A Futuristic Look at Neutrino Telescopes: Sources, Decay, Non-Unitarity and Extra Dimensions

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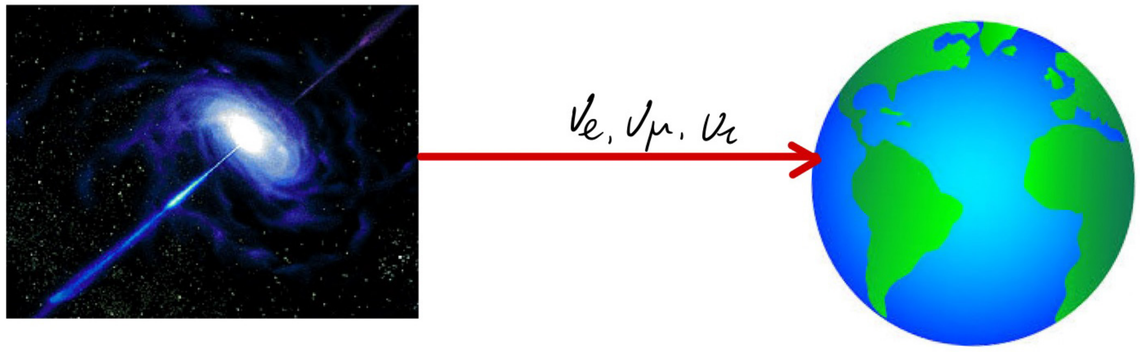
Queen's UNIVERSITY

High Energy Neutrinos



- Pion decay $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 2 : 0)$

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\mu^+ \to e^+ + \nu_\mu + \bar{\nu}_e$$

- Muon-damped $(\nu_e : \nu_\mu : \nu_\tau) = (0 : 1 : 0)$

$$\pi^+ \to \mu^+ + \nu_\mu$$

$$\cancel{\mu^+} \to e^+ + \nu_\mu + \bar{\nu}_e$$

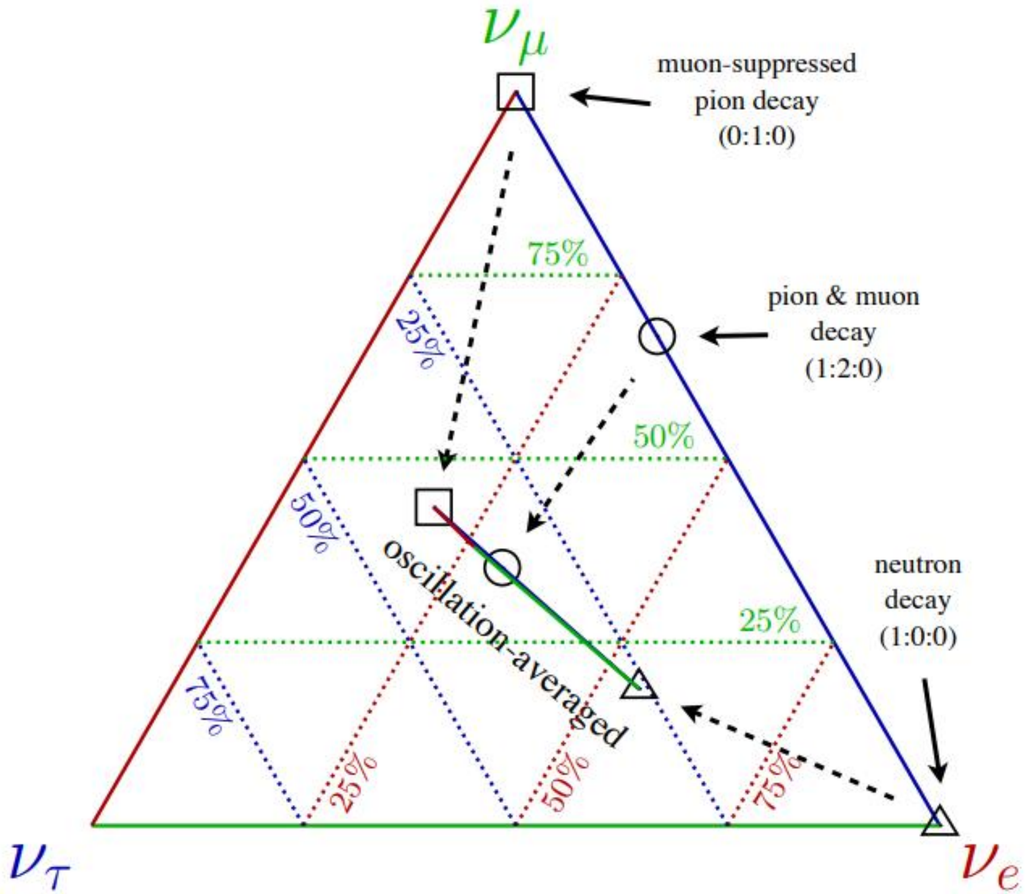
- Neutron decay $(\nu_e : \nu_\mu : \nu_\tau) = (1 : 0 : 0)$

$$n \to p + e^- + \bar{\nu}_e$$

Neutrino Flavor at Earth

- Neutrinos oscillate from source to Earth

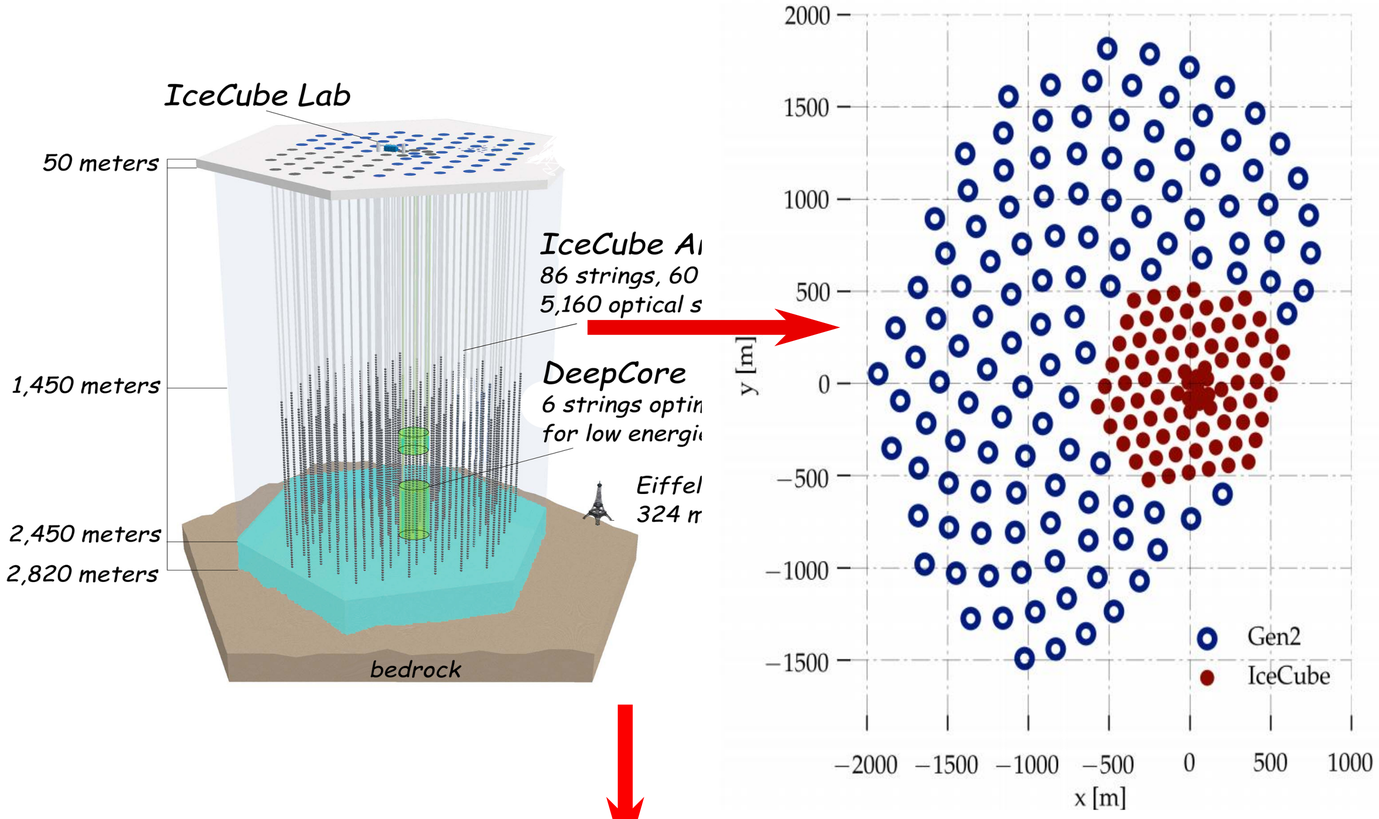
$$P_{\alpha\beta}^{s\to\oplus} = \sum_{ij} U_{\beta i} U_{\beta j}^{*} U_{\alpha j} U_{\alpha i}^{*} \exp(-i\frac{\Delta m_{ij}^2 L}{2E})$$
$$= \sum_{i} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

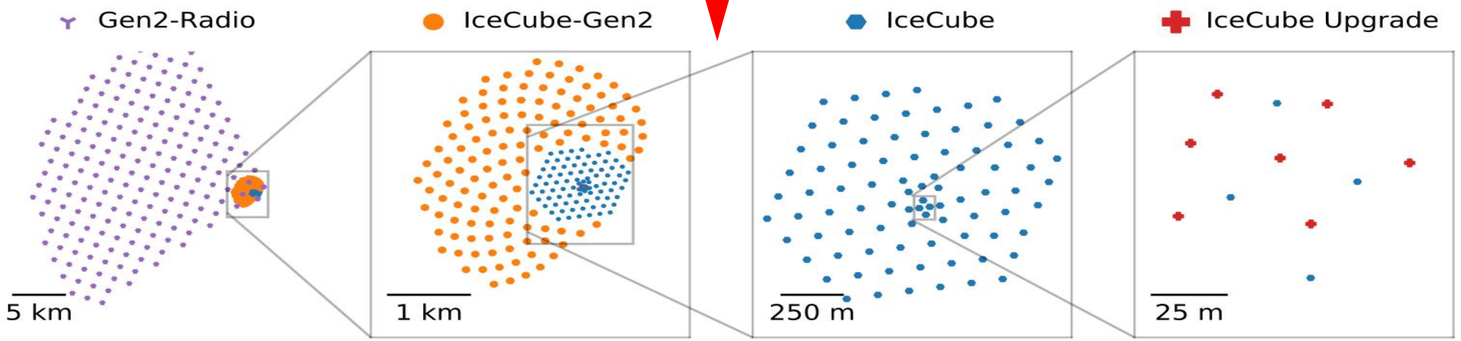


Gen2 collaboration, 1412.5106

- $f_S = (1/3,\ 2/3,\ 0) \to f_\oplus = (0.3,\ 0.36,\ 0.34)$

IceCube+Gen2

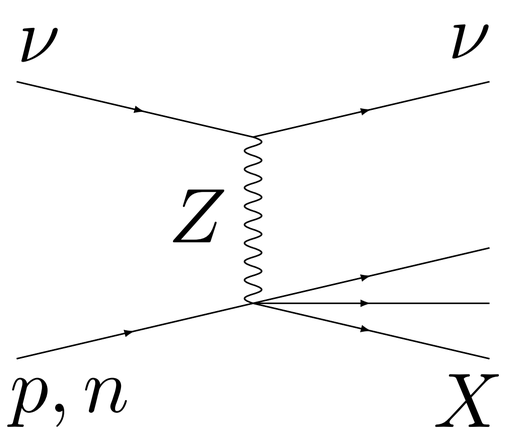


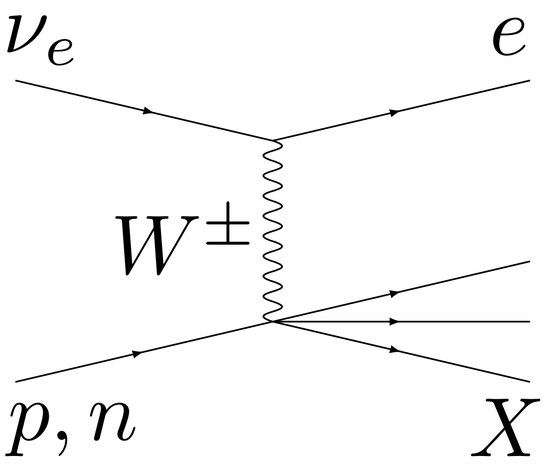


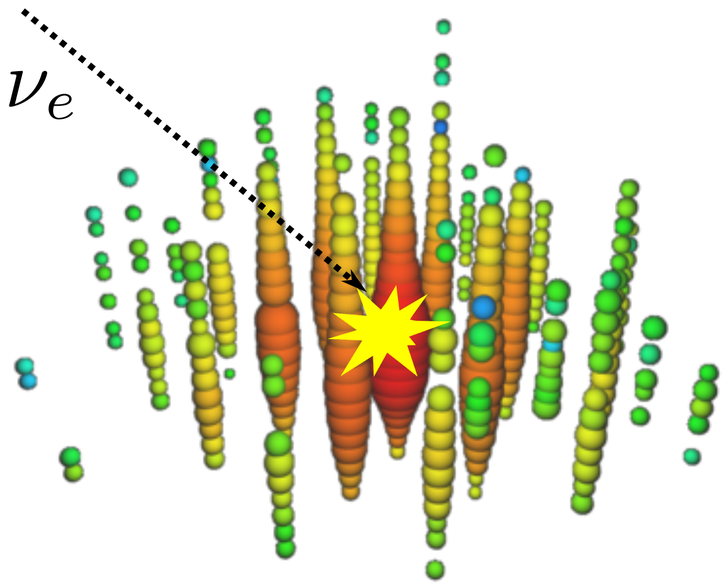
IceCube collaboration

Shower

- Neutral current (NC) & ν_e charged current (CC)



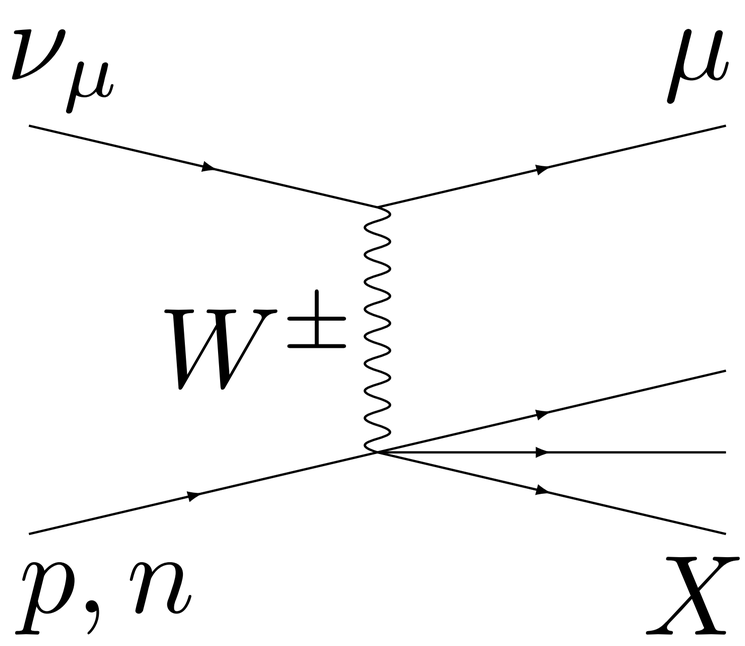


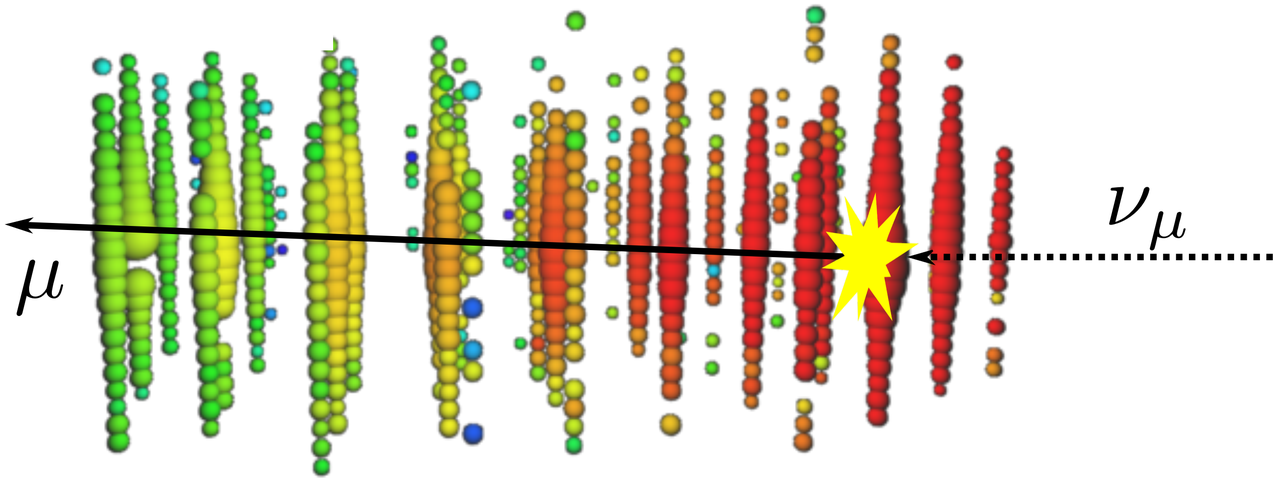


icecube.wisc.edu

Track

- ν_μ charged current (CC)





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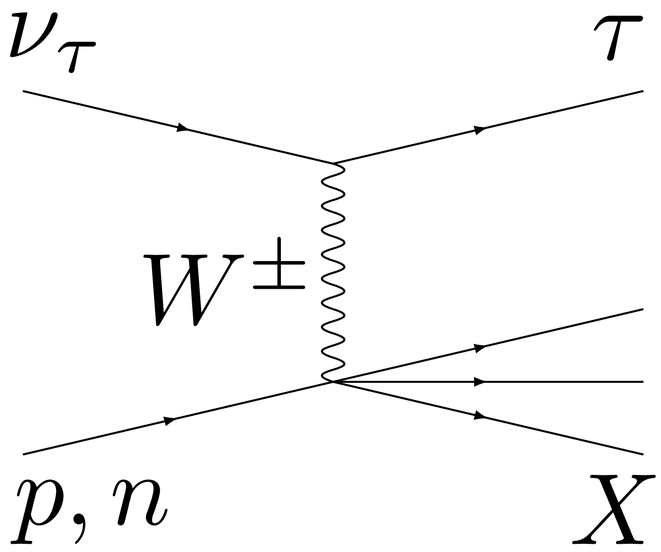
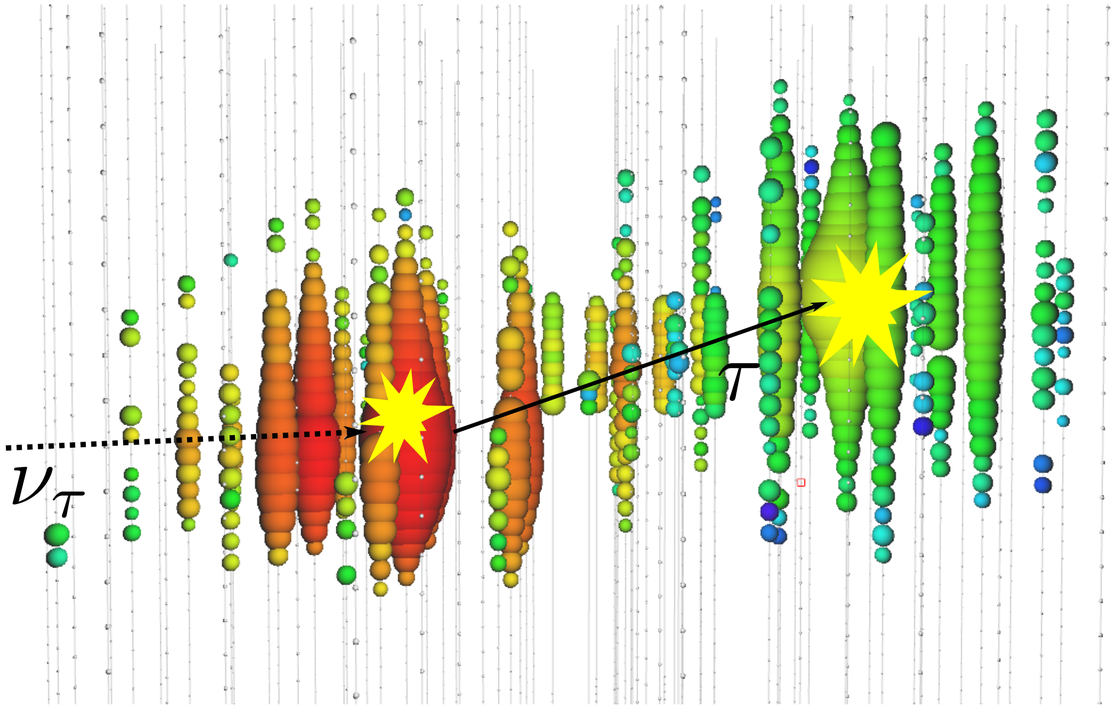
Double bang

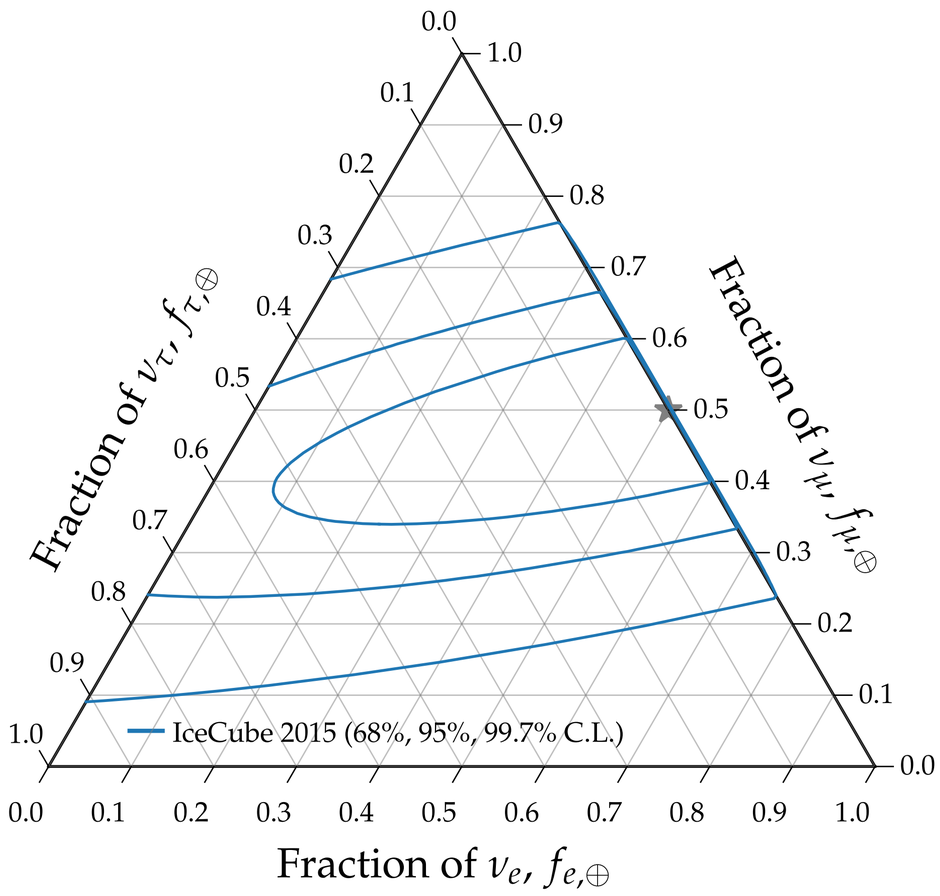
- High-E ν_τ charged current (CC)





