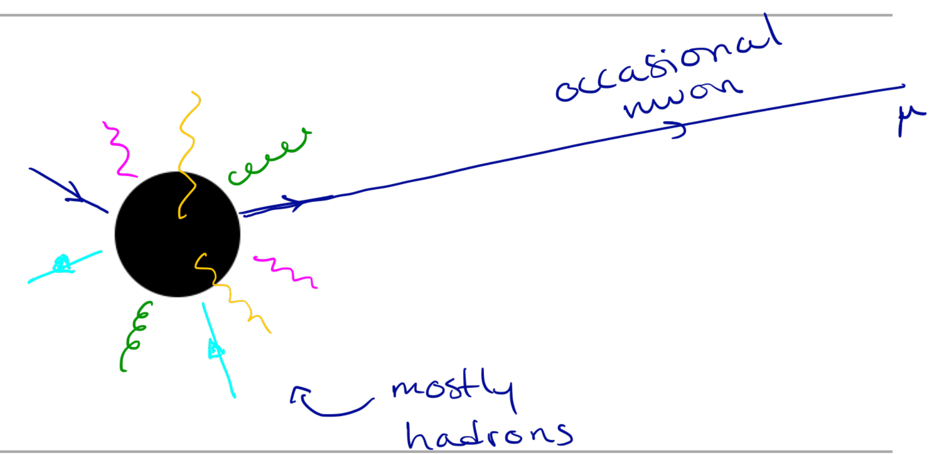
high $(1-y) \equiv \frac{E_\ell}{E_\nu}$

Black hole

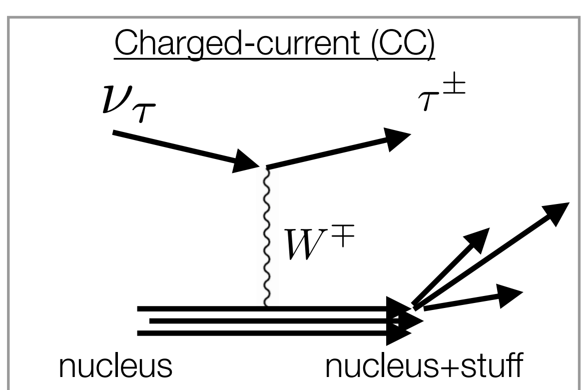
Lepton only carries $\sim 1/N$ of the total energy, where N is the number of emitted particles

