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CCAPP THE OHIO STATE UNIVERSITY

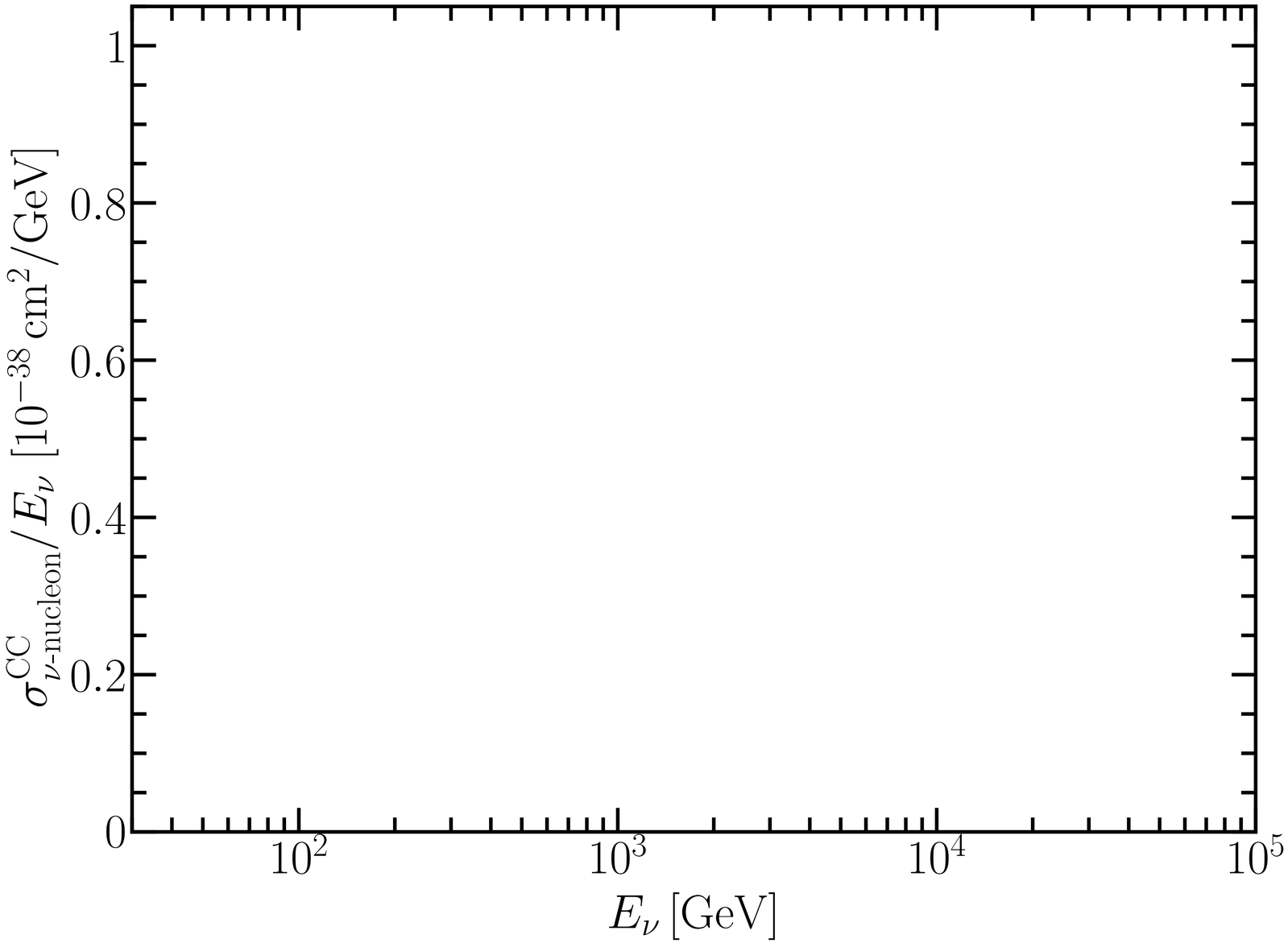
Neutrino-nucleon cross section extraction around the TeV

Rasmi E. Hajjar Muñoz

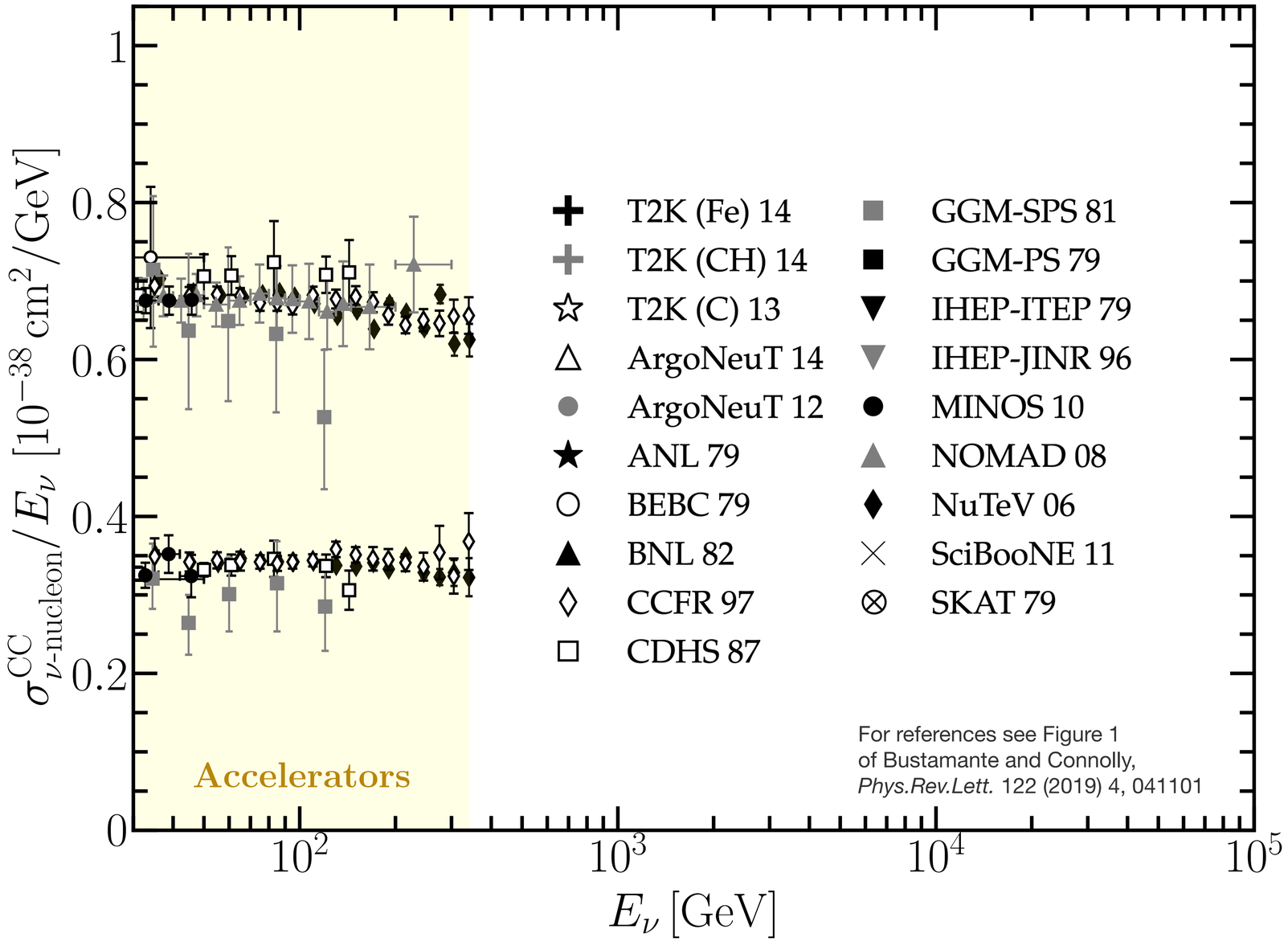
TeVPA 2025

based on arXiv:2511.XXXXX
in collaboration with Sergio Palomares-Ruiz and Mauricio Bustamante

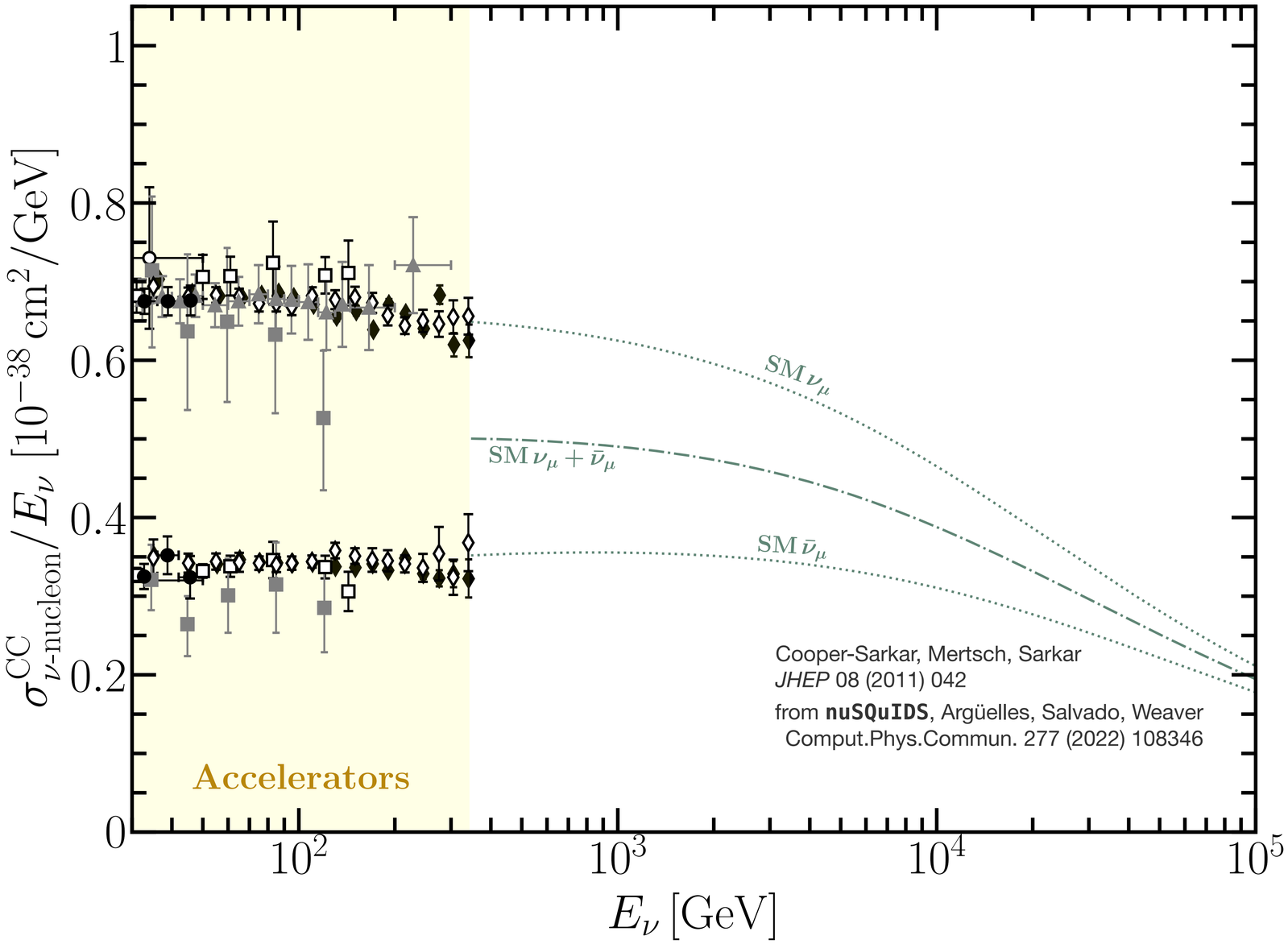
Motivation


$\sigma^{\mathrm{CC}}_{\nu\text{-nucleon}}/E_\nu\ [10^{-38}\,\mathrm{cm}^2/\mathrm{GeV}]$
0
0.2
0.4
0.6
0.8
1
10^2
10^3
10^4
10^5
$E_\nu\,[\mathrm{GeV}]$

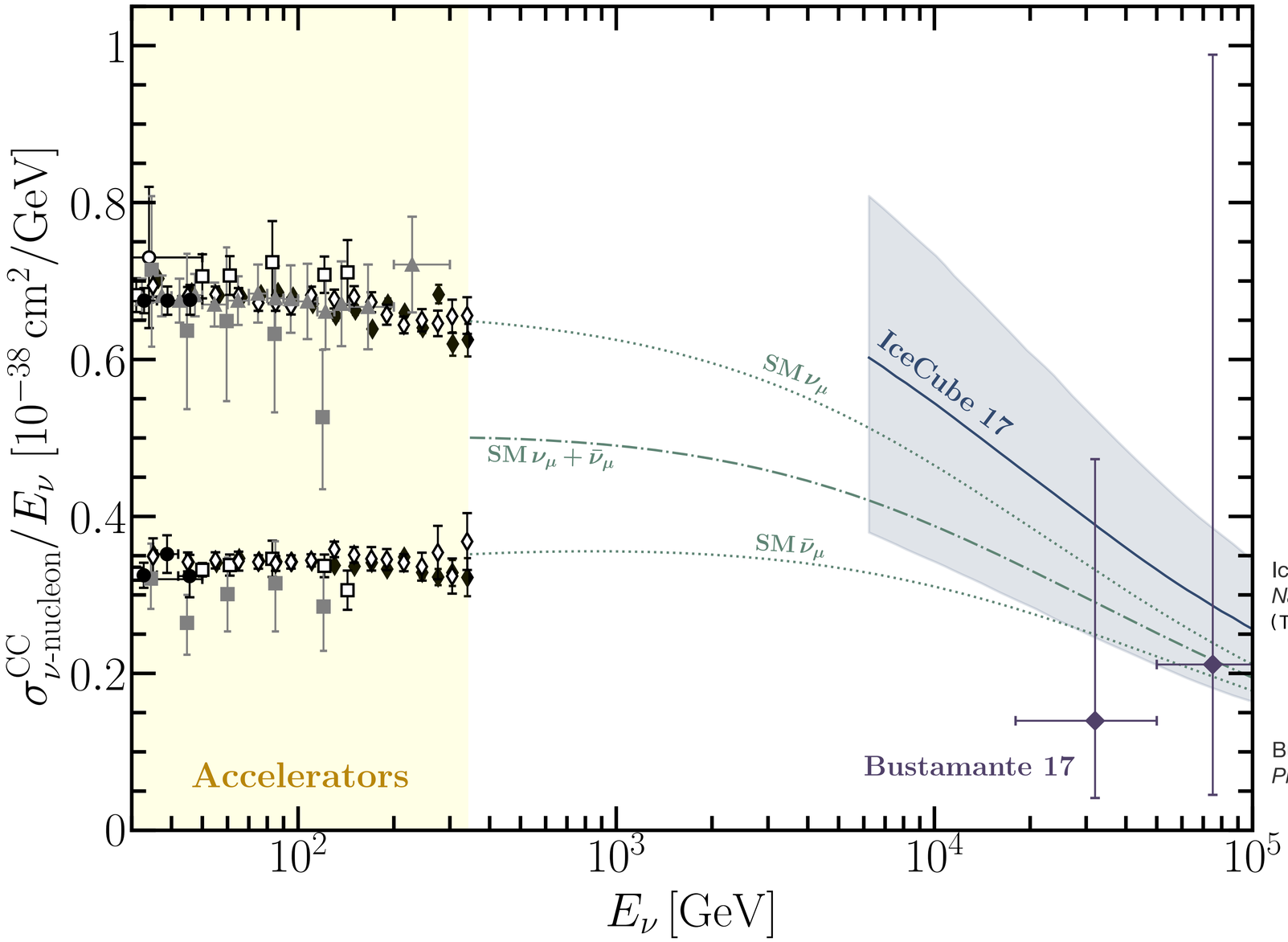
Motivation


$\sigma^{CC}_{\nu\text{-nucleon}}/E_\nu$ $[10^{-38}\,\mathrm{cm}^2/\mathrm{GeV}]$
E_ν [GeV]
Accelerators
T2K (Fe) 14
T2K (CH) 14
T2K (C) 13
ArgoNeuT 14
ArgoNeuT 12
ANL 79
BEBC 79
BNL 82
CCFR 97
CDHS 87
GGM-SPS 81
GGM-PS 79
IHEP-ITEP 79
IHEP-JINR 96
MINOS 10
NOMAD 08
NuTeV 06
SciBooNE 11
SKAT 79
For references see Figure 1
of Bustamante and Connolly,
Phys.Rev.Lett. 122 (2019) 4, 041101

Motivation


$\sigma^{\mathrm{CC}}_{\nu\text{-nucleon}}/E_\nu\ [10^{-38}\,\mathrm{cm}^2/\mathrm{GeV}]$
$E_\nu\ [\mathrm{GeV}]$
$\mathrm{SM}\,\nu_\mu$
$\mathrm{SM}\,\nu_\mu + \bar{\nu}_\mu$
$\mathrm{SM}\,\bar{\nu}_\mu$
Accelerators
Cooper-Sarkar, Mertsch, Sarkar
JHEP 08 (2011) 042
from **nuSQuIDS**, Argüelles, Salvado, Weaver
Comput.Phys.Commun. 277 (2022) 108346