icecube.wisc.edu

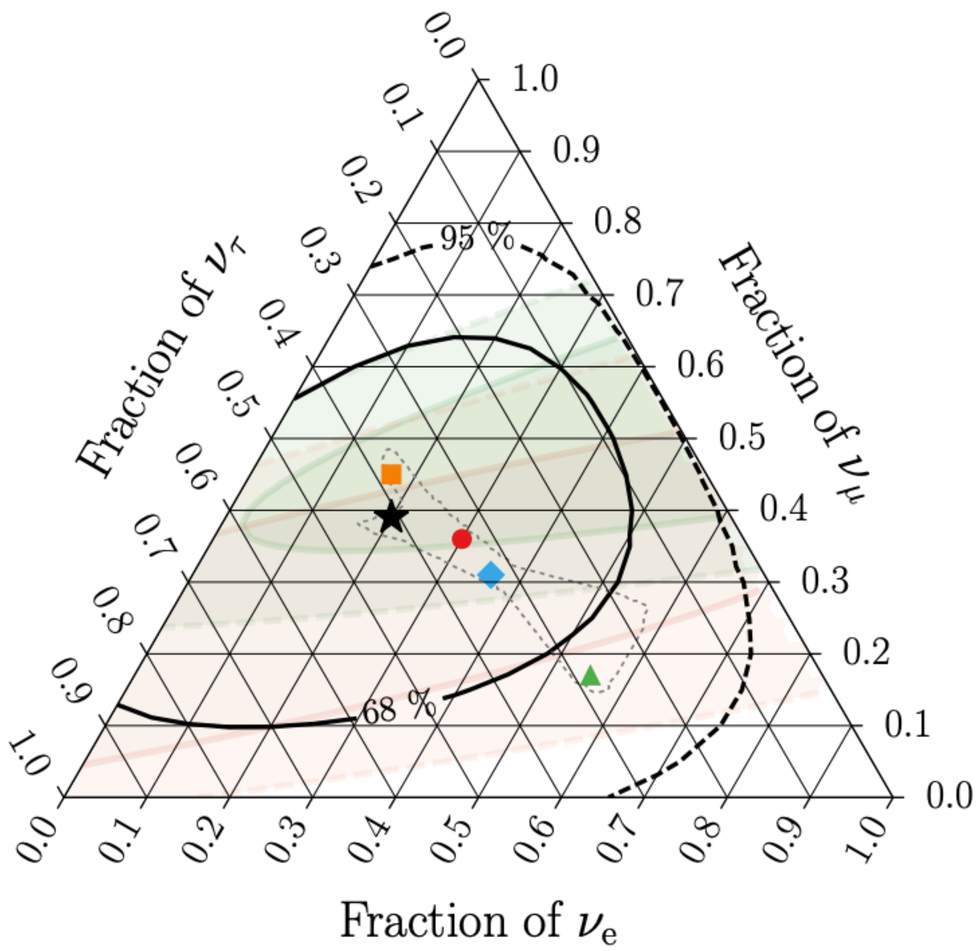
Where We Are

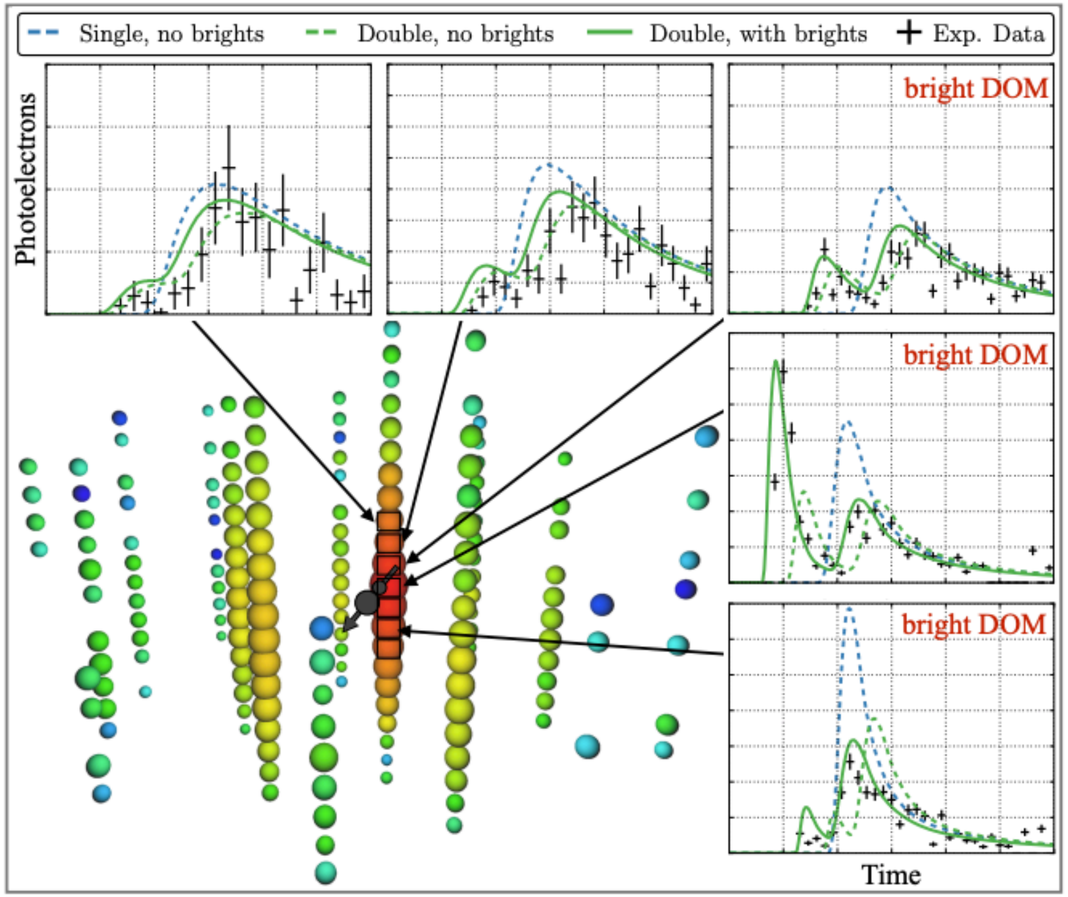


IceCube Collaboration, 1507.03991

Double Cascades

IceCube Collaboration, 2011.03561





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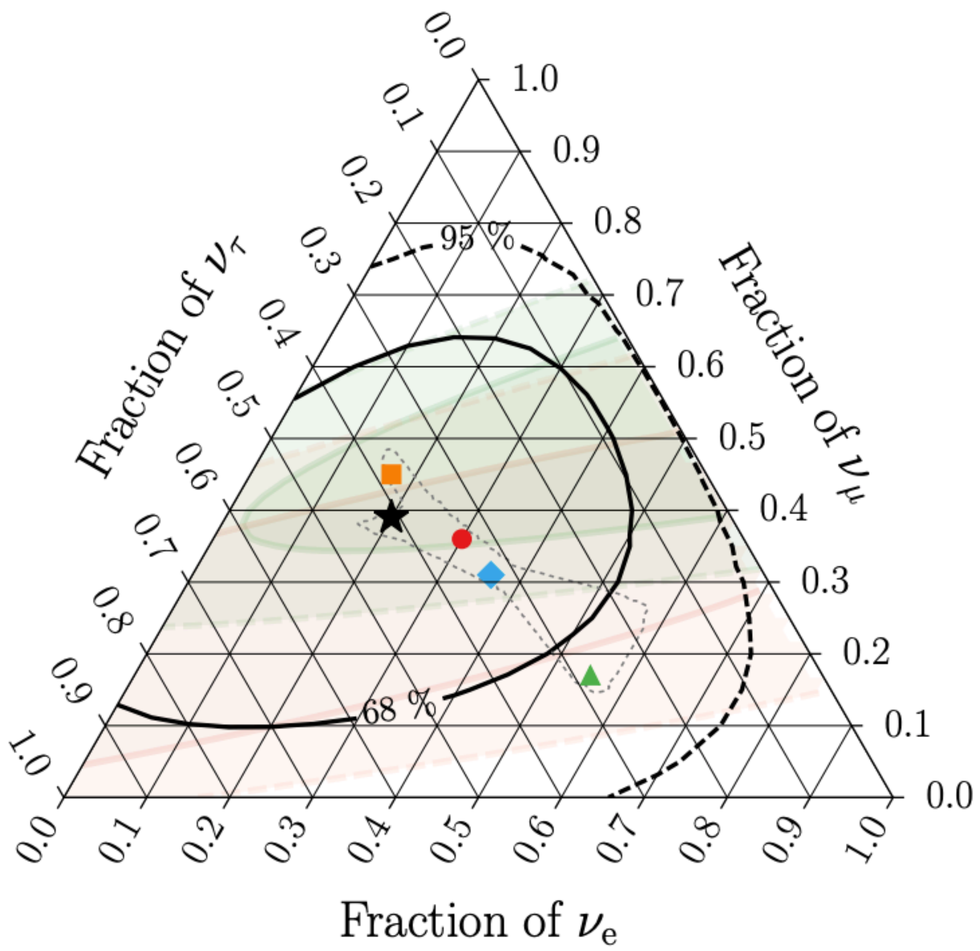


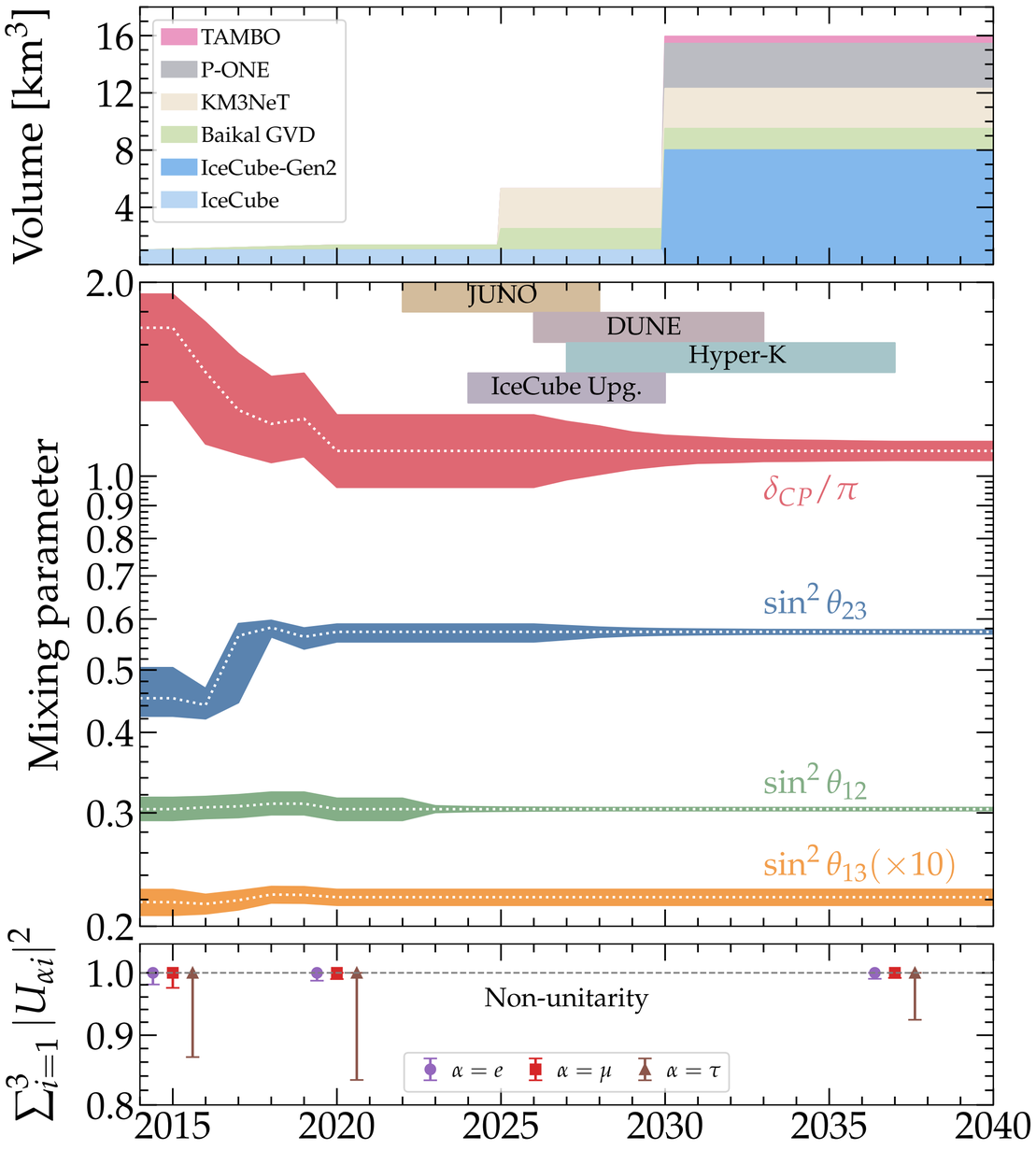
IceCube Collaboration, 2011.03561

NuFIT 5.0 (2020)

		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 2.7$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
without SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.78}_{-0.75}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.570^{+0.018}_{-0.024}$	$0.407 \to 0.618$	$0.575^{+0.017}_{-0.021}$	$0.411 \to 0.621$
	$\theta_{23}/^\circ$	$49.0^{+1.1}_{-1.4}$	$39.6 \to 51.8$	$49.3^{+1.0}_{-1.2}$	$39.9 \to 52.0$
	$\sin^2\theta_{13}$	$0.02221^{+0.00068}_{-0.00062}$	$0.02034 \to 0.02430$	$0.02240^{+0.00062}_{-0.00062}$	$0.02053 \to 0.02436$
	$\theta_{13}/^\circ$	$8.57^{+0.13}_{-0.12}$	$8.20 \to 8.97$	$8.61^{+0.12}_{-0.12}$	$8.24 \to 8.98$
	$\delta_{CP}/^\circ$	195^{+51}_{-25}	$107 \to 403$	286^{+27}_{-32}	$192 \to 360$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.514^{+0.028}_{-0.027}$	$+2.431 \to +2.598$	$-2.497^{+0.028}_{-0.028}$	$-2.583 \to -2.412$
		Normal Ordering (best fit)		Inverted Ordering ($\Delta\chi^2 = 7.1$)	
		bfp $\pm 1\sigma$	3σ range	bfp $\pm 1\sigma$	3σ range
with SK atmospheric data	$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	$0.269 \to 0.343$	$0.304^{+0.013}_{-0.012}$	$0.269 \to 0.343$
	$\theta_{12}/^\circ$	$33.44^{+0.77}_{-0.74}$	$31.27 \to 35.86$	$33.45^{+0.78}_{-0.75}$	$31.27 \to 35.87$
	$\sin^2\theta_{23}$	$0.573^{+0.016}_{-0.020}$	$0.415 \to 0.616$	$0.575^{+0.016}_{-0.019}$	$0.419 \to 0.617$
	$\theta_{23}/^\circ$	$49.2^{+0.9}_{-1.2}$	$40.1 \to 51.7$	$49.3^{+0.9}_{-1.1}$	$40.3 \to 51.8$
	$\sin^2\theta_{13}$	$0.02219^{+0.00062}_{-0.00063}$	$0.02032 \to 0.02410$	$0.02238^{+0.00063}_{-0.00062}$	$0.02052 \to 0.02428$
	$\theta_{13}/^\circ$	$8.57^{+0.12}_{-0.12}$	$8.20 \to 8.93$	$8.60^{+0.12}_{-0.12}$	$8.24 \to 8.96$
	$\delta_{CP}/^\circ$	197^{+27}_{-24}	$120 \to 369$	282^{+26}_{-30}	$193 \to 352$
	$\frac{\Delta m^2_{21}}{10^{-5}\ \mathrm{eV}^2}$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$	$7.42^{+0.21}_{-0.20}$	$6.82 \to 8.04$
	$\frac{\Delta m^2_{3\ell}}{10^{-3}\ \mathrm{eV}^2}$	$+2.517^{+0.026}_{-0.028}$	$+2.435 \to +2.598$	$-2.498^{+0.028}_{-0.028}$	$-2.581 \to -2.414$

Esteban, Gonzalez-Garcia, Maltoni, Schwetz, Zhou, 2007.14792

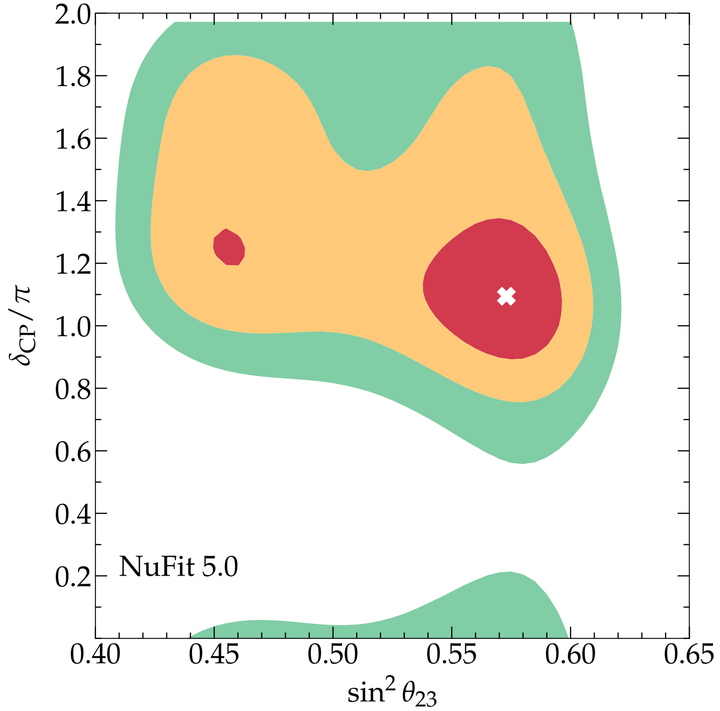
What We Expect

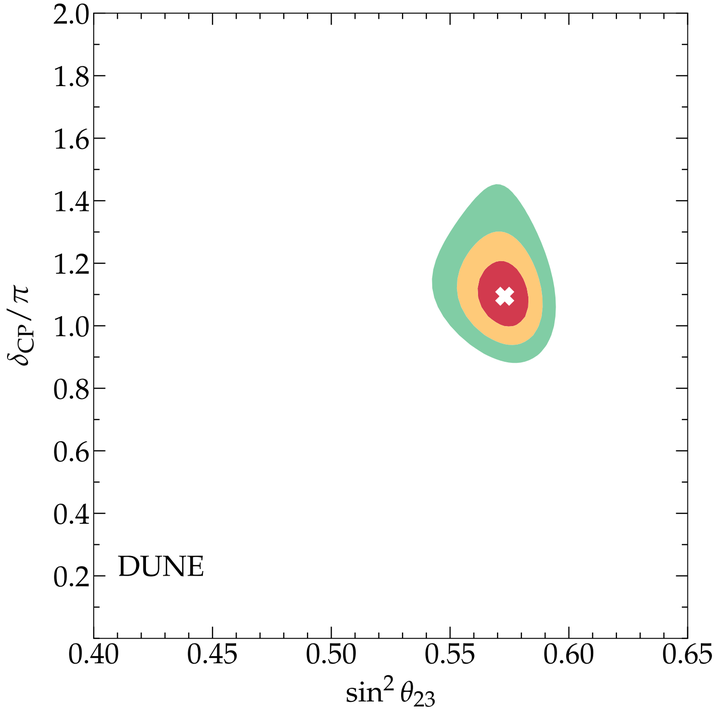


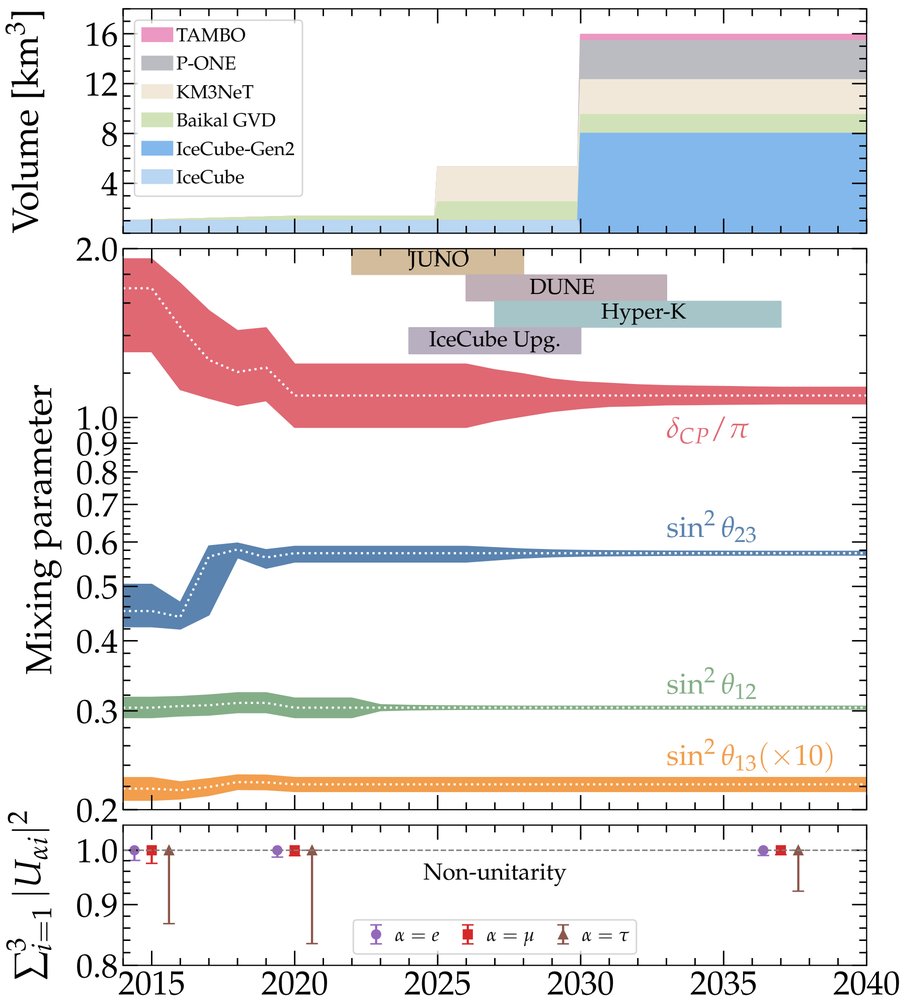
NS, Li, Argüelles, Bustamante, Vincent, 2012.xxxxx

What We Expect

- More precise oscillation parameters: JUNO, DUNE, Hyper-K







NS, Li, Argüelles, Bustamante, Vincent, 2012.xxxxx

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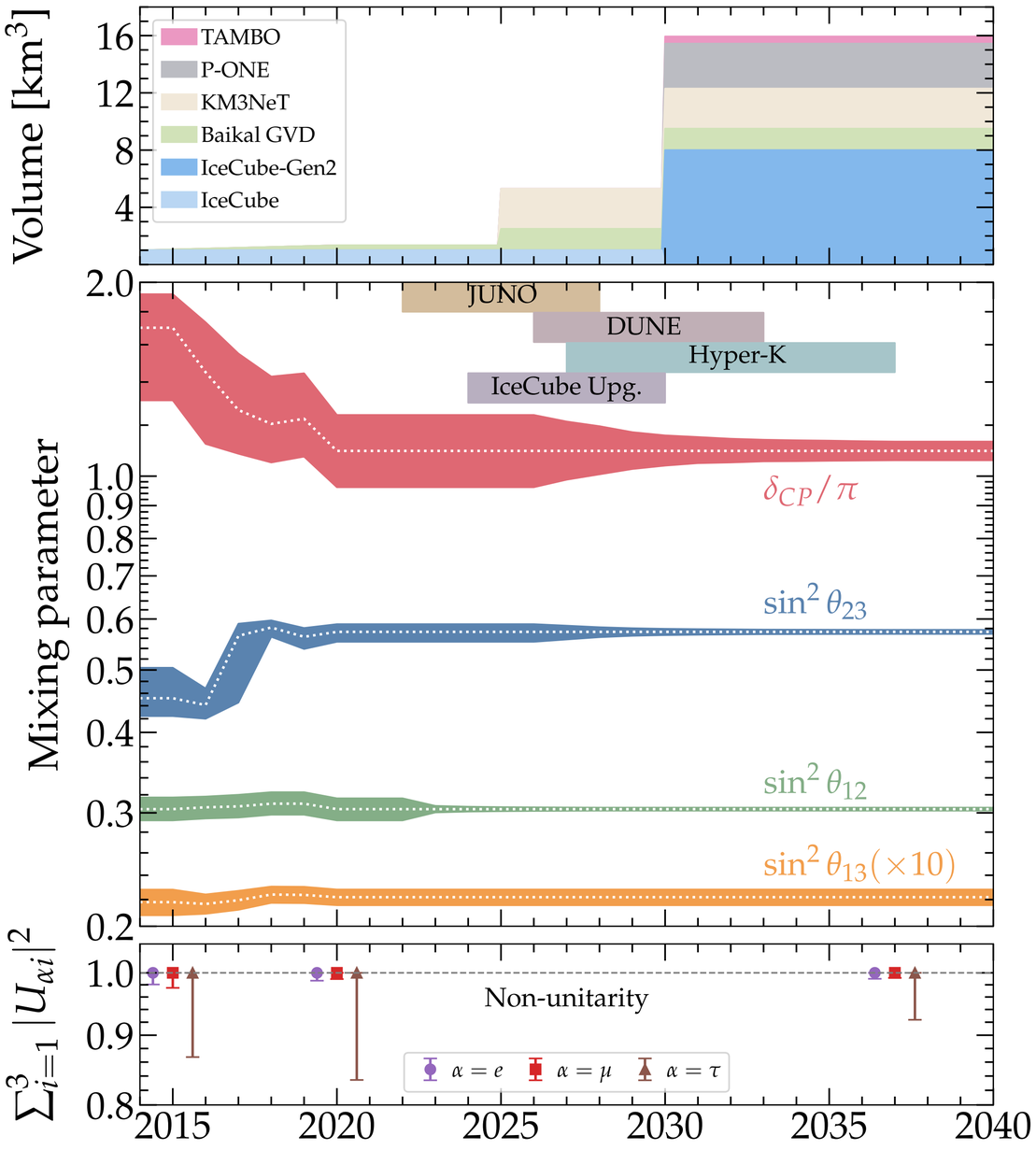
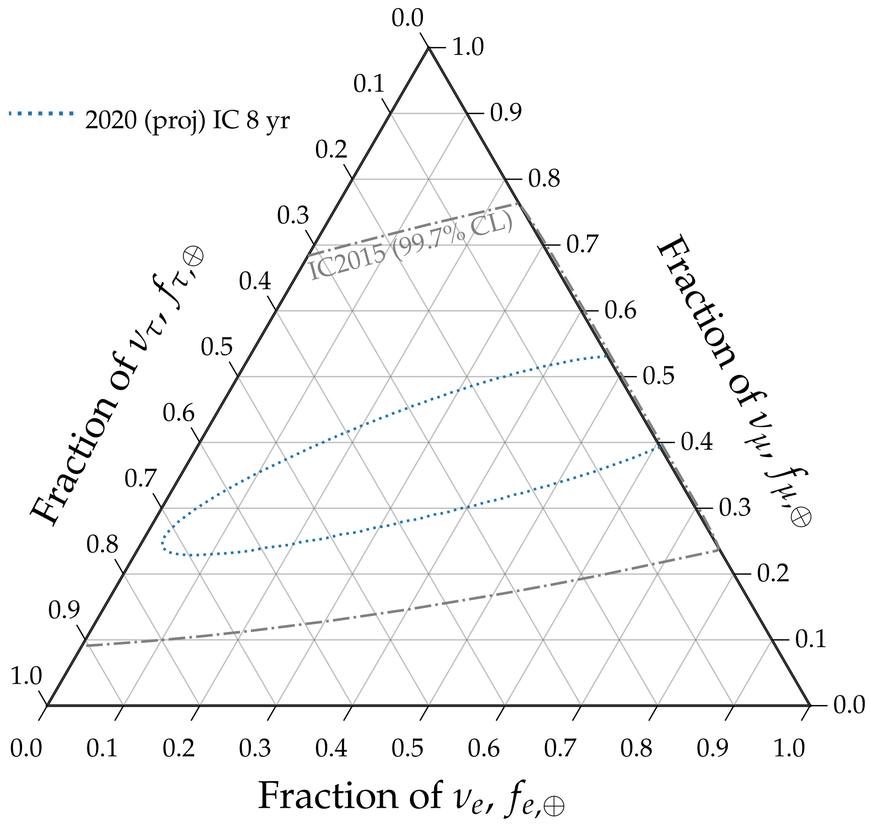