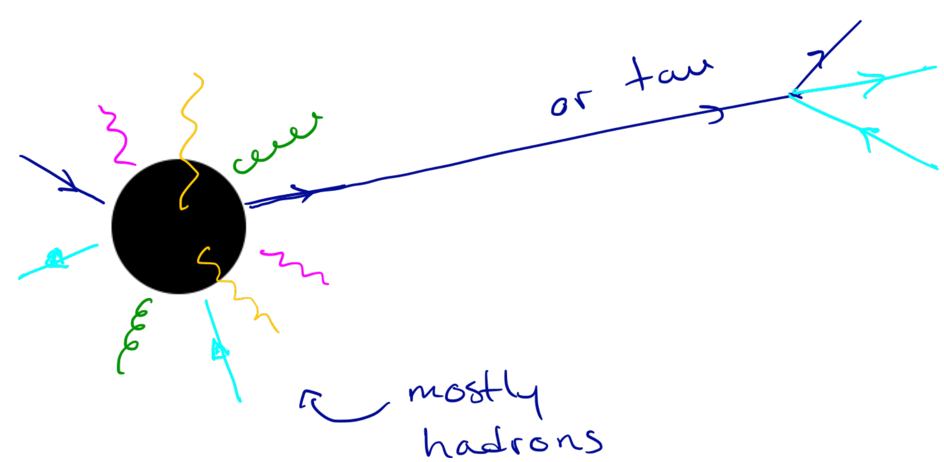
Tracks



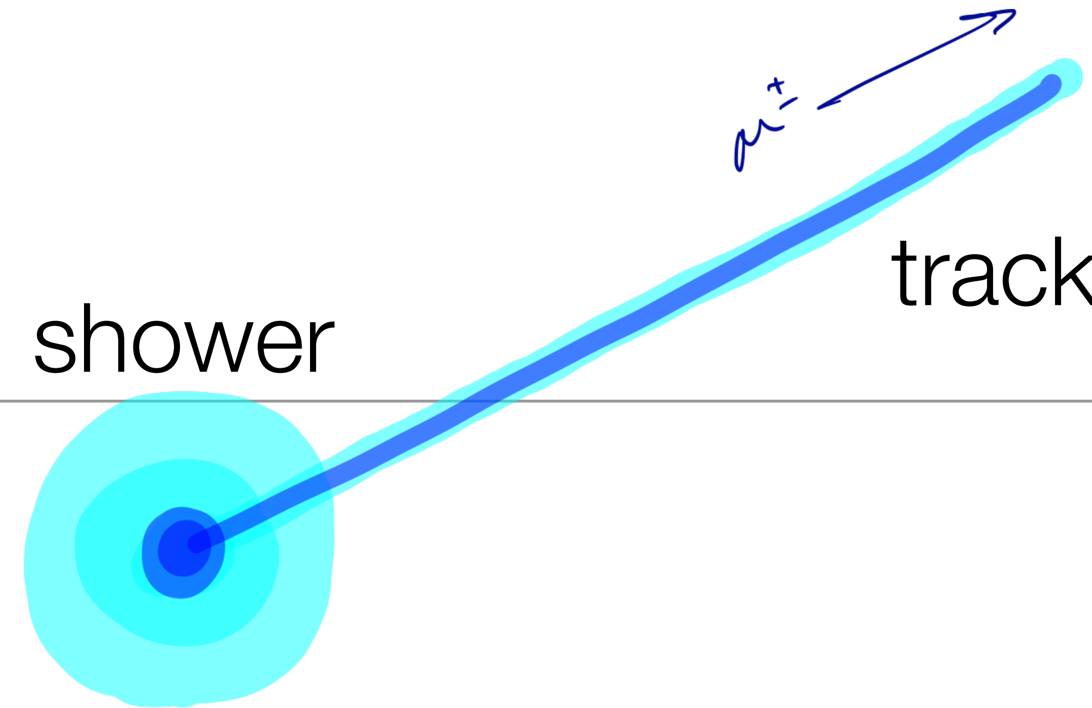


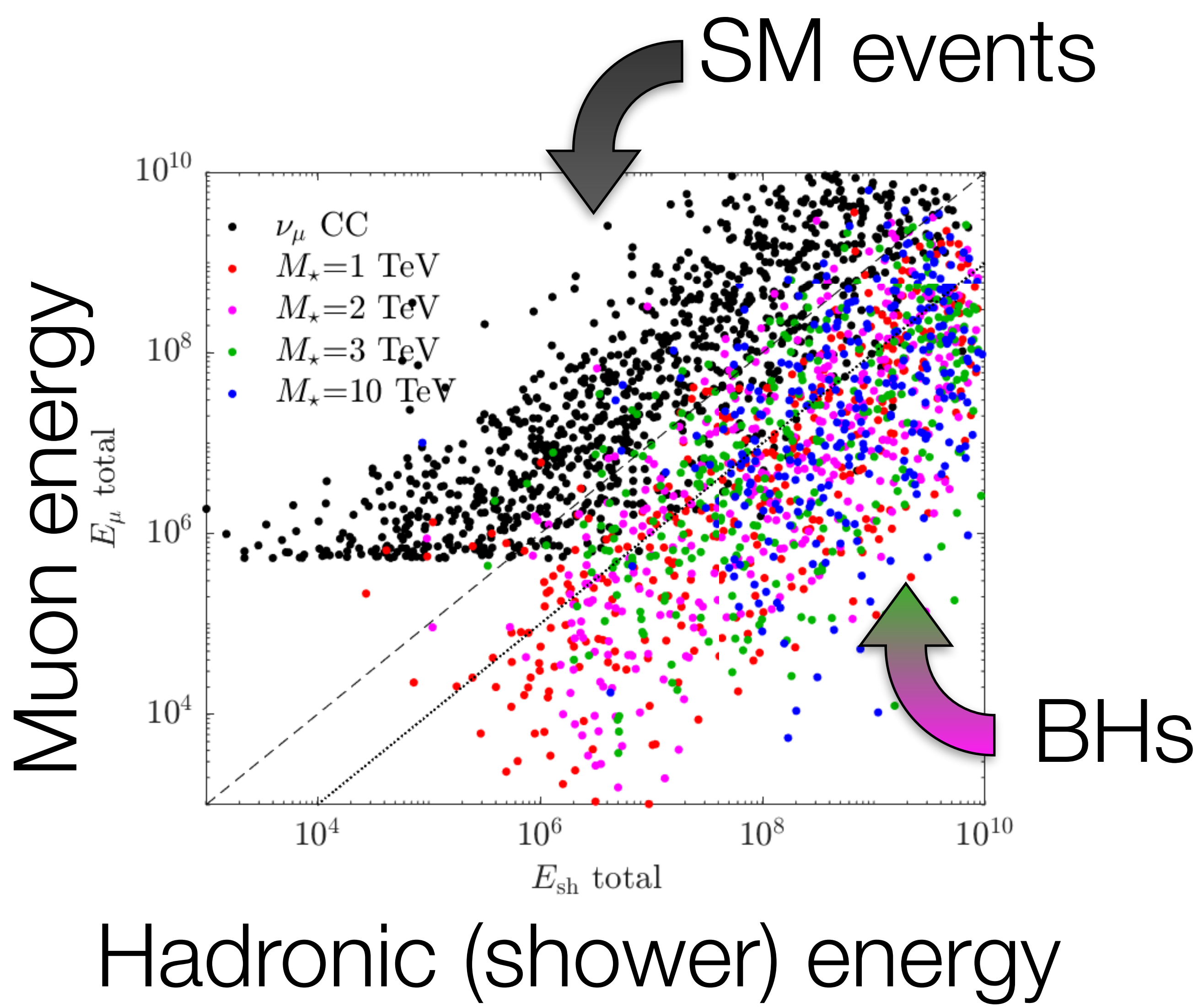
double-bangs



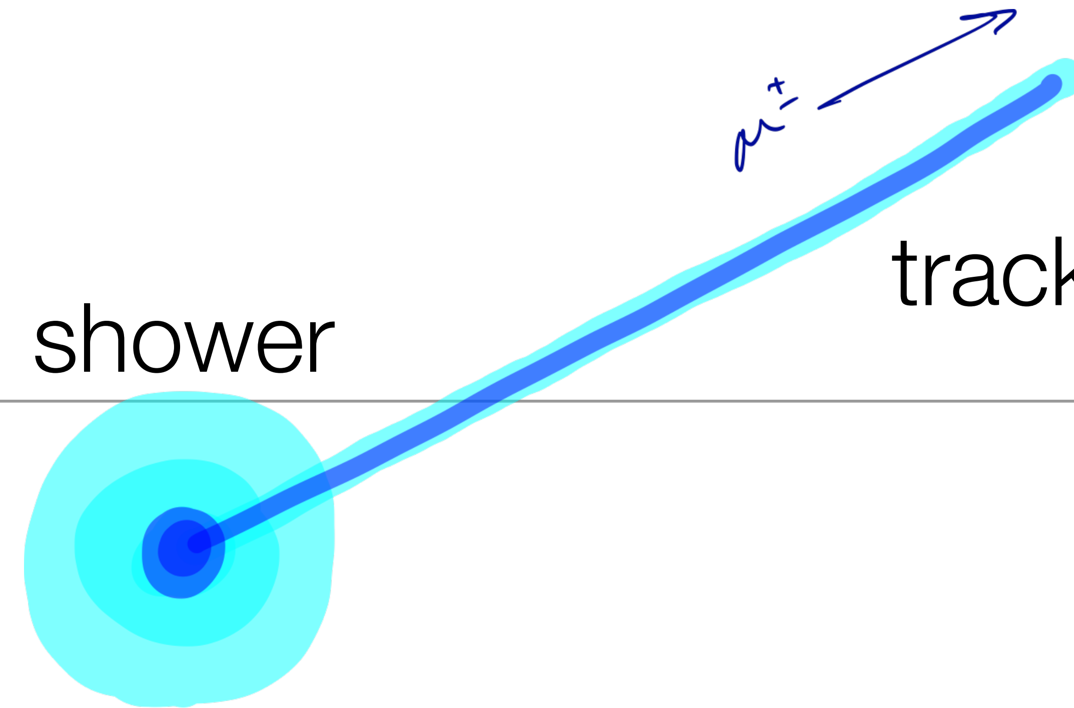


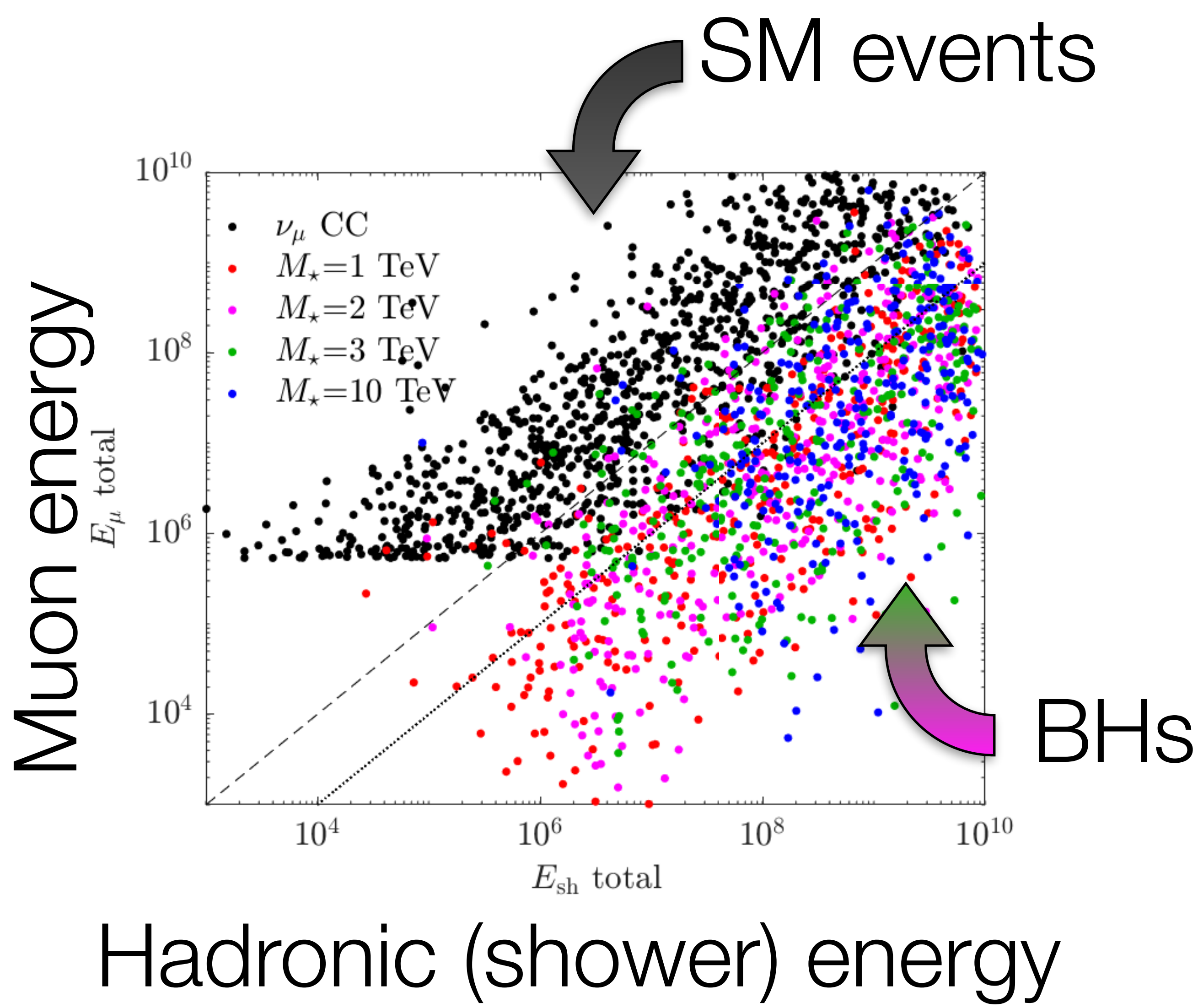
Muon track energy ratio

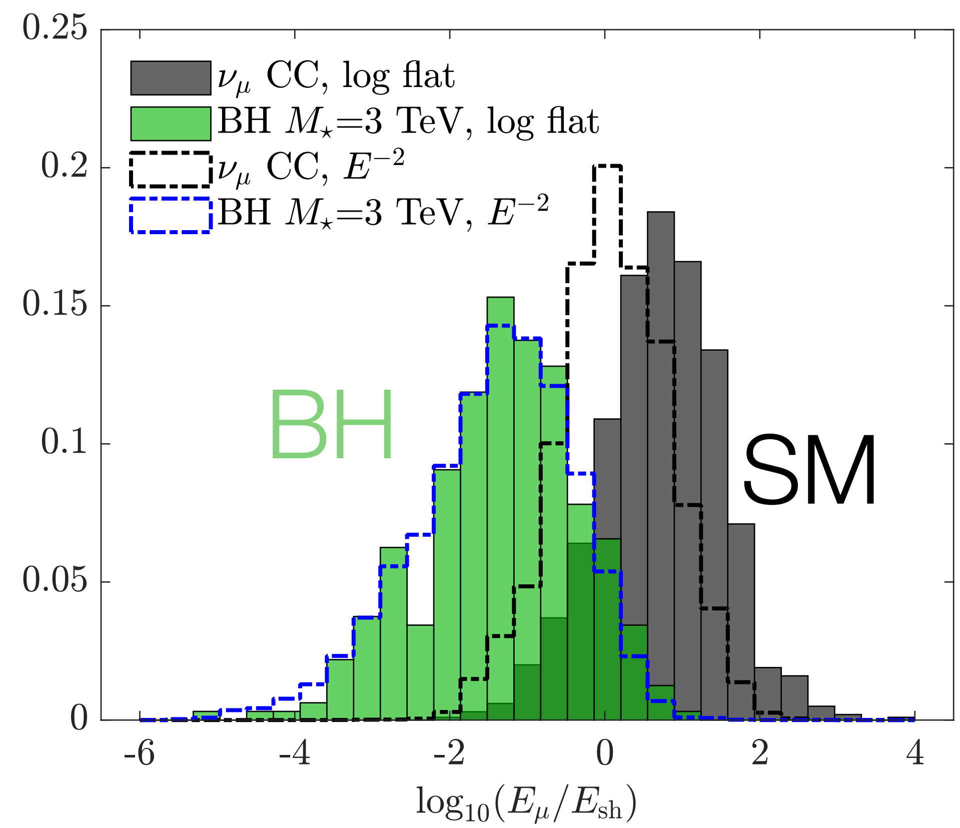




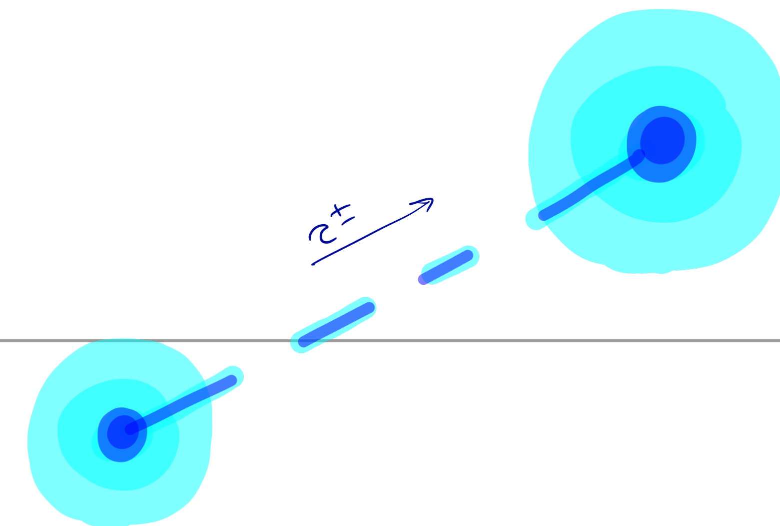
Muon track energy ratio

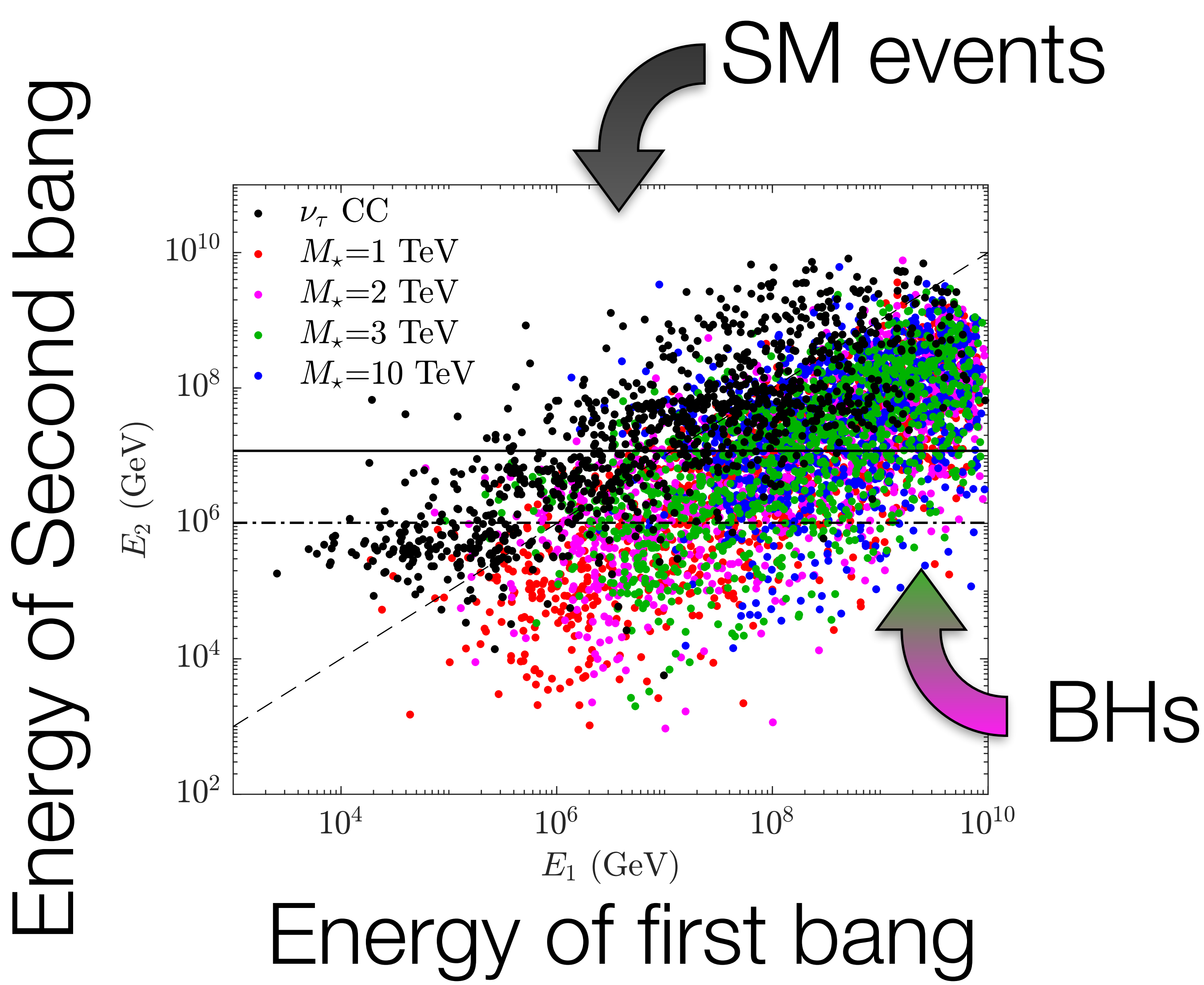


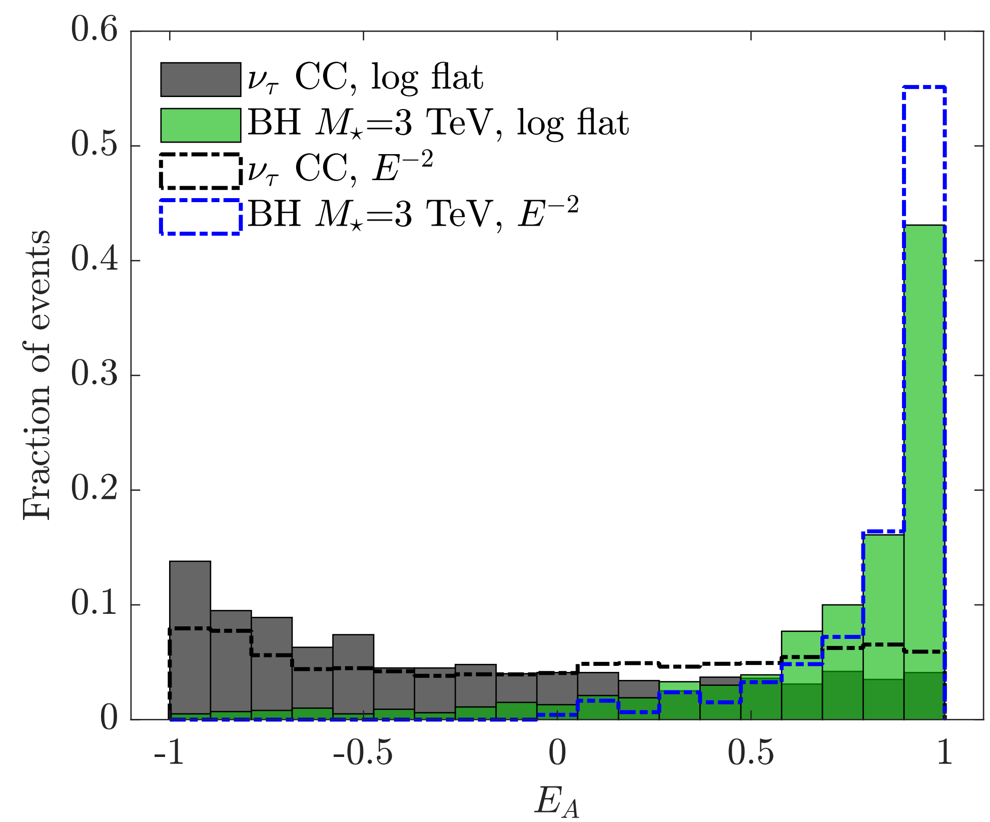




Double bang energy ratio







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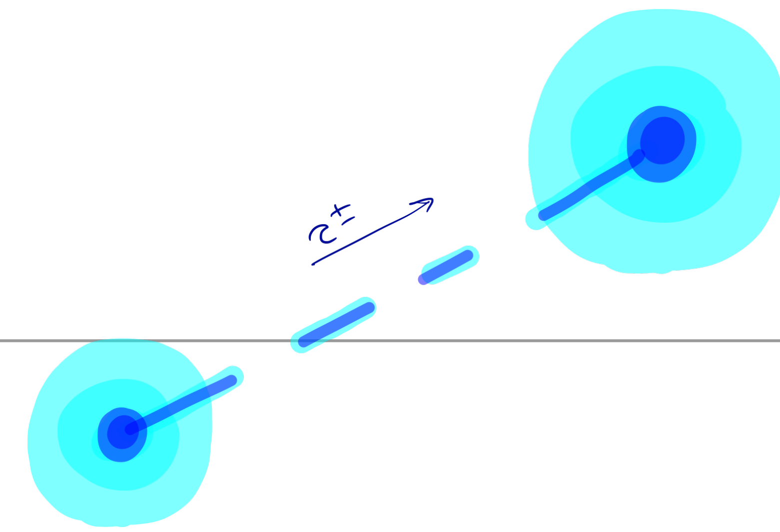
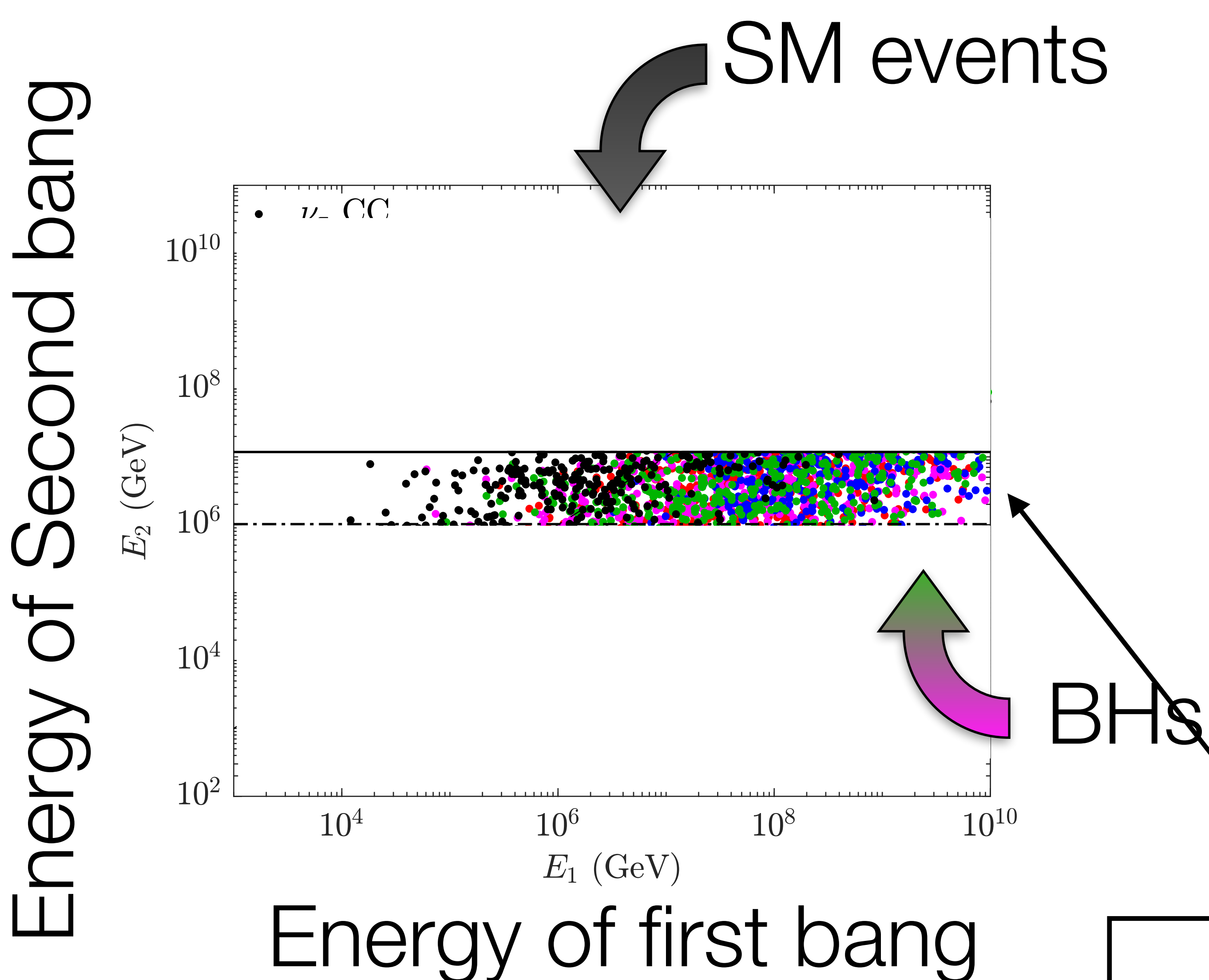