Motivation

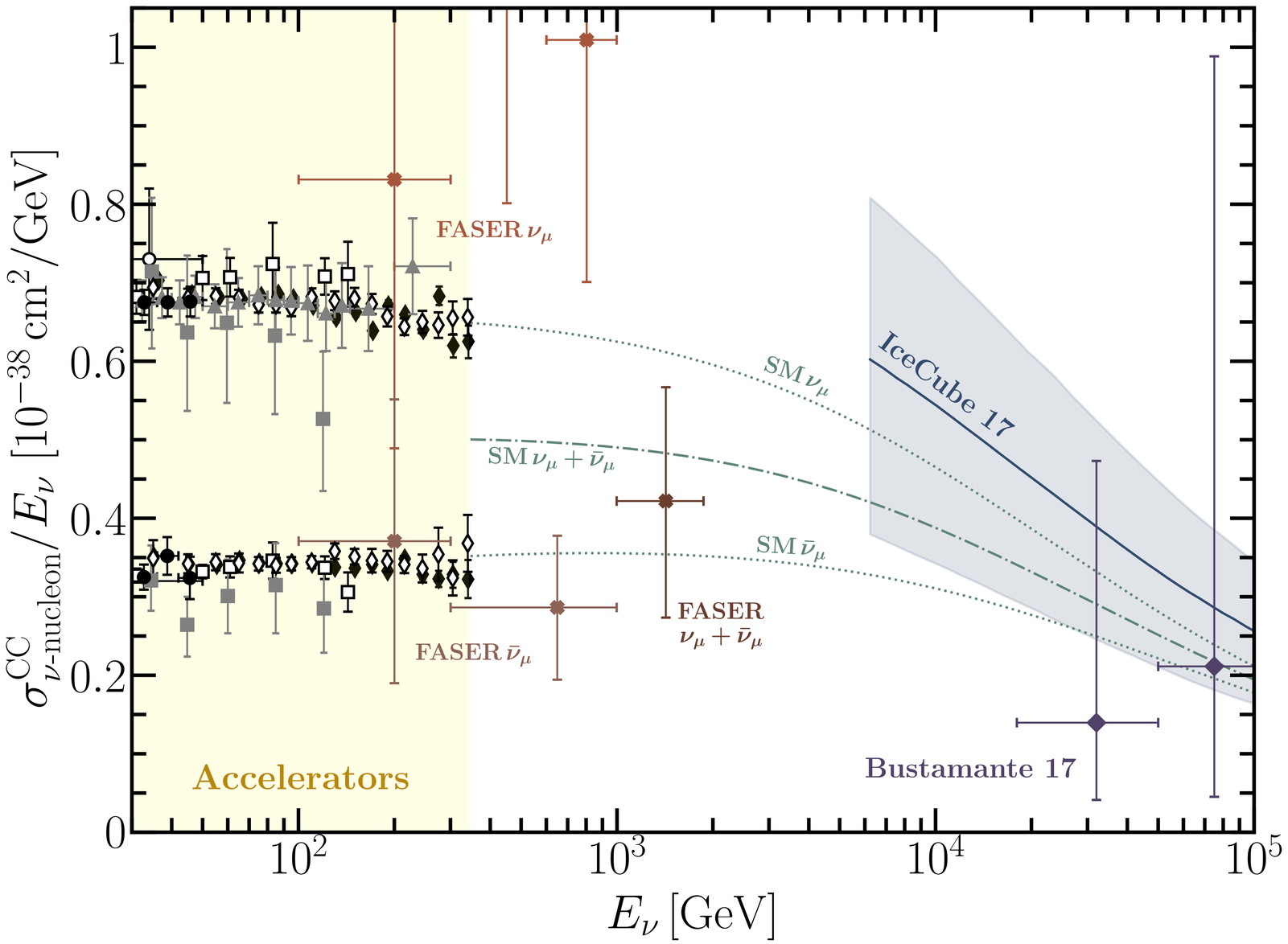


IceCube Collaboration,
Nature 551 (2017) 596-600
(Total number of events: 10784)

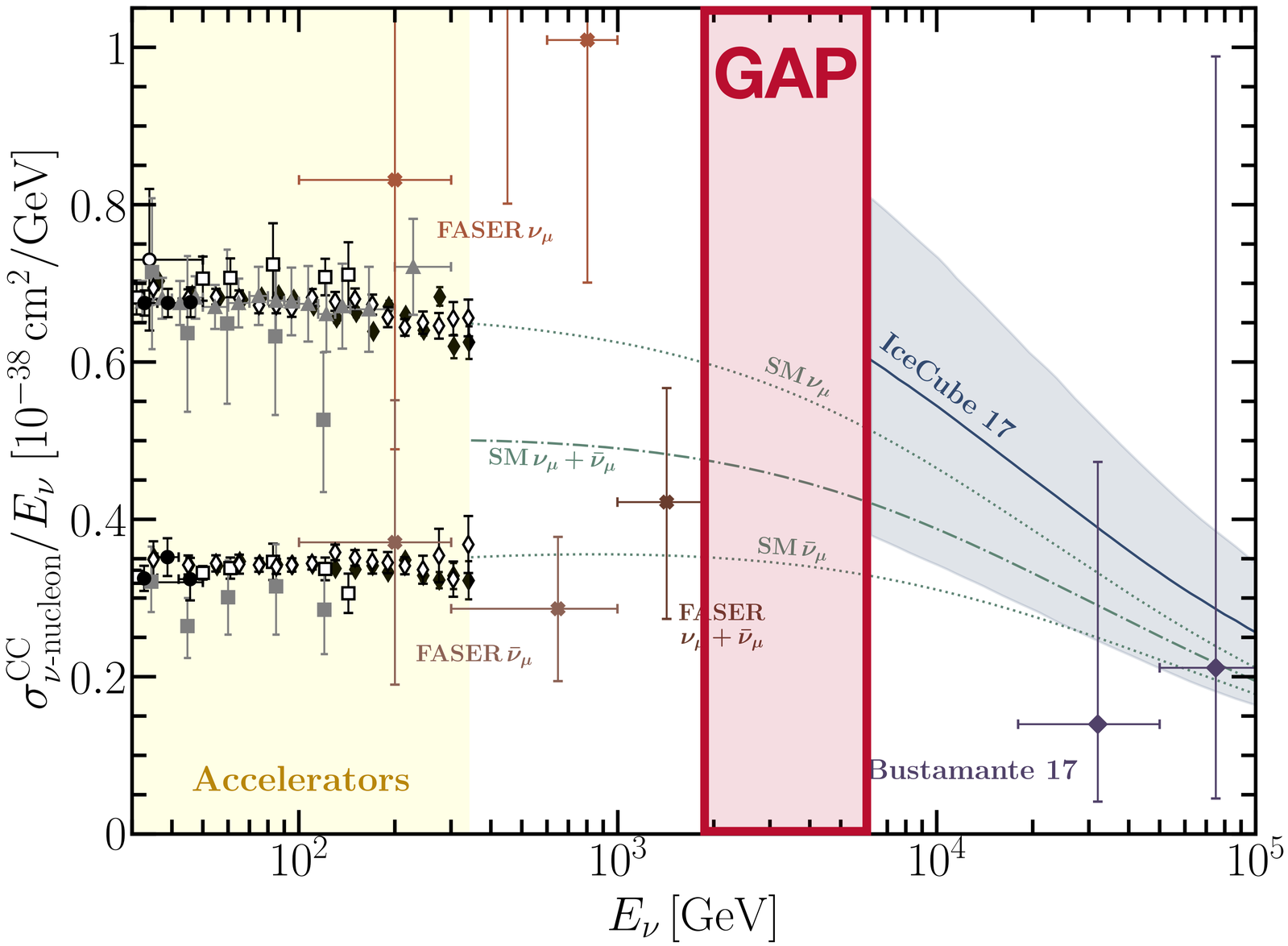
Bustamante and Connolly,
Phys.Rev.Lett. 122 (2019) 4, 041101

Motivation

FASER Collaboration,
Phys.Rev.Lett. 134 (2025) 21, 211801



Motivation: close the gap



IceCube Collaboration. 2024. “Replication Data for: Searching for Decoherence from Quantum Gravity at the IceCube South Pole Neutrino Observatory.” Harvard Dataverse. https://doi.org/10.7910/DVN/9WGYQN
IceCube Collaboration, Nature Phys. 20 (2024) 6, 913-920

How?

T = 7.6 years

Total number of events: 305735

(x28 IceCube band at higher energies)

IceCube Collaboration. 2024. “Replication Data for: Searching for Decoherence from Quantum Gravity at the IceCube South Pole Neutrino Observatory.” Harvard Dataverse. https://doi.org/10.7910/DVN/9WGYQN
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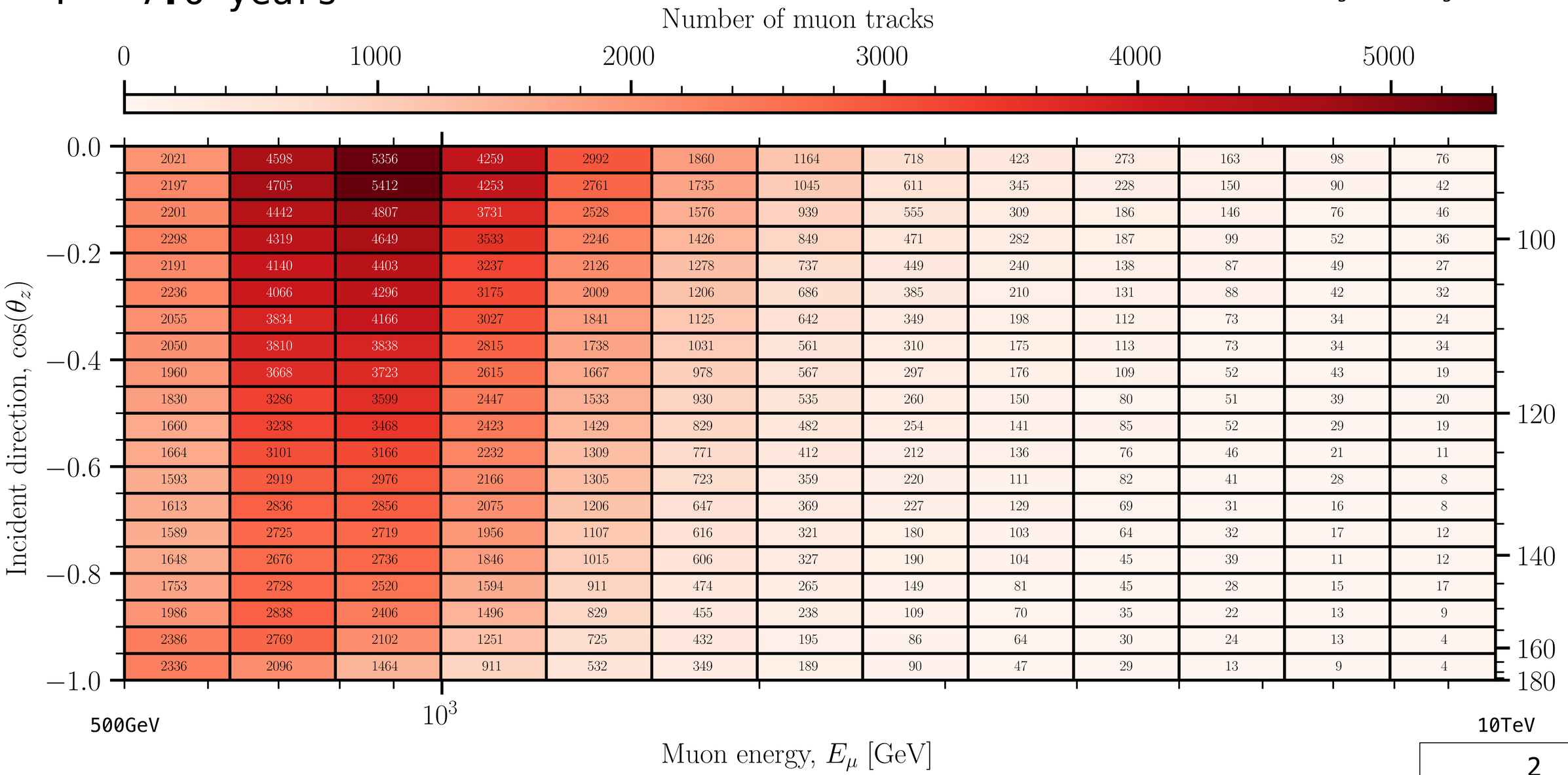
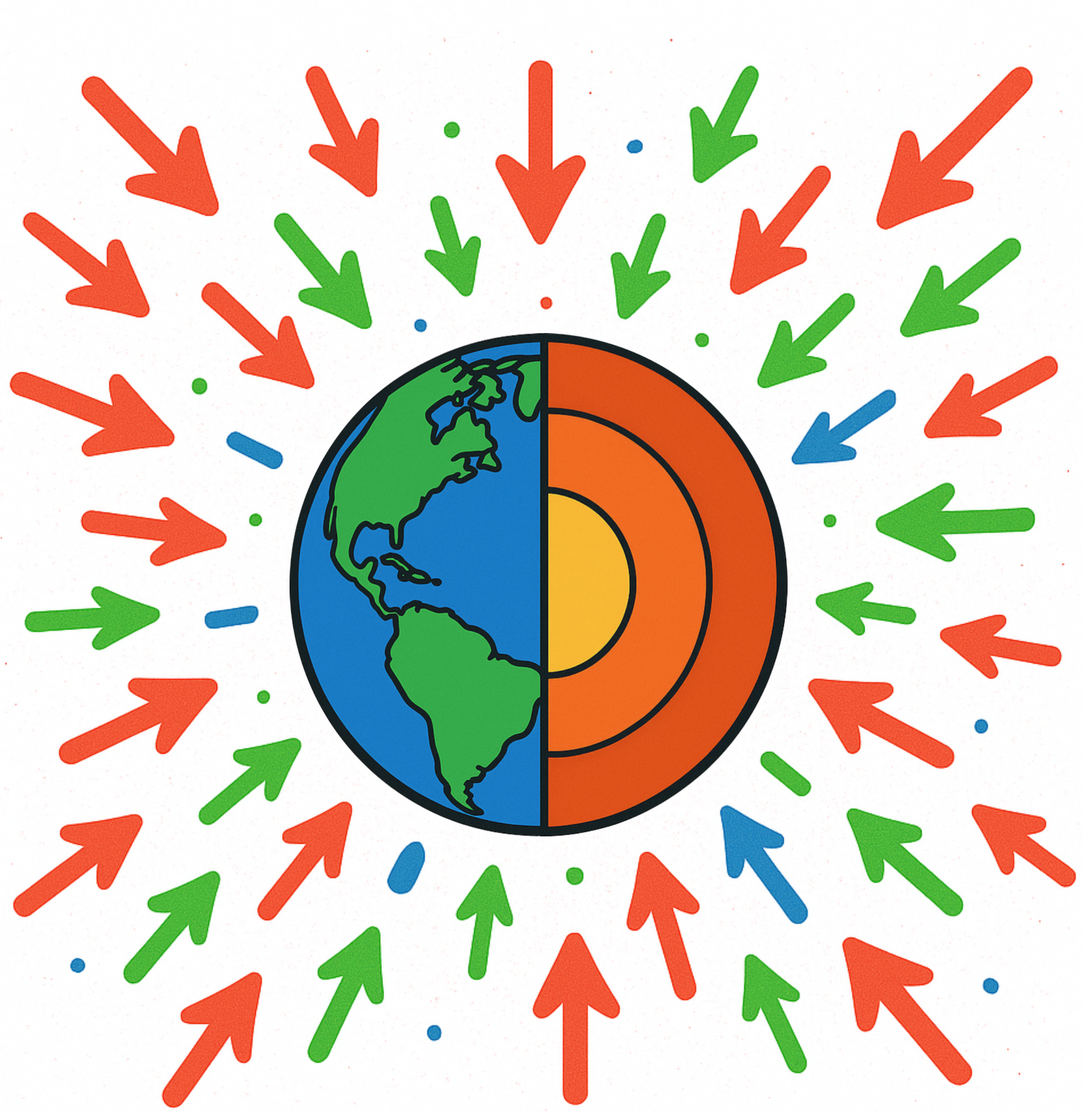
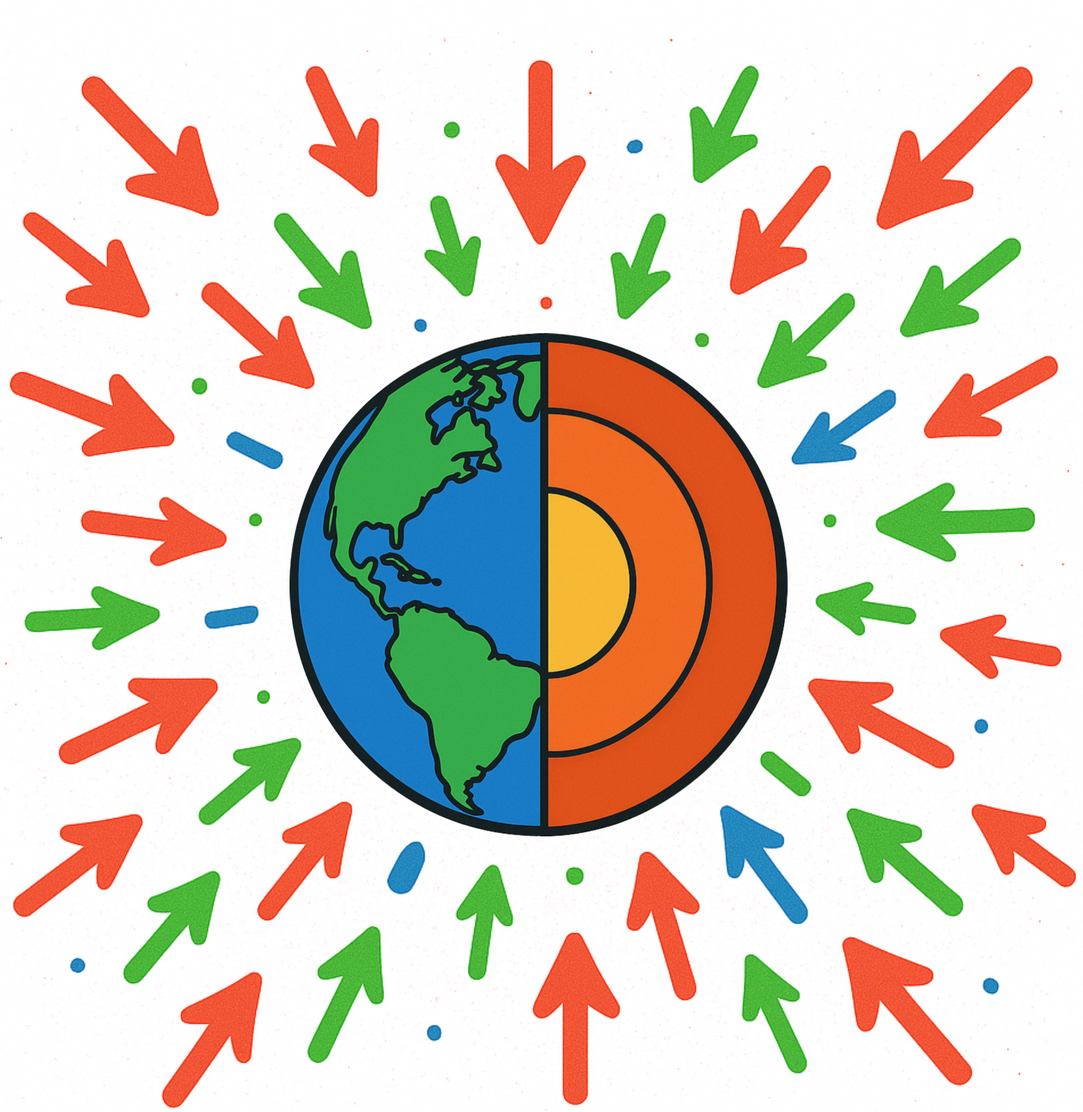