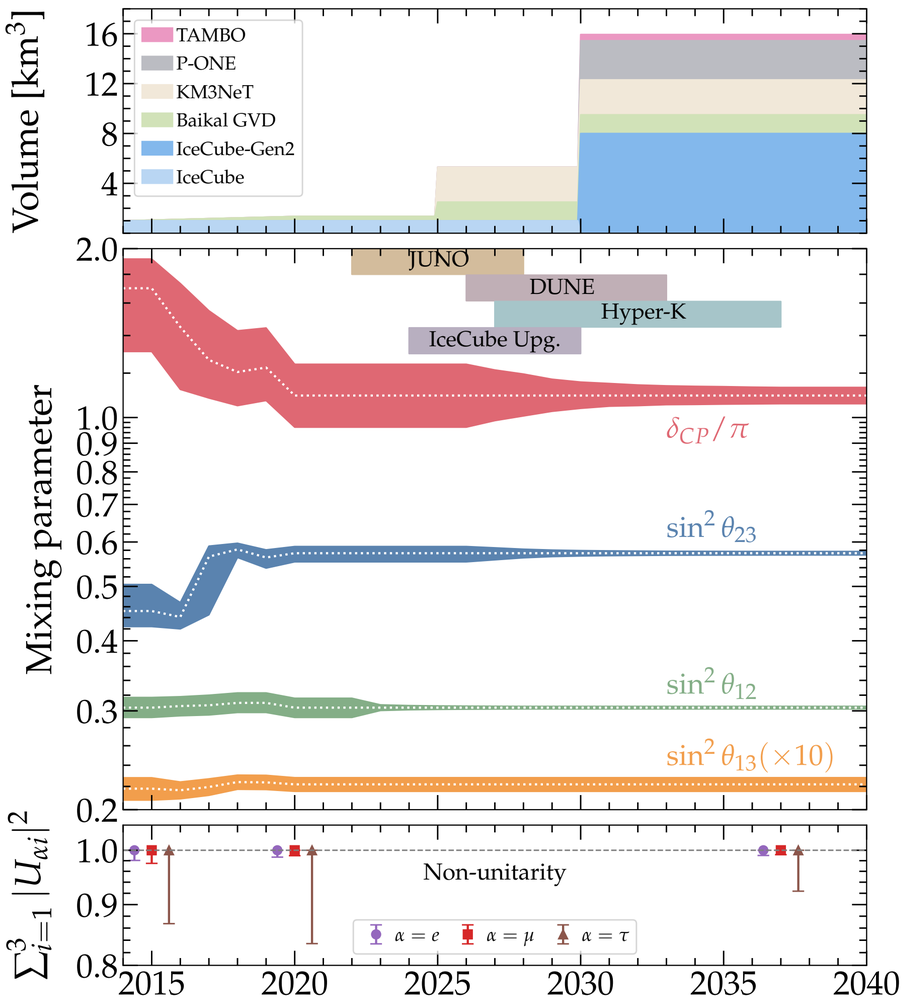
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots \\ U_{\tau} & U_{\tau 2} & U_{\tau 3} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

NS, Li, Argüelles, Bustamante, Vincent, 2012.xxxxx

What We Expect

- Better flavor measurement: Gen2, P-ONE, KM3NeT, GVD, TAMBO





NS, Li, Argüelles, Bustamante, Vincent, 2012.xxxxx

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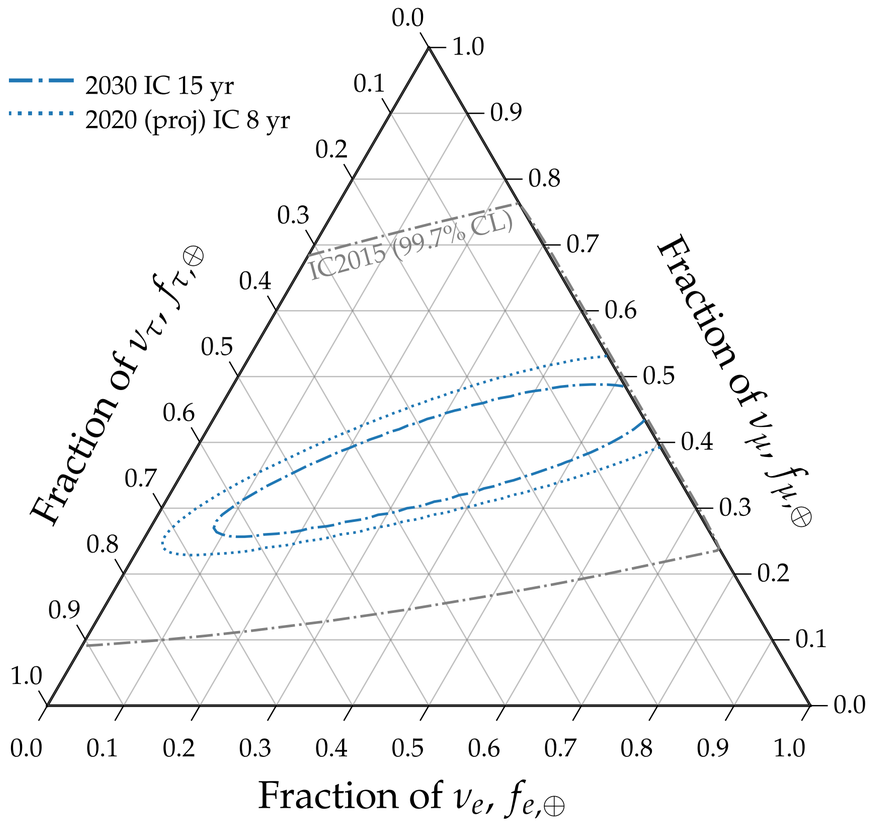

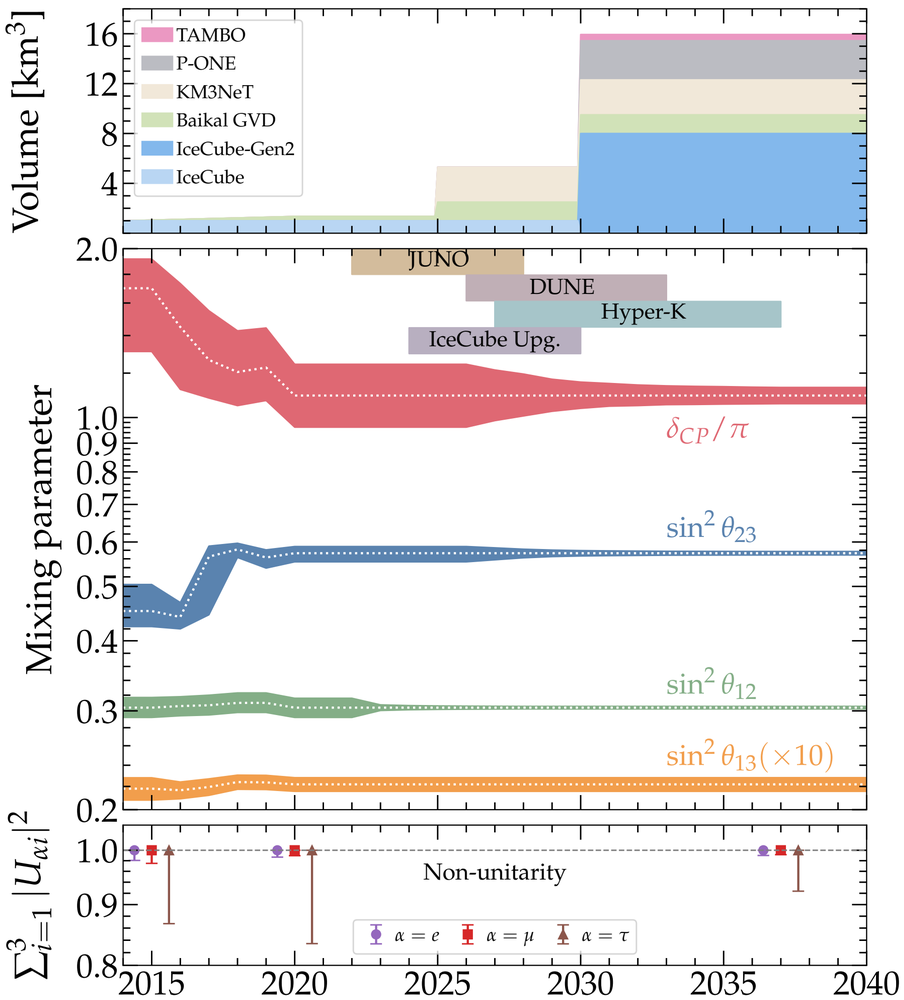

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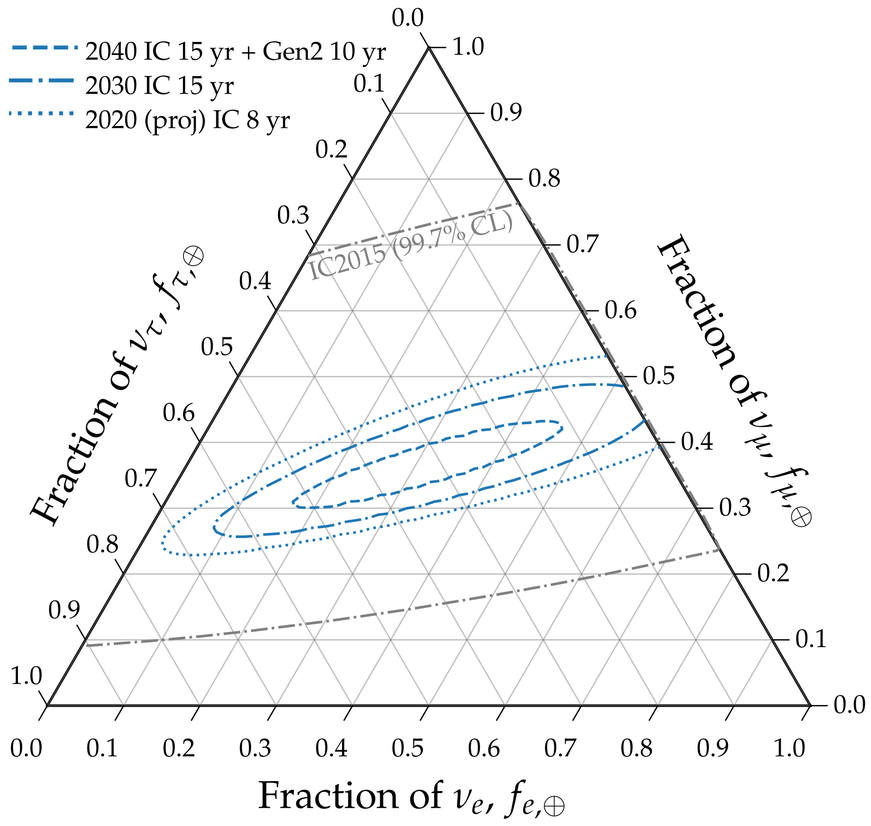

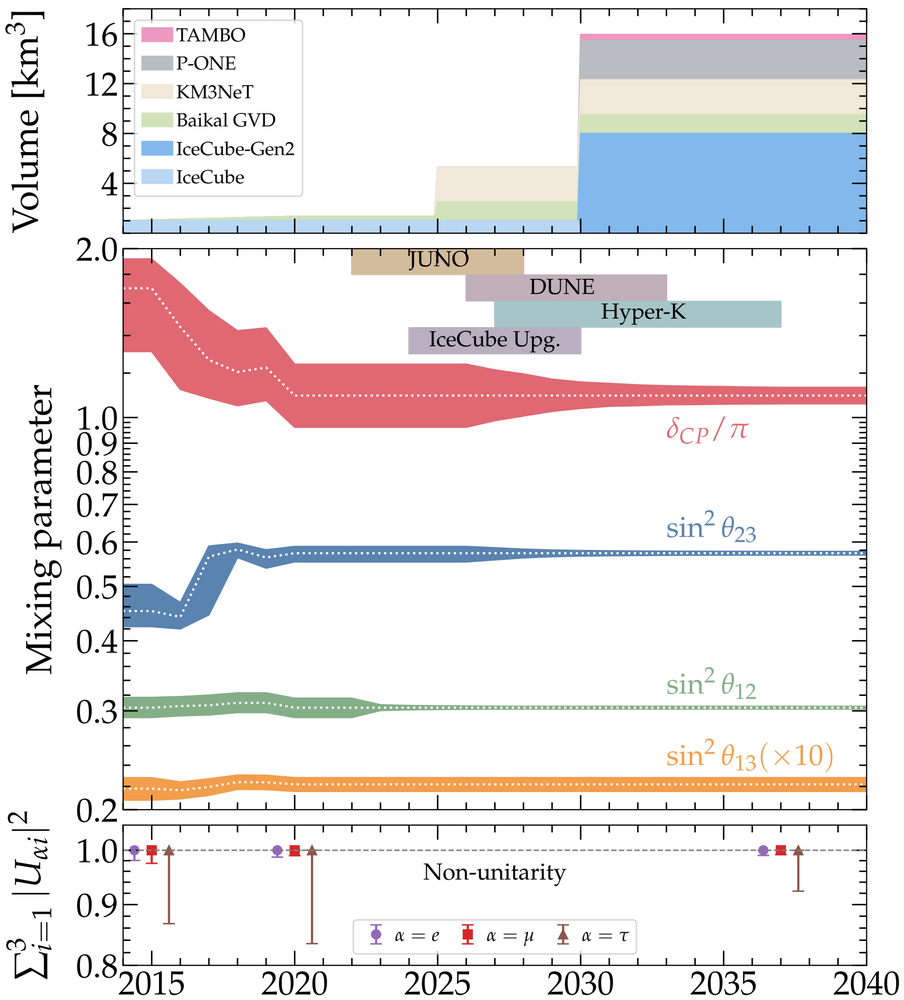

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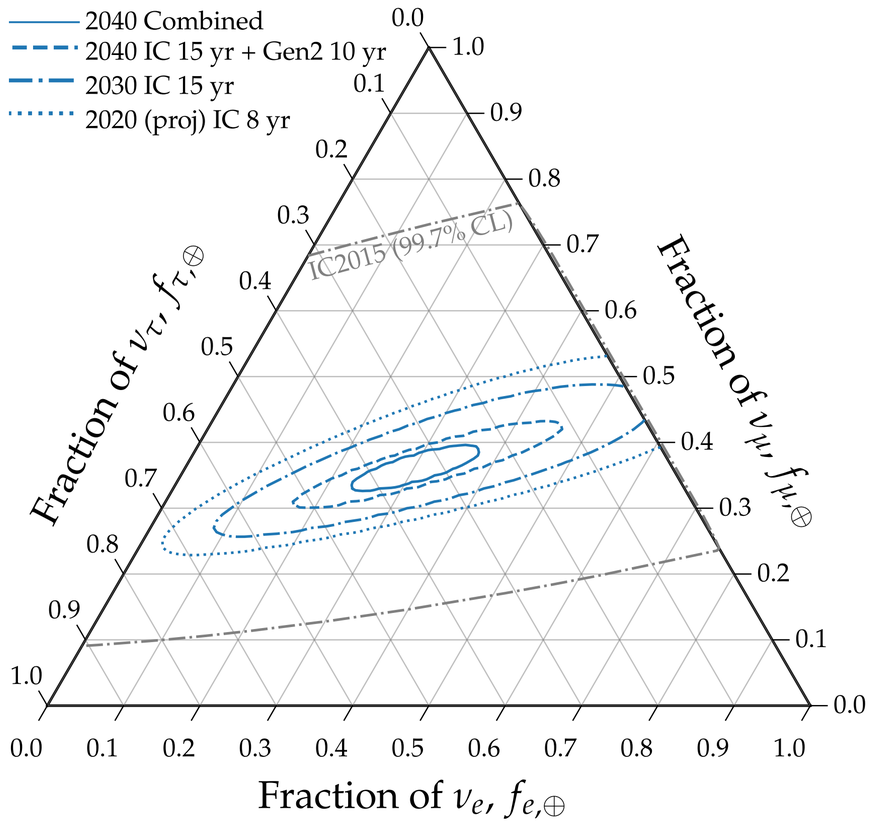
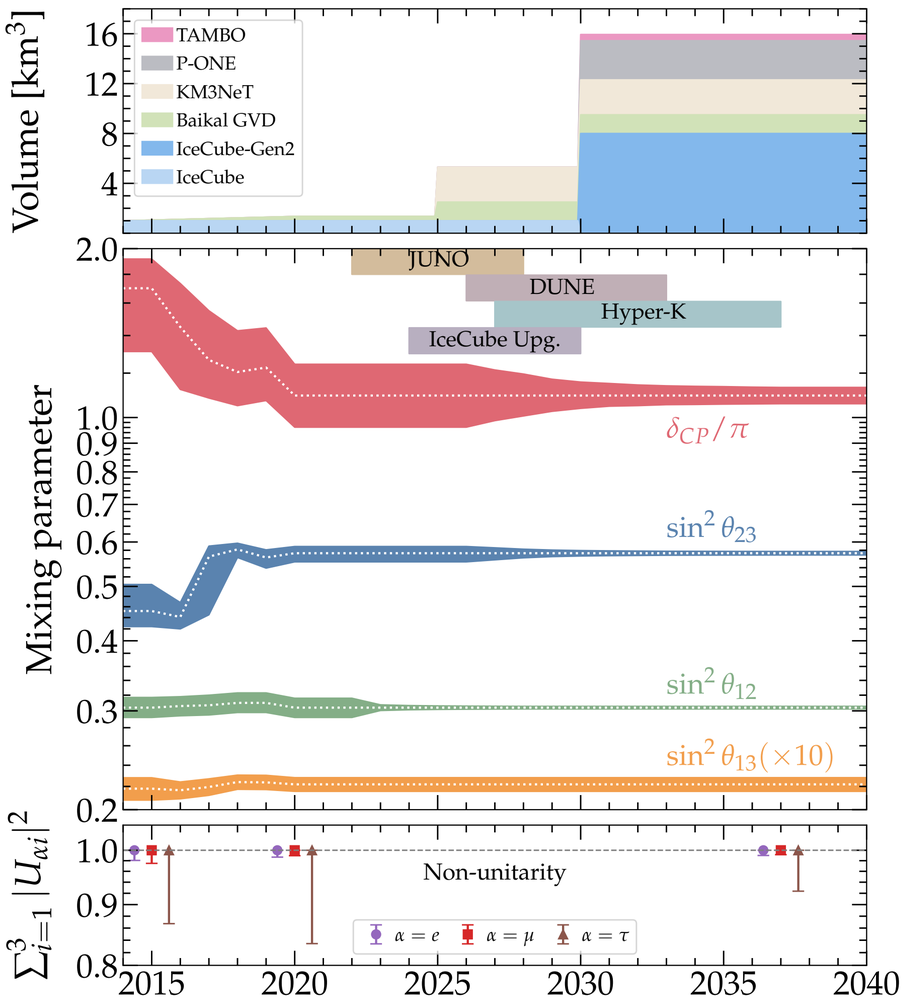
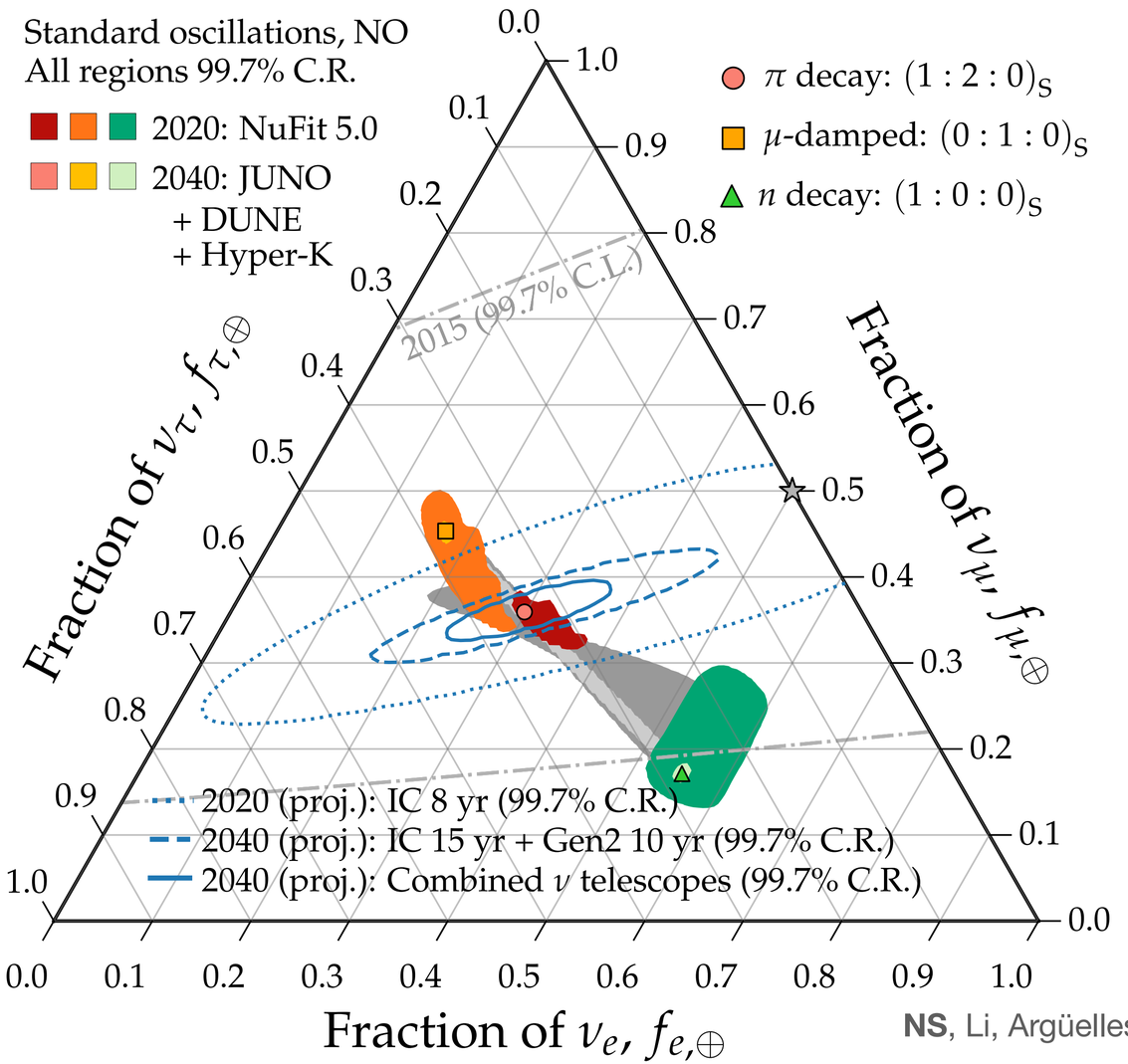