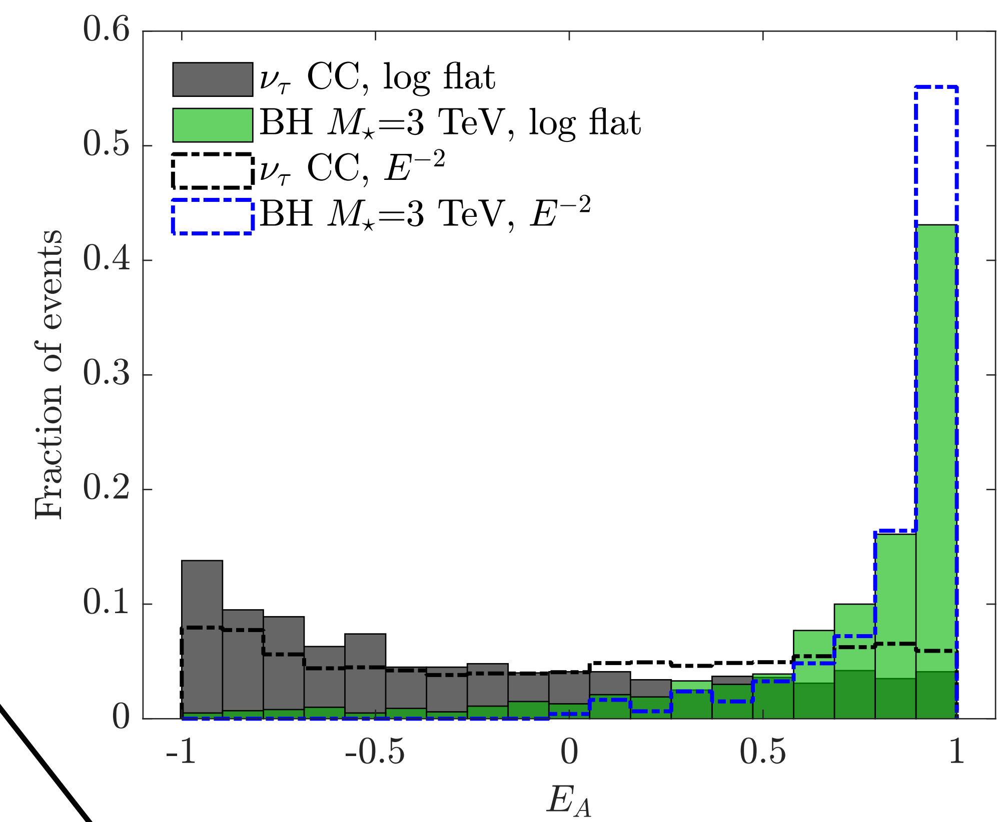
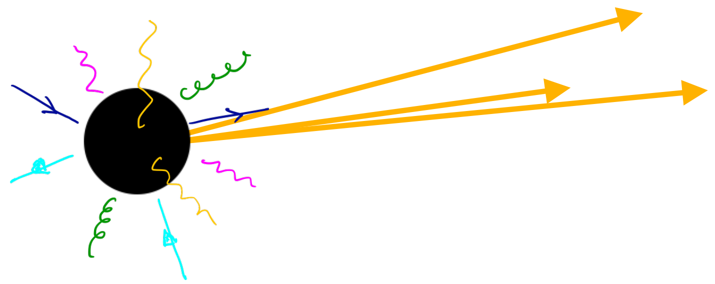






Caveat: we only see this band:
Lower limit: tau decays too close to first shower, and they are not distinguishable
Upper limit: Tau escapes the detector: no second bang

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 that 0.01˚ — IC can see at best 0.1˚)

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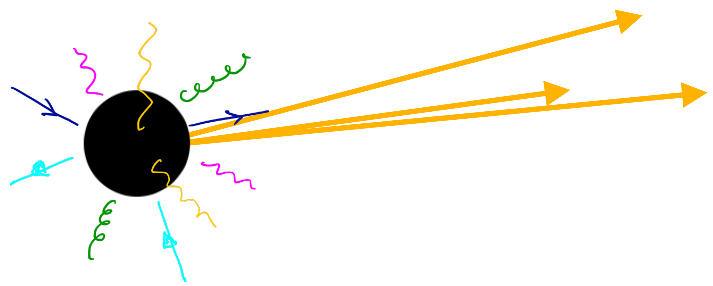

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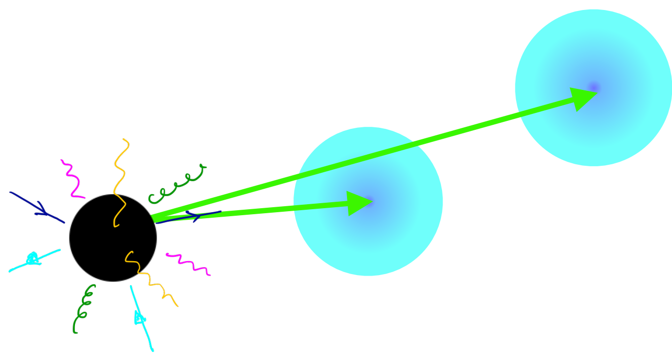

n-bang**:** multiple tau leptons decay hadronically, leaving a string of cascades separated by $d = c\Delta t$. These occur in about 0.2% of black hole events.