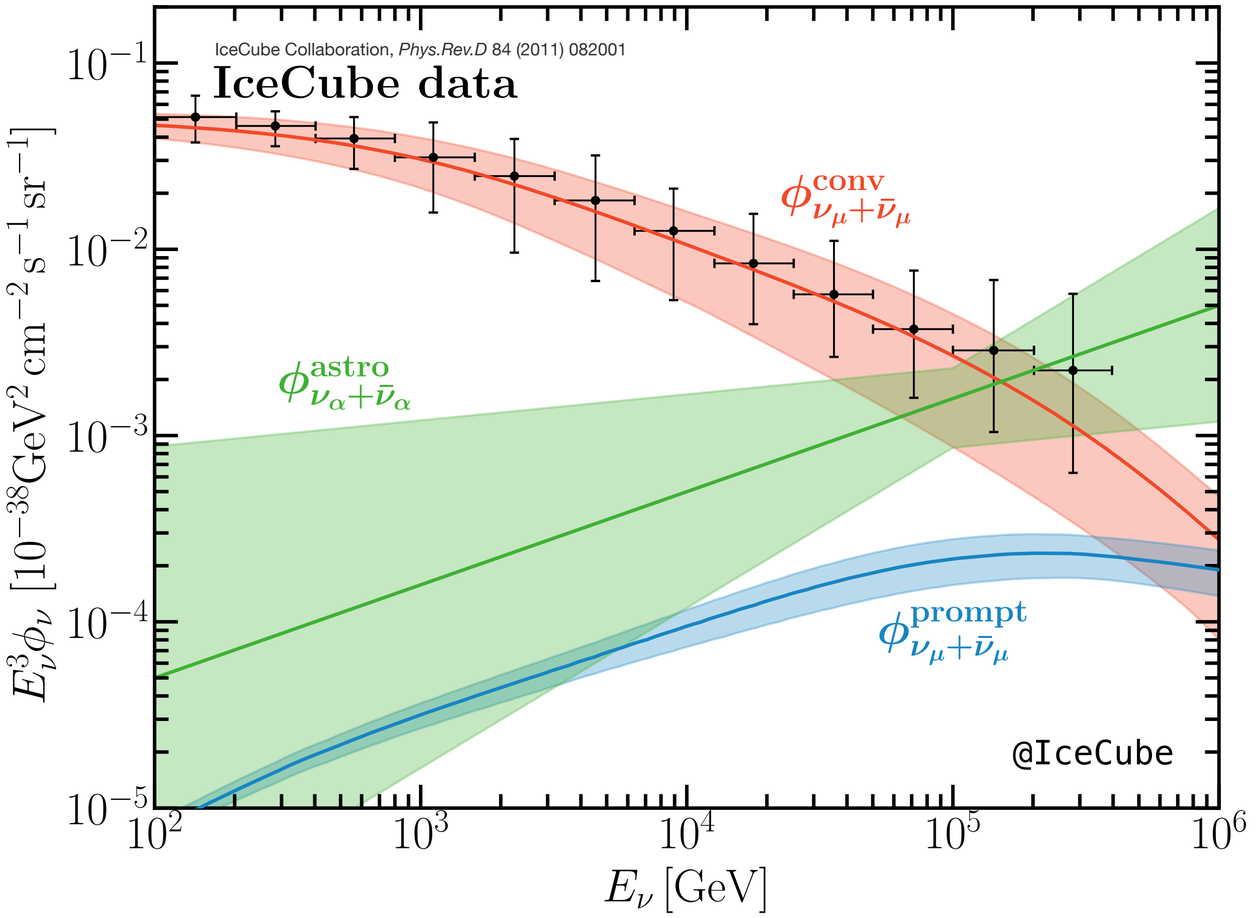
2021	4598	5356	4259	2992	1860	1164	718	423	273	163	98	76
2197	4705	5412	4253	2761	1735	1045	611	345	228	150	90	42
2201	4442	4807	3731	2528	1576	939	555	309	186	146	76	46
2298	4319	4649	3533	2246	1426	849	471	282	187	99	52	36
2191	4140	4403	3237	2126	1278	737	449	240	138	87	49	27
2236	4066	4296	3175	2009	1206	686	385	210	131	88	42	32
2055	3834	4166	3027	1841	1125	642	349	198	112	73	34	24
2050	3810	3838	2815	1738	1031	561	310	175	113	73	34	34
1960	3668	3723	2615	1667	978	567	297	176	109	52	43	19
1830	3286	3599	2447	1533	930	535	260	150	80	51	39	20
1660	3238	3468	2423	1429	829	482	254	141	85	52	29	19
1664	3101	3166	2232	1309	771	412	212	136	76	46	21	11
1593	2919	2976	2166	1305	723	359	220	111	82	41	28	8
1613	2836	2856	2075	1206	647	369	227	129	69	31	16	8
1589	2725	2719	1956	1107	616	321	180	103	64	32	17	12
1648	2676	2736	1846	1015	606	327	190	104	45	39	11	12
1753	2728	2520	1594	911	474	265	149	81	45	28	15	17
1986	2838	2406	1496	829	455	238	109	70	35	22	13	9
2386	2769	2102	1251	725	432	195	86	64	30	24	13	4
2336	2096	1464	911	532	349	189	90	47	29	13	9	4