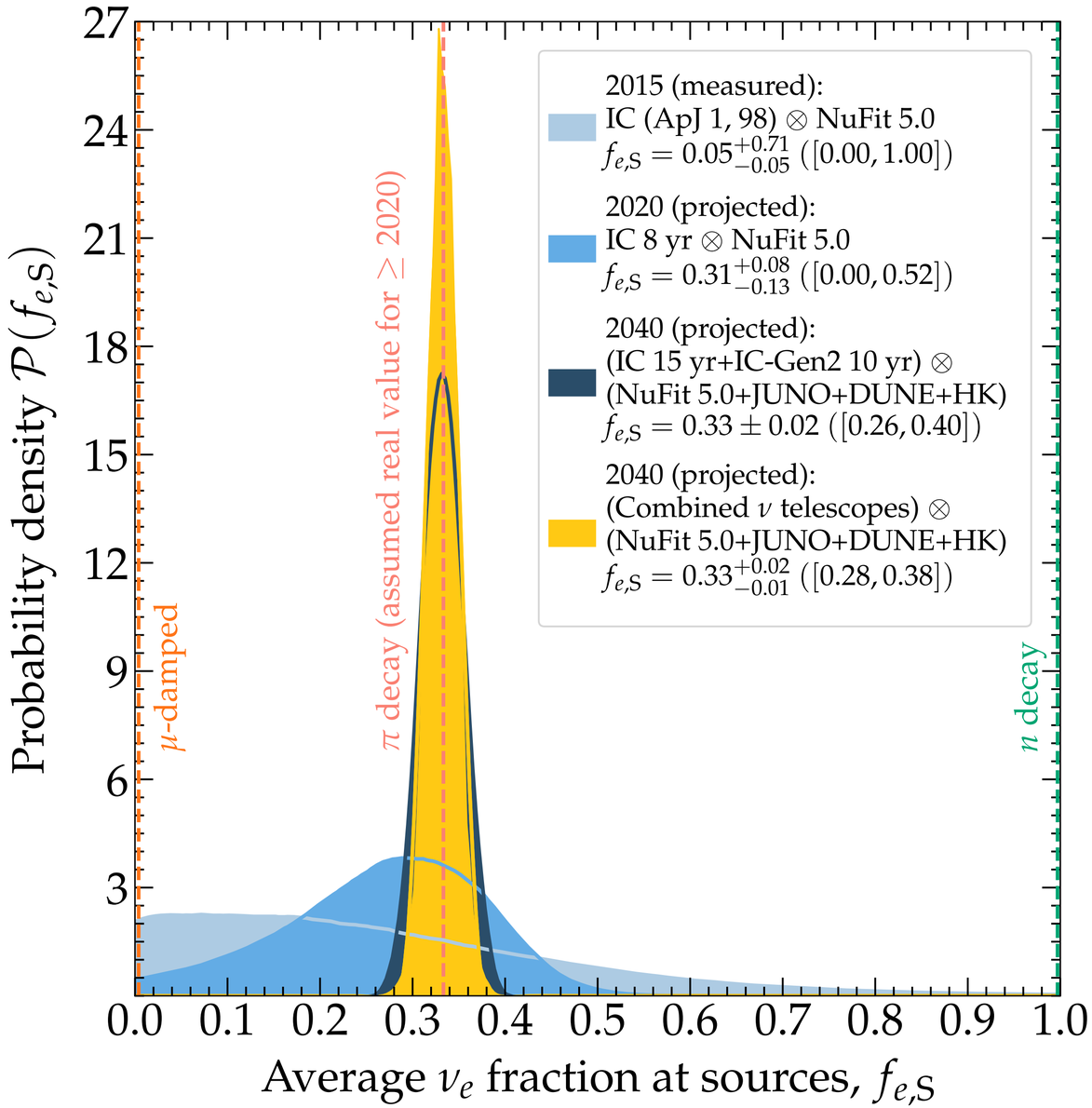
NS, Li, Argüelles, Bustamante, Vincent, 2012.xxxxx

Flavor Composition at Earth



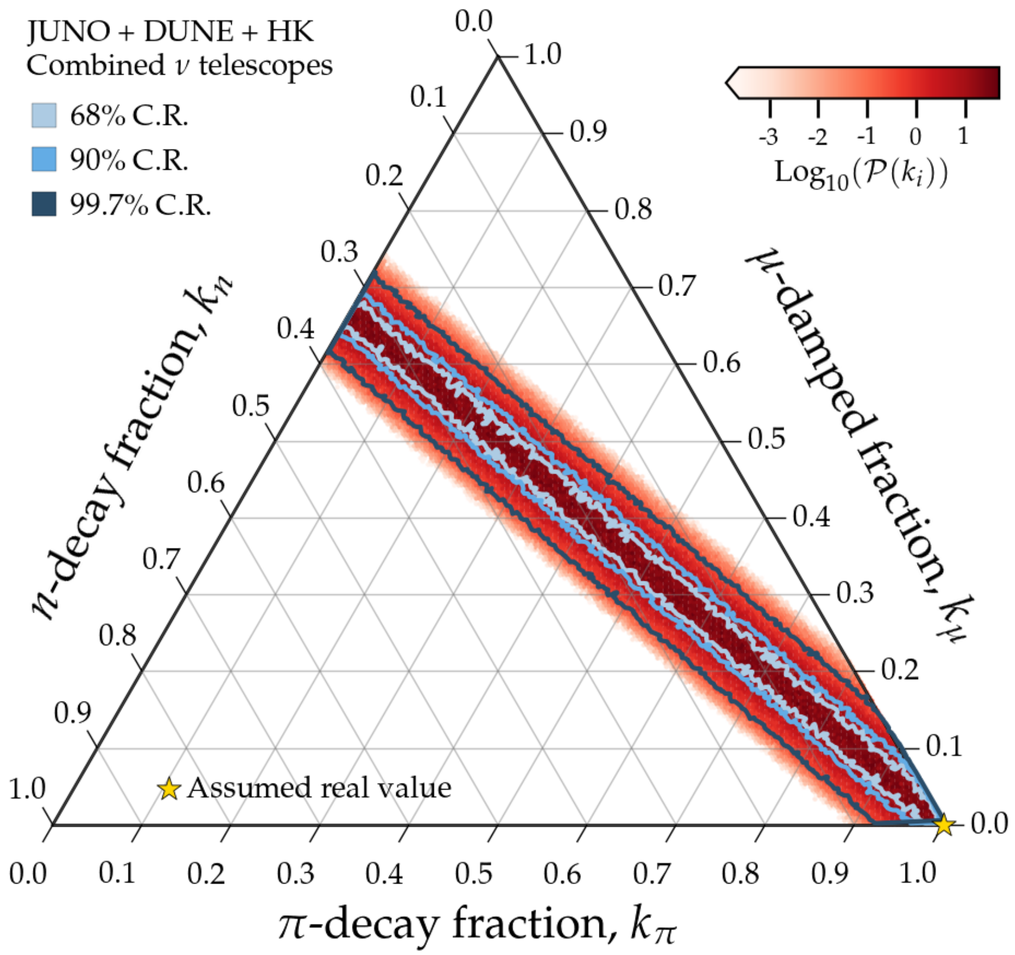
NS, Li, Argüelles, Bustamante, Vincent, 2012.xxxxx

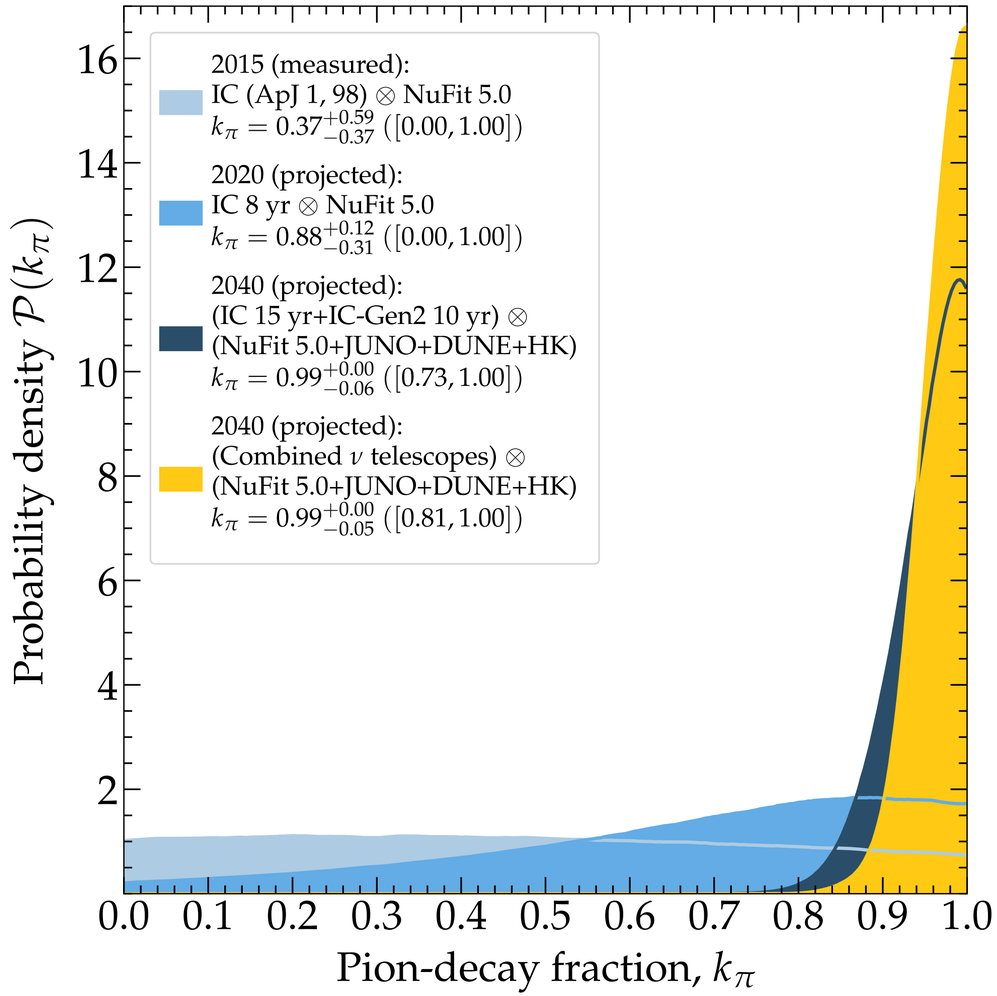
Flavor Composition at Source



NS, Li, Argüelles, Bustamante, Vincent, 2012.xxxxx

Flavor Composition at Source





NS, Li, Argüelles, Bustamante, Vincent, 2012.xxxxx

Leptonic Non-unitarity

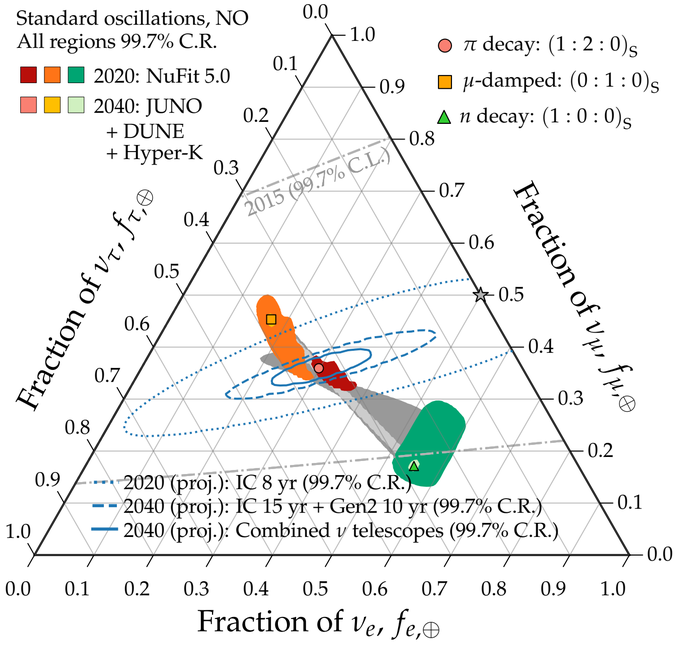
- Assuming non-unitarity

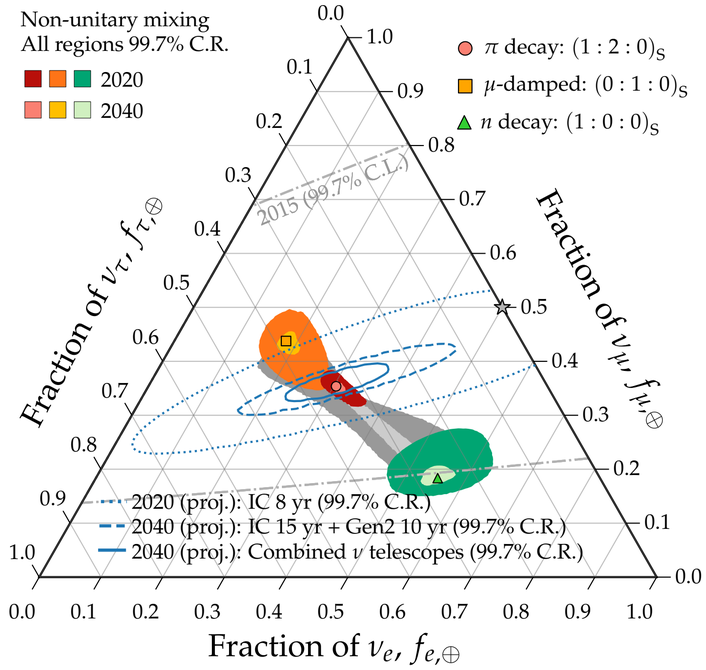
$$U = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} & \cdots \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} & \cdots \\ U_{\tau} & U_{\tau 2} & U_{\tau 3} & \cdots \\ \vdots & \vdots & \vdots & \ddots \end{pmatrix}$$

- Oscillation probability

$$P^{\rm NU}_{\alpha\beta} = \frac{1}{N_\alpha N_\beta} \sum_{i=1}^{3} |U_{\alpha i}|^2 |U_{\beta i}|^2$$

$$N_\alpha \equiv \sum_{i=1}^{3} |U_{\alpha i}|^2$$

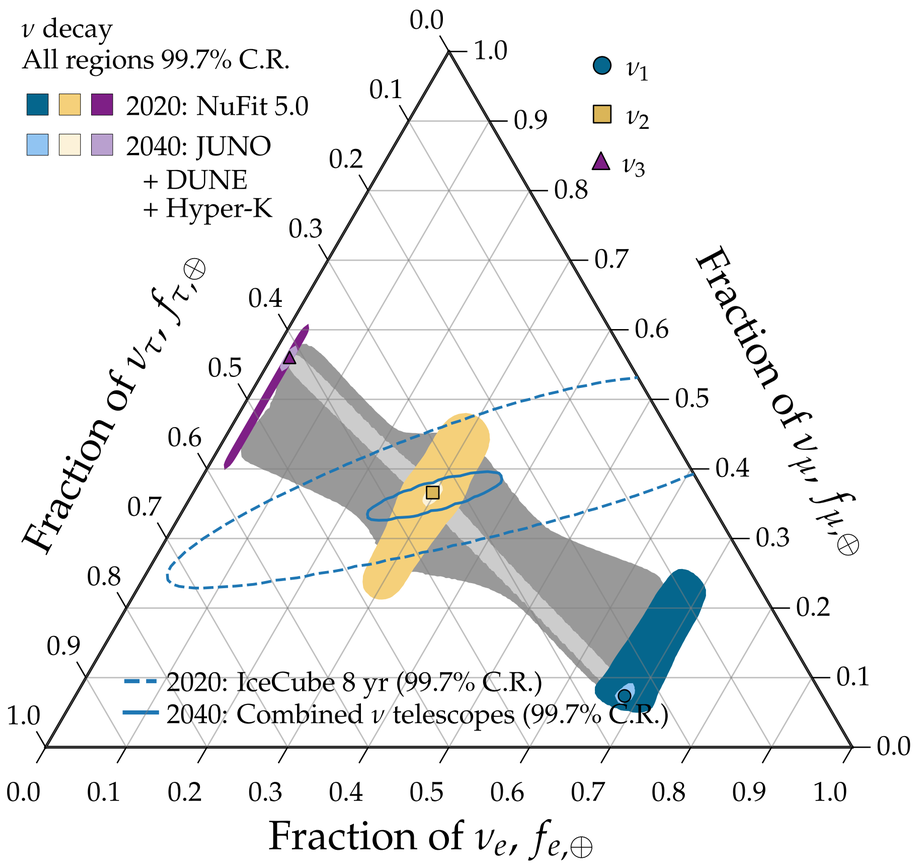


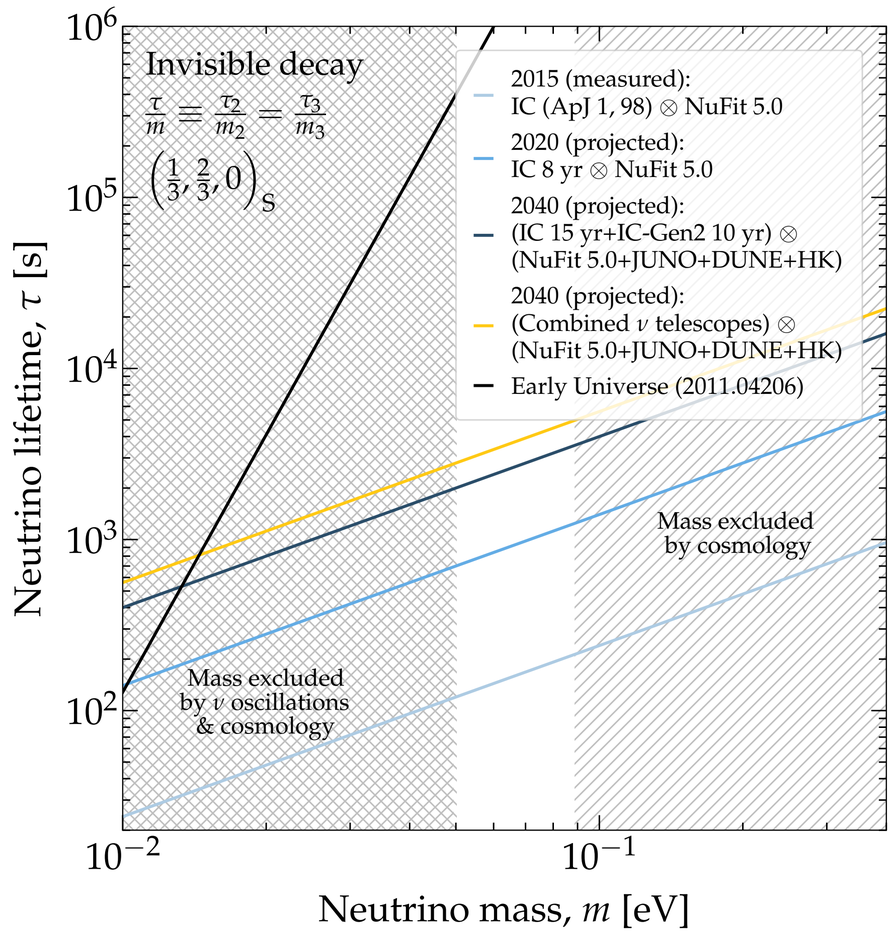


NS, Li, Argüelles, Bustamante, Vincent, 2012.xxxxx

Neutrino Decay

ν telescopes $\otimes$ oscillation experiments	m_ν/τ_ν (eV s^{-1})
2015 (measured): IC $\otimes$ NuFit 5.0	4.1×10^{-4}
2020 (projected): IC 8 yr $\otimes$ NuFit 5.0	7.4×10^{-5}
2040 (projected): IC 15 yr + IC-Gen2 10 yr $\otimes$ (NuFit 5.0 + JUNO + DUNE + HK)	2.5×10^{-5}
2040 (projected): All ν telescopes $\otimes$ (NuFit 5.0 + JUNO + DUNE + HK)	1.8×10^{-5}

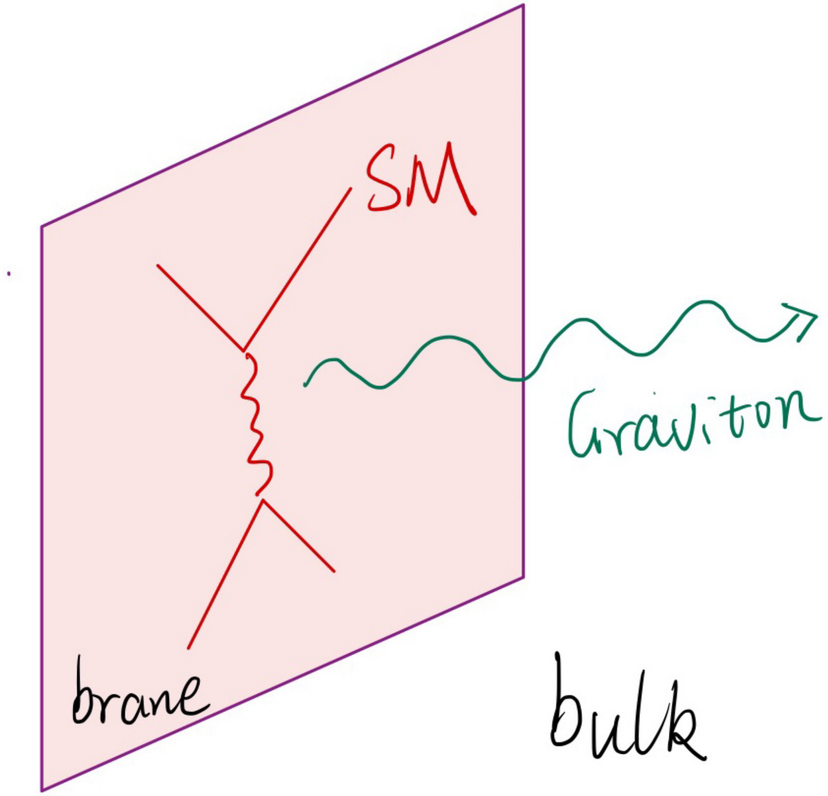




NS, Li, Argüelles, Bustamante, Vincent, 2012.xxxxx

Large Extra Dimensions (LEDs)

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



Arkani-Hamed, Dimopoulos, Dvali, PRD 1998

Large Extra Dimensions (LEDs)

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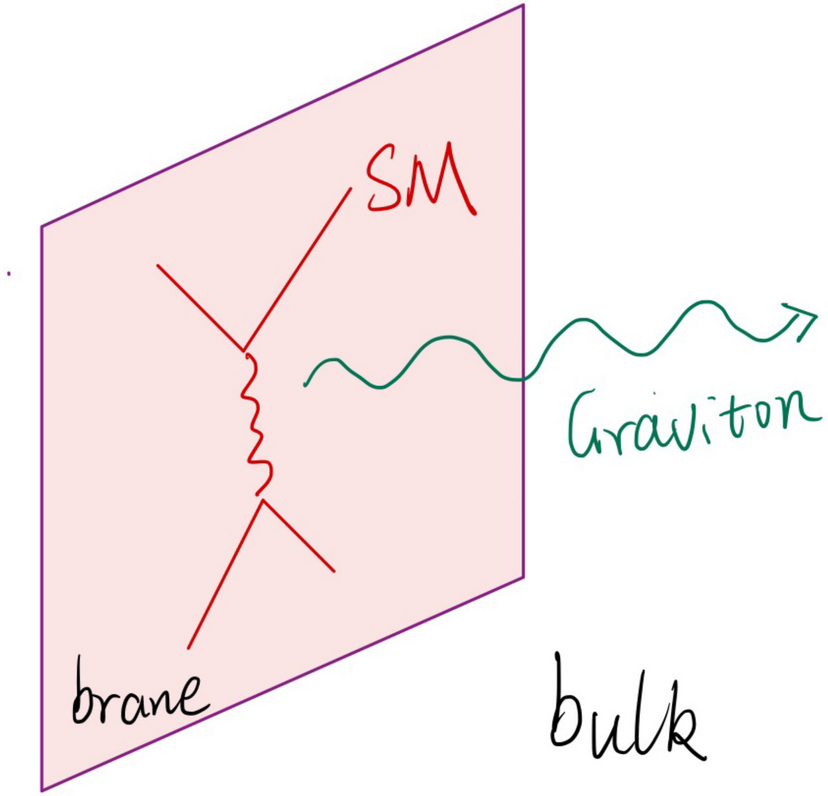
- Gravitons can propagate in the 3+n D "bulk"

Gravitational potential

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

Match two conditions at $r \sim R$

$$\boxed{M_{pl}^2 \sim M_\star^{2+n} R^n}$$



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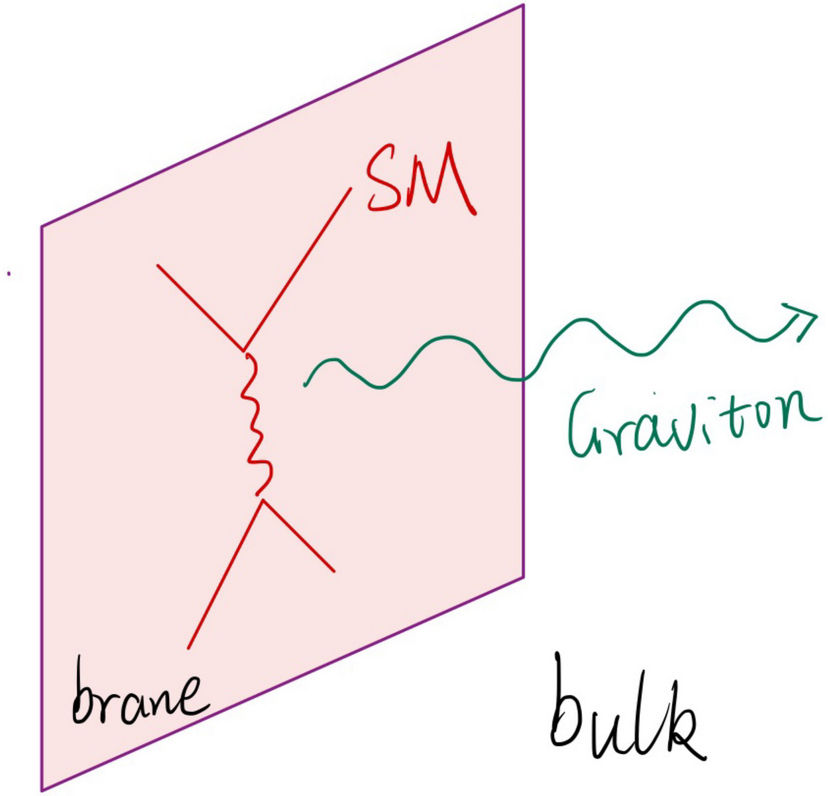
Match two conditions at $r \sim R$

