Neutrino physics with the XENONnT water Cherenkov Veto

Nuclear and Subnuclear Physics
Master's Thesis

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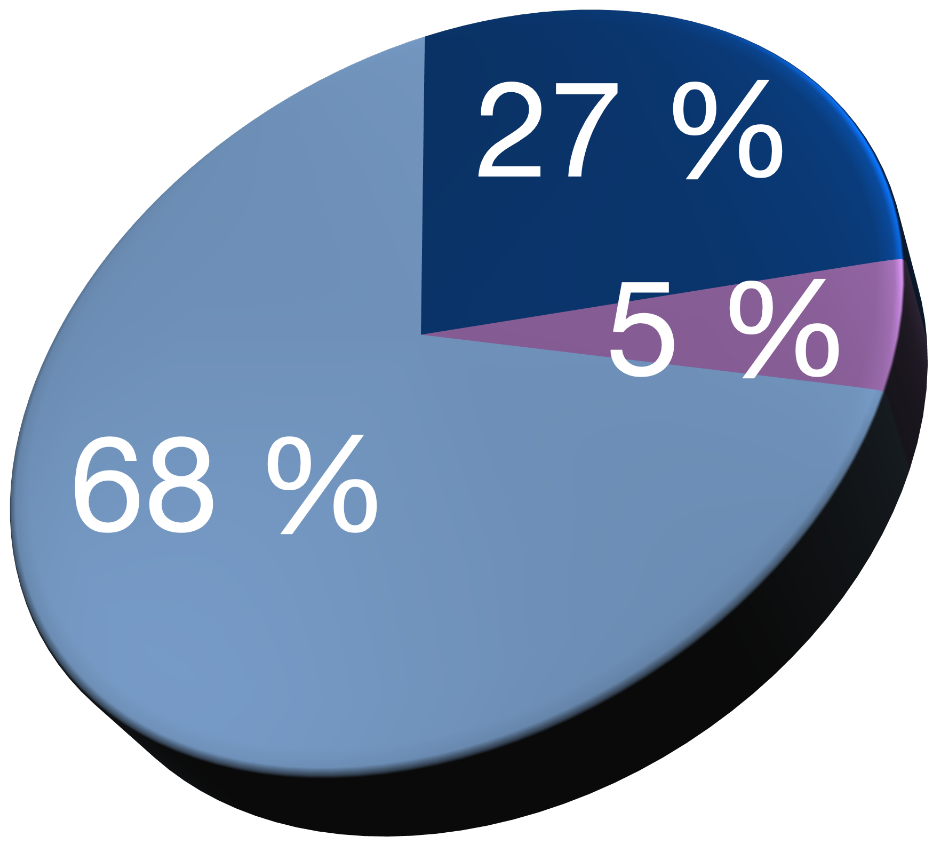
Istituto Nazionale di Fisica Nucleare

Dark Matter



Energy density of the Universe

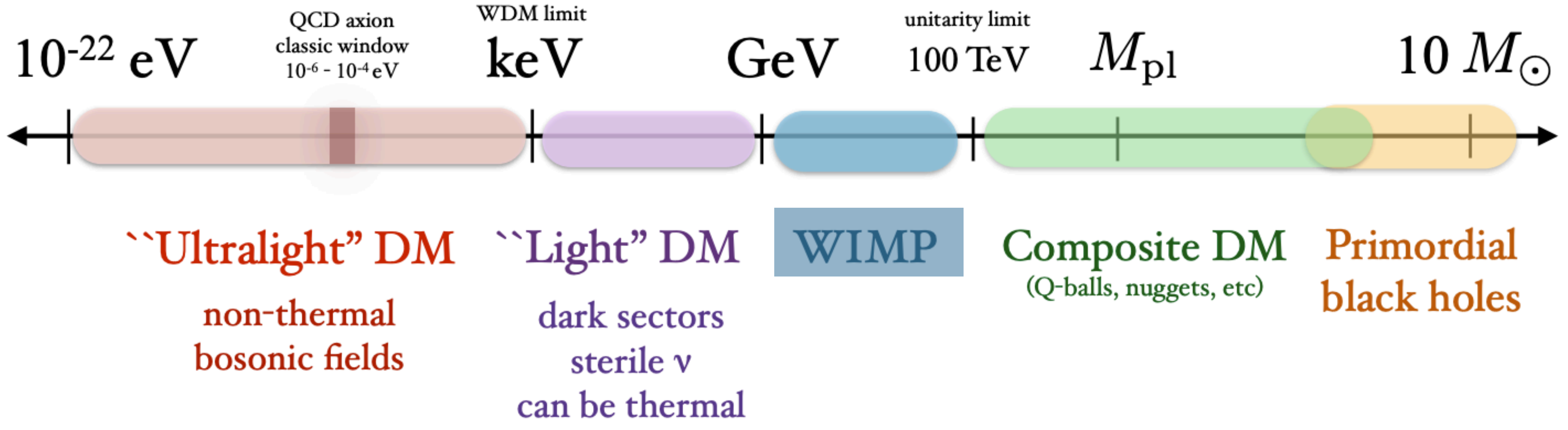
- Dark Matter
- Ordinary Matter
- Dark Energy