Neutrino journey: generation

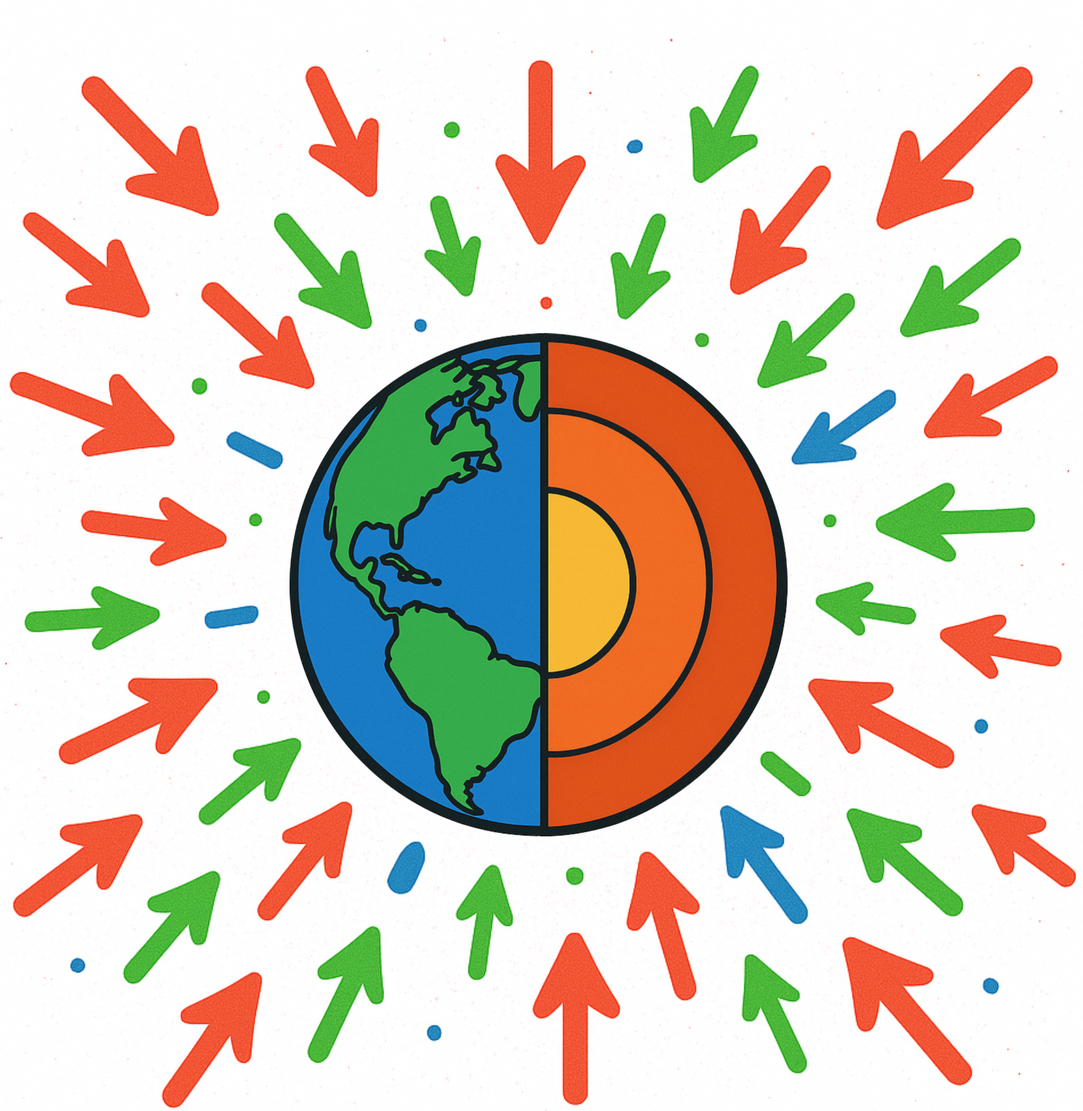


Initial fluxes





Initial fluxes

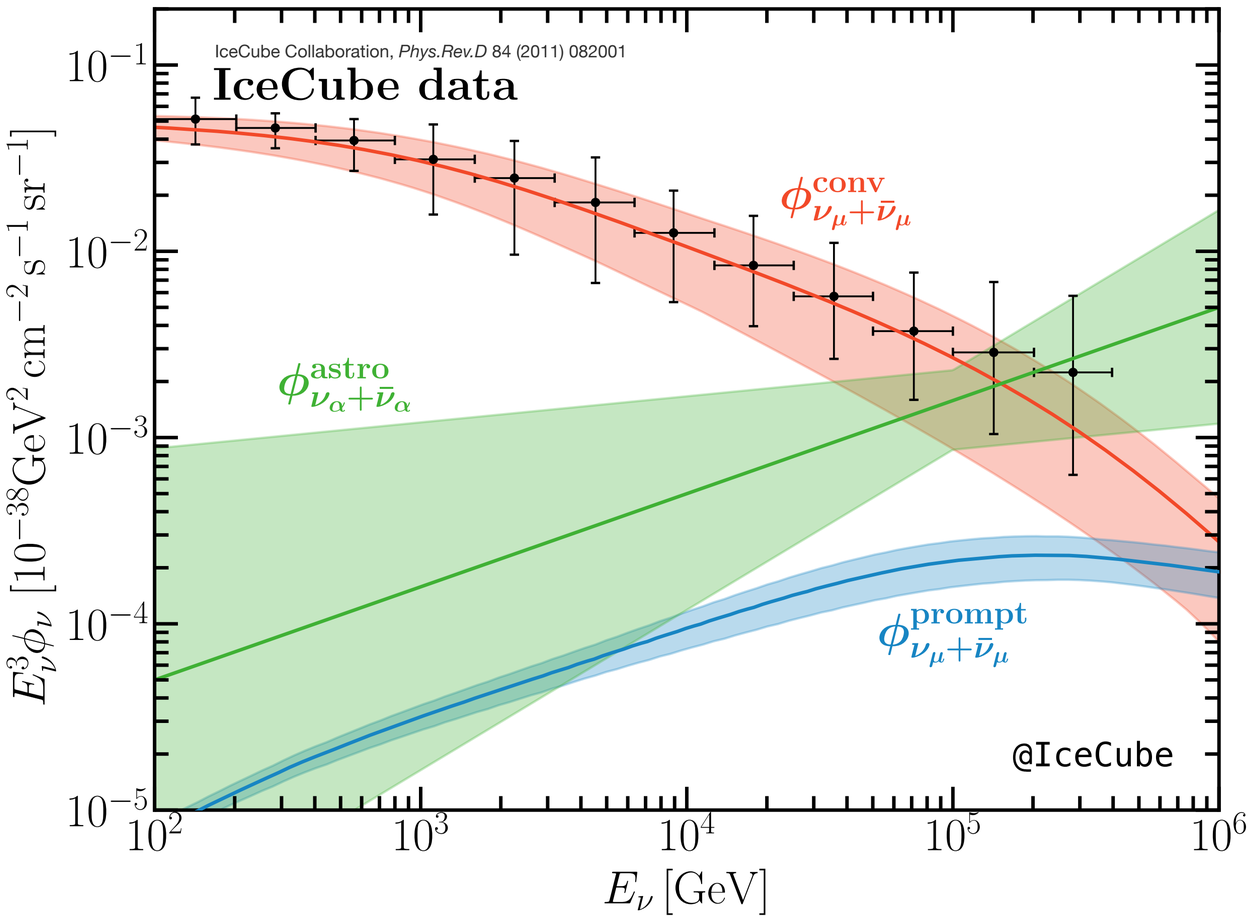


Yañez and Fedynitch,
Phys.Rev.D 107 (2023) 12, 123037

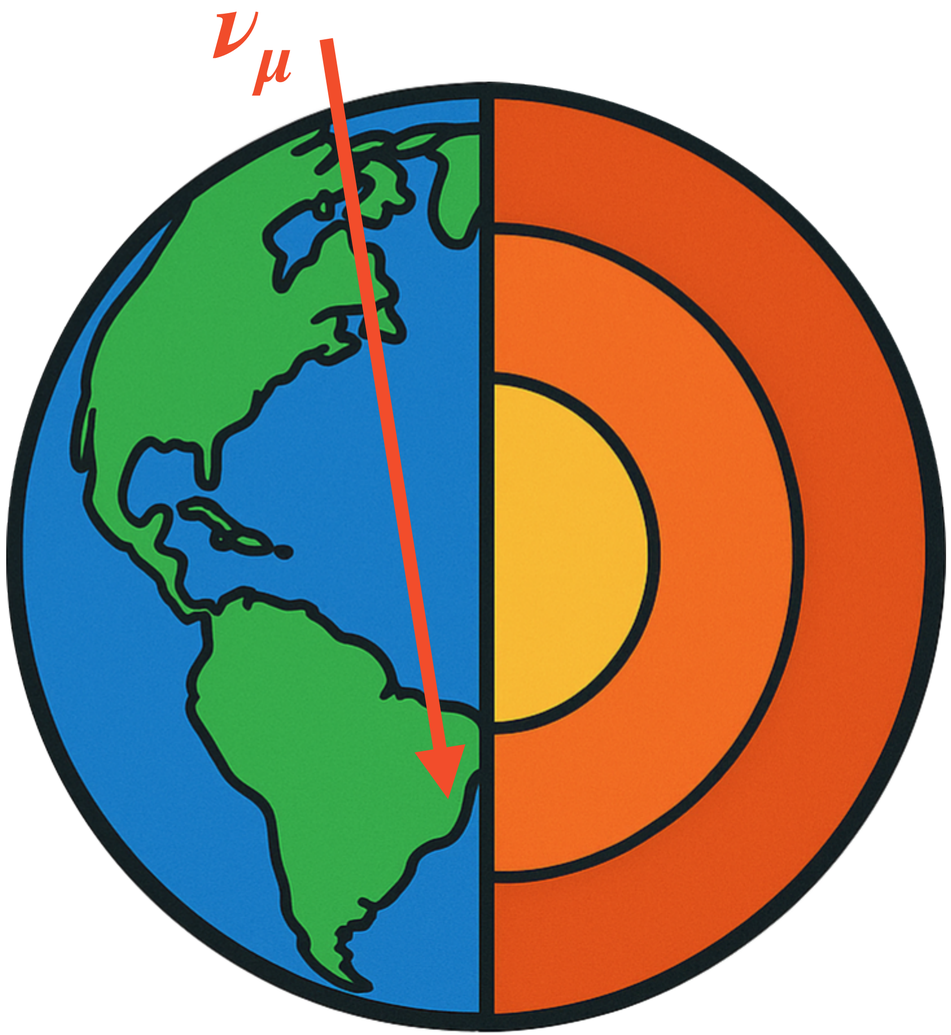
daemonflux

$$\phi_0 \left(\frac{E}{100\,\mathrm{TeV}} \right)^{\gamma}$$

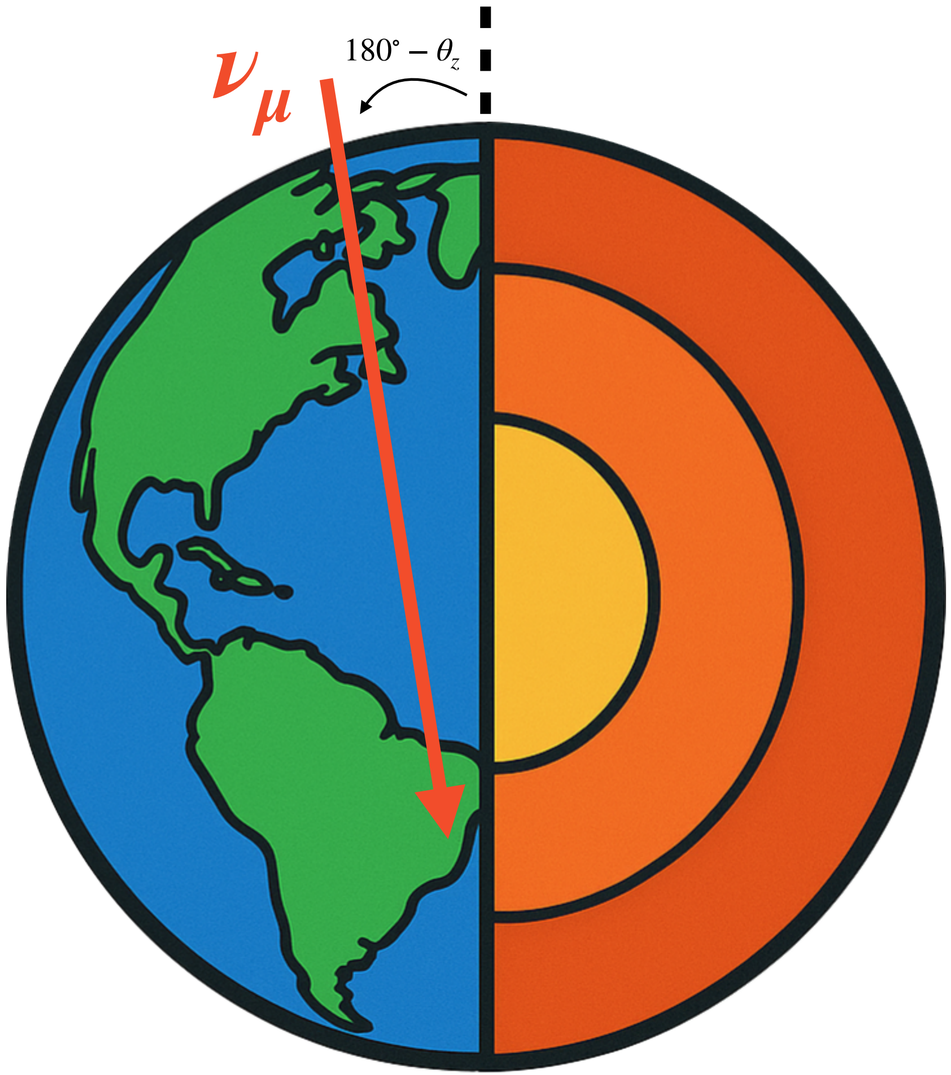
Conventional Prompt Astrophysical

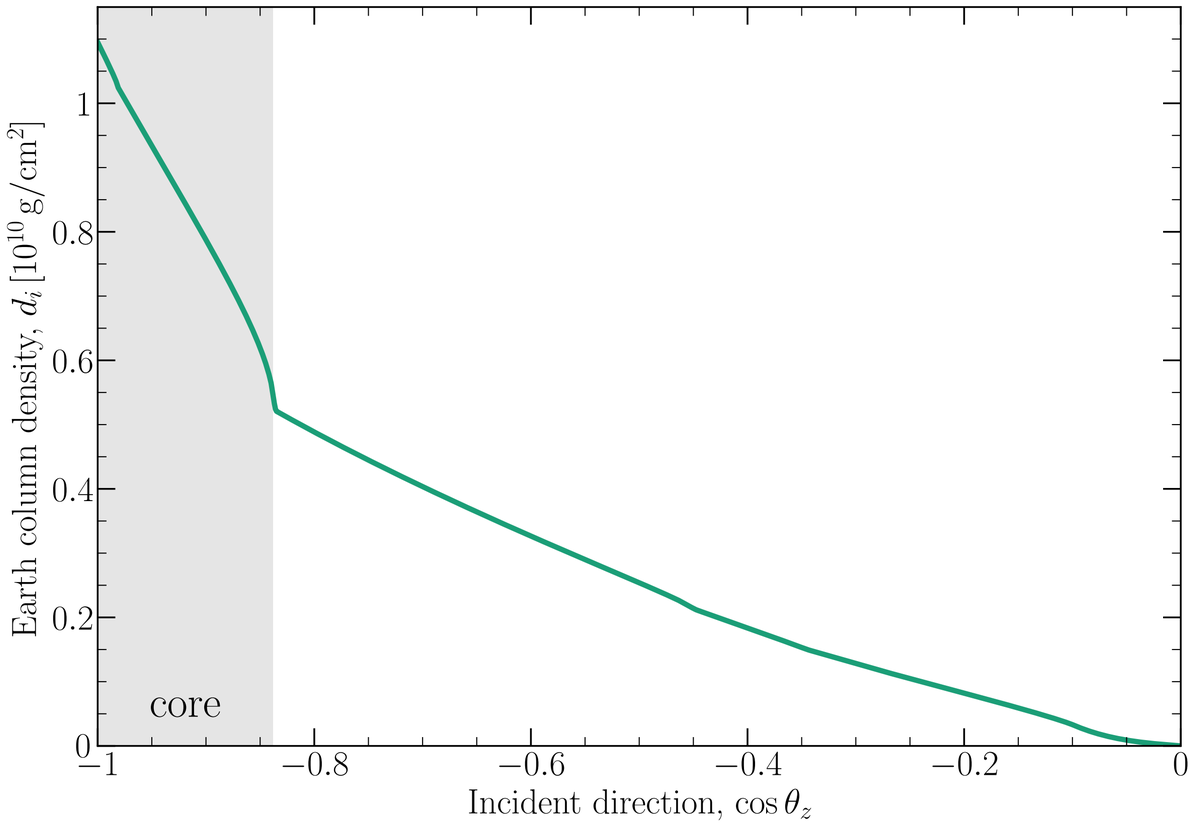


Neutrino journey: transport

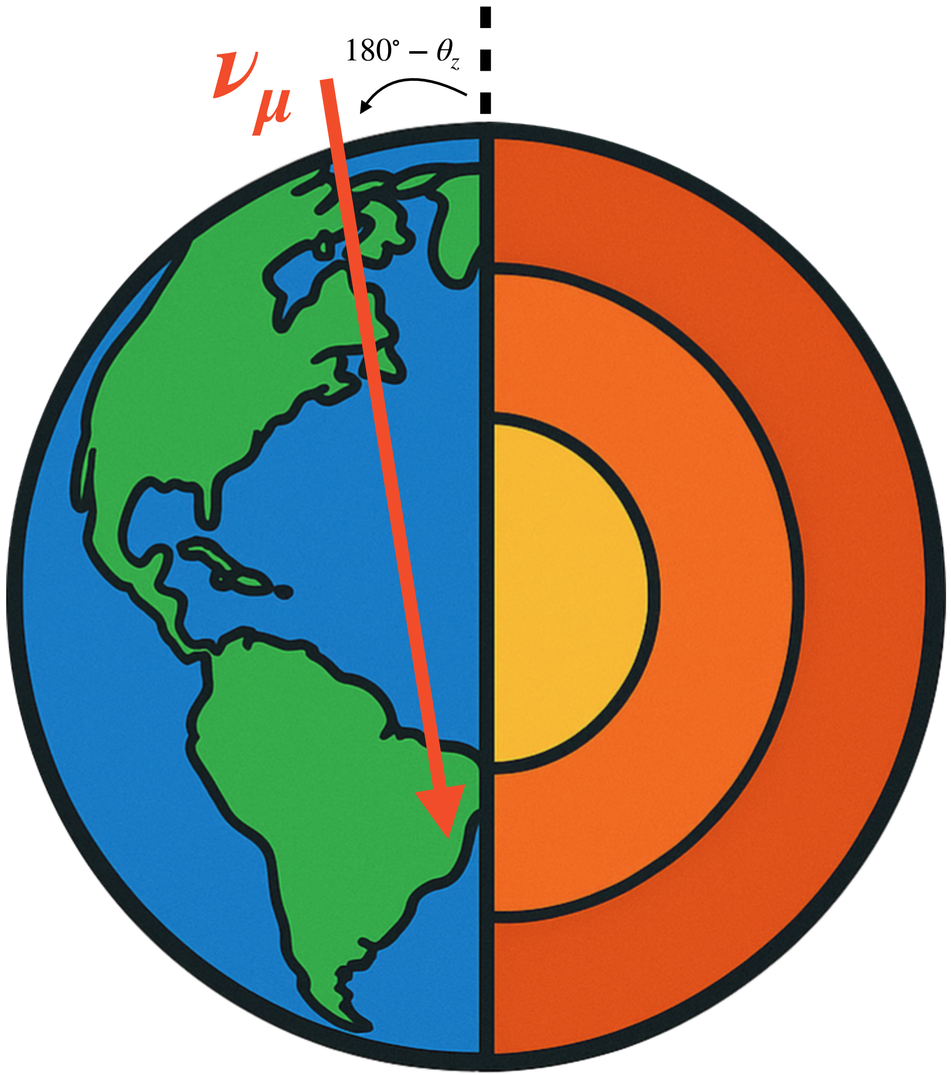


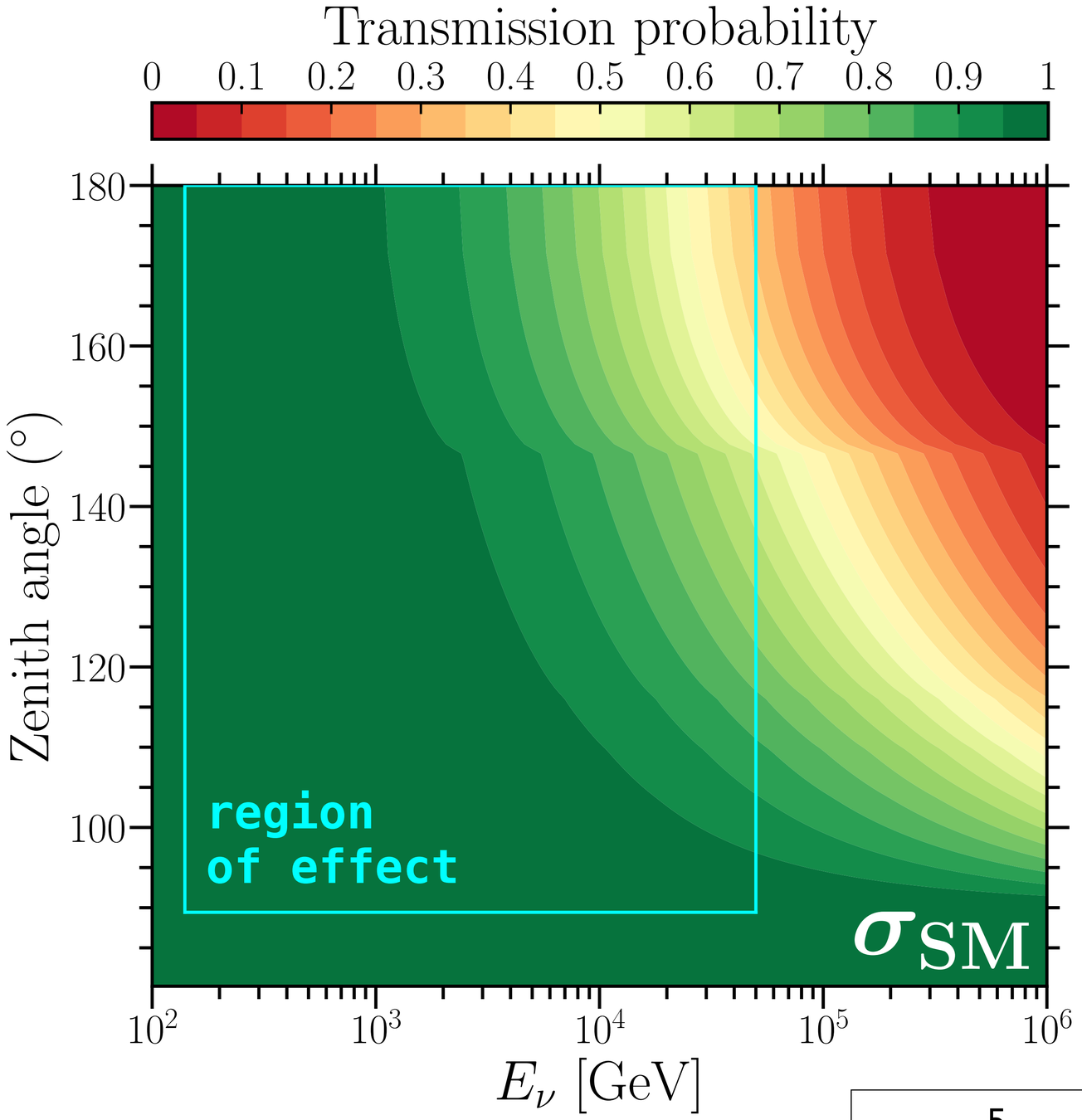
Neutrino journey: transport





Absorption

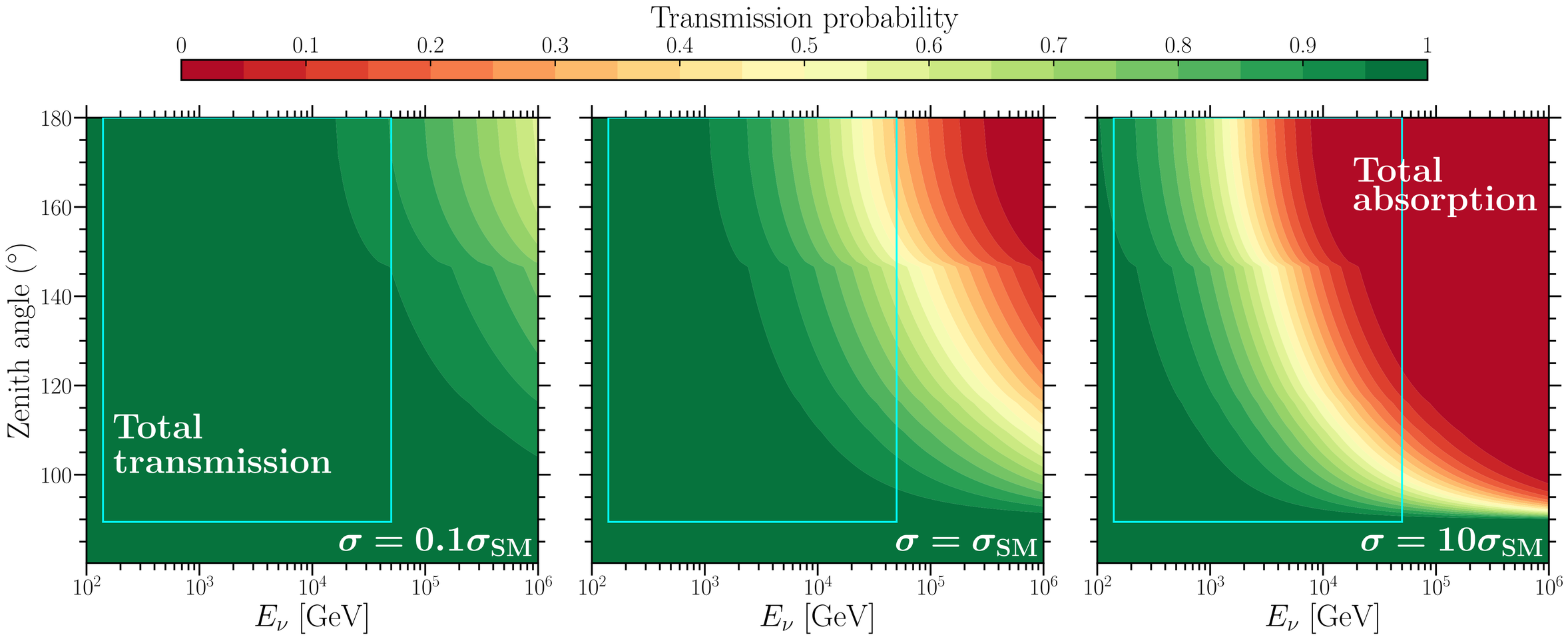




Earth propagation using **nuSQuIDS**
Argüelles, Salvado, Weaver,
Comput.Phys.Commun. 277 (2022), 108346