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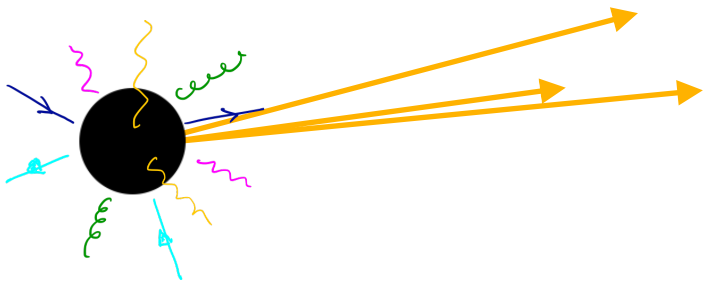

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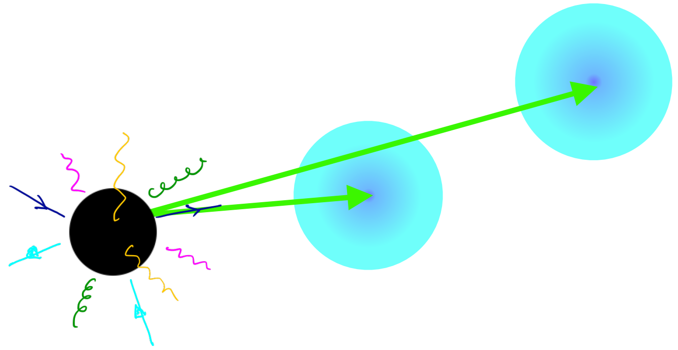

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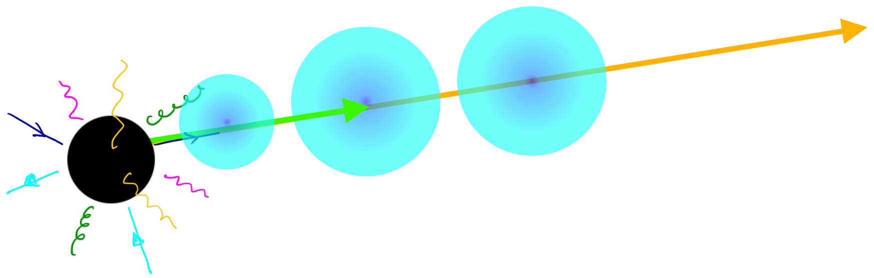

Kebab: At least one high energy muon and tau are produced, yielding several bangs and a track. This occurs in about 3% of cases.

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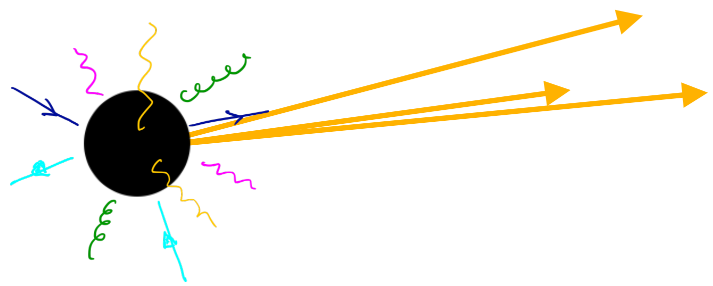

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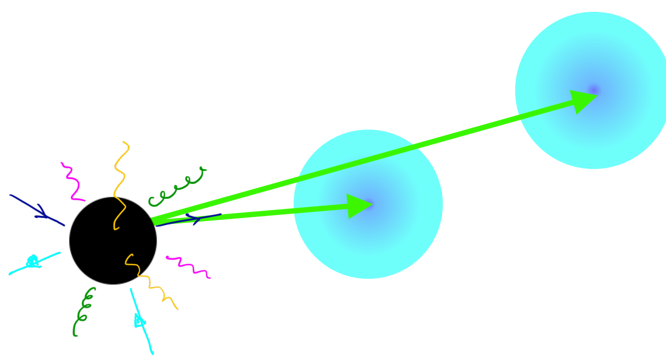