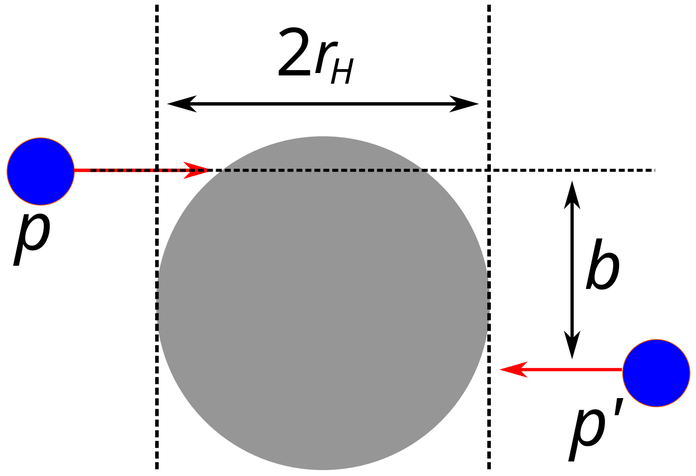
$$\boxed{M_{pl}^2 \sim M_\star^{2+n} R^n}$$

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



Arkani-Hamed, Dimopoulos, Dvali, PRD 1998

Microscopic Black Holes and Hoop conjecture

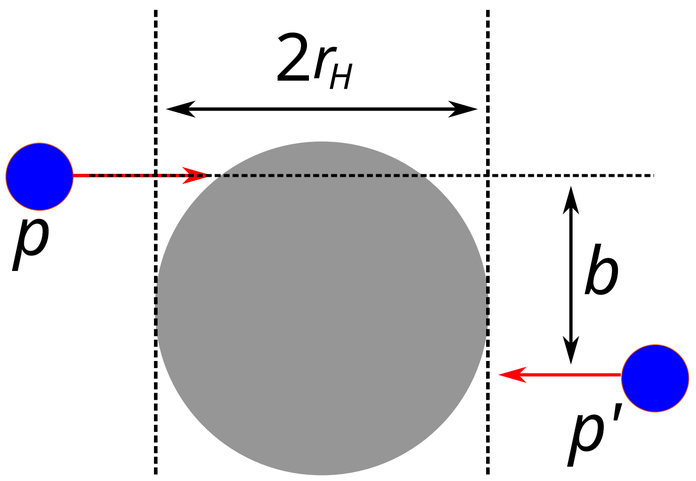


- BH production only allowed if the impact parameter

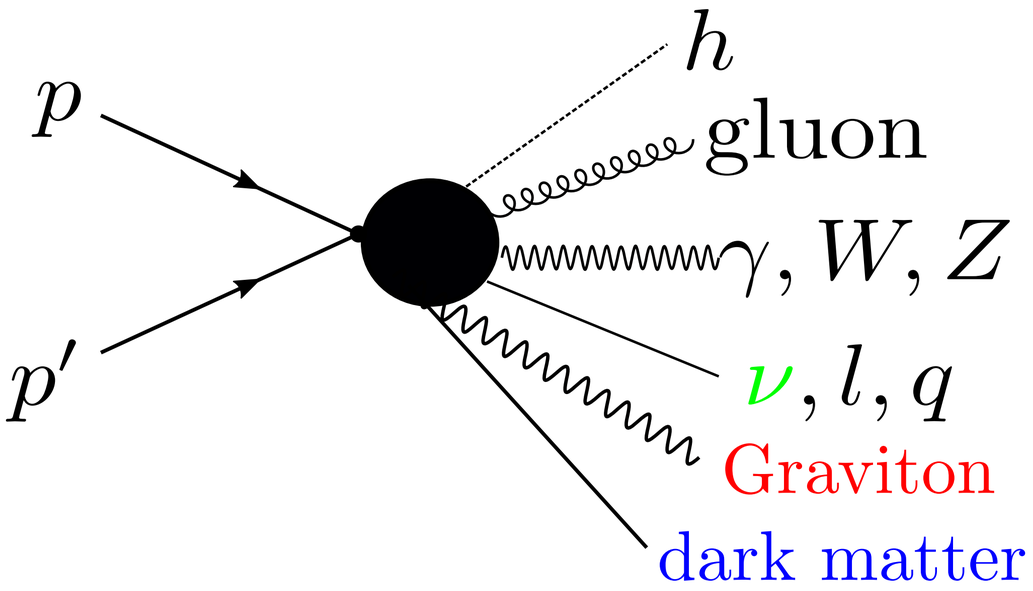
$$\boxed{b \leq b_{\max} = 2r_H(E_{\mathrm{CM}}, n, M_\star)}$$

Microscopic Black Holes and Hoop conjecture

- BH production allowed if $b < b_{\max}$ or $E_{cm} \gtrsim M_\star$
- BHs can be produced in high energy particle collisions:
  - Cosmic neutrino-nucleon scattering
  - pp collision in FCC
  - High energy cosmic ray detection
  - Cosmic ray-cosmic ray collision
  - Hot plasma in the early Universe
  - …



Hawking radiation



- BHs decay to all possible degree of freedom

Mack, McNees' 2018

Current Limits

- $n = 1$ excluded by solar-scale gravity
- LHC exclude $M_\star > 5 \sim 10$ TeV depending on n
- $E_{CM} = 5\ \text{TeV} = \sqrt{2m_p E_\nu} \Rightarrow E_\nu \simeq 13\ \text{PeV}$

n=1 killed

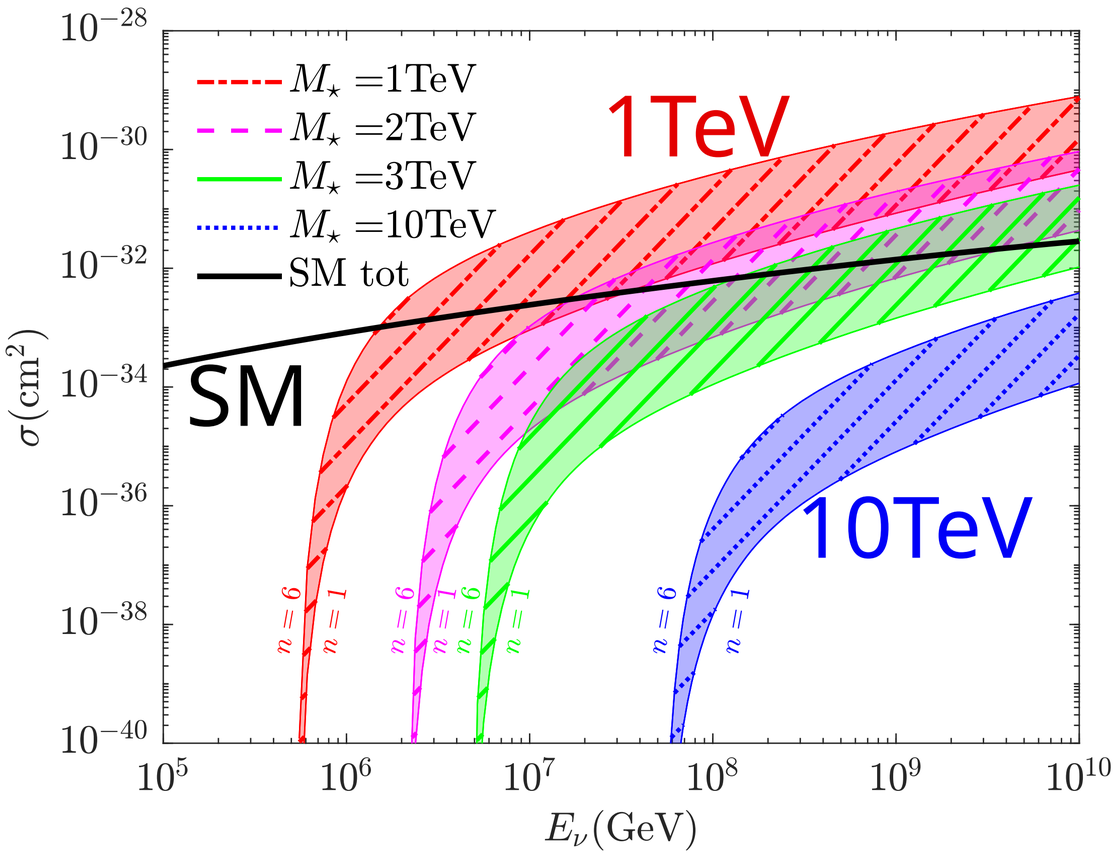
extra dimensions

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	$M_\star > 5 \sim 10$ TeV
		5	12.8	
		6	12.7	

Mack, McNees, 1809.05089

Black Hole Production Cross Section

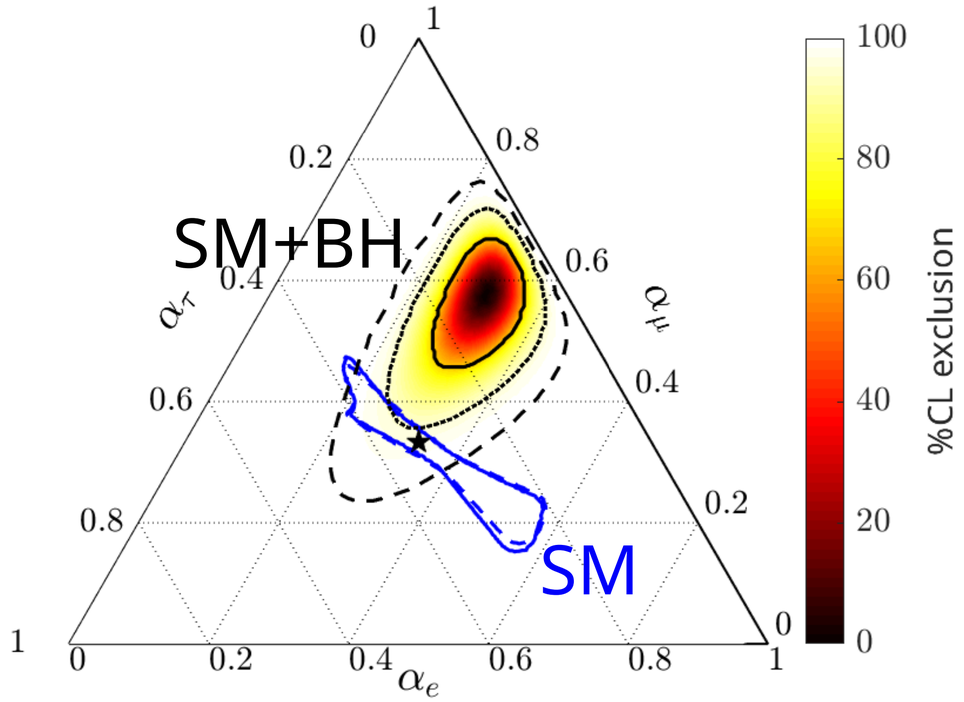


Mack, **NS**, Vincent, JHEP 2019/1912.06656

- 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

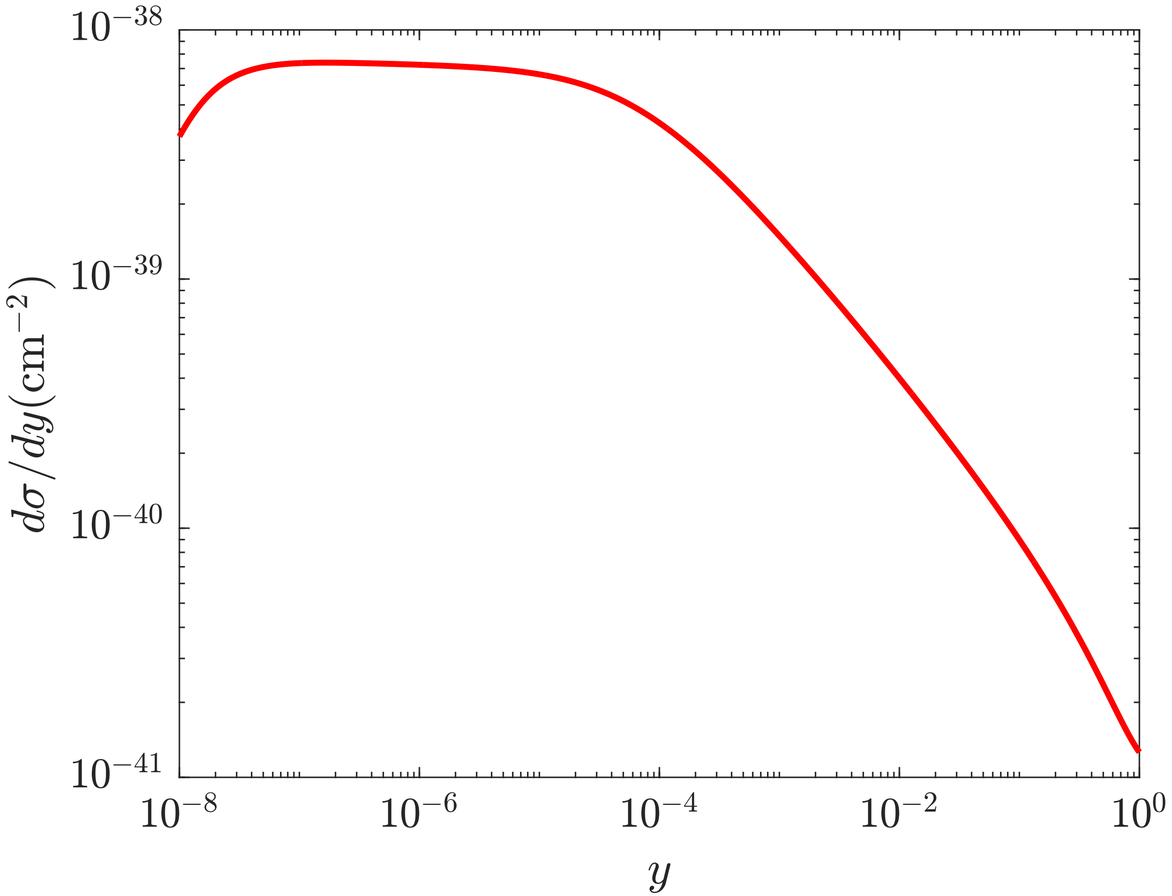
- more events expected from the same flux if $M_\star = 3$ TeV
- more tracks from μ, τ
- rarer double bang due to energy asymmetry condition



Mack, **NS**, Vincent, JHEP 2019/1912.06656

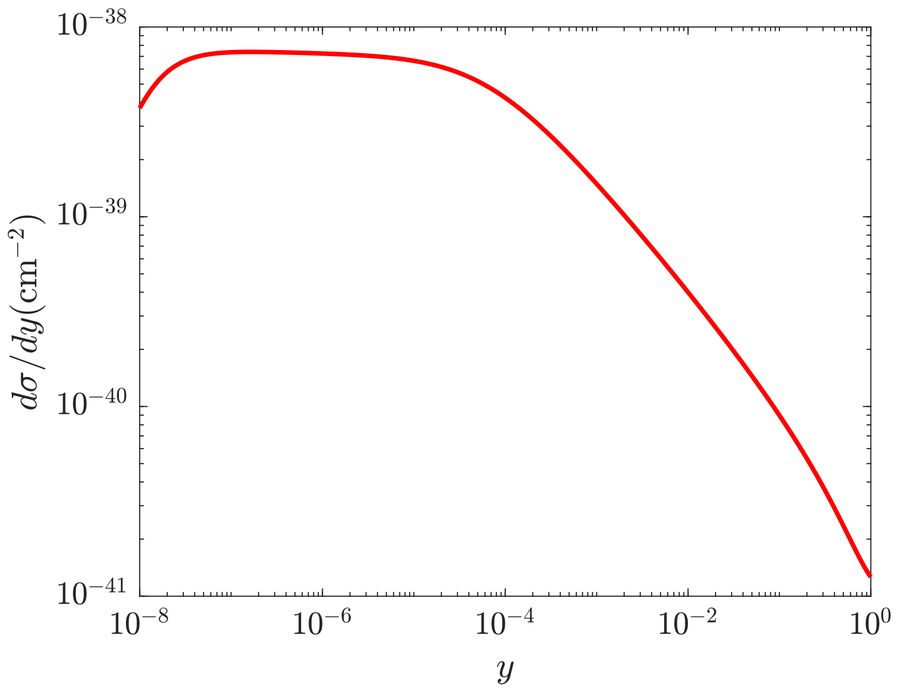
	shower	track	double bang
ν_e SM	28.58	0	0
ν_μ SM	2.31	8.31	0
ν_τ SM	5.07	5.39	2.83
All Flavor Total SM	35.96	13.70	2.83
All Flavor Total BH	62.96	36.36	0.20

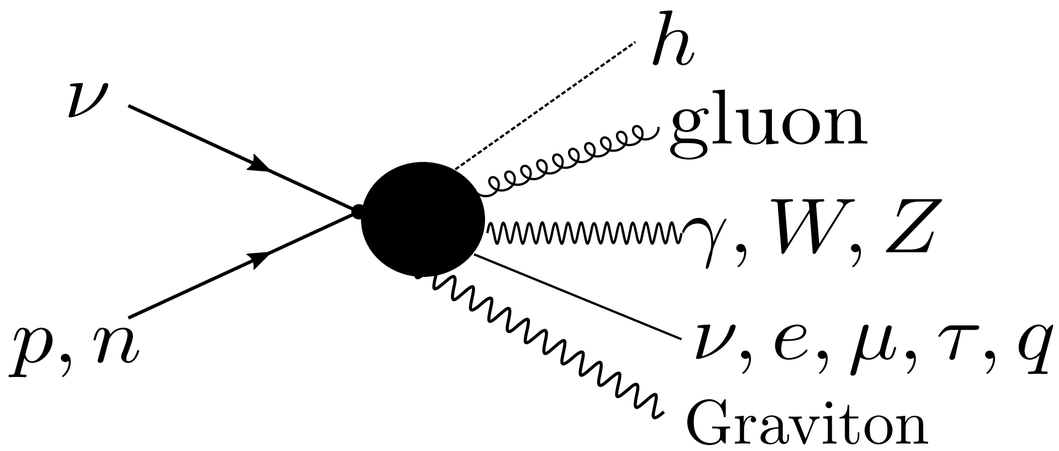
Differential Cross Section



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

Standard Model Events vs Black Holes





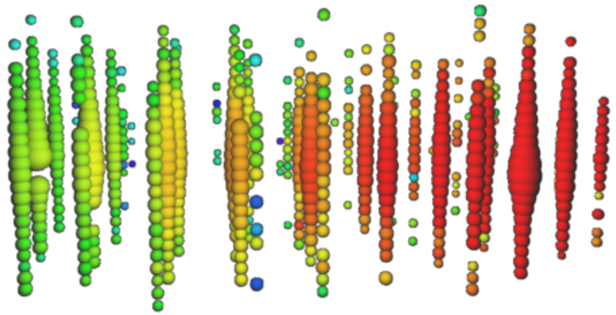
- SM
  - $y = 1 - E_l/E_\nu$
  - $E_l \sim E_\nu$

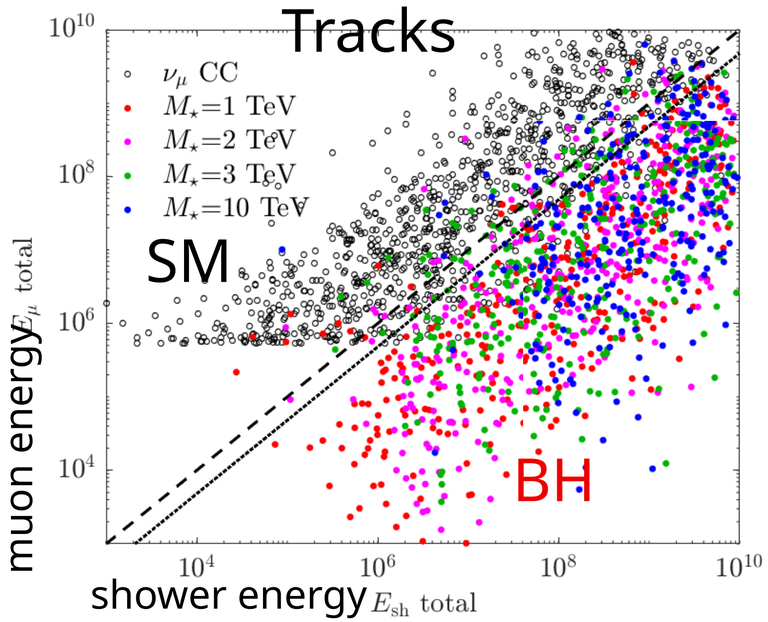
BHs

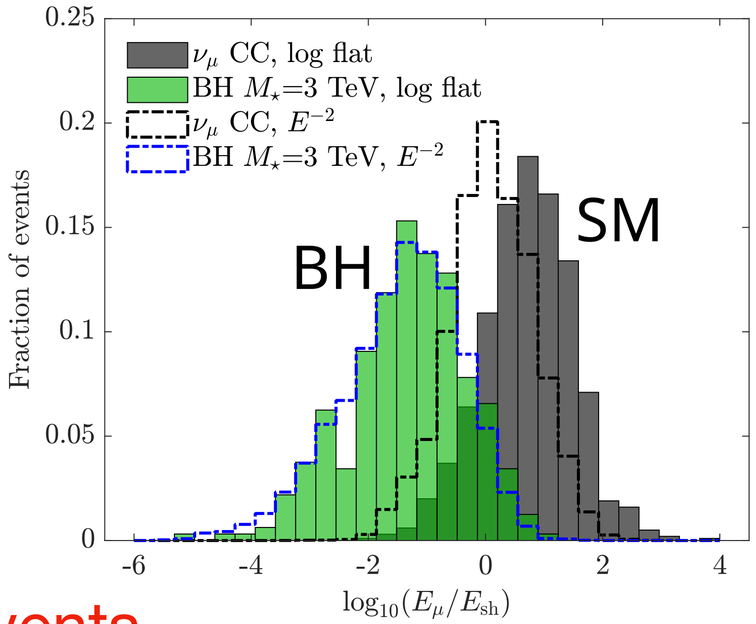
- $N \sim 6 - 20$ primary decay particles
- $E_l \sim E_\nu/N$

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

Muon Energy Ratio in BH Tracks



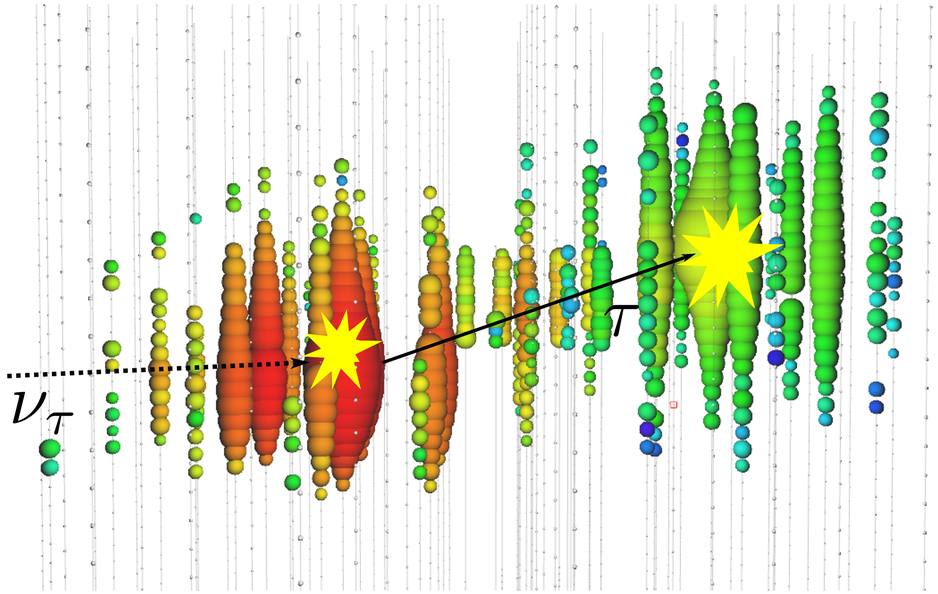


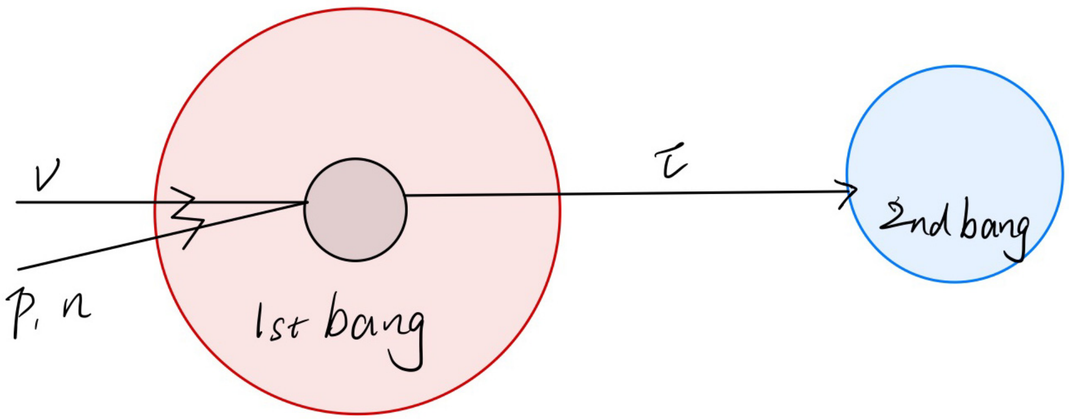


- Tracks produced in $\nu_{\mu,\tau}$ CC
  - SM $E_\mu > E_{hadron}$
  - BH $E_{hadron} > E_\mu$