Astrophysical evidences: Galactic rotation curves, the Bullet Cluster
Cosmological evidences: CMB, large scale structure of the Universe

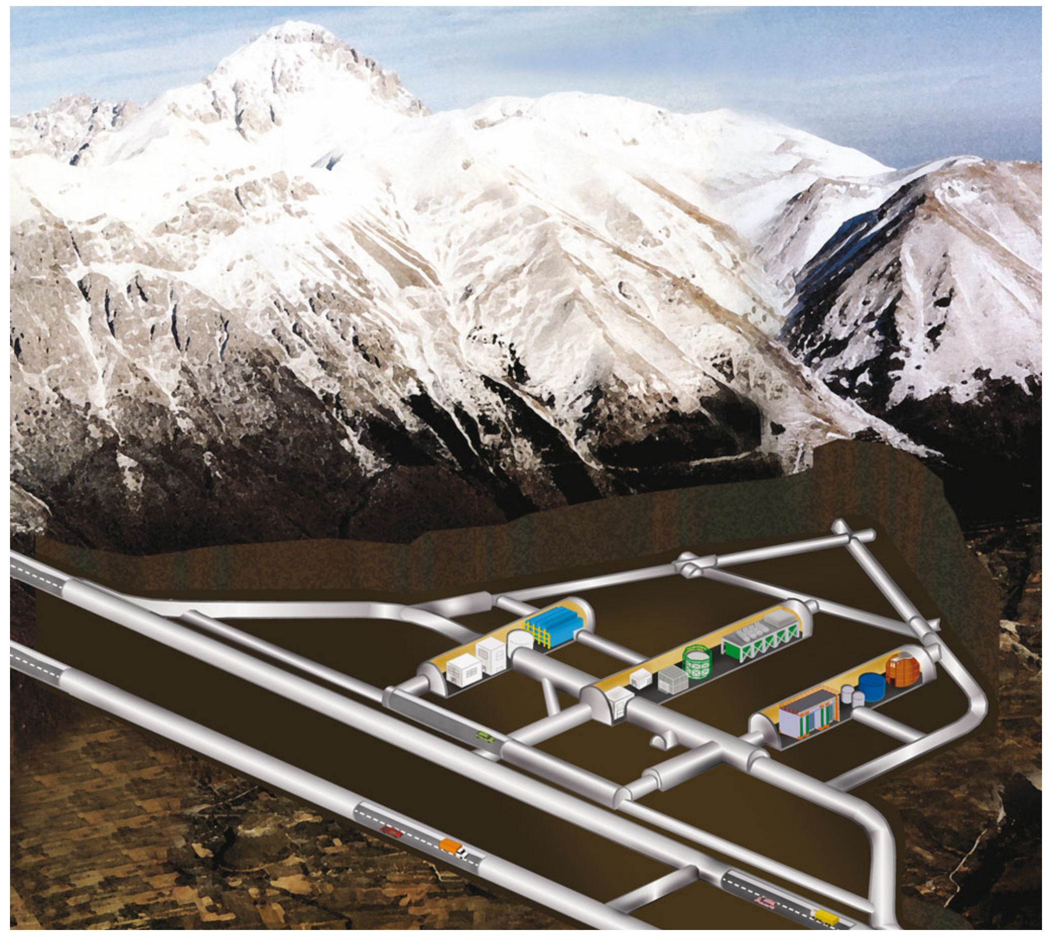
Properties:

- Massive
- Electrically and color neutral
- Stable or long-lived particle
- Cold or warm

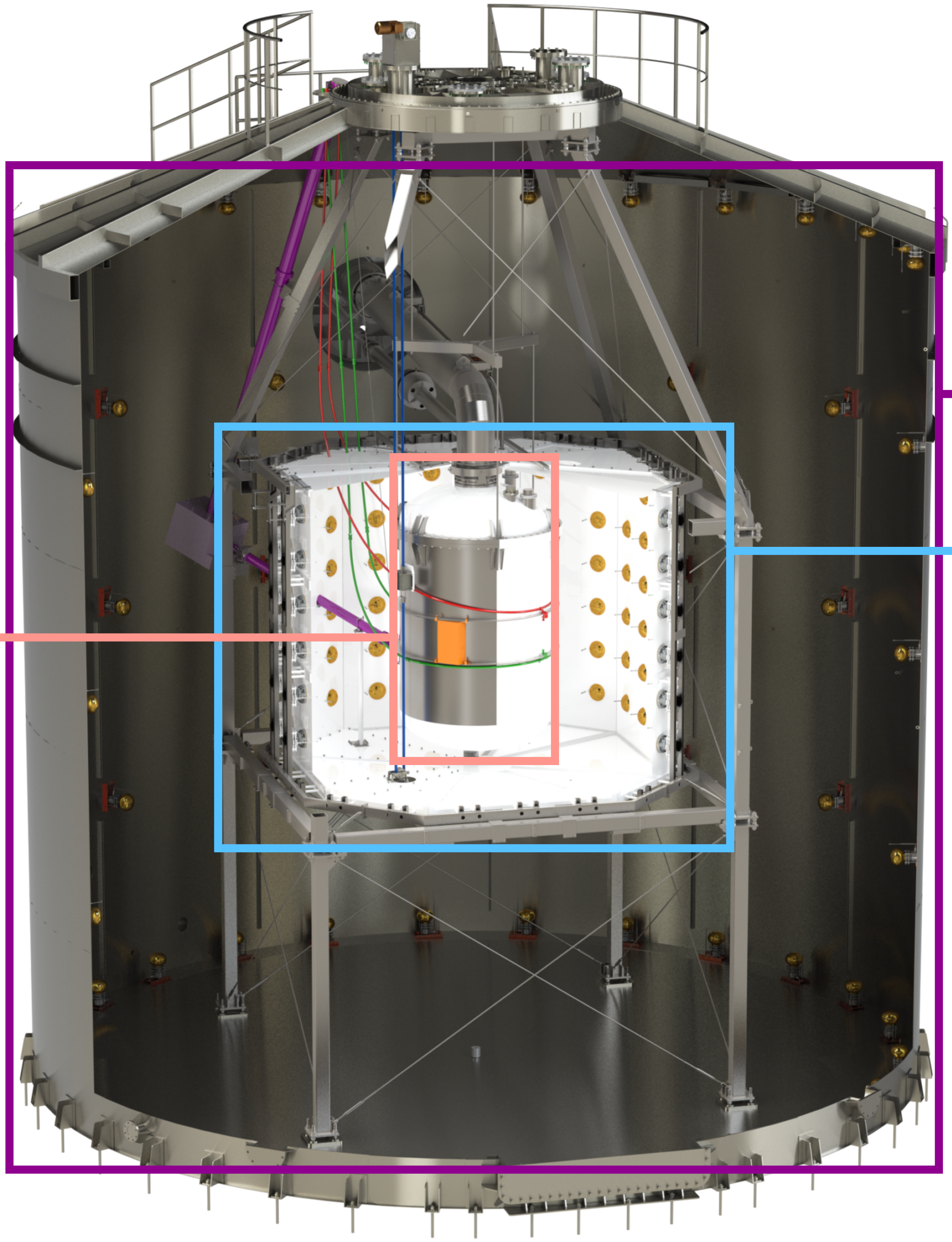
Candidates:



The XENONnT Experiment



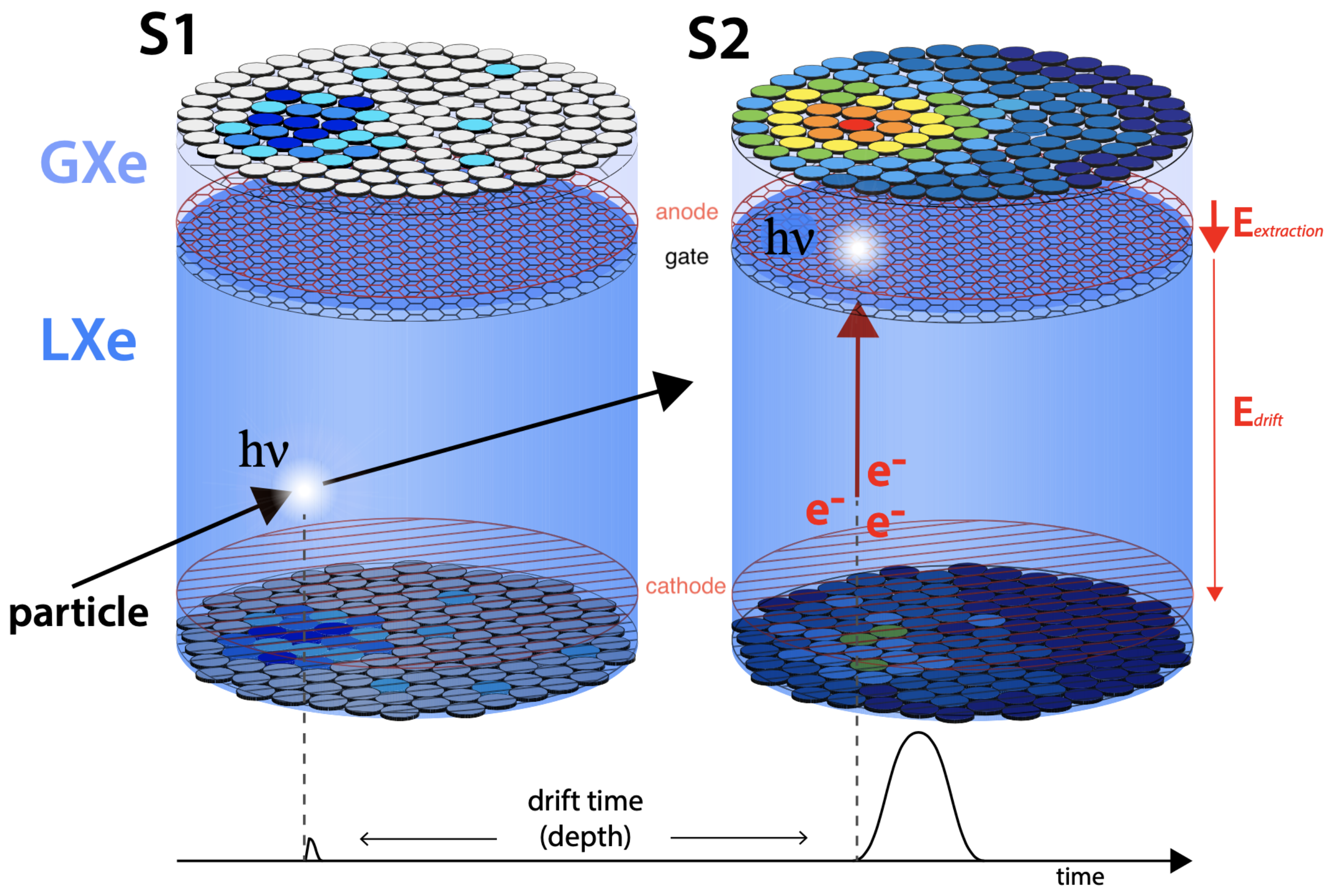
Dark Matter direct detection with 6 t LXe at the underground INFN LNGS