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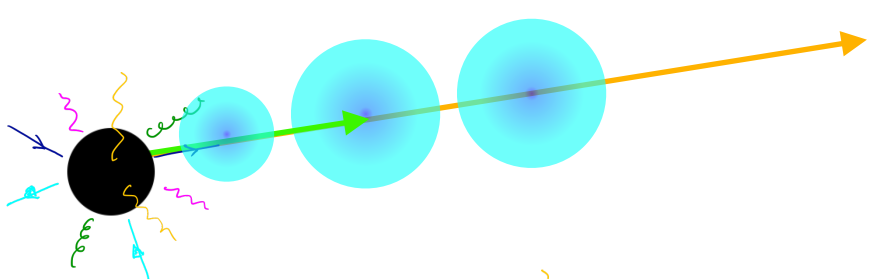

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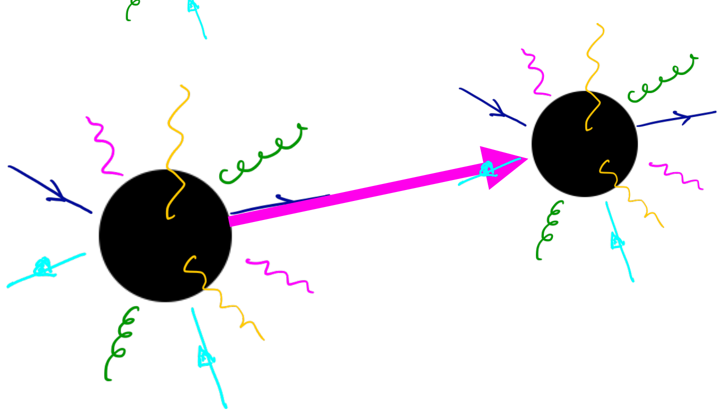

Double black hole bang**:** If one of the decay products is 1) energetic enough and 2) can travel far enough, it can collide and form a second black hole, again separated by $d = c\Delta t$

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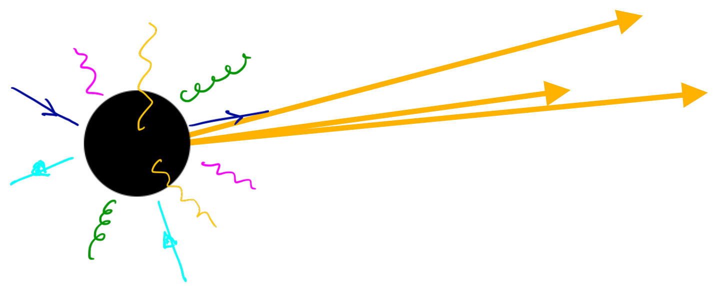

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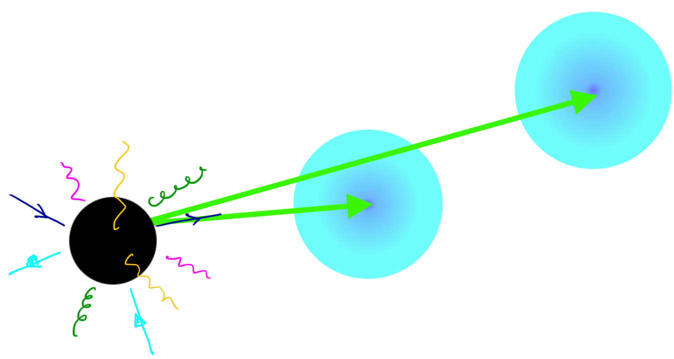

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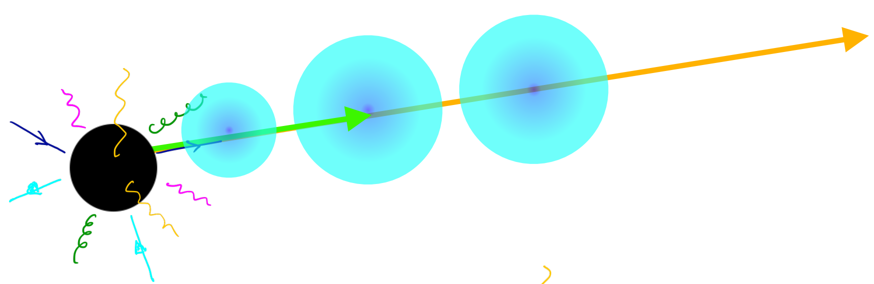

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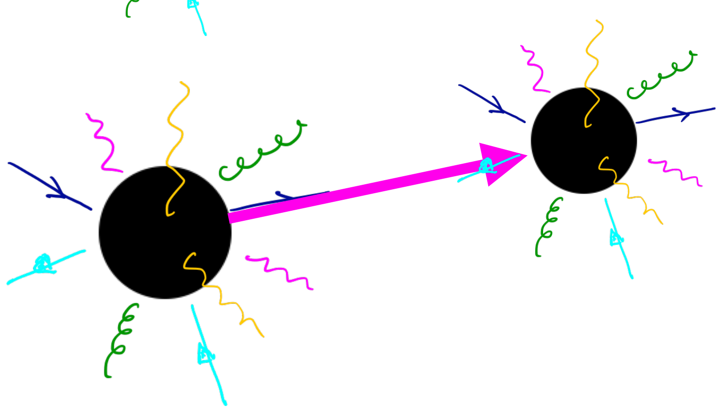


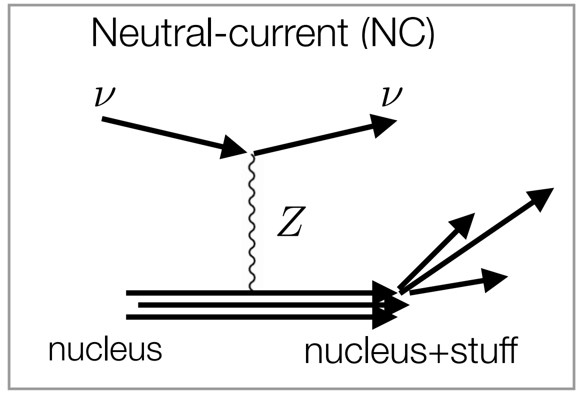
Double black hole bang: If one of the decay products is 1) energetic enough and 2) can travel far enough, it can collide and form a second black hole, again separated by $d = c\Delta t$

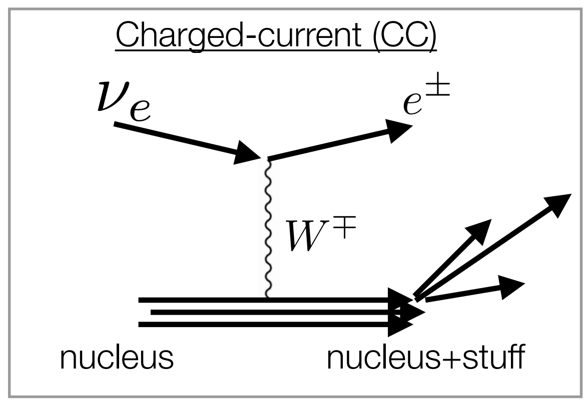
These are rare, but if we see even one we can suspect LEDs are involved!!

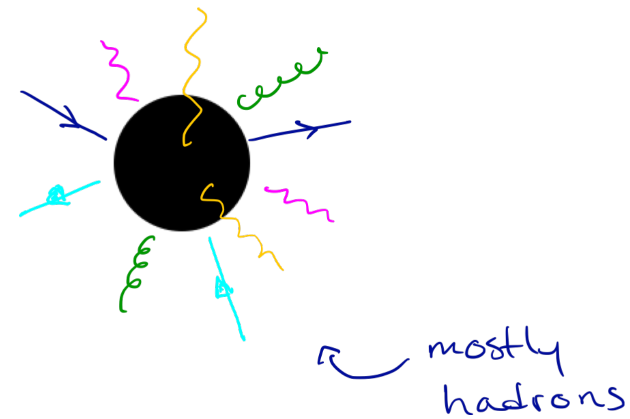
SM

Black hole

Showers







some electrons

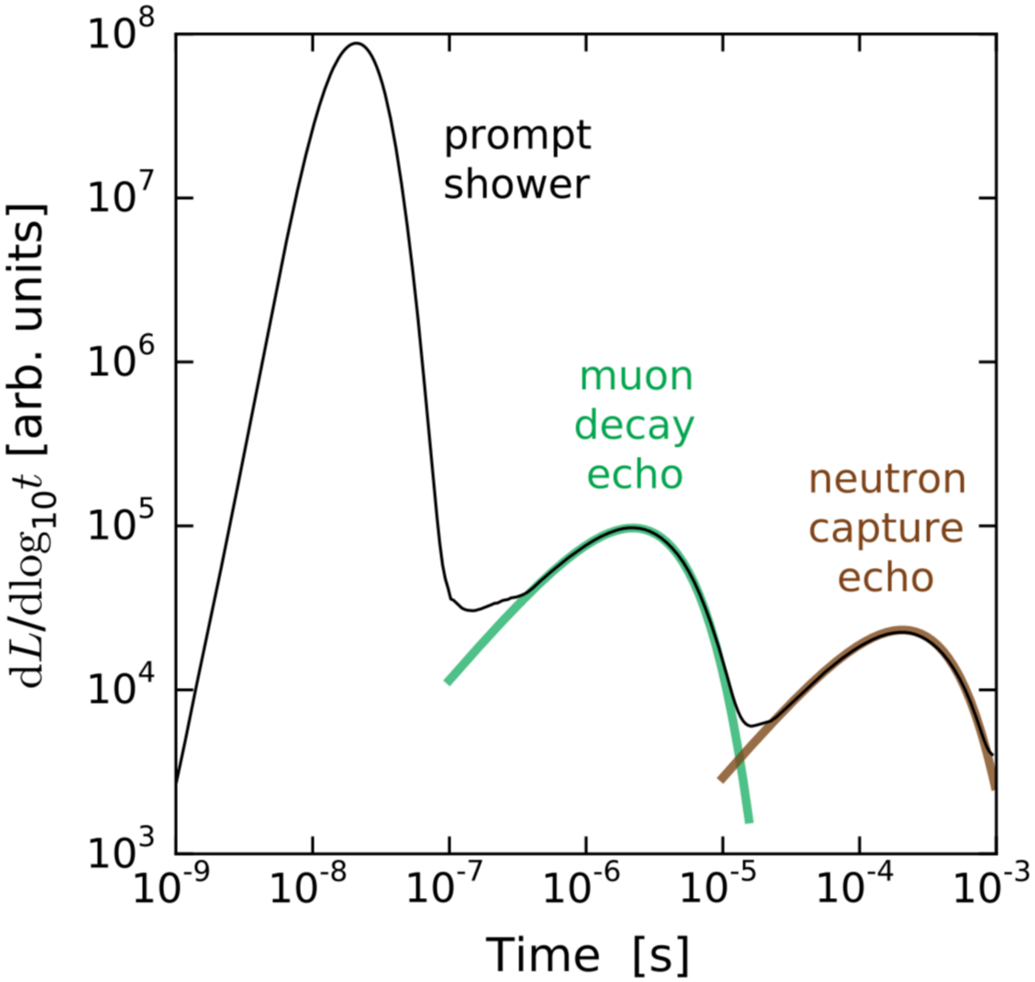
What about these showers?