Lower track energy/shower energy ratio in BH events

Energy Asymmetry in BH Double Bangs

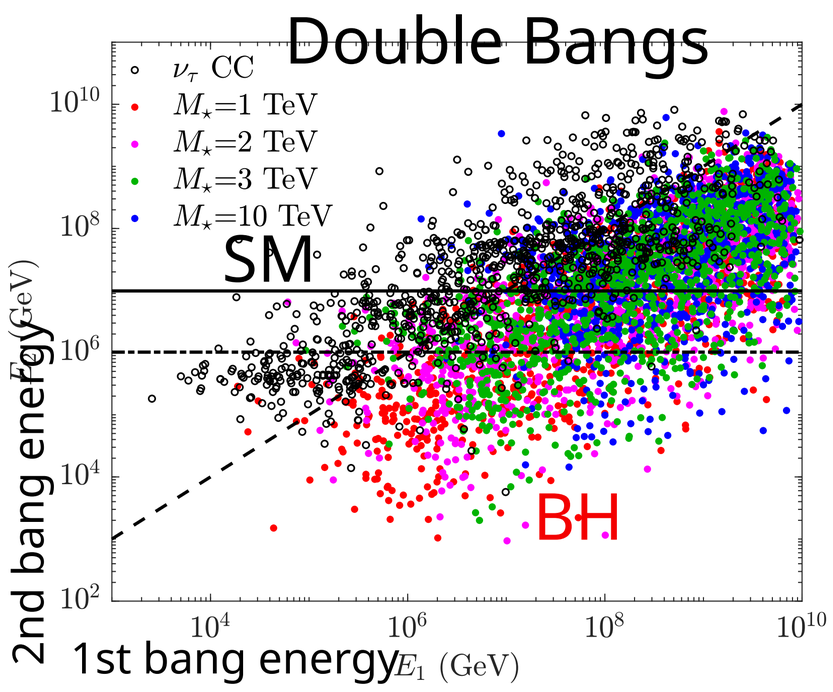


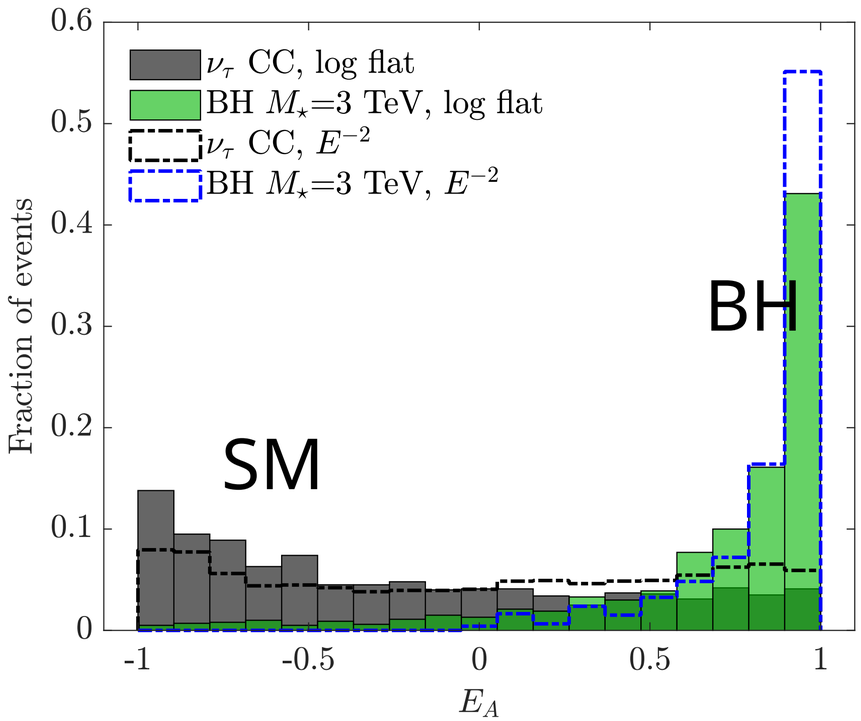


- Double bang produced in ν_τ CC
- $E_1 < E_2$

- Double bang in BH decay
- $E_1 > E_2$

Energy Asymmetry in BH Double Bangs



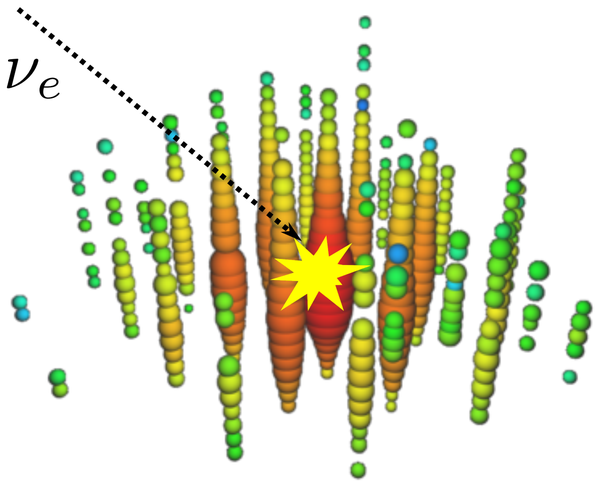


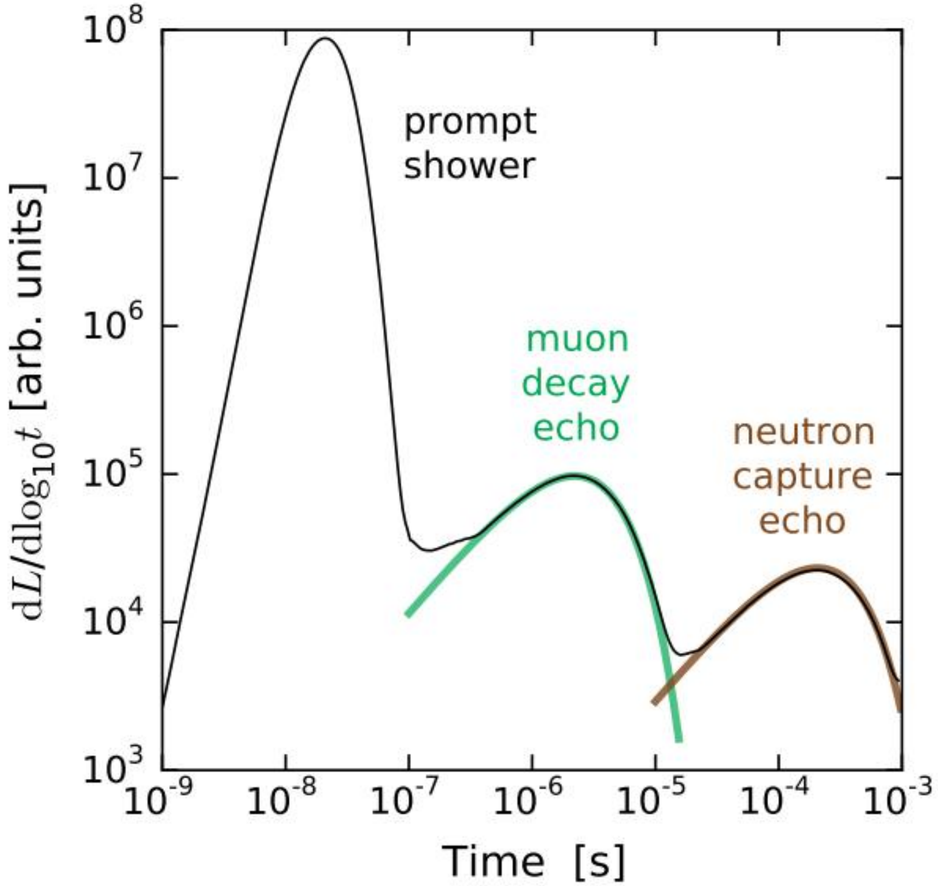
Mack, **NS**, Vincent, JHEP 2019/1912.06656

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

Mostly positive energy asymmetry expected in BH events

Cherenkov Light Echos



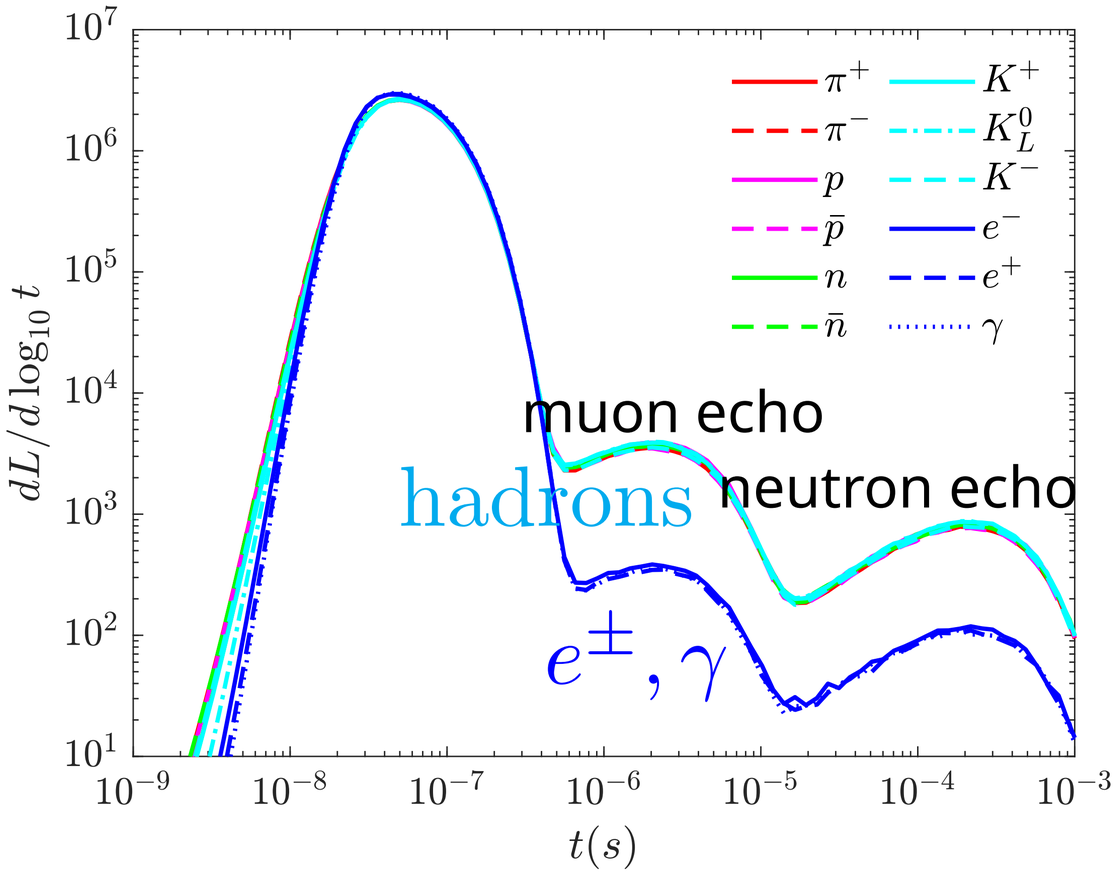


Li, Bustamante, Beacom, 1606.06290

- 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

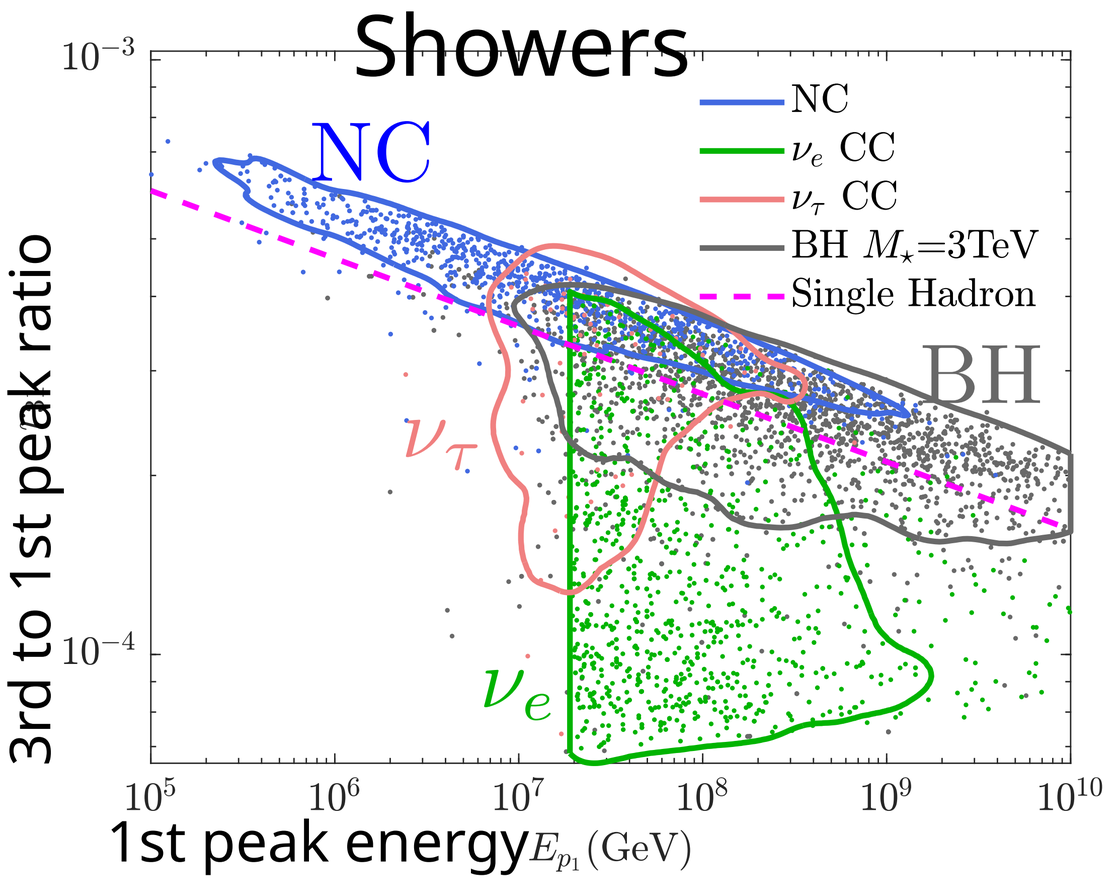
- Electromagnetic shower: electrons and gamma produce EM showers, featured with less muons and neutrons in the final states
- Hadronic shower: hadrons produce hadronic showers, featured with copious muons and neutrons in the final states
- Muon echo and neutron echo are closely correlated