Muon water Cherenkov Veto

Neutron water Cherenkov Veto

Dual-phase Time Projection Chamber



Neutrino detection in the XENONnT TPC

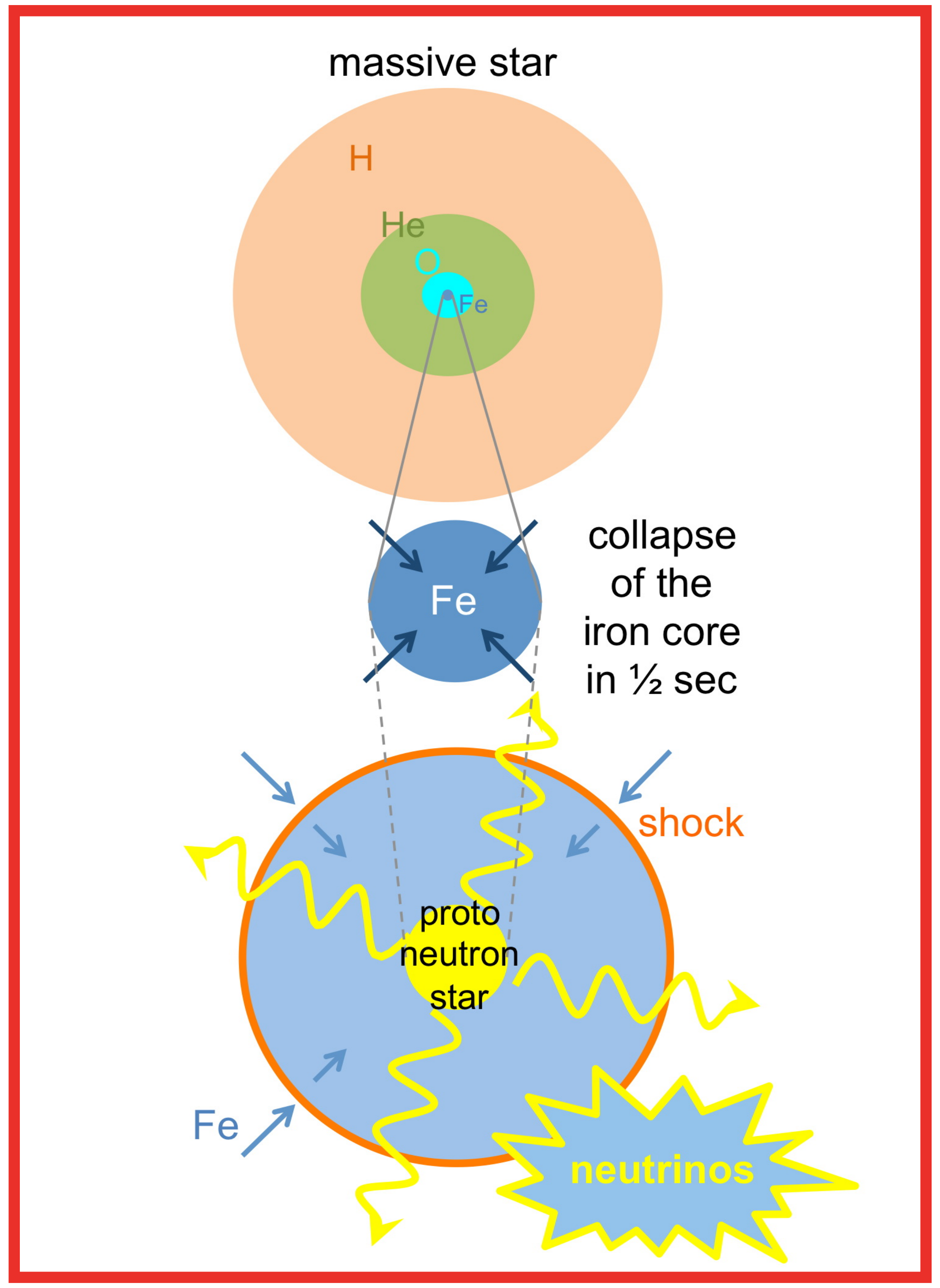
- First direct measurements of Xe nuclear recoils from ^8B solar neutrinos with 2.73σ (PRL 133 (2024) 19, 191002)