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

BH: shower should look like a very big hadronic shower

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.



Li, Bustamante, Beacom
1606.06290

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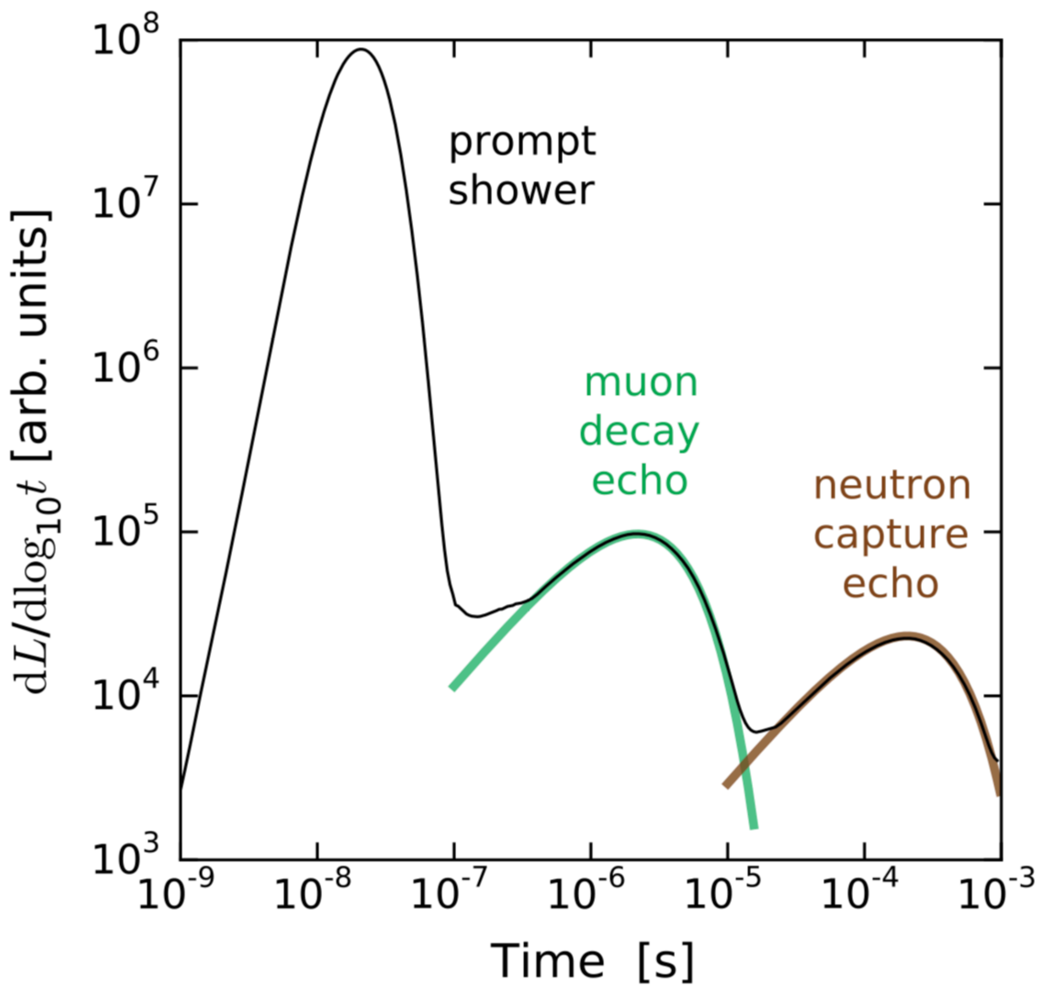

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Muons produced during hadronization and propagation are low-energy, and therefore live $\sim 10^{-6}$s, leading to a second **muon echo** as they decay

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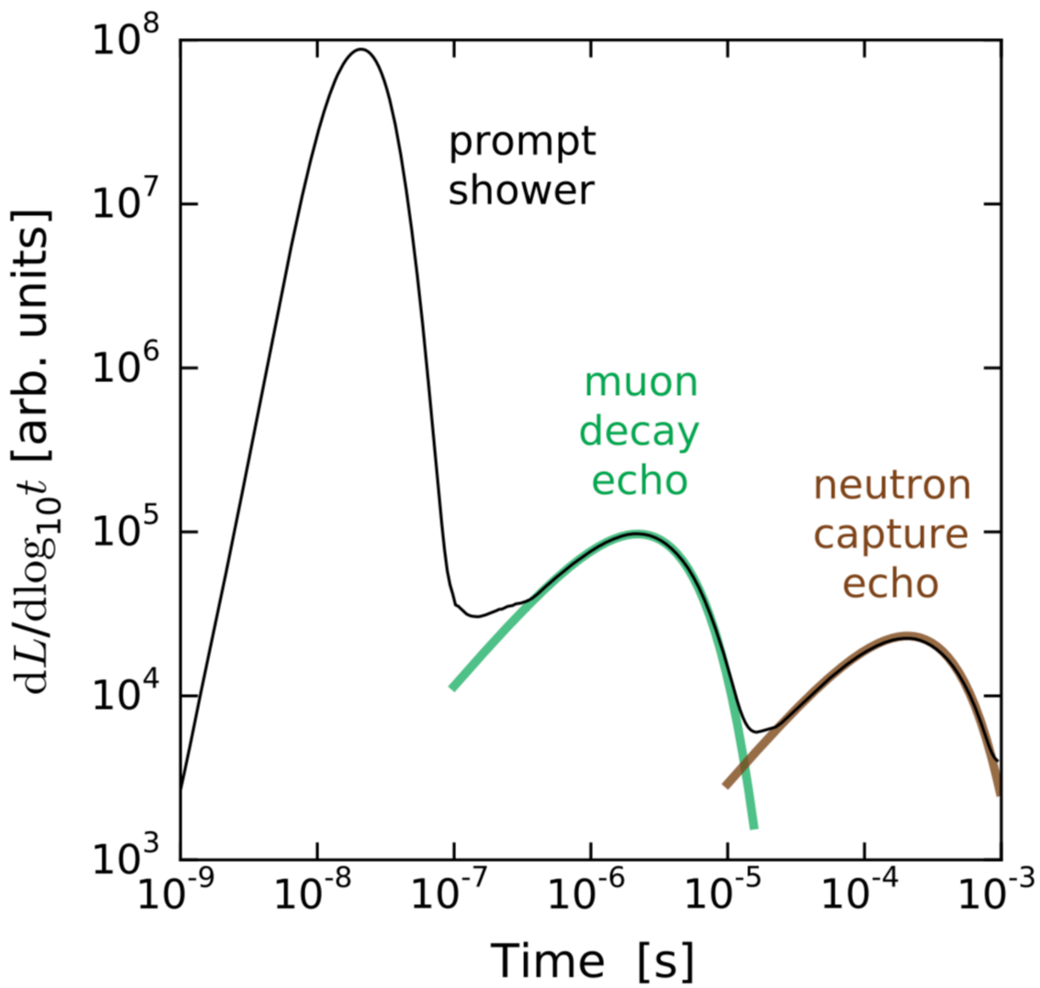

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Muons produced during hadronization and propagation are low-energy, and therefore live $\sim 10^{-6}$s, leading to a second **muon echo** as they decay