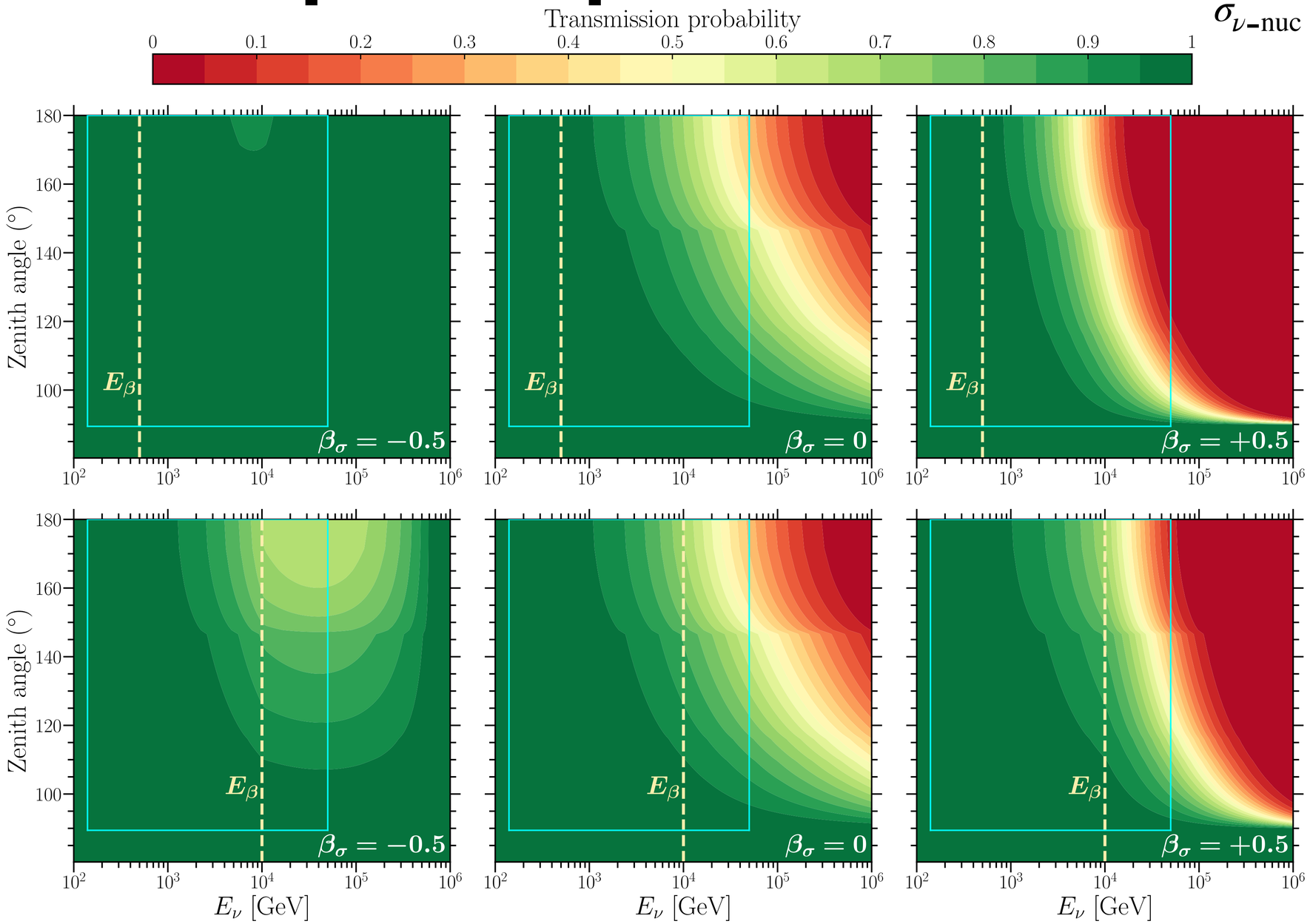
Absorption: normalization

$$\sigma_{\nu\text{-nuc}} = n_\sigma \, \sigma^{\text{SM}}_{\nu\text{-nuc}}$$

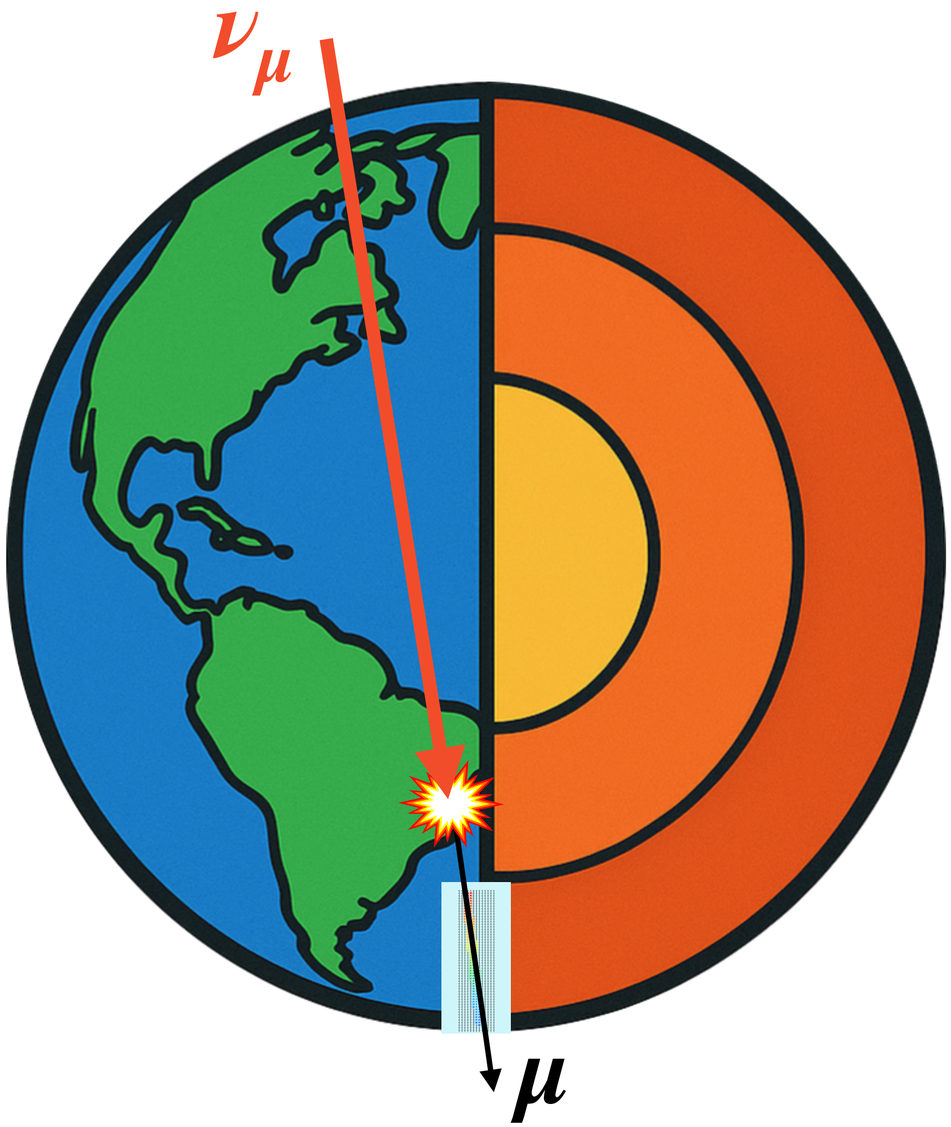


Absorption: spectral shift

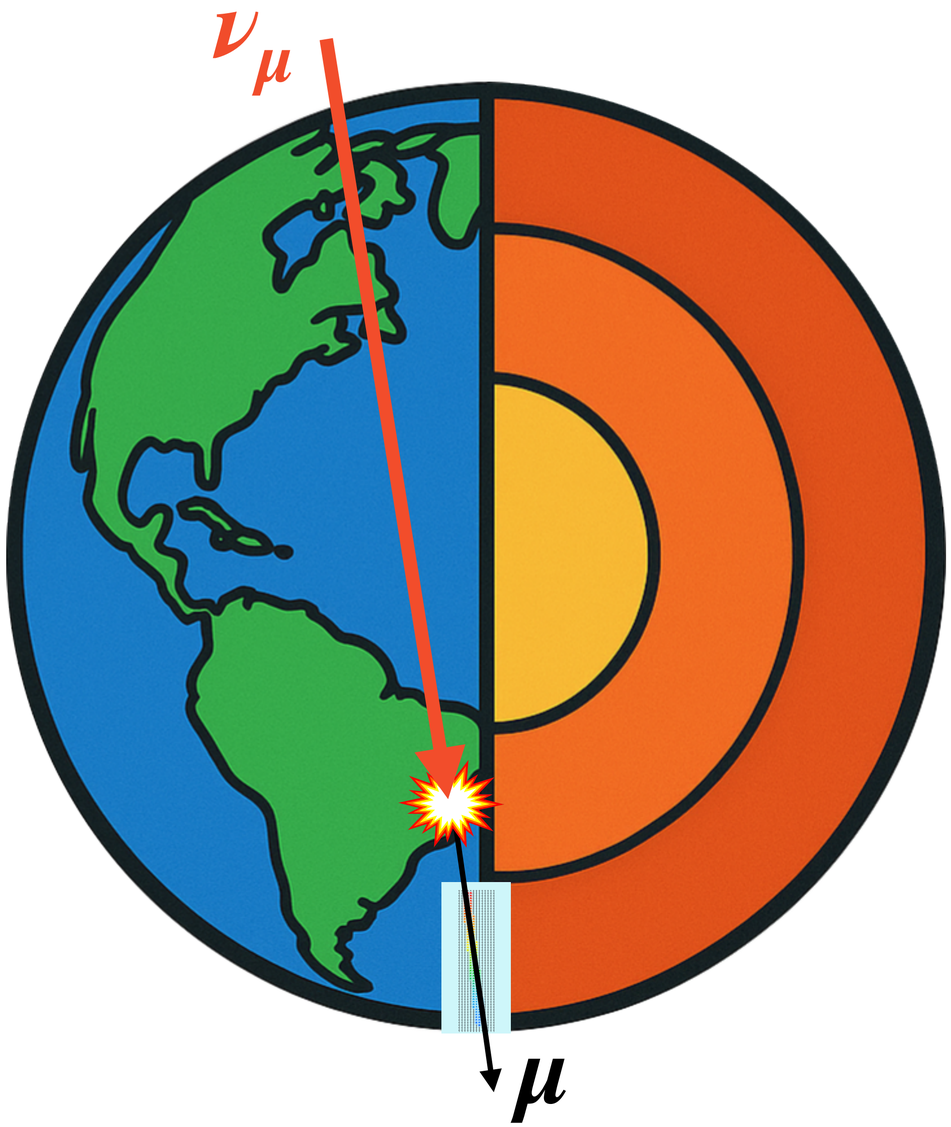
$$\sigma_{\nu\text{-nuc}} = \begin{cases} \sigma^{\text{SM}}_{\nu\text{-nuc}}\,, & \text{if } E \le E_\beta\,, \\ \left(\dfrac{E}{E_\beta}\right)^{\beta_\sigma} \sigma^{\text{SM}}_{\nu\text{-nuc}},\,, & \text{if } E > E_\beta\,. \end{cases}$$



Neutrino journey: detection



Neutrino journey: detection

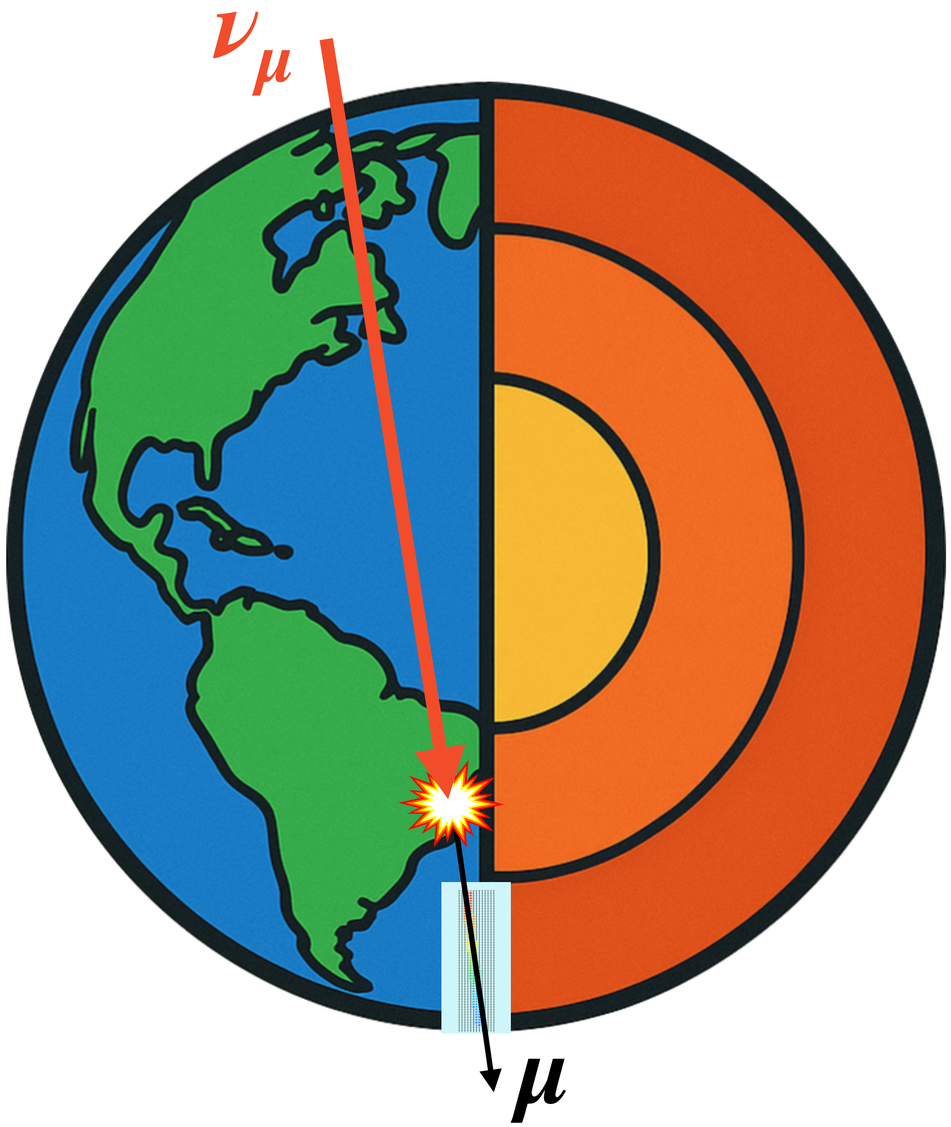


Detection process

$$N_{\mathrm{ev}} \sim T_{\mathrm{obs}} \int \mathrm{d}\Omega \mathrm{d}E_\nu \, A_{\mathrm{eff}} \, \phi_\nu^{\mathrm{ini}}$$

$$N_{\mathrm{ev}}^{\mathrm{MC}} = T_{\mathrm{obs}} \times w_{\mathrm{IC}} \times \phi_\nu^{\mathrm{det}}$$