Mack, **NS**, Vincent, JHEP 2019/1912.06656

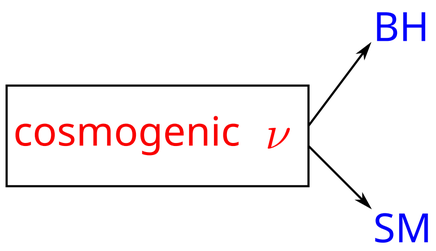
Cherenkov Light Echos

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

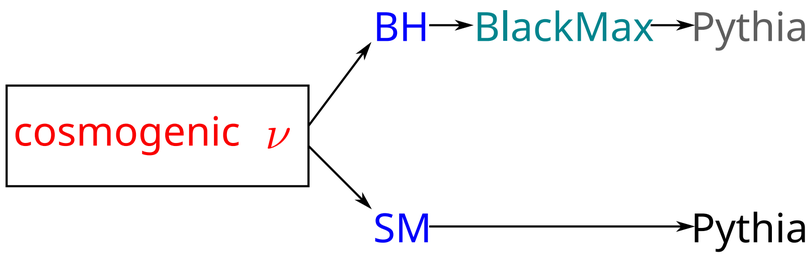


Mack, **NS**, Vincent, JHEP 2019/1912.06656

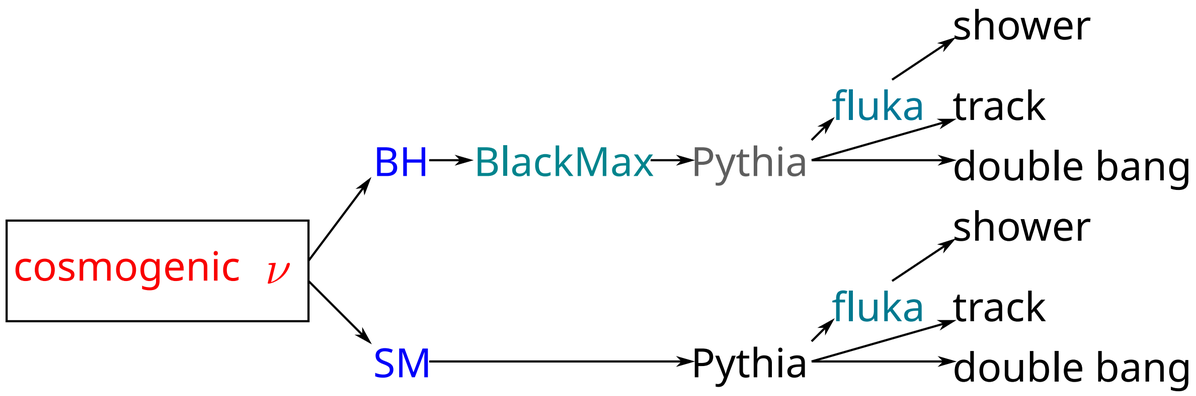
Statistical Analysis



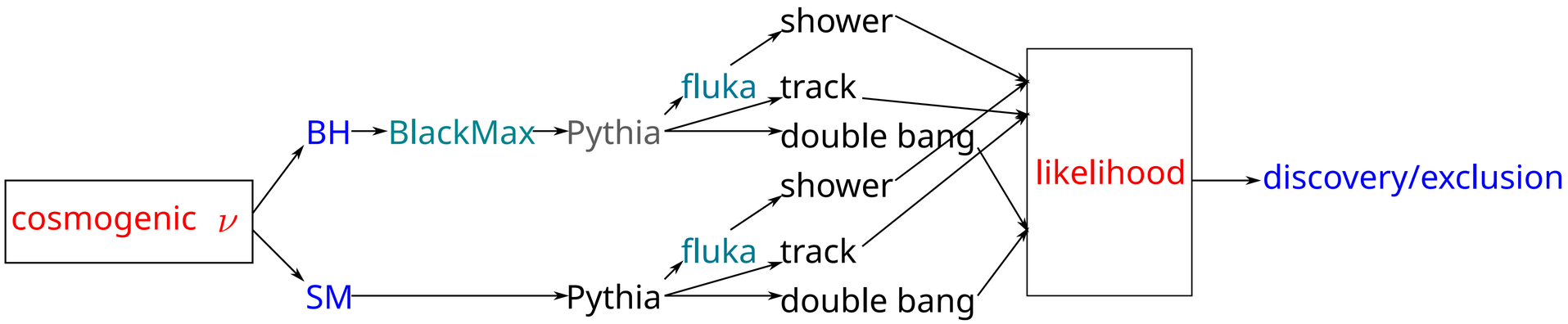
Statistical Analysis



Statistical Analysis

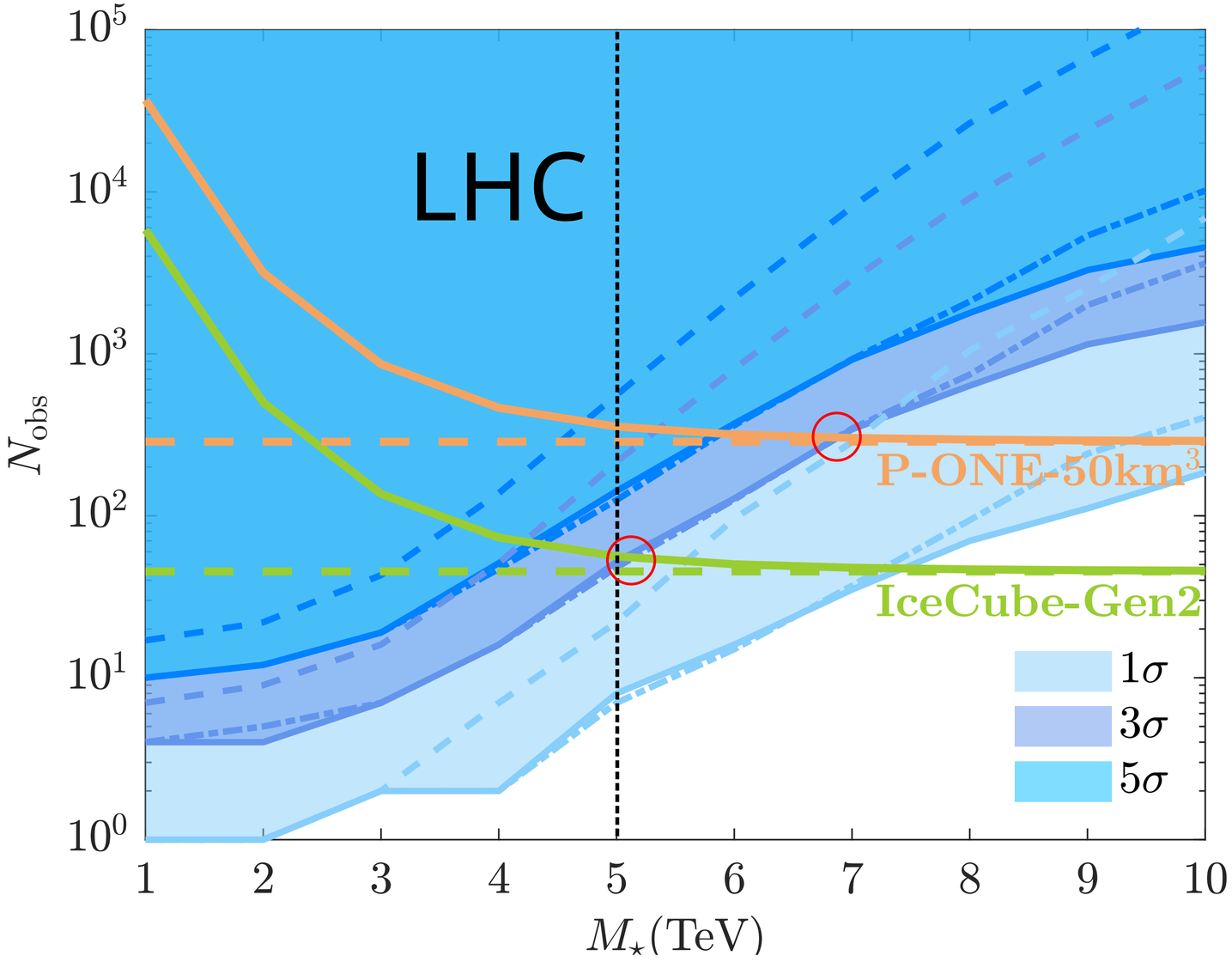


Statistical Analysis

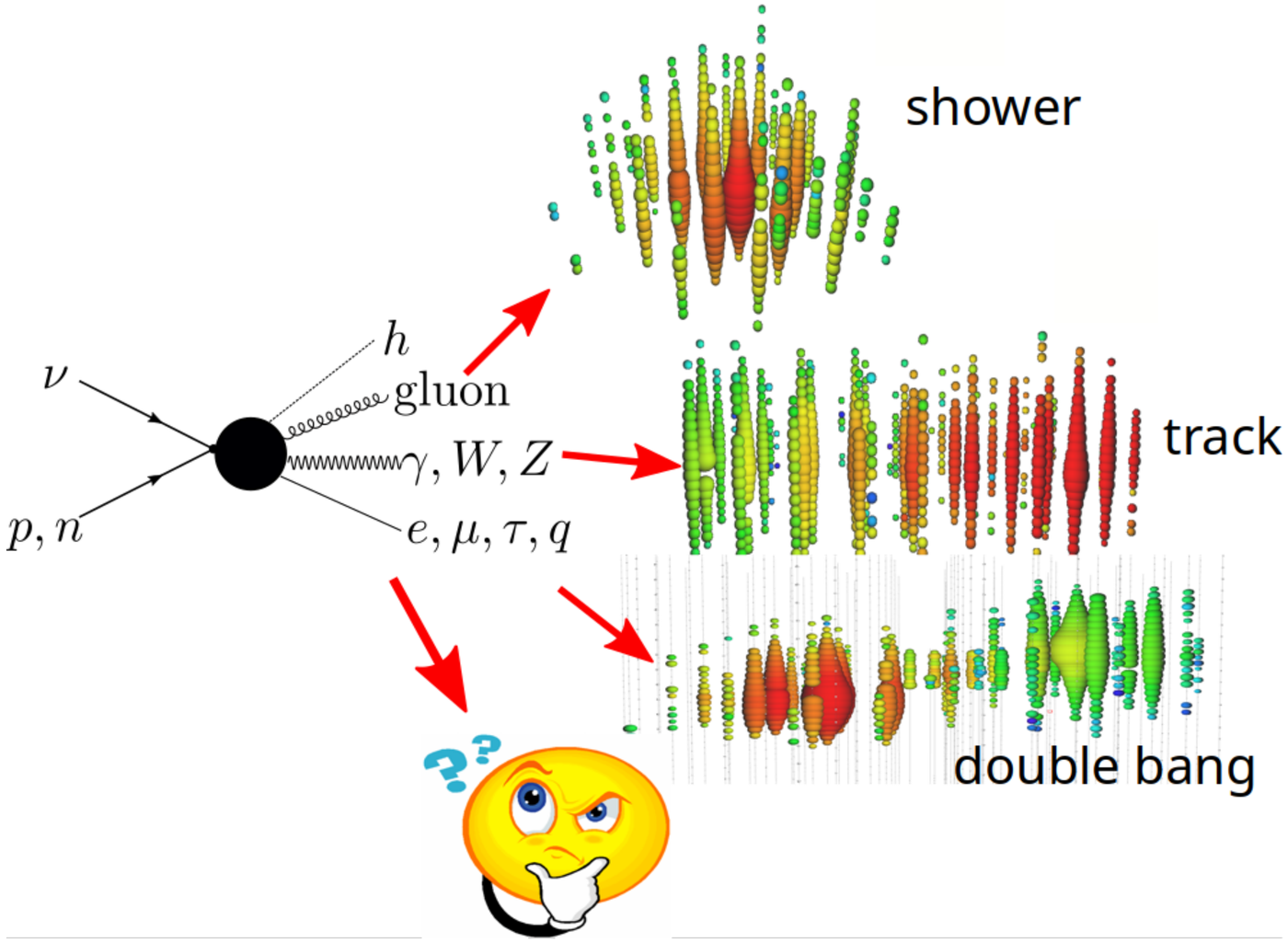


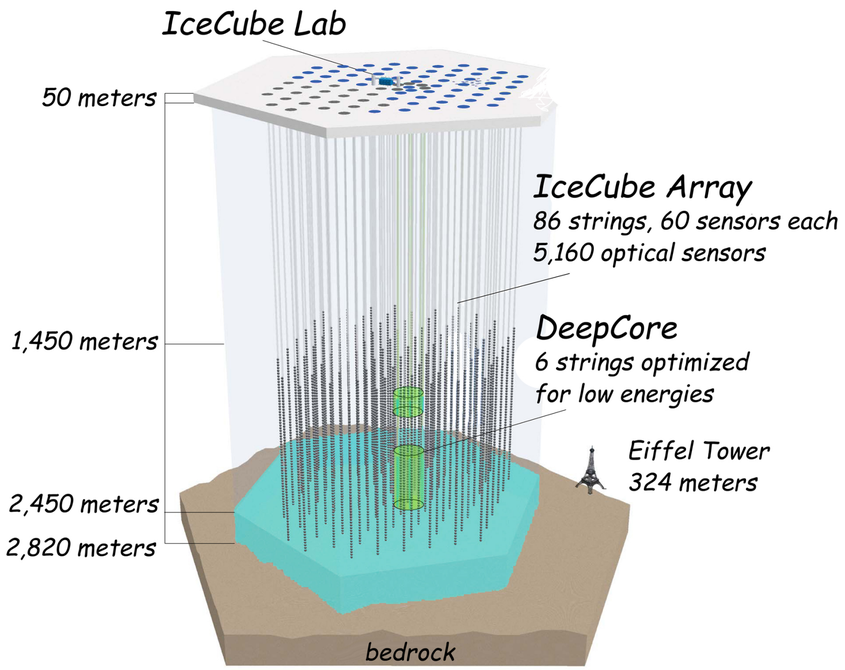
BH Discovery Limit

Mack, **NS**, Vincent, JHEP 2019/1912.06656



Micro Black Holes at IceCube

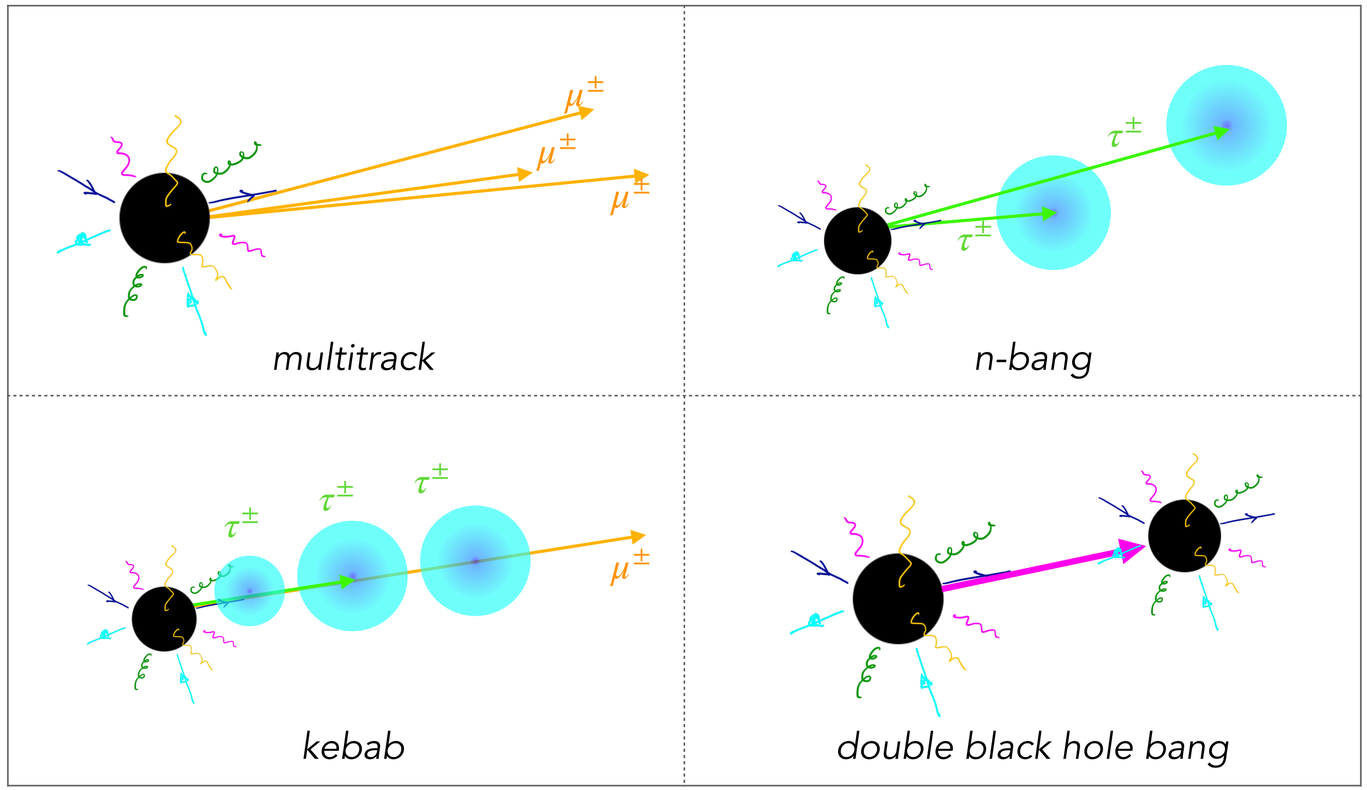




Micro Black Holes at IceCube

New topologies not expected in SM!

- Mutitrack: BHs produce multiple muons or taus (12% of BH events, typically below 0.02°, IceCube at best 0.1°)

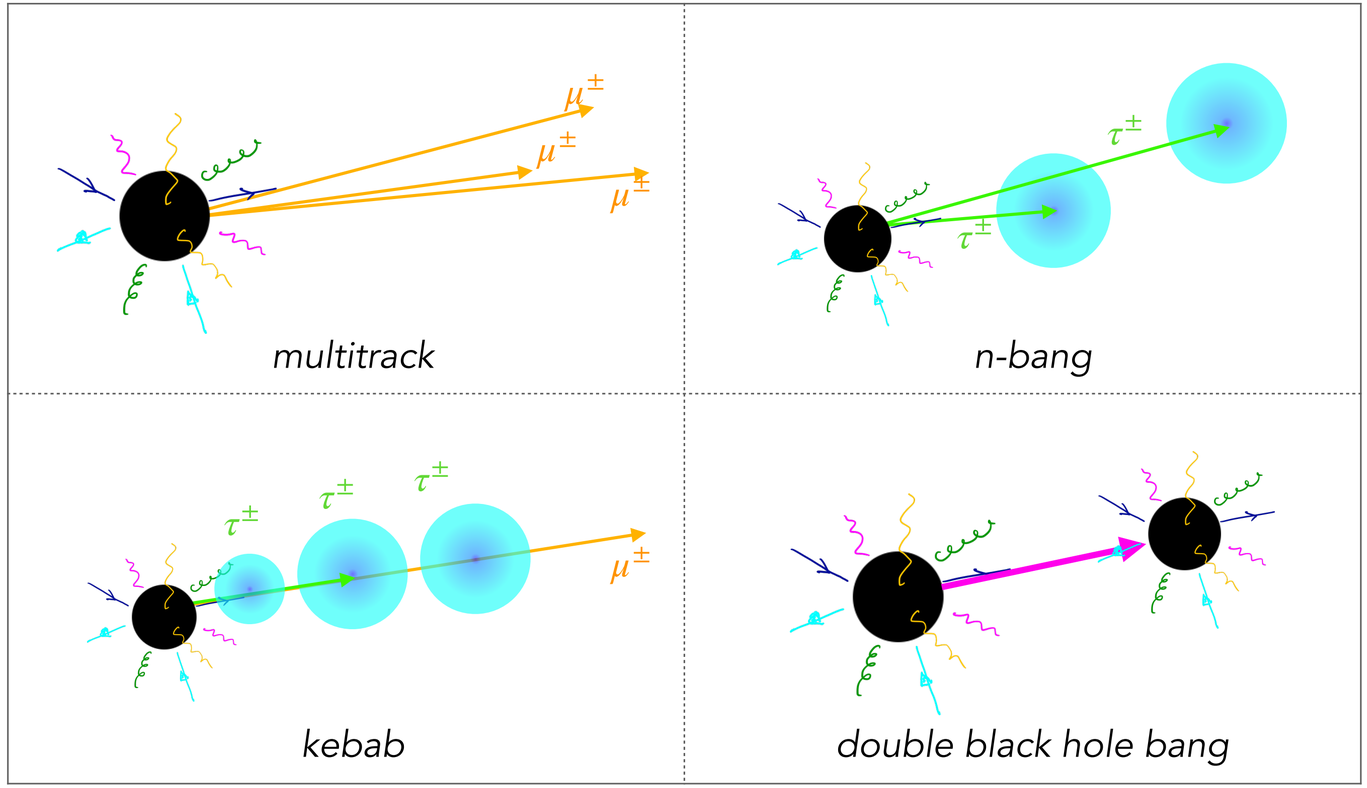


Mack, **NS**, Vincent, JHEP 2019/1912.06656

Micro Black Holes at IceCube

New topologies not expected in SM!

- Mutitrack: BHs produce multiple muons or taus
- N-bang: Multiple taus decay (about 0.2% of BH events)

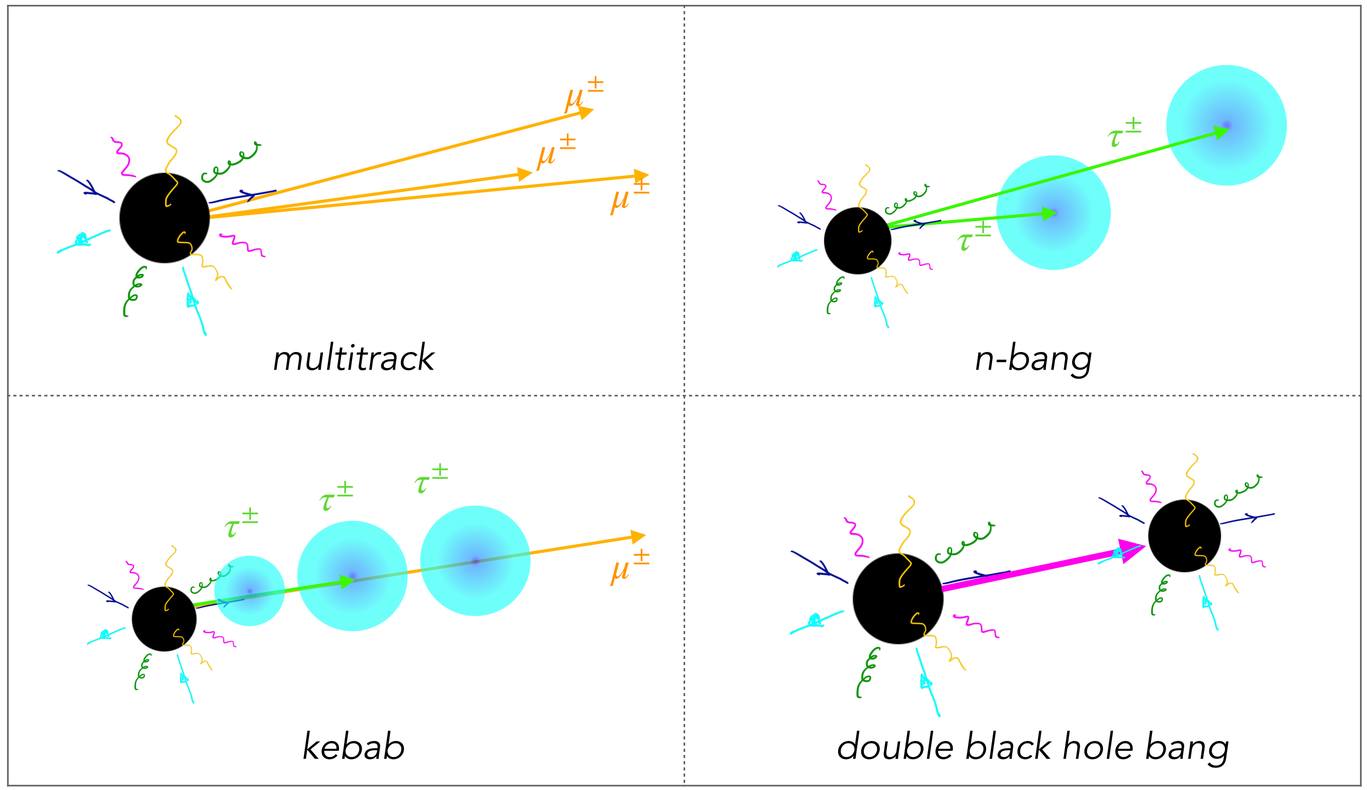


Mack, **NS**, Vincent, JHEP 2019/1912.06656

Micro Black Holes at IceCube

New topologies not expected in SM!

- Mutitrack: BHs produce multiple muons or taus
- N-bang: Multiple taus decay
- Kebab: Multiple taus decay along with a track (about 3% of BH events)

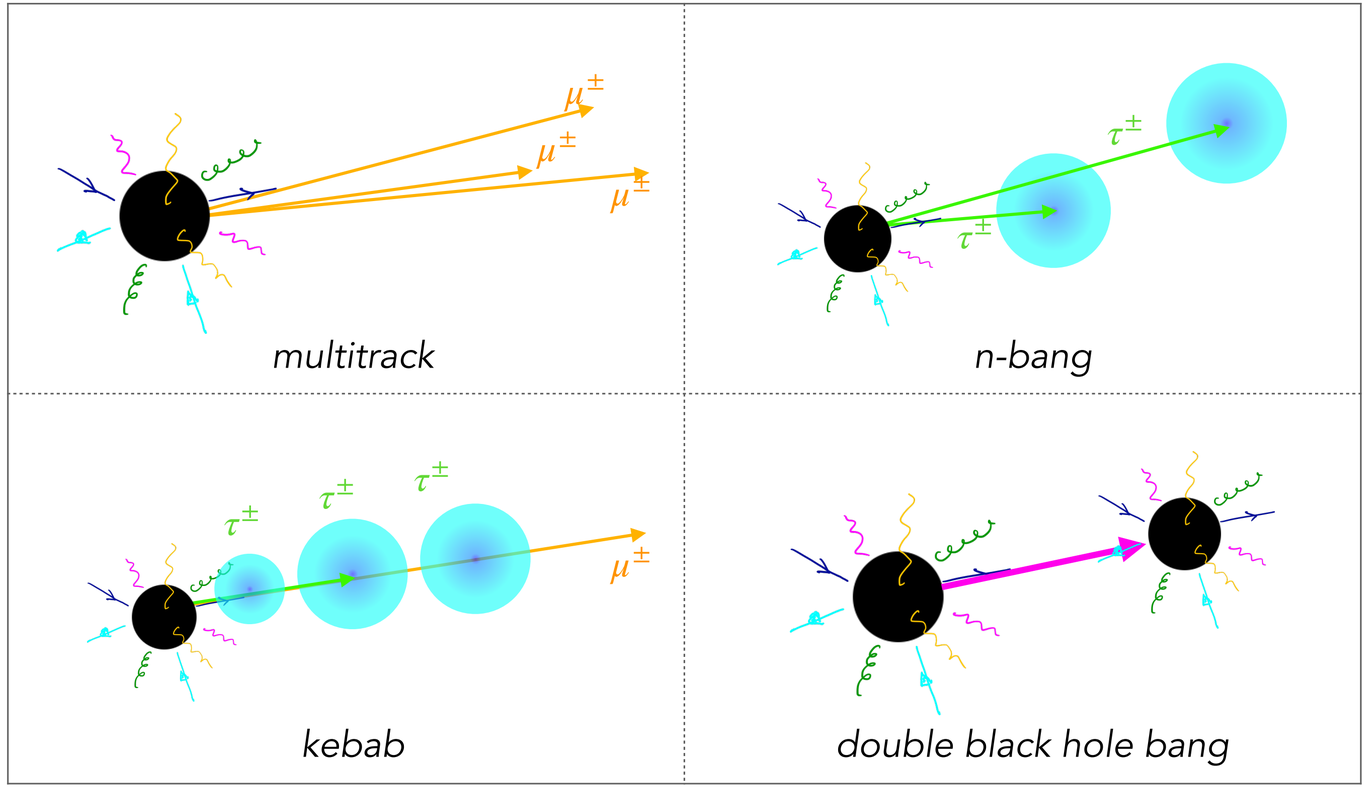


Mack, **NS**, Vincent, JHEP 2019/1912.06656

Micro Black Holes at IceCube

New topologies not expected in SM!

- Mutitrack: BHs produce multiple muons or taus
- N-bang: Multiple taus decay
- Kebab: Multiple taus decay along with a track
- Double BH bang: BH decay product produces another BH

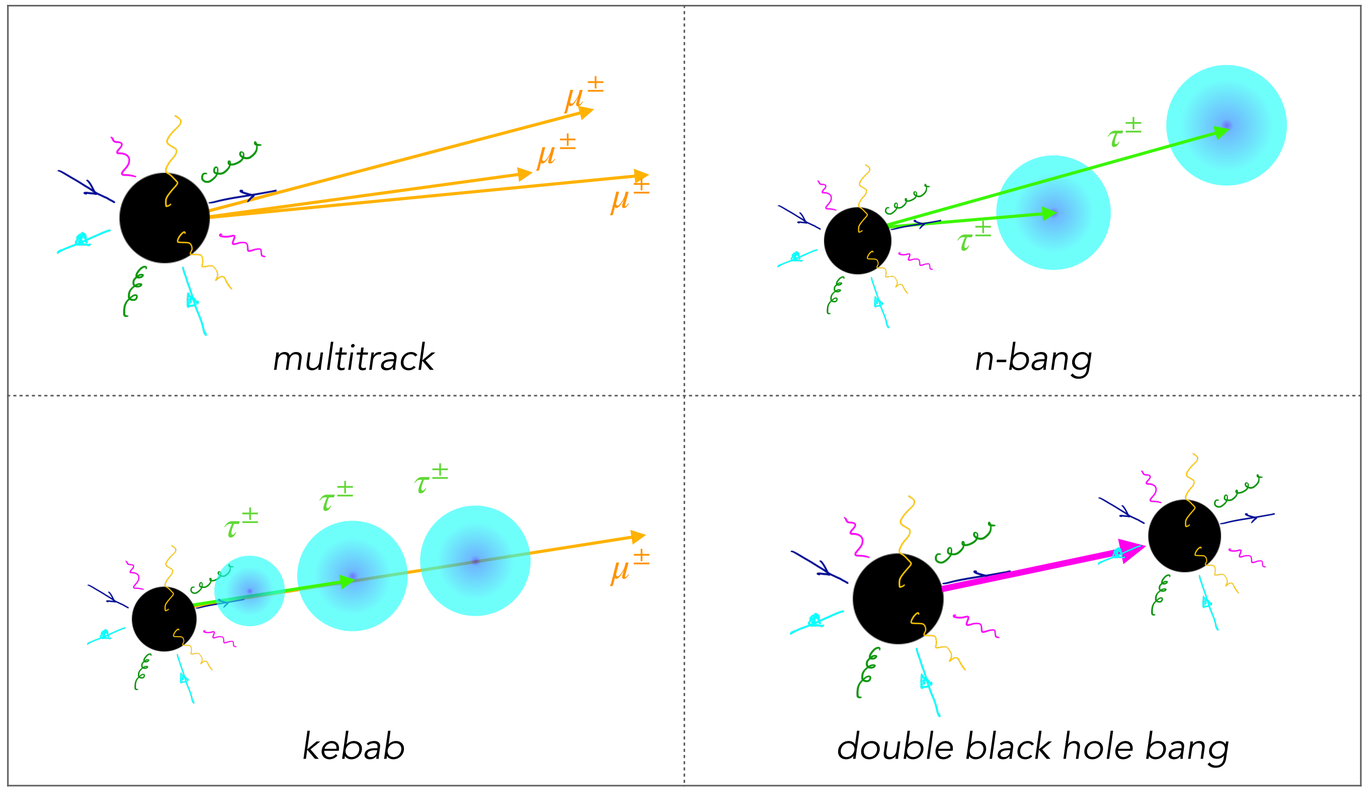


Mack, **NS**, Vincent, JHEP 2019/1912.06656

Micro Black Holes at IceCube

Rare but smoking-gun evidence!

- Mutitrack: BHs produce multiple muons or taus
- N-bang: Multiple taus decay
- Kebab: Multiple taus decay along with a track
- Double BH bang: BH decay product produces another BH



Mack, **NS**, Vincent, JHEP 2019/1912.06656

Conclusions

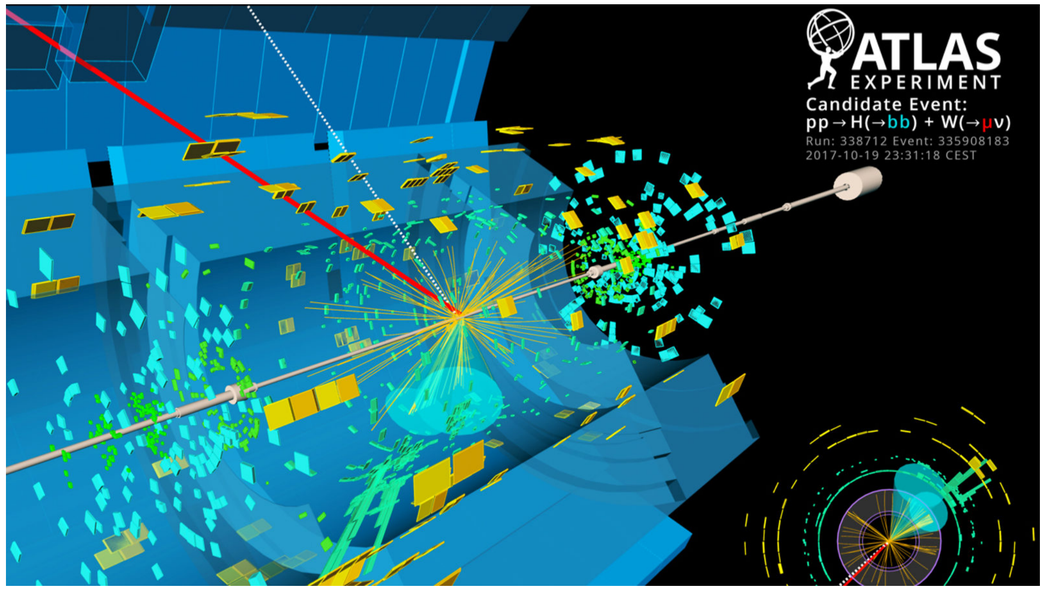
- More precise neutrino mixing parameters at oscillation experiments: JUNO, DUNE, HK…
- Better flavor measurement with much more HESE events: Gen2, P-ONE, KM3NeT, GVD, TAMBO…
- Pin down the production mechanism at source
- Constrain neutrino lifetime
- Discover microscopic black holes if large extra dimensions exist

Backup Slides

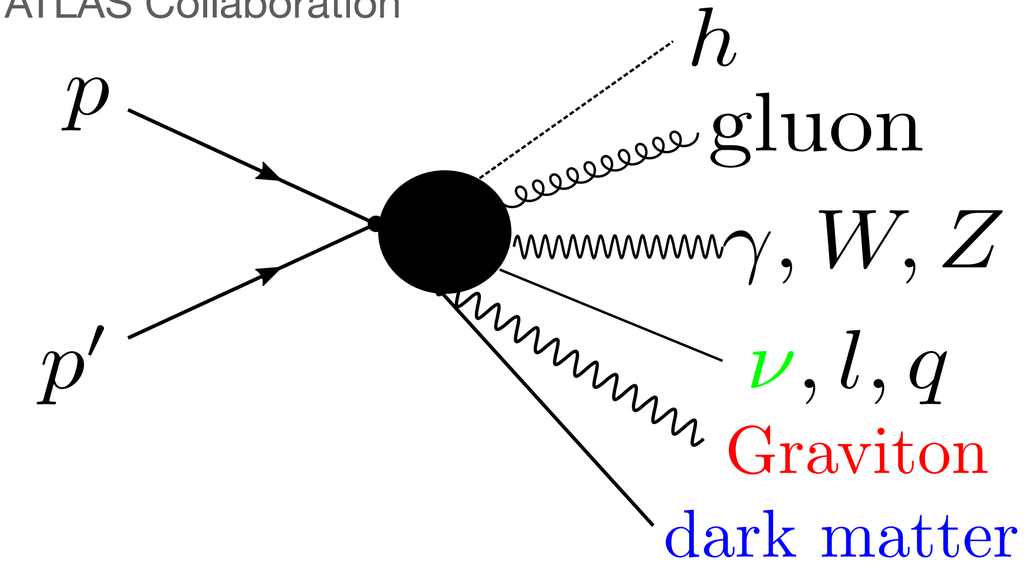
Micro Black Holes at Colliders

Dark matter contributes to missing transverse momentum at colliders!