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

Analysis

BlackMax:
predict
decay products

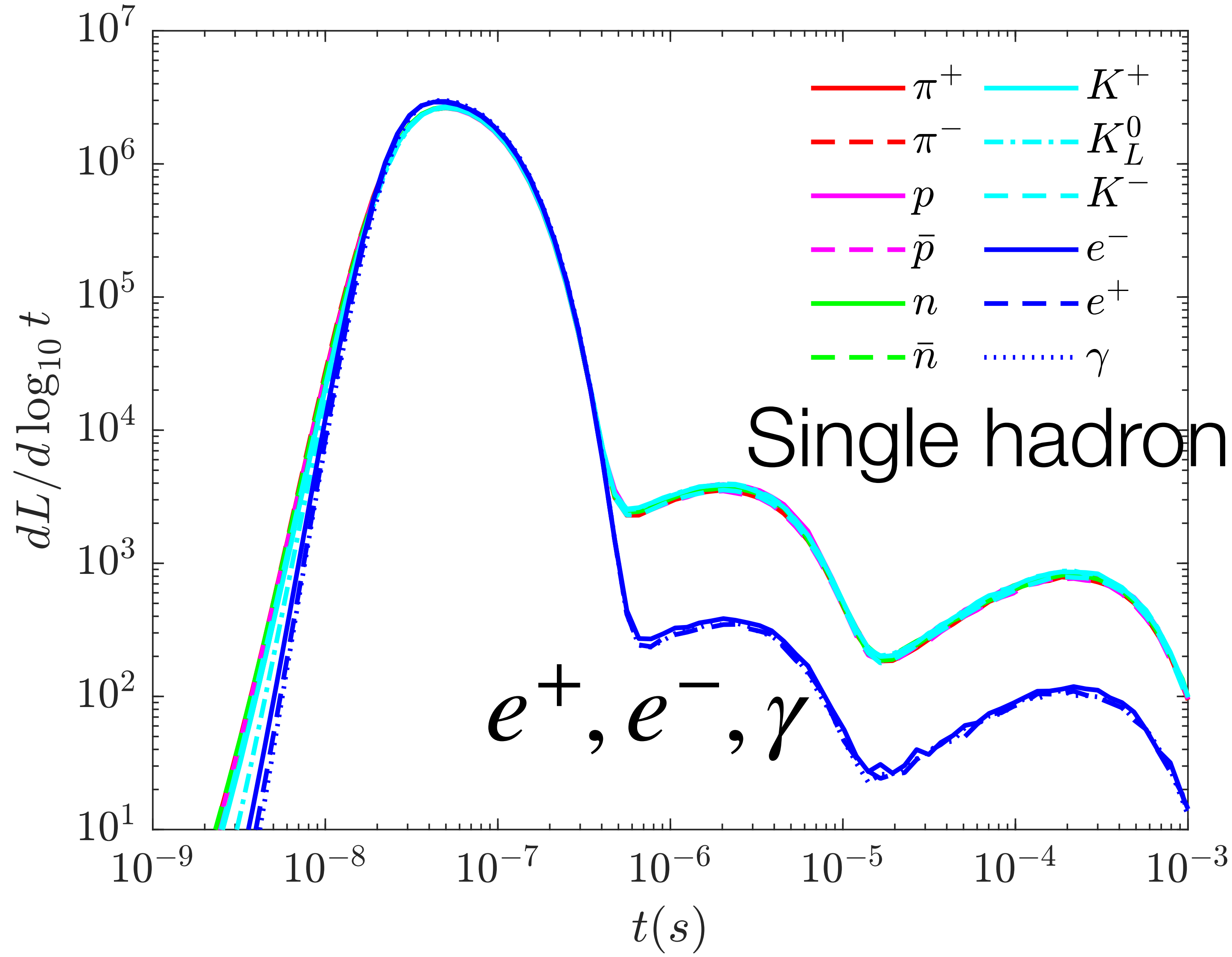
SM:
electroweak cross
sections

Pythia 8:
Decay heavy stuff,
hadronize

FLUKA:
inject products
into ice, count
Čerenkov Photons

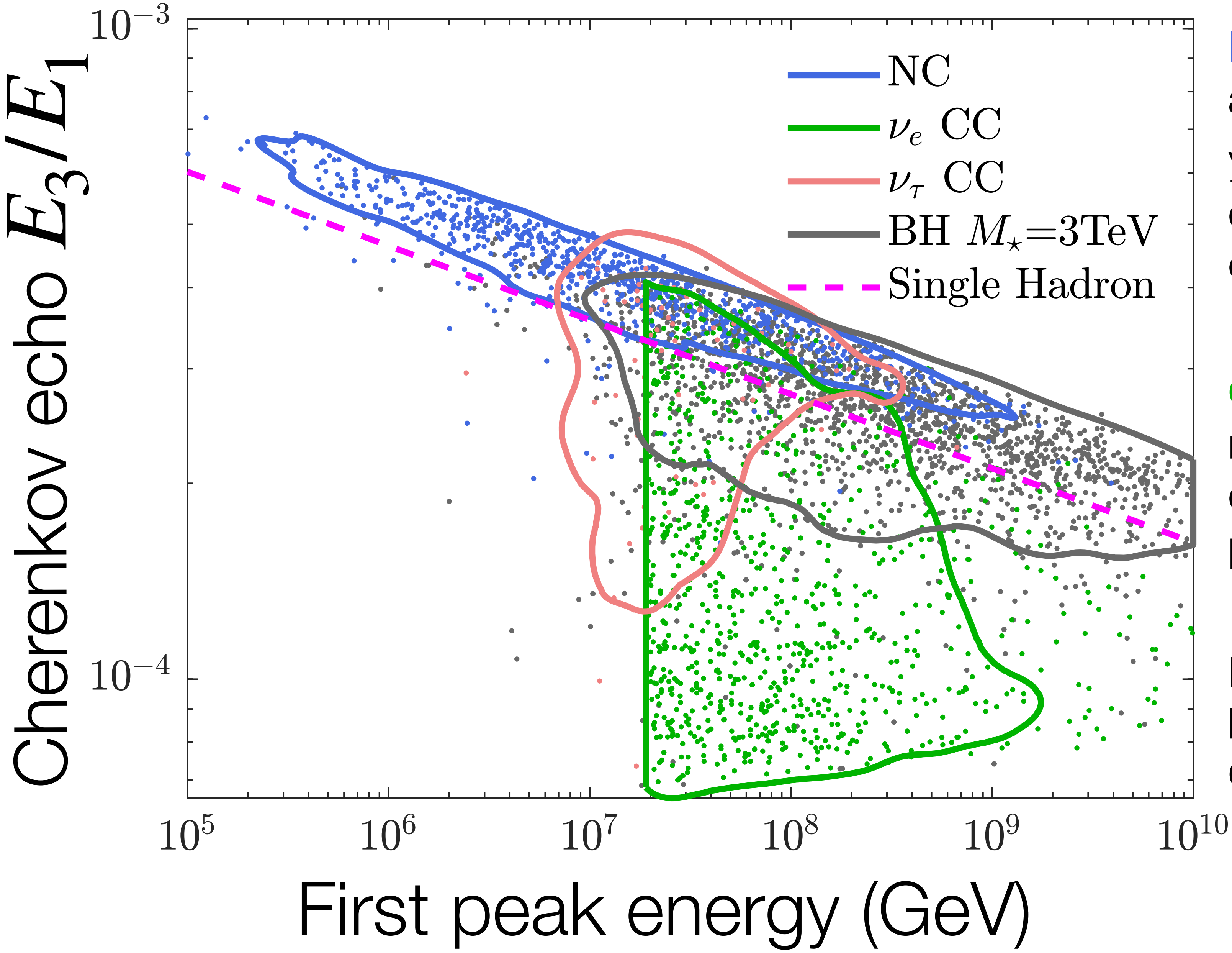
Cherenkov light echos

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



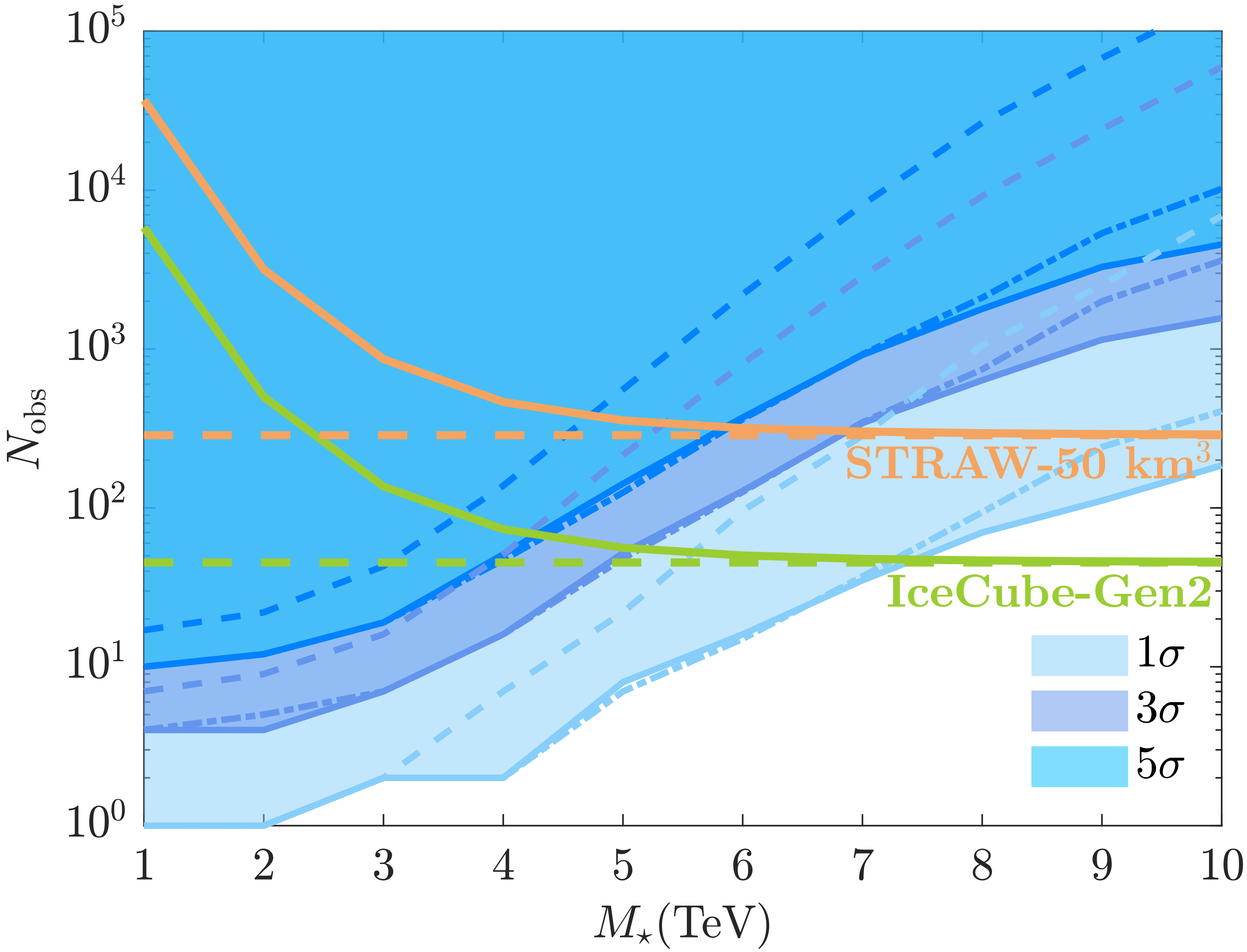
Neutral current events: above the hadron line since hadronization yields mostly hadrons + a few γ. Low energy because neutrino takes away most of the E.