Neutrino journey: detection

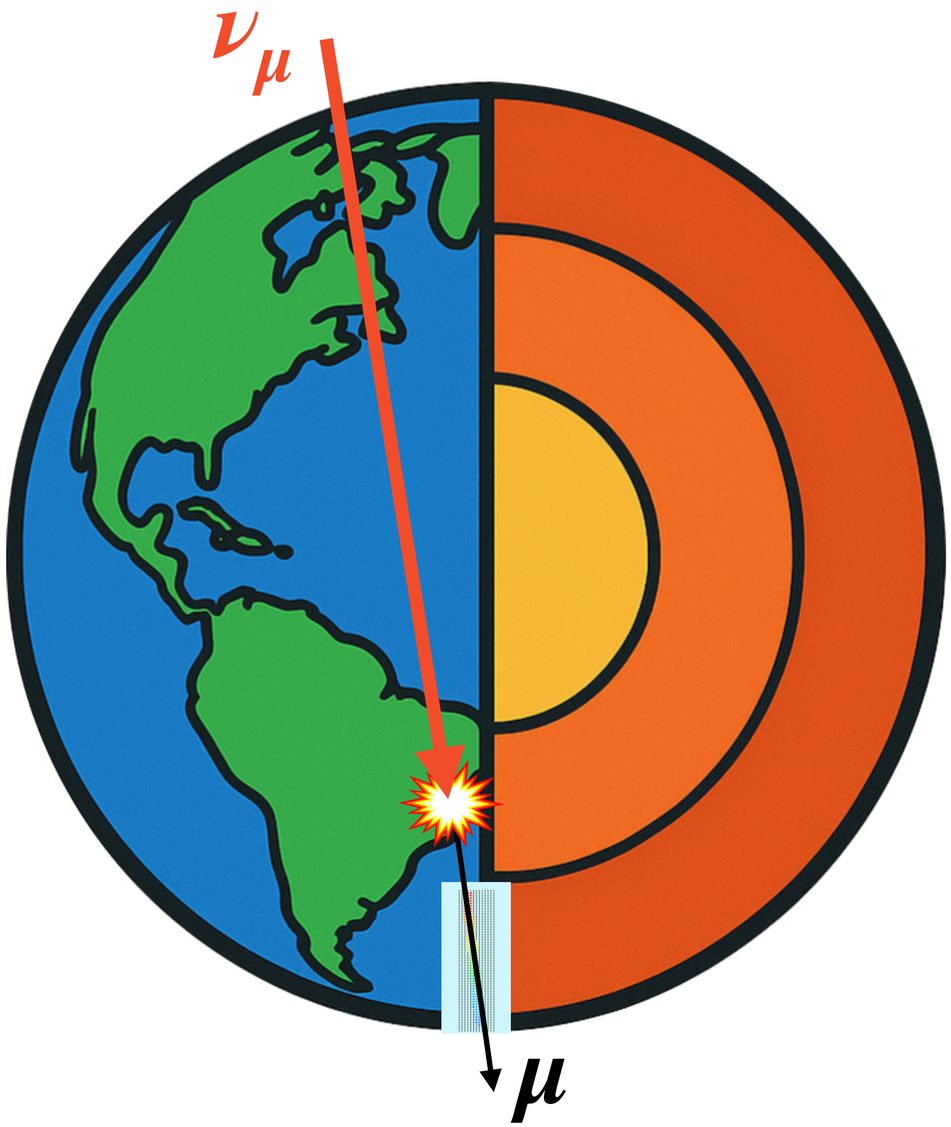


Detection process

$$N_{\mathrm{ev}} \sim T_{\mathrm{obs}} \int \mathrm{d}\Omega \mathrm{d}E_\nu \, \mathscr{D}_{\mathrm{det}} \, \phi_\nu^{\mathrm{det}} \, \sigma_{\nu\text{-nuc}}$$

$$N_{\mathrm{ev}}^{\mathrm{MC}} = T_{\mathrm{obs}} \times w_{\mathrm{IC}} \times \phi_\nu^{\mathrm{det}}$$

Neutrino journey: detection



Detection process

$$N_{\text{ev}} \sim T_{\text{obs}} \int \mathrm{d}\Omega \mathrm{d}E_\nu \, \mathscr{D}_{\text{det}} \, \phi_\nu^{\text{det}} \, \sigma_{\nu\text{-nuc}}$$

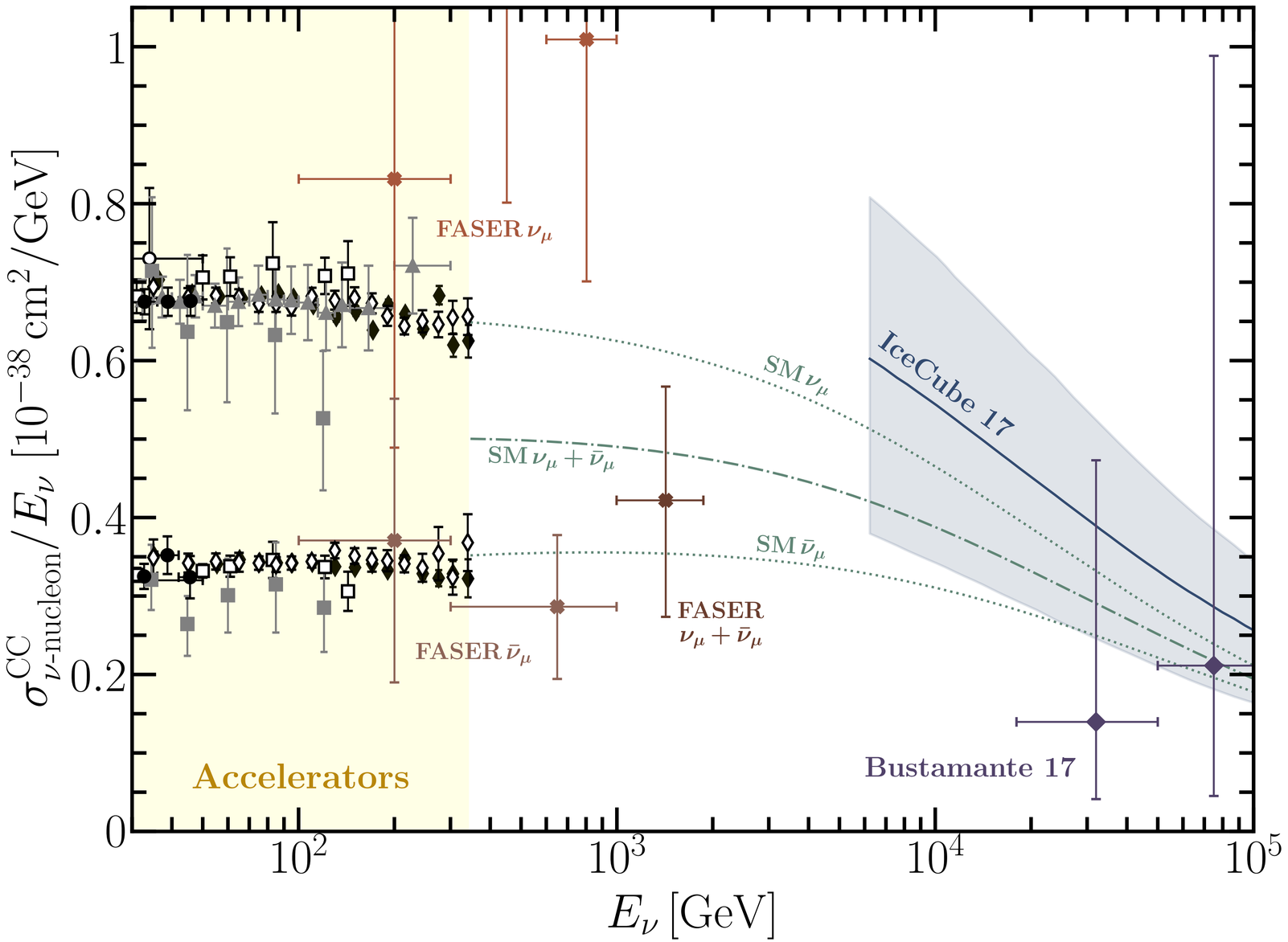
$$N_{\text{ev}}^{\text{MC}} = T_{\text{obs}} \times w_{\text{IC}} \times \phi_\nu^{\text{det}}$$

IceCube data release ($\mathscr{D}_{\text{det}}$)

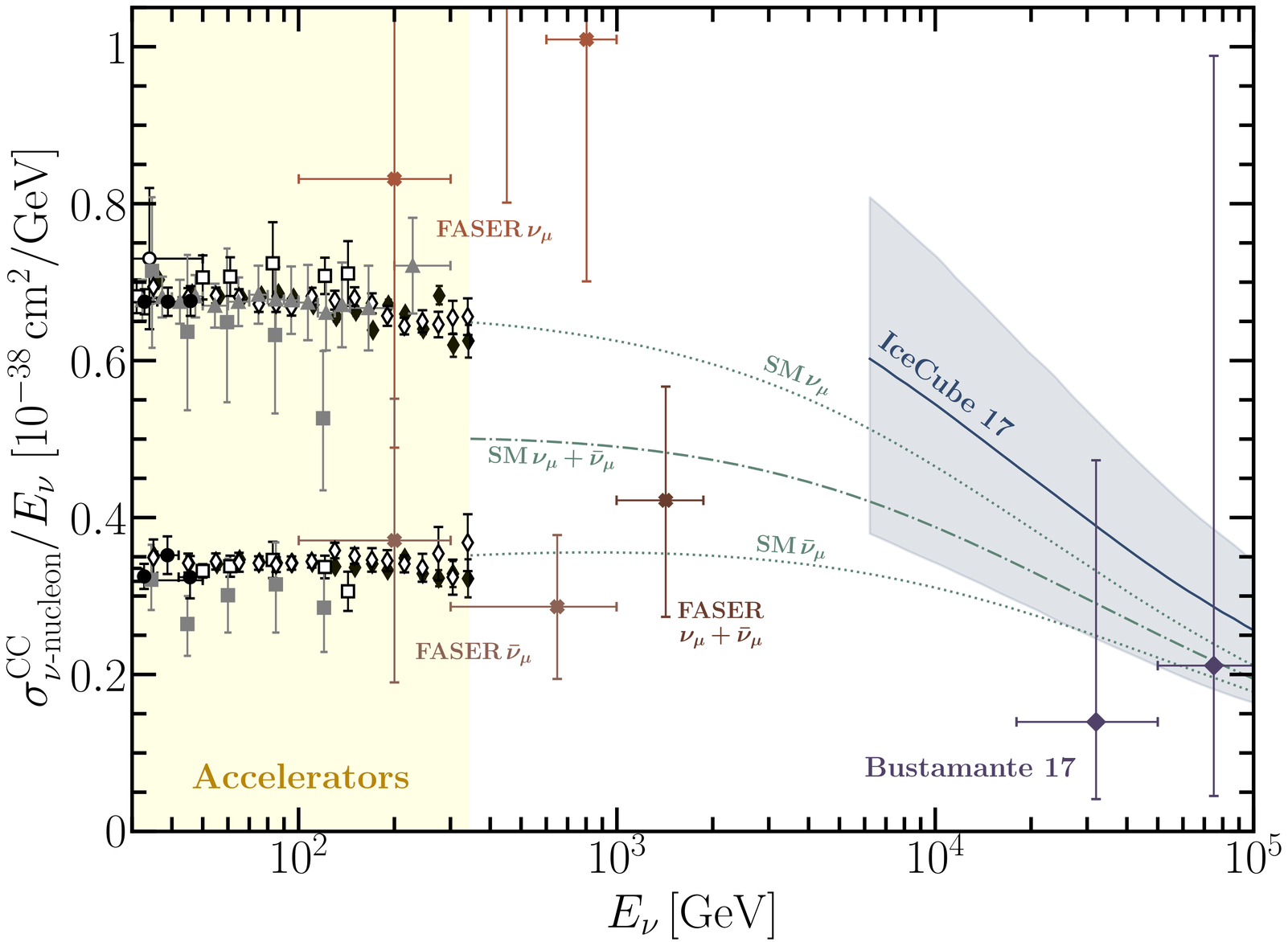
IceCube Collaboration, Nature Phys. 20 (2024) 6, 913-920

Parameter	Prior	Value at Best Fit ($n = 0$) Phase Perturbation	State Selection
Detector Parameters			
DOM Efficiency	0.97 ± 0.10	0.96	0.96
Bulk Ice Gradient 0	0.0± 1.0*	-0.08	-0.07
Bulk Ice Gradient 1	0.0± 1.0*	0.58	0.60
Forward Hole Ice (p_2)	-1.0±10.0	-3.32	-3.30

Results


FASER ν_μ
SM ν_μ
IceCube 17
SM $\nu_\mu + \bar{\nu}_\mu$
SM $\bar{\nu}_\mu$
FASER
$\nu_\mu + \bar{\nu}_\mu$
FASER $\bar{\nu}_\mu$
Accelerators
Bustamante 17
$\sigma^{\mathrm{CC}}_{\nu\text{-nucleon}}/E_\nu$ [10^{-38} cm^2/GeV]
E_ν [GeV]
0
0.2
0.4
0.6
0.8
1
10^2
10^3
10^4
10^5