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



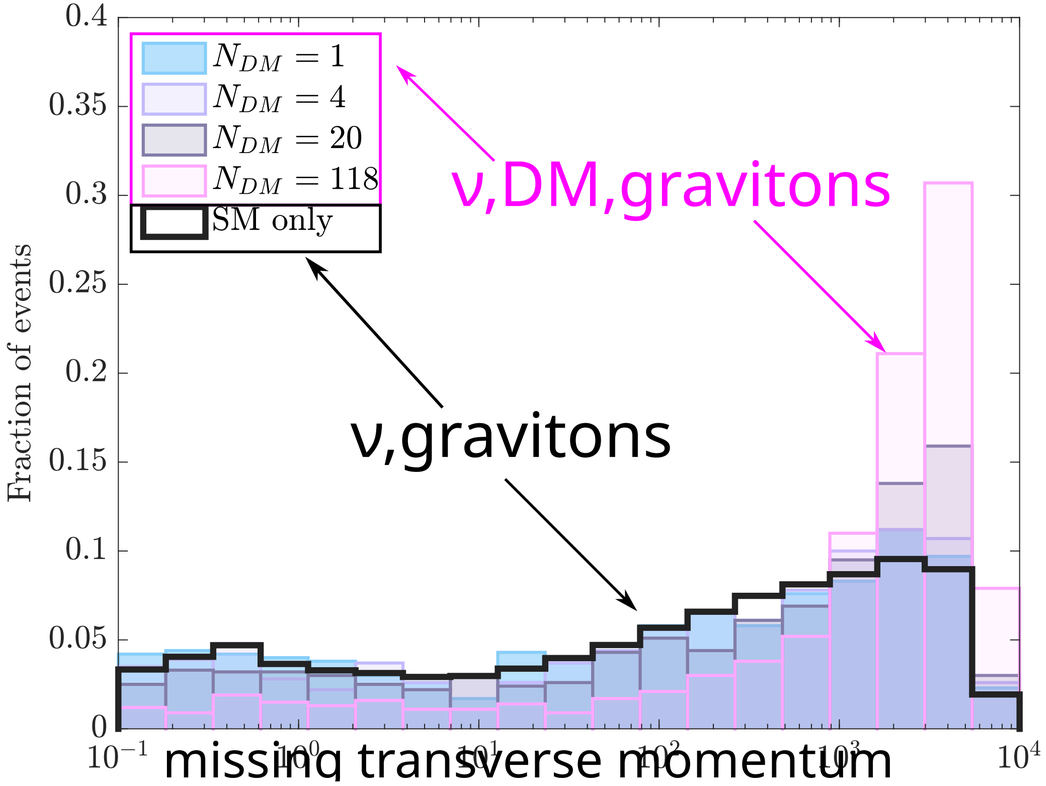
ATLAS Collaboration



Micro Black Holes at Colliders

Dark matter contributes to missing transverse momentum at colliders!

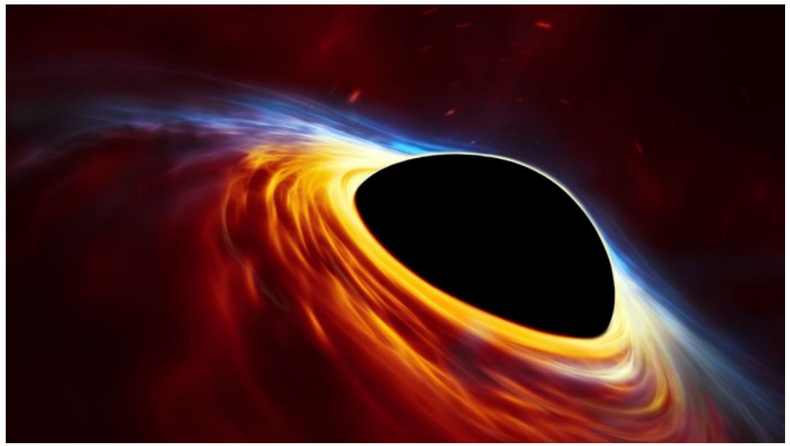
- Missing $p_\perp$ from BH decay to DM+SM vs BH decay to SM
- Dark sector can be inferred from missing $p_\perp$ distributions
- Only $\mathcal{O}(100)$ to $\mathcal{O}(10000)$ BHs required to resolve the dark sector if $N_{DM} \geq 4$ at FCC

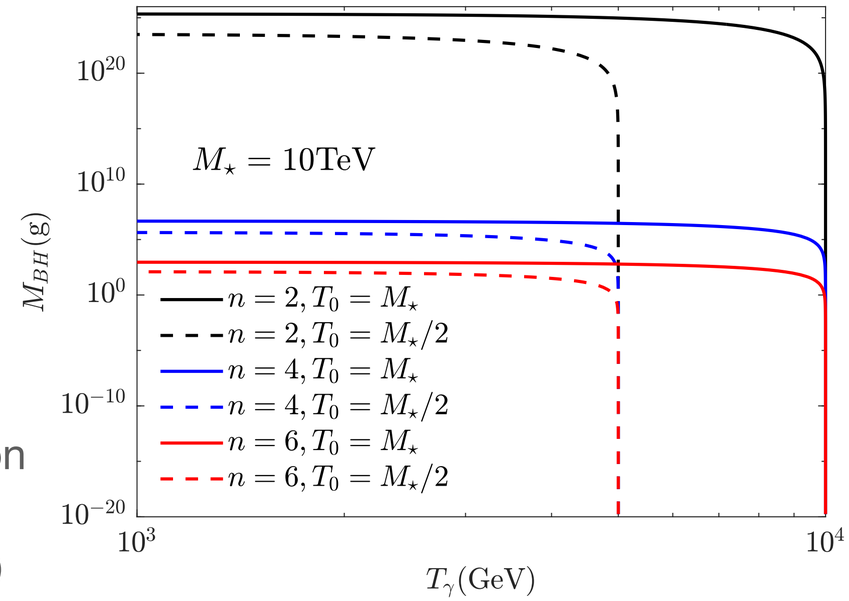


Song, Vincent' PRL 2020

Macro 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

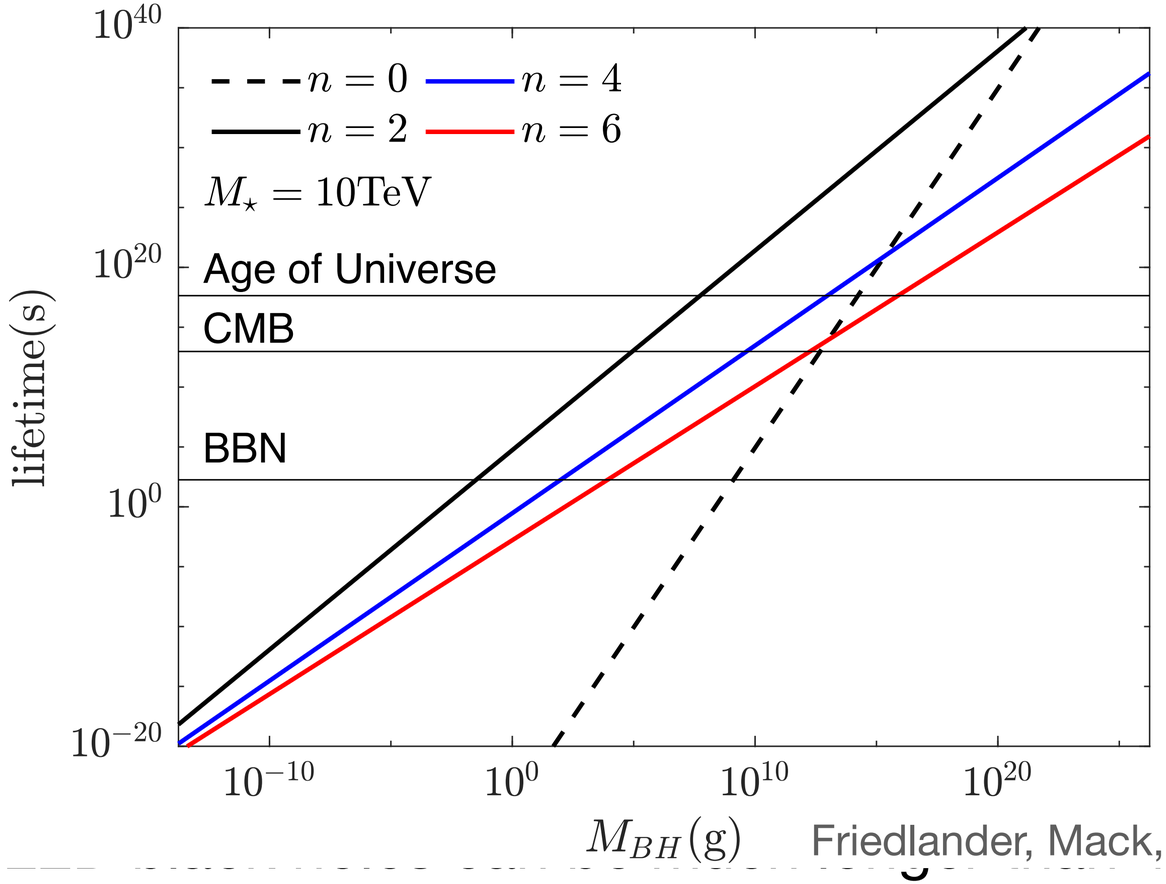




Friedlander, Mack, Schon, Song, Vincent, in preparation

Ningqiang Song (ningqiang.song@queensu.ca)

Lifetime of Black Holes

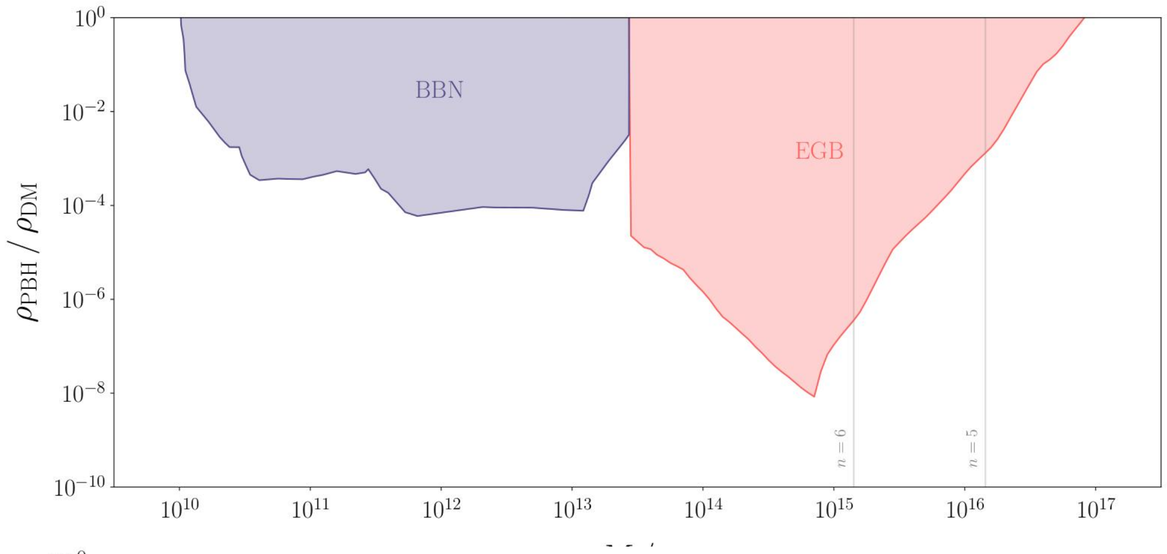


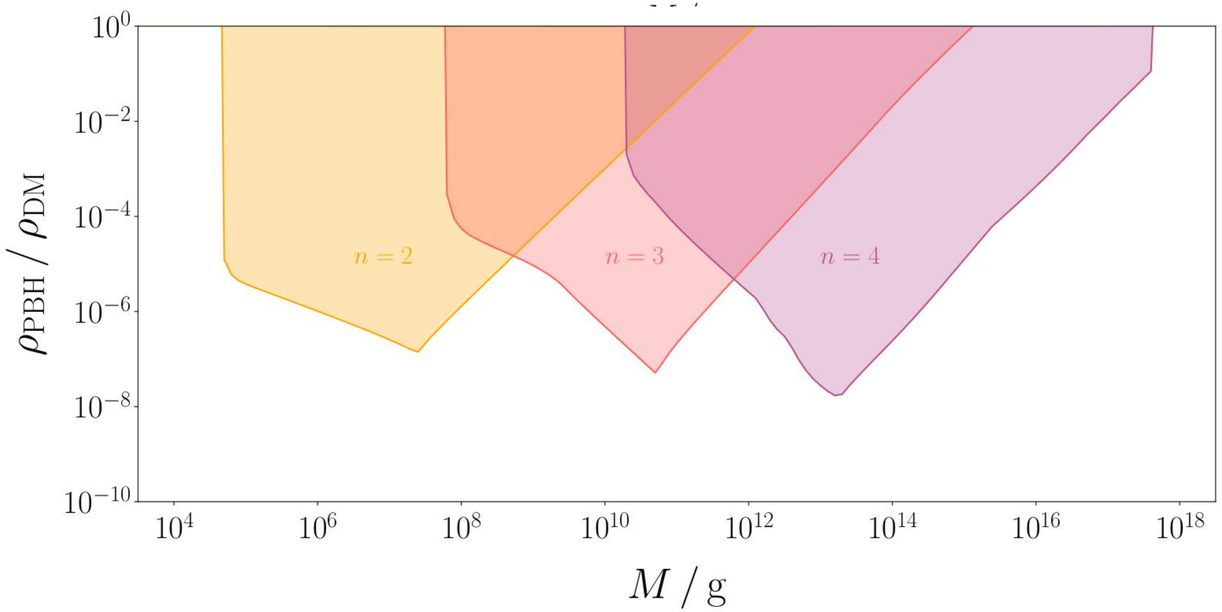
Friedlander, Mack, Schon, Song, Vincent, in preparation

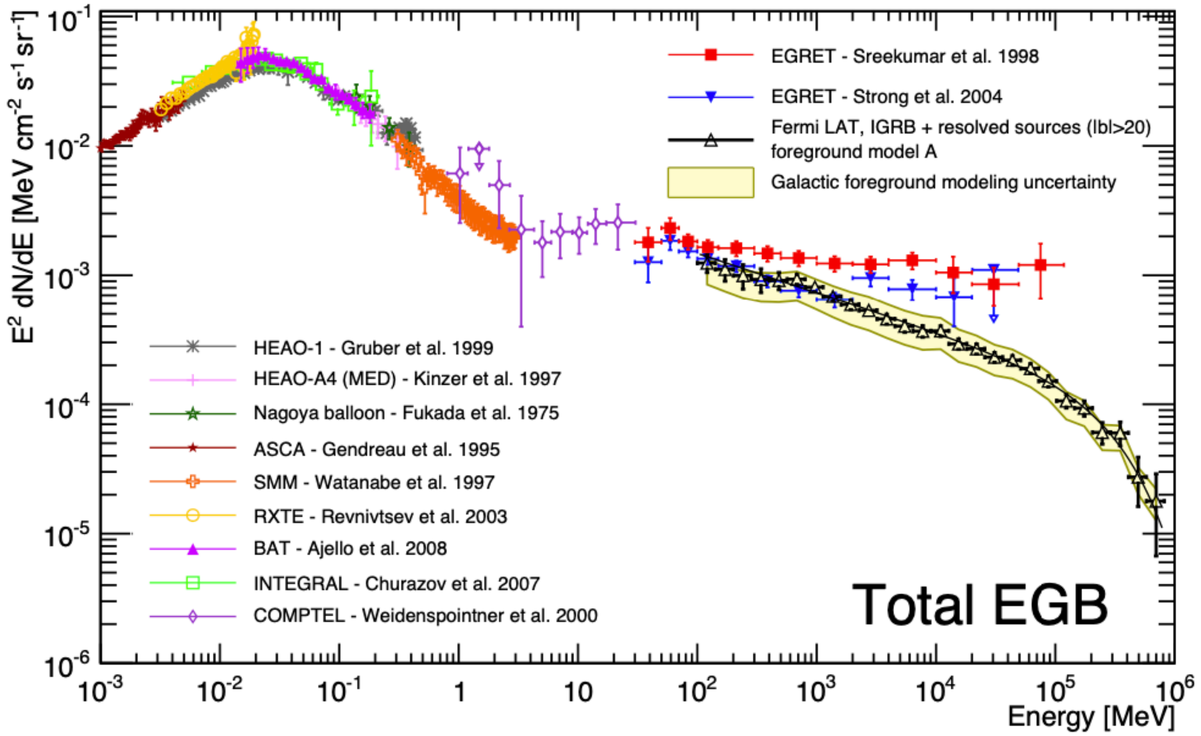
- The lifetime of [illegible] ack holes, depending on the number of extra dimensions

Extragalatic Photon Background

FermiLAT' 2014





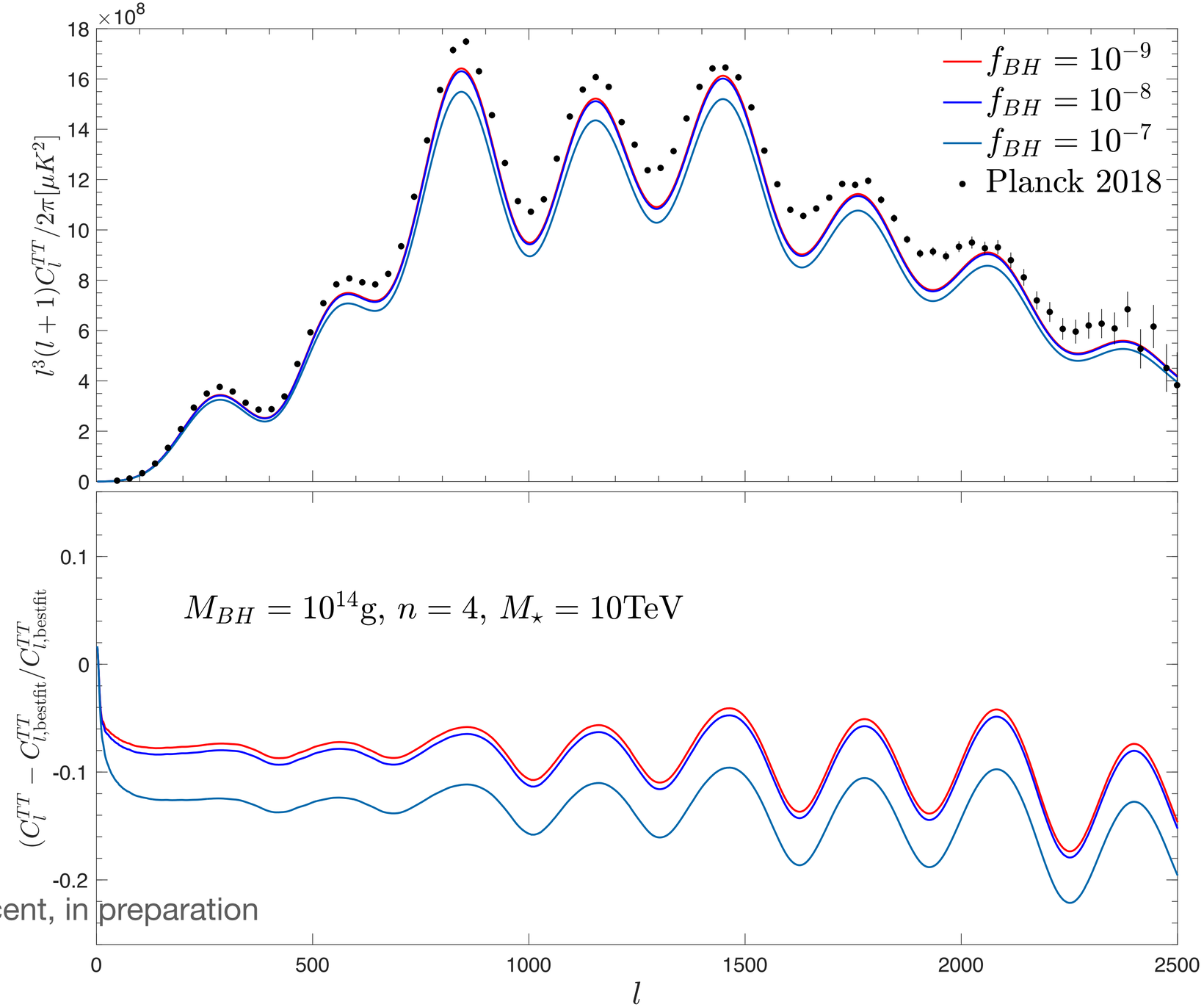


Johnson' 2020

CMB

- BHs inject energy into the plasma from Hawking radiation
- High-l anisotropies damped due to Thomson scattering
- Implement LED BHs with ExoClass

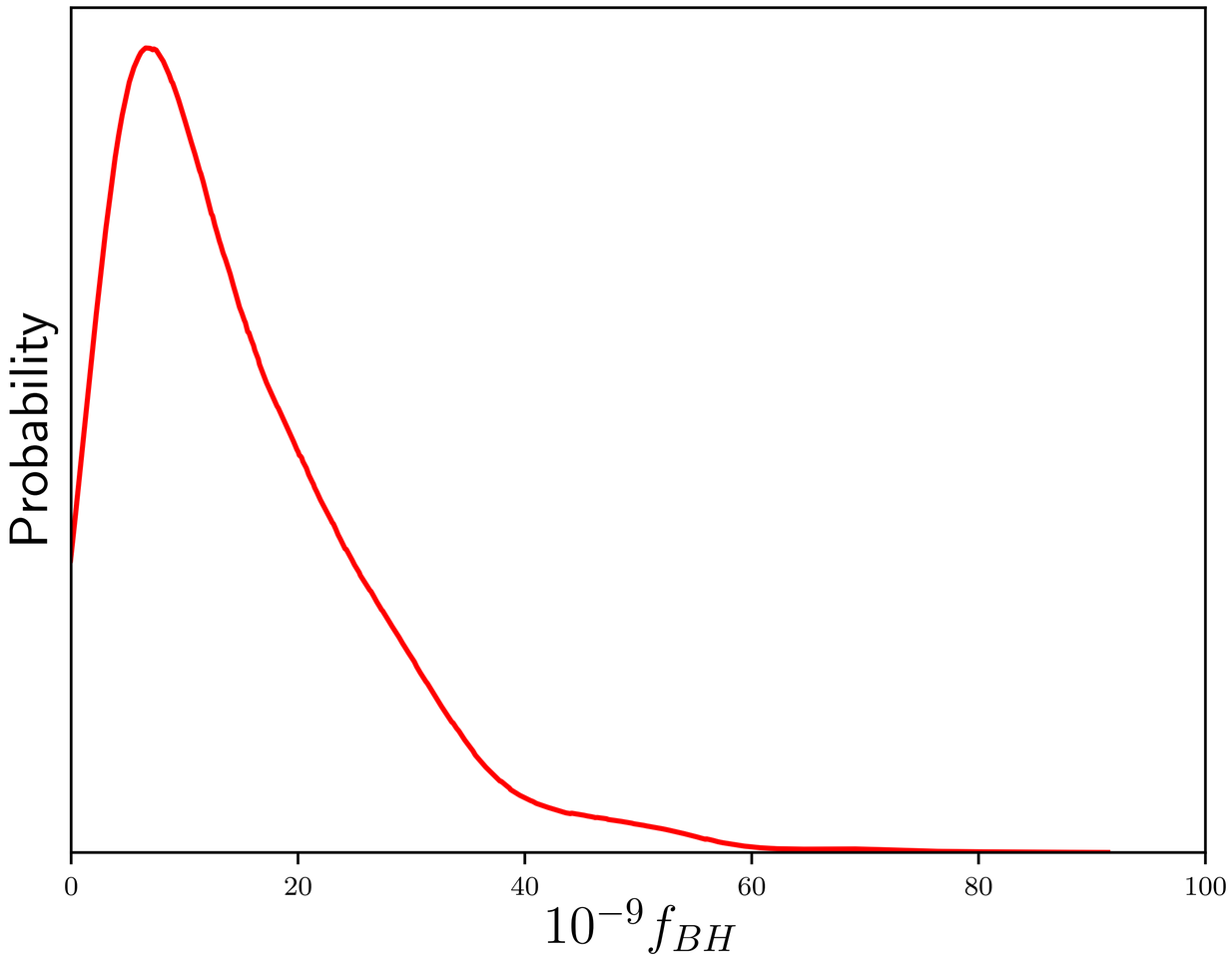
Stocker et al 2018



Friedlander, Mack, Schon, Song, Vincent, in preparation

CMB Constraints

- ExoClass+MontePython to infer the posterior of BH fraction
- $f_{BH} > 10^{-7}$ strongly disfavoured for 10^{14}g BH in $n = 4$ extra dimensions



Conclusions and Prospects

- Microscopic BHs can be produced in particle collisions if *large extra dimensions* exist
- Micro BHs produce unique signatures in neutrino telescopes
- Micro BHs may unveil the dark sector at future colliders
- BHs produced in the early Universe will be constrained by cosmological observations