Neutrinos

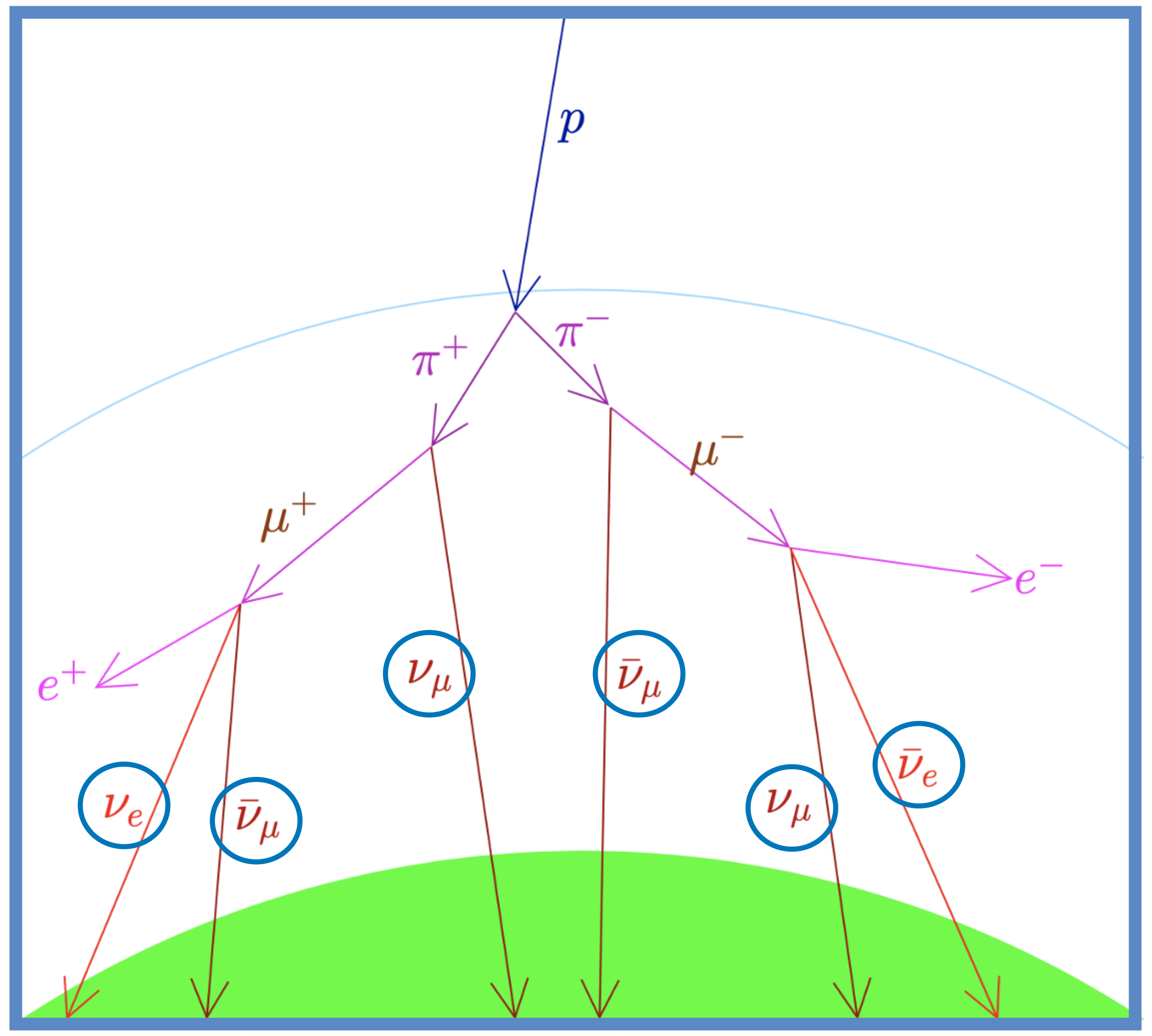
Supernova and atmospheric neutrinos

Core-collapse supernova neutrinos

- 99% of the supernova energy emitted as a ~10^{58} neutrino and antineutrino burst of all flavors
- Mean neutrino energies range between 10 and 20 MeV



Core-collapse supernova neutrinos



Atmospheric neutrinos

Atmospheric neutrinos