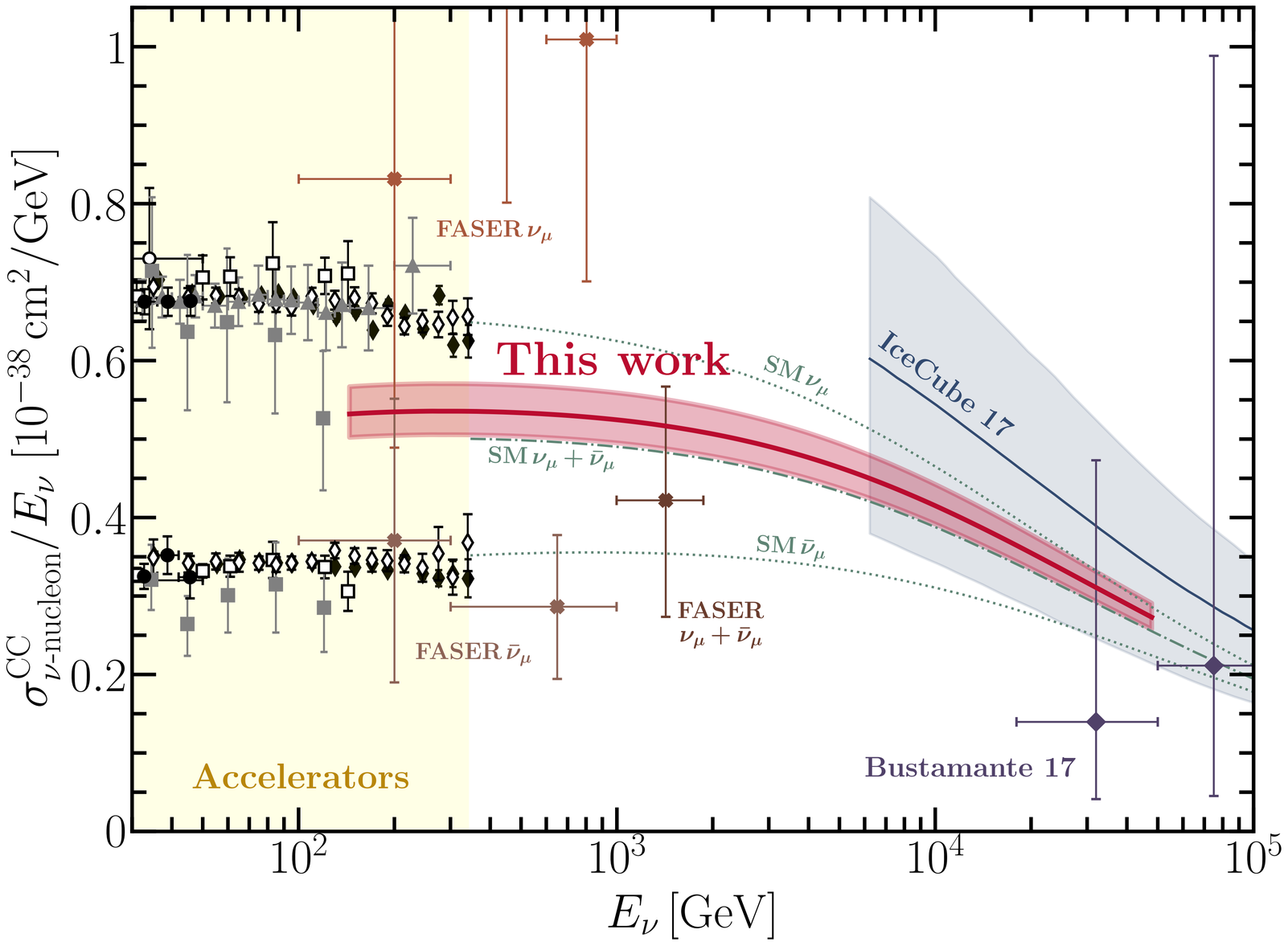
Results: norm



CASE NORM

$$\sigma_{\nu\text{-nuc}} = n_\sigma \, \sigma^{\rm SM}_{\nu\text{-nuc}}$$

Results: norm

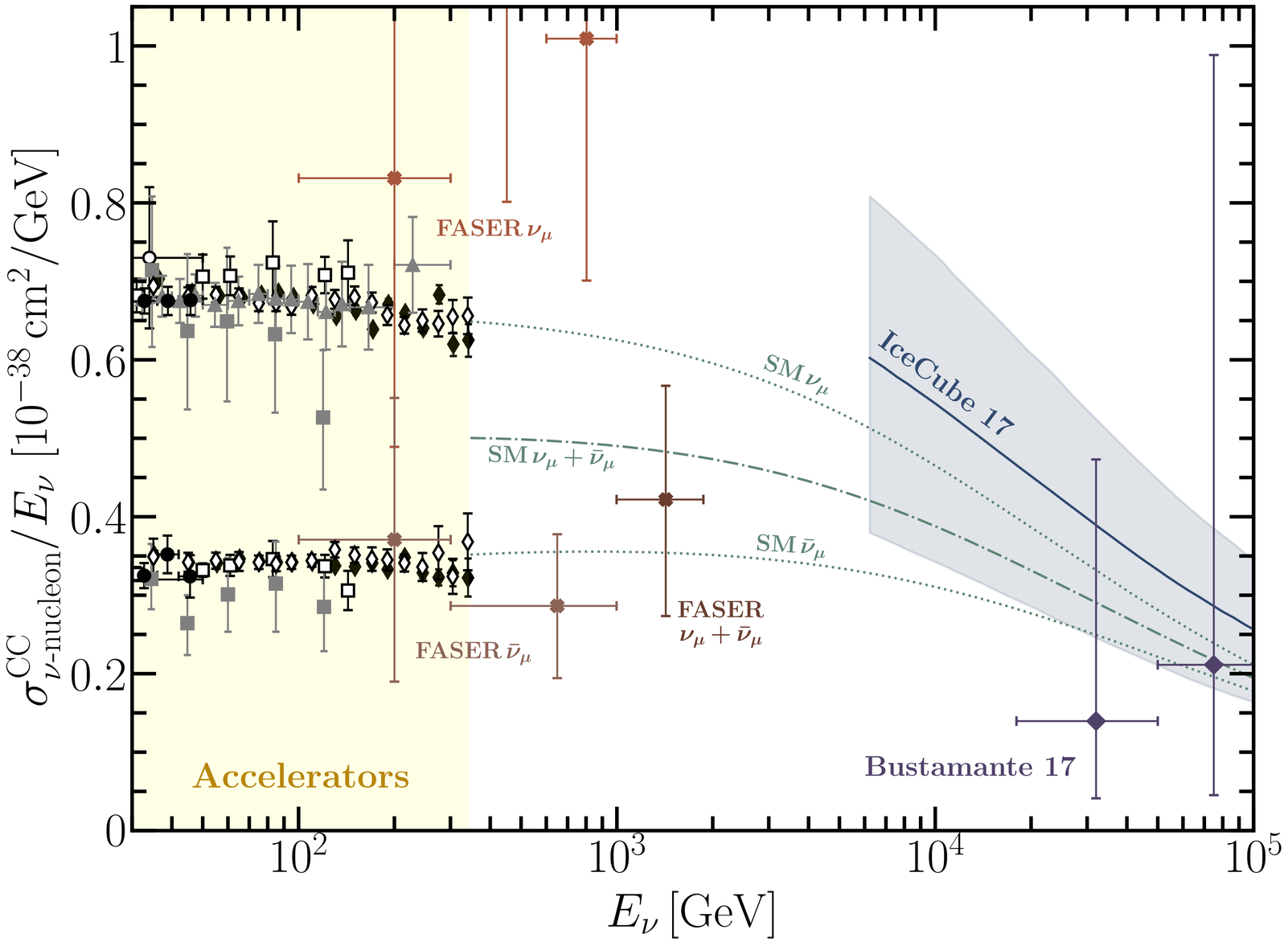


CASE NORM

$$\sigma_{\nu\text{-nuc}} = n_\sigma \, \sigma^{\rm SM}_{\nu\text{-nuc}}$$

$$n_\sigma = 1.07^{+0.07}_{-0.06}$$

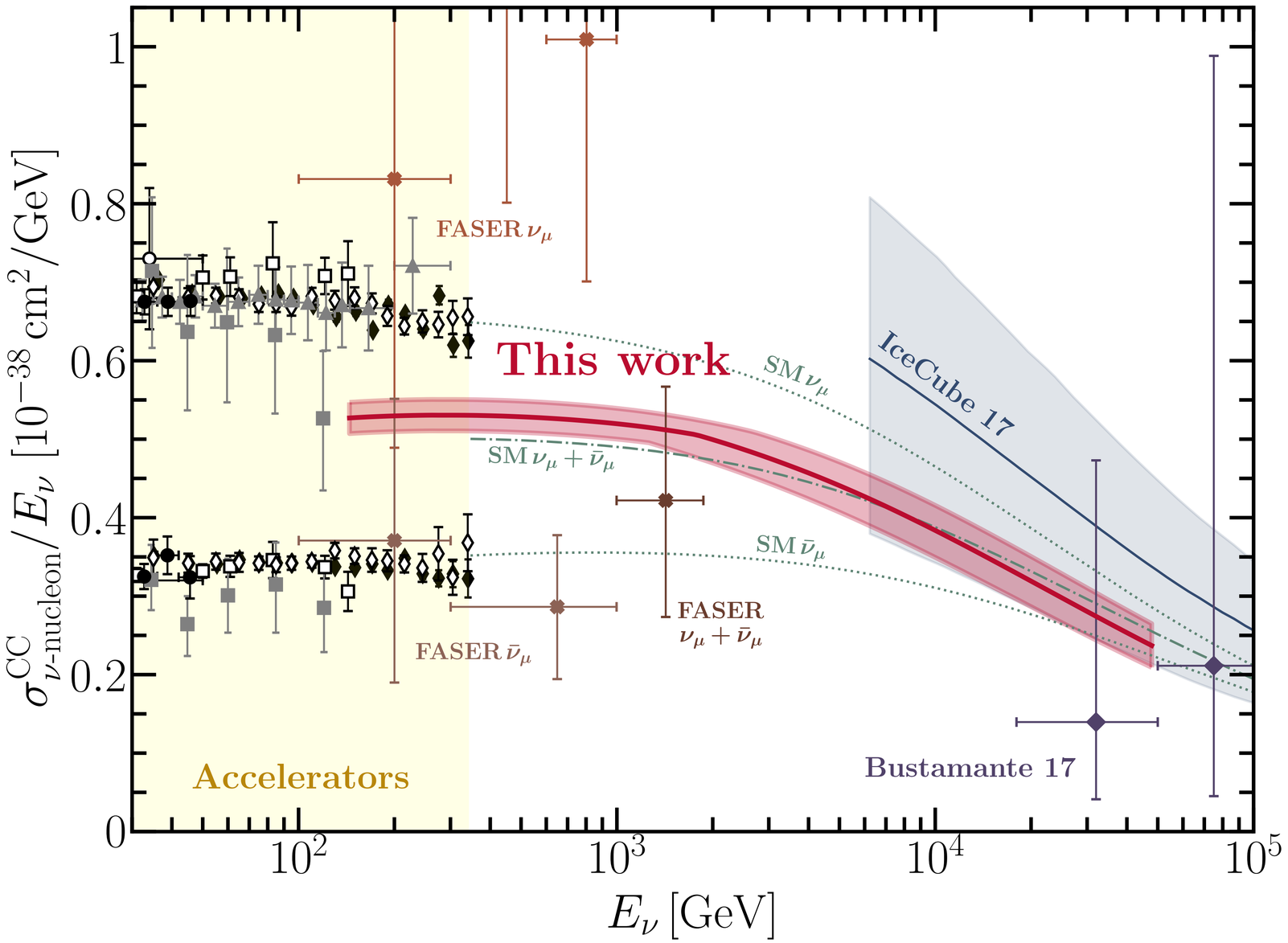
Results: norm + tilt



CASE NORM+TILT

$$\sigma_{\nu\text{-nuc}} = \begin{cases} n_\sigma\, \sigma^{\rm SM}_{\nu\text{-nuc}}\,, & \text{if } E \le E_\beta\,, \\ n_\sigma \left(\dfrac{E}{E_\beta}\right)^{\beta_\sigma} \sigma^{\rm SM}_{\nu\text{-nuc}},\,, & \text{if } E > E_\beta\,. \end{cases}$$

Results: norm + tilt



CASE NORM+TILT

$$\sigma_{\nu\text{-nuc}} = \begin{cases} n_\sigma \, \sigma^{\rm SM}_{\nu\text{-nuc}}\,, & \text{if } E \le E_\beta\,, \\ n_\sigma \left(\dfrac{E}{E_\beta}\right)^{\beta_\sigma} \sigma^{\rm SM}_{\nu\text{-nuc}},\,, & \text{if } E > E_\beta\,. \end{cases}$$

$$n_\sigma = 1.06^{+0.04}_{-0.04}$$

$$\beta_\sigma = -\,0.04^{+0.02}_{-0.02}$$

$$\log_{10}\left(\frac{E_\beta}{\rm TeV}\right) = 0.28^{+0.15}_{-0.18}$$

Take home message

Determined the neutrino-nucleon cross section around TeV.

$$\text{muon data range} \sim [500\,\text{GeV} - 10\,\text{TeV}]$$

$$\text{neutrino influence range} \sim [150\,\text{GeV} - 50\,\text{TeV}]$$

Closed the unknown energy gap!

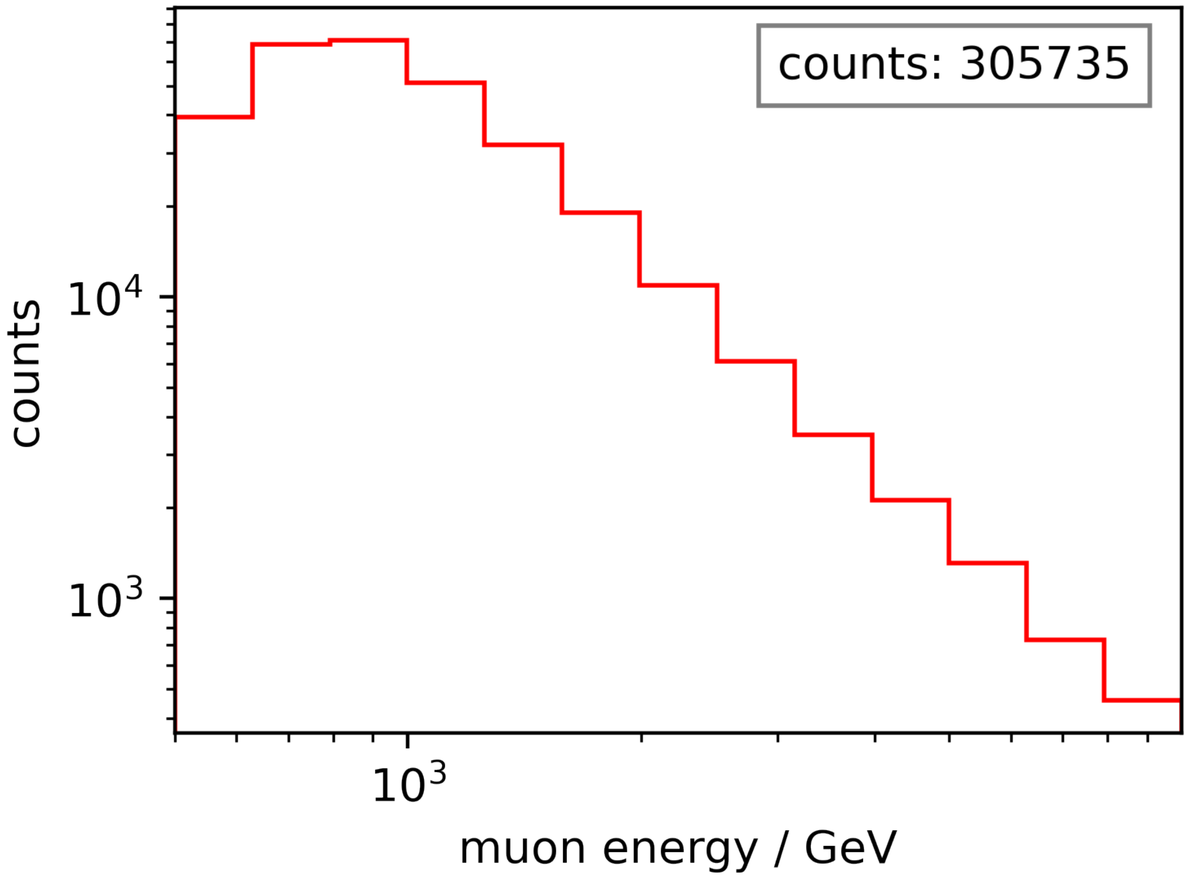
Competitive precision for the TeV energy range.

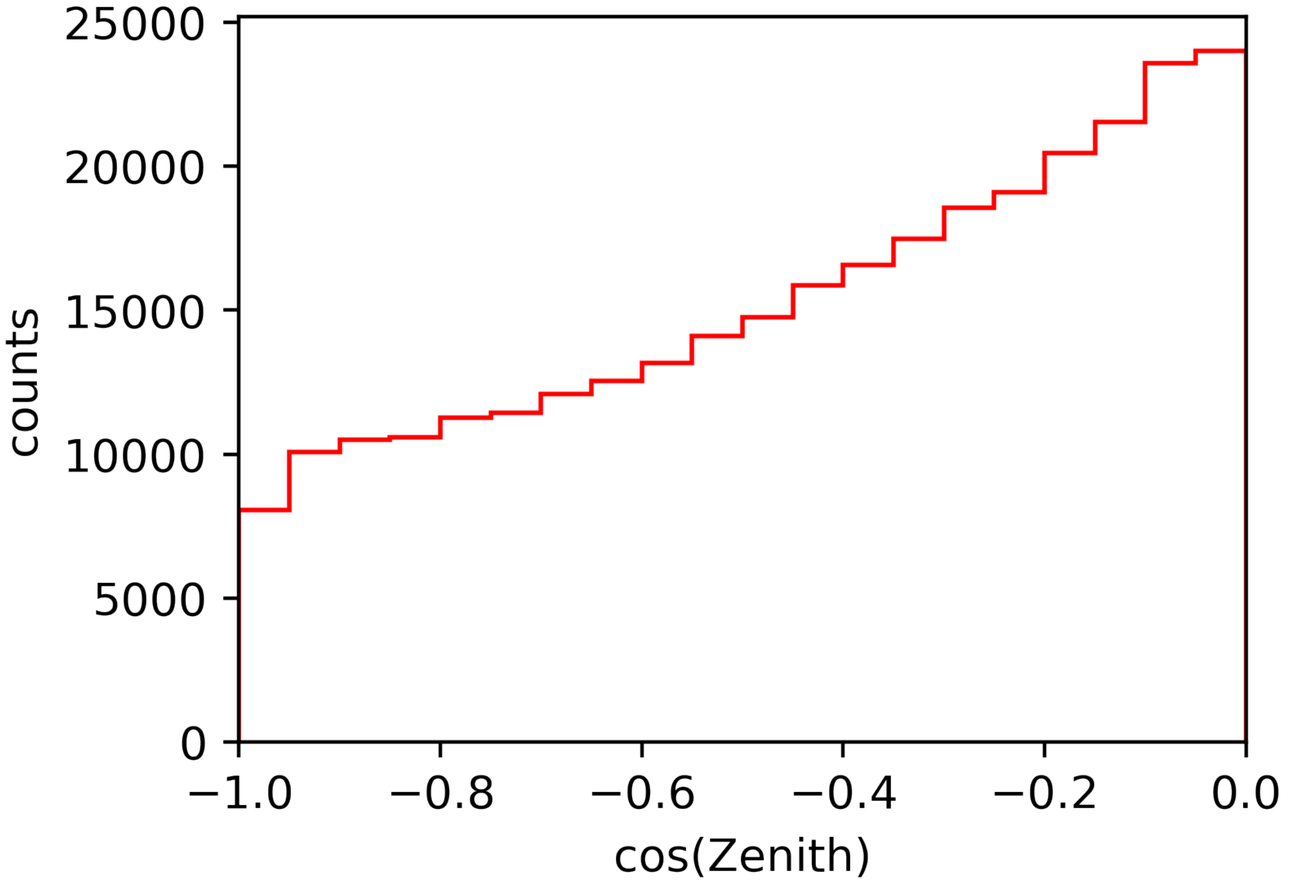
Neutrino-nucleon cross section extraction around the TeV

Backup slides

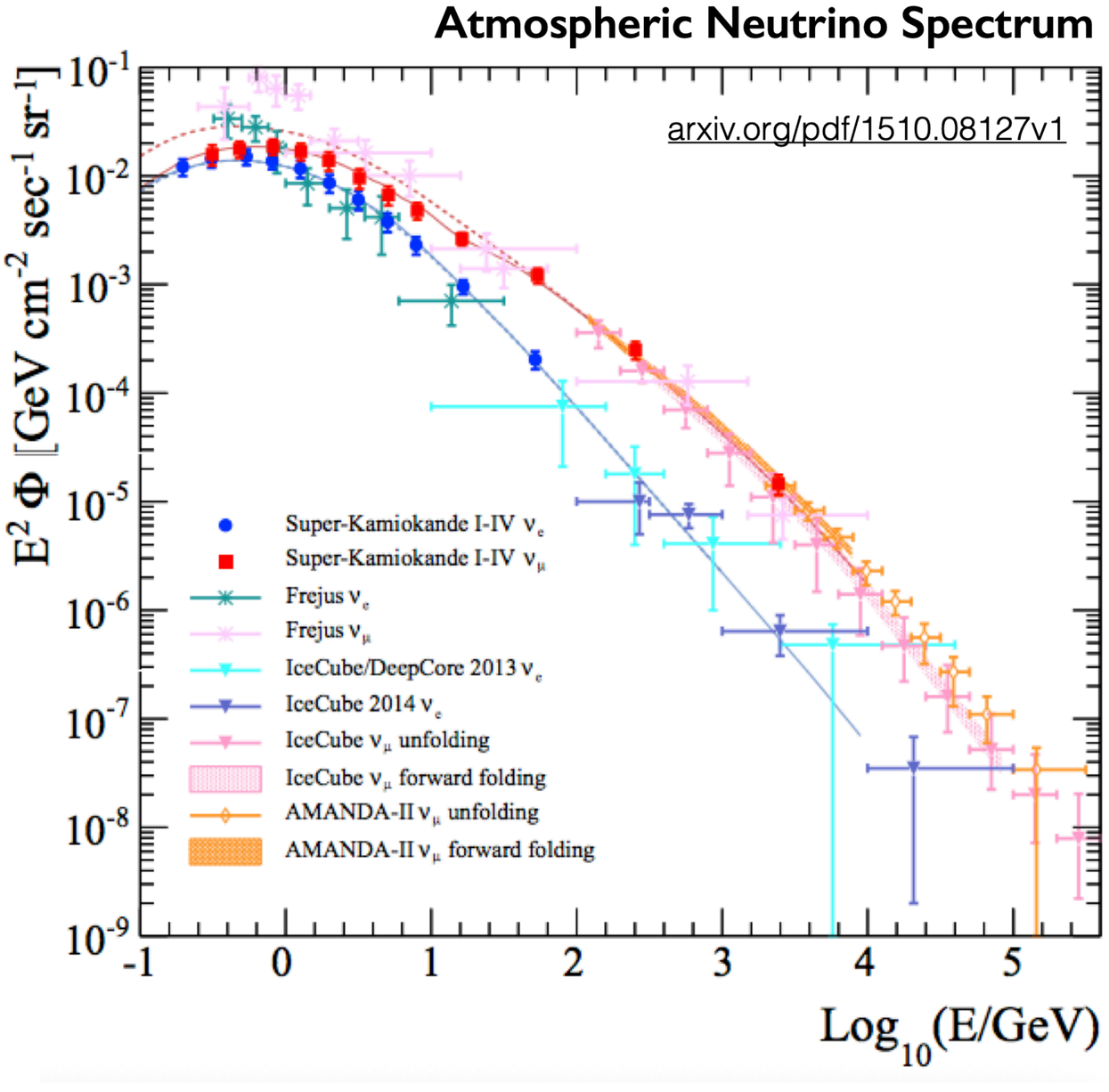
IceCube Collaboration. 2024. “Replication Data for: Searching for Decoherence from Quantum Gravity at the IceCube South Pole Neutrino Observatory.” Harvard Dataverse. https://doi.org/10.7910/DVN/9WGYQN
IceCube Collaboration, Nature Phys. 20 (2024) 6, 913-920