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)

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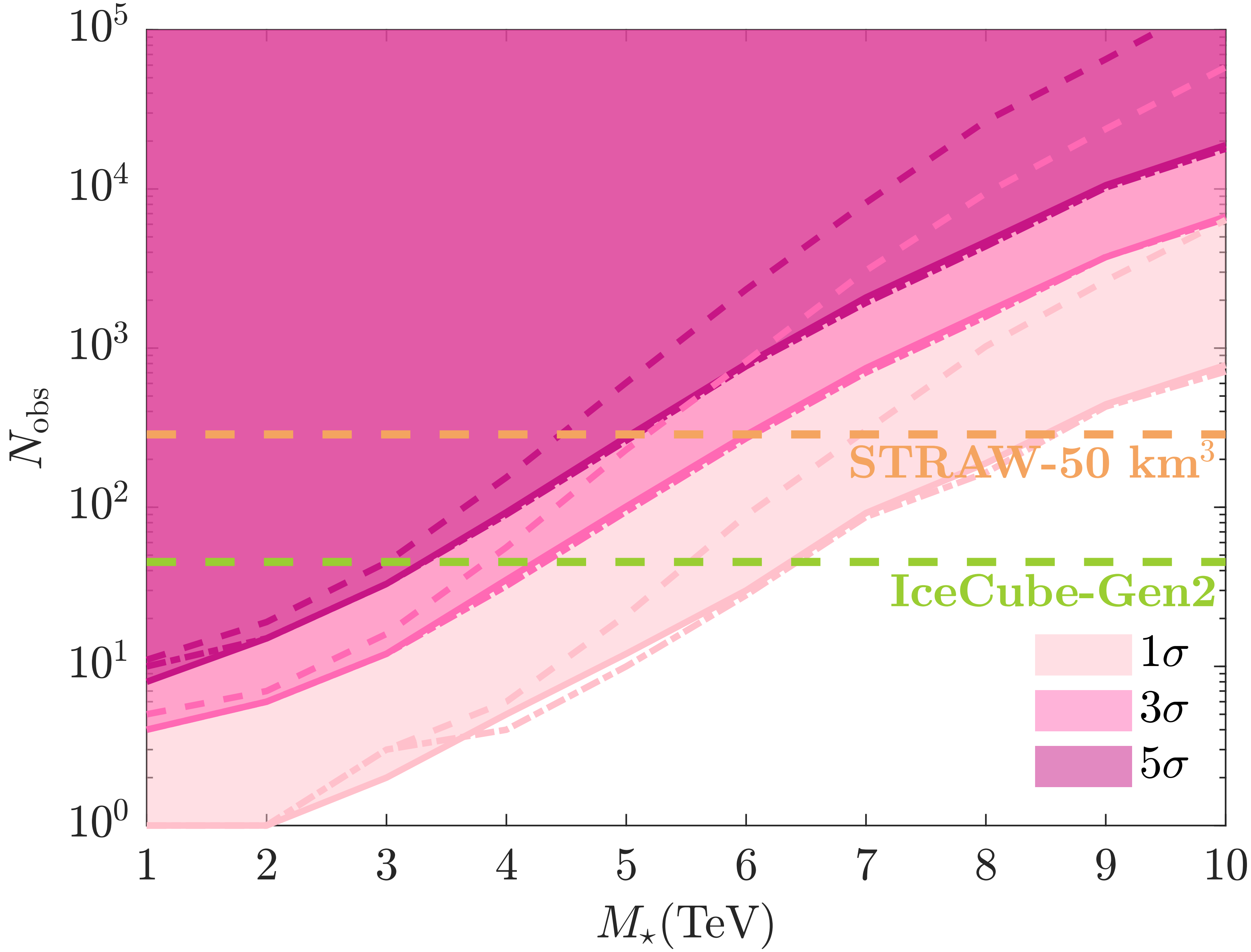
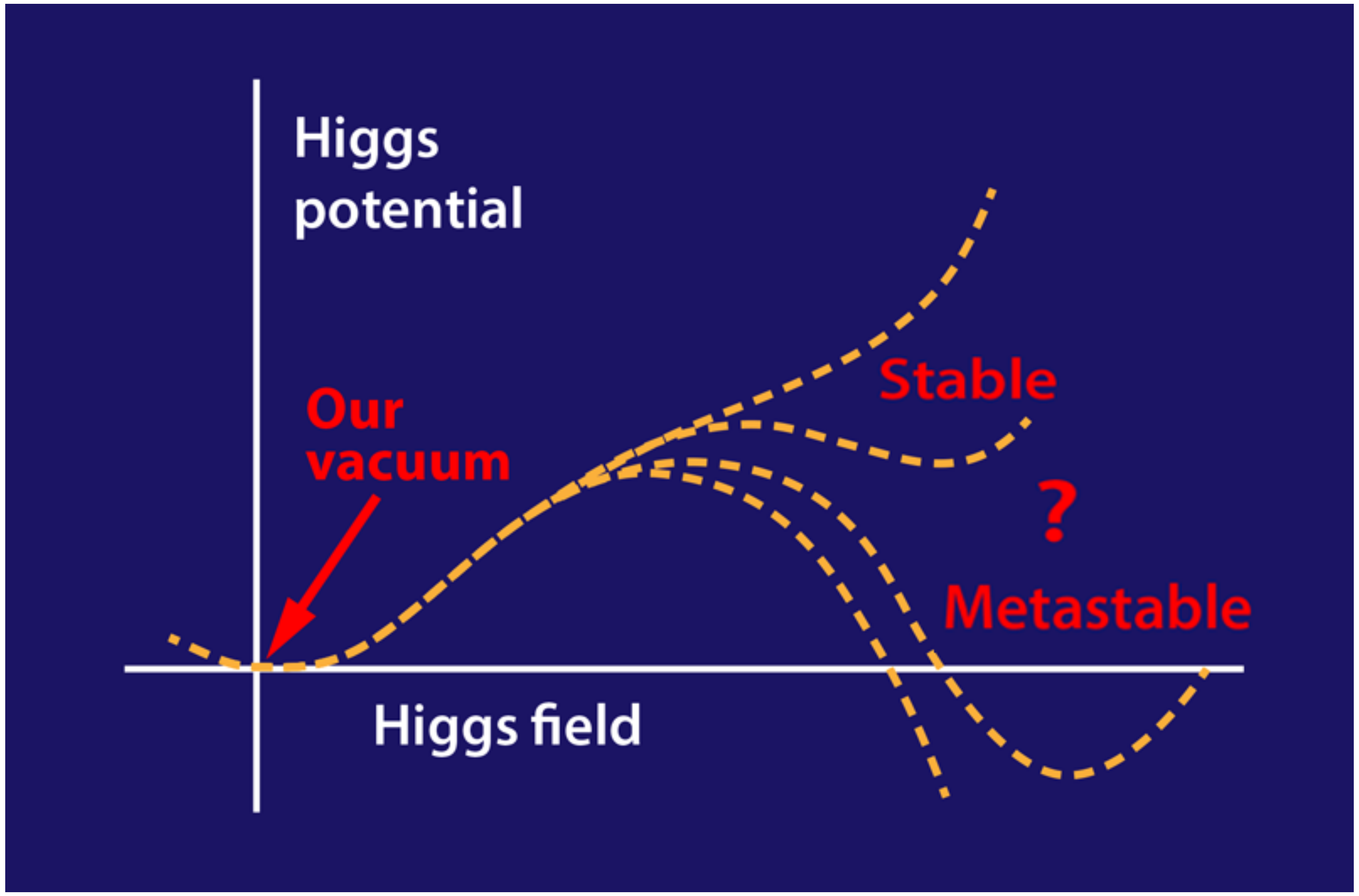


Stability of the Universe



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.**

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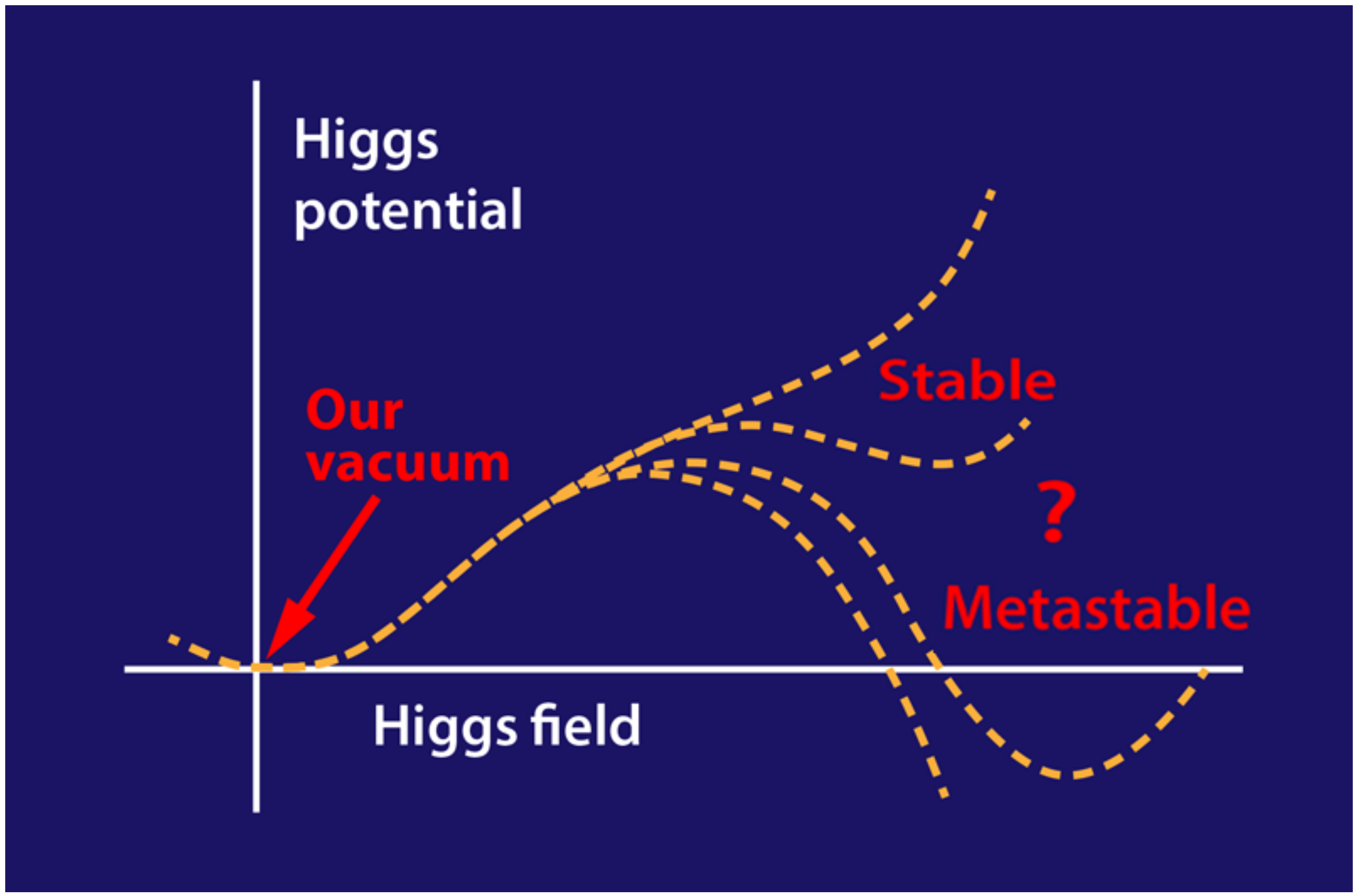

If the Higgs potential actually puts us in a metastable vacuum, the extremely high curvature near a microscopic black hole can make tunnelling to true vacuum **much more probable.**

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