1D distribution of data

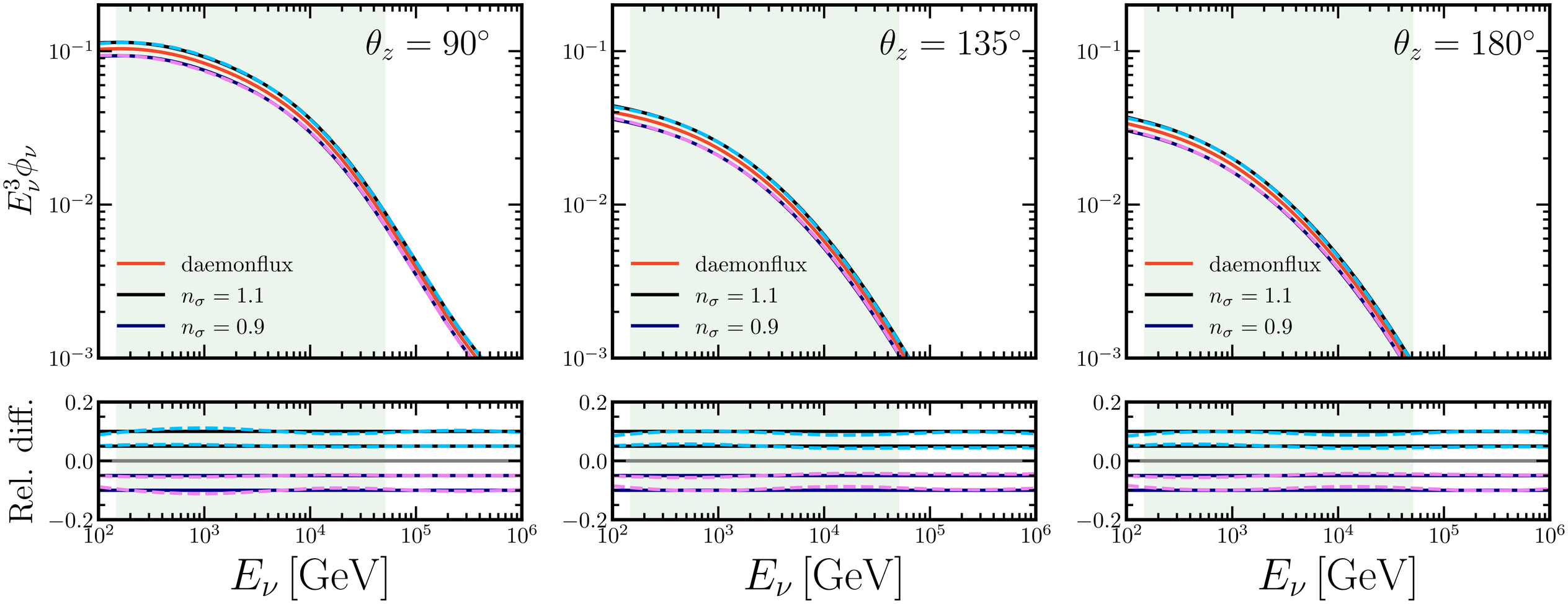




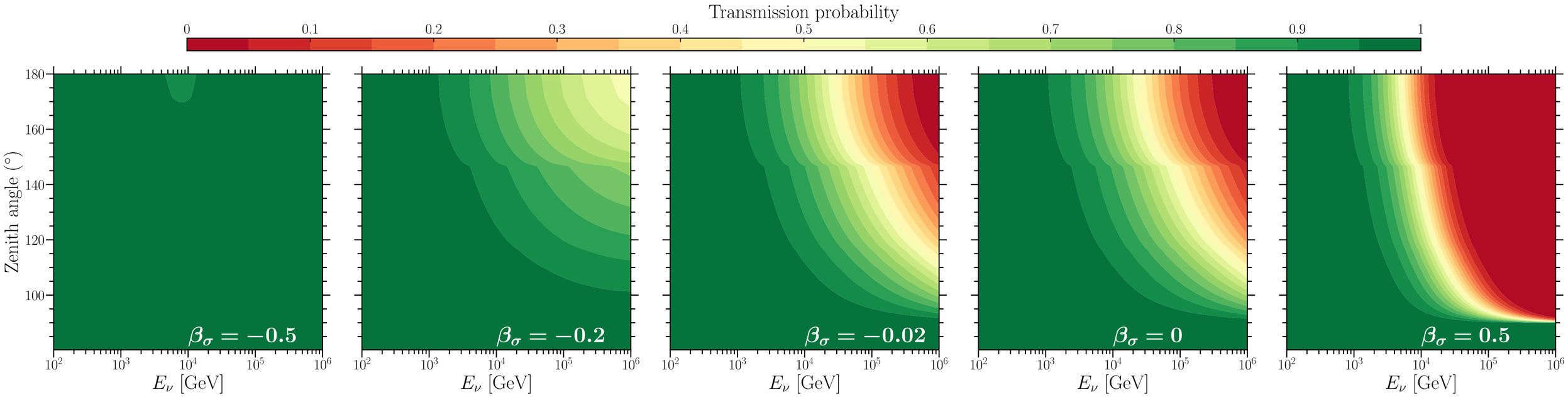
Flux: neutrino measurements



Flux: effective normalizations



Absorption: tilt pattern



Analysis: Priors

Data Release analysis priors

IceCube Collaboration, Nature Phys. 20 (2024) 6, 913-920

Parameter	Prior	Value at Best Fit ($n = 0$) Phase Perturbation	State Selection
Detector Parameters			
DOM Efficiency	0.97 ± 0.10	0.96	0.96
Bulk Ice Gradient 0	0.0± 1.0*	-0.08	-0.07
Bulk Ice Gradient 1	0.0± 1.0*	0.58	0.60
Forward Hole Ice (p_2)	-1.0±10.0	-3.32	-3.30
Conventional Flux Parameters			
Normalization($\Phi_{conv.}$)	1.0±0.4	1.10	1.10
Spectral Shift ($\Delta_{conv.}$)	0.00±0.03	0.07	0.07
Atmospheric Density	0.0±1.0	-0.10	-0.11
Barr WM	0.00±0.40	-0.01	-0.00
Barr WP	0.00±0.40	0.01	0.01
Barr YM	0.00±0.30	-0.06	-0.06
Barr YP	0.00±0.30	-0.04	-0.04
Barr ZM	0.00±0.12	-0.01	-0.01
Barr ZP	0.00±0.12	-0.02	-0.02
Astrophysical Flux Parameters			
Normalization($\Phi_{astro.}$)	0.79± 0.36*	0.84	0.84
Spectral Shift ($\Delta_{astro.}$)	0.00± 0.36*	-0.02	-0.01
Cross sections			
Cross section (σ_{ν_μ})	1.00±0.03	1.00	1.00
Cross section ($\sigma_{\overline{\nu}_\mu}$)	1.00±0.075	1.01	1.01
Kaon re-interaction (σ_{KA})	0.0±1.0	-0.16	-0.14

Our priors

Parameter	Symbol [unit]	Prior	Boundaries
ν-nucleon cross section			
Normalization of σ_{SM}	n_σ	$\mathcal{U}[0.05, 20]$	[0.05, 20]
Spectral shift of σ_{SM}	β_σ	$\mathcal{U}[-2, 2]$	[-2, 2]
Pivot point of σ_{SM}	E_β [TeV]	$\mathcal{U}[0.1, 50]$	[0.1, 50]
`daemonflux` atmospheric flux			
K^+ node at 158 GeV	$K^+_{158\mathrm{G}}$	$\mathcal{N}[0, 1]$	[-2, 2]
K^- node at 158 GeV	$K^-_{158\mathrm{G}}$	$\mathcal{N}[0, 1]$	[-2, 2]
π^+ node at 20 TeV	$\pi^+_{20\mathrm{T}}$	$\mathcal{N}[0, 1]$	[-2, 2]
π^- node at 20 TeV	$\pi^-_{20\mathrm{T}}$	$\mathcal{N}[0, 1]$	[-2, 2]
K^+ node at 2 PeV	$K^+_{2\mathrm{P}}$	$\mathcal{N}[0, 1]$	[-2, 2]
K^- node at 2 PeV	$K^-_{2\mathrm{P}}$	$\mathcal{N}[0, 1]$	[-1.5, 2]
π^+ node at 2 PeV	$\pi^+_{2\mathrm{P}}$	$\mathcal{N}[0, 1]$	[-2, 2]
π^- node at 2 PeV	$\pi^-_{2\mathrm{P}}$	$\mathcal{N}[0, 1]$	[-2, 2]
proton node at 2 PeV	$p_{2\mathrm{P}}$	$\mathcal{N}[0, 1]$	[-2, 2]
neutron node at 2 PeV	$n_{2\mathrm{P}}$	$\mathcal{N}[0, 1]$	[-2, 2]
Cosmic ray spectrum 1	GSF_1	$\mathcal{N}[0, 1]$	[-4, 4]
Cosmic ray spectrum 2	GSF_2	$\mathcal{N}[0, 1]$	[-4, 4]
Cosmic ray spectrum 3	GSF_3	$\mathcal{N}[0, 1]$	[-4, 4]
Cosmic ray spectrum 4	GSF_4	$\mathcal{N}[0, 1]$	[-4, 4]
Cosmic ray spectrum 5	GSF_5	$\mathcal{N}[0, 1]$	[-4, 4]
Cosmic ray spectrum 6	GSF_6	$\mathcal{N}[0, 1]$	[-4, 4]
Conventional atmospheric flux			
Atmospheric density	ρ_{atm}	$\mathcal{N}[0, 1]$	[-3, 3]
Kaon reinteraction	$\sigma_{K\text{-Air}}$	$\mathcal{N}[0, 1]$	[-3, 3]
Astrophysical diffuse flux			
Astro normalization	Φ_{astro} $[10^{-18}/\mathrm{GeV/sr/s/cm^2}]$	$\mathcal{N}[0.79, 0.36]$	[0, 3.0]
Astro spectral shift	$\Delta\gamma_{\mathrm{astro}}$	$\mathcal{N}[0, 0.36]$	[-2, 2]
Detector response			
DOM Efficiency	ϵ_{dom}	$\mathcal{N}[0.97, 0.1]$	[0.94, 1.03]
Bulk Ice Gradient 0	b_0	$\mathcal{N}[0, 1]$	[-3, 3]
Bulk Ice Gradient 1	b_1	$\mathcal{N}[0, 1]$	[-3, 3]
Forward Hole Ice	p_2	$\mathcal{N}[-1, 10]$	[-5, 3]

Analysis: Priors

Latest IceCube analysis priors

IceCube Collaboration, Phys.Rev.D 110 (2024) 9, 092009

	Nuisance parameter	Central value	1σ width of prior	Allowed range	Pull Null Fit (σ)	Pull Best Fit (σ)	Pull Difference |Null-Best Fit| (σ)
Overall normalization (Sec. III C)							
	Norm	1.00	0.2	0.10,3.00	-0.05	0.41	0.46
Local response of DOMs (Sec. III F)							
	DOM efficiency	1.00	0.10	0.97,1.06	0.02	0.03	0.01
	Forward hole ice	-1.00	10.00	-5.35,1.85	0.28	0.27	0.01
Bulk ice (Sec. III E)							
	Amplitude 0	0.00	1.00	-3.00,3.00	0.64	0.69	0.05
	Amplitude 1	0.00	1.00	-3.00,3.00	1.36	1.19	0.17
	Amplitude 2	0.00	1.00	-3.00,3.00	1.35	1.42	0.07
	Amplitude 3	0.00	1.00	-3.00,3.00	0.74	0.75	0.01
	Amplitude 4	0.00	1.00	-3.00,3.00	1.12	1.16	0.04
	Phase 1	0.00	1.00	-3.00,3.00	-1.60	-1.67	0.07
	Phase 2	0.00	1.00	-3.00,3.00	-0.59	-0.54	0.05
	Phase 3	0.00	1.00	-3.00,3.00	-0.21	-0.08	0.13
	Phase 4	0.00	1.00	-3.00,3.00	0.10	0.27	0.17
Conventional flux (Sec. III A)							
	Atm. density (ρ_{atm})	0.00	1.00	-3.00,3.00	-0.48	-0.55	0.07
	Kaon energy loss ($\sigma_{\text{K-Air}}$)	0.00	1.00	-3.00,3.00	0.66	0.51	0.15
Hadronic production	K^+_{158G}	0.00	1.00	-2.00,2.00	0.93	0.89	0.04
Hadronic production	K^-_{158G}	0.00	1.00	-2.00,2.00	0.29	0.24	0.05
Hadronic production	π^+_{20T}	0.00	1.00	-2.00,2.00	0.15	-0.06	0.21
Hadronic production	π^-_{20T}	0.00	1.00	-2.00,2.00	0.17	-0.03	0.20
Hadronic production	K^+_{2P}	0.00	1.00	-2.00,2.00	0.28	0.09	0.19
Hadronic production	K^-_{2P}	0.00	1.00	-1.50,2.00	0.24	0.01	0.23
Hadronic production	π^+_{2P}	0.00	1.00	-2.00,2.00	-1.50	-1.23	0.27
Hadronic production	π^-_{2P}	0.00	1.00	-2.00,2.00	-1.08	-0.85	0.23
Hadronic production	p_{2P}	0.00	1.00	-2.00,2.00	-0.25	-0.18	0.07
Hadronic production	n_{2P}	0.00	1.00	-2.00,2.00	-0.17	-0.15	0.02
CR spectrum	GSF_1	0.00	1.00	-4.00,4.00	-0.33	0.10	0.43
CR spectrum	GSF_2	0.00	1.00	-4.00,4.00	-0.12	-0.28	0.16
CR spectrum	GSF_3	0.00	1.00	-4.00,4.00	-0.12	-0.05	0.07
CR spectrum	GSF_4	0.00	1.00	-4.00,4.00	-0.13	-0.25	0.12
CR spectrum	GSF_5	0.00	1.00	-4.00,4.00	1.82	2.24	0.42
CR spectrum	GSF_6	0.00	1.00	-4.00,4.00	-1.17	-1.31	0.14
Non-conventional flux (Sec. III B)							
	$\Phi^{\text{HE}}/10^{-18}\text{GeV}^{-1}\text{sr}^{-1}\text{s}^{-1}\text{cm}^{-2}$	0.787	0.36	0.00,3.00	0.25	0.61	0.36
	$\log_{10}$ of pivot energy, $E^{\text{HE}}_{\text{break}}/\text{GeV}$	-	-	4.00,6.00	*4.25	*4.31	N/A, see caption
	$\Delta\gamma^{\text{HE}}_1$, tilt from -2.5	0.00	0.36	-2.00,2.00	2.62	2.39	0.23
	$\Delta\gamma^{\text{HE}}_2$, tilt from -2.5	0.00	0.36	-2.00,2.00	-0.22	0.10	0.21
Neutrino attenuation (Sec. III D)							
	ν attenuation	1.00	0.10	0.82, 1.18	0.12	-0.14	0.26
	$\bar{\nu}$ attenuation	1.00	0.10	0.82, 1.18	0.04	-0.02	0.06

Our priors

Parameter	Symbol [unit]	Prior	Boundaries
ν-nucleon cross section			
Normalization of σ_{SM}	n_σ	$\mathcal{U}[0.05, 20]$	[0.05, 20]
Spectral shift of σ_{SM}	β_σ	$\mathcal{U}[-2, 2]$	[-2, 2]
Pivot point of σ_{SM}	E_β [TeV]	$\mathcal{U}[0.1, 50]$	[0.1, 50]
`daemonflux` atmospheric flux			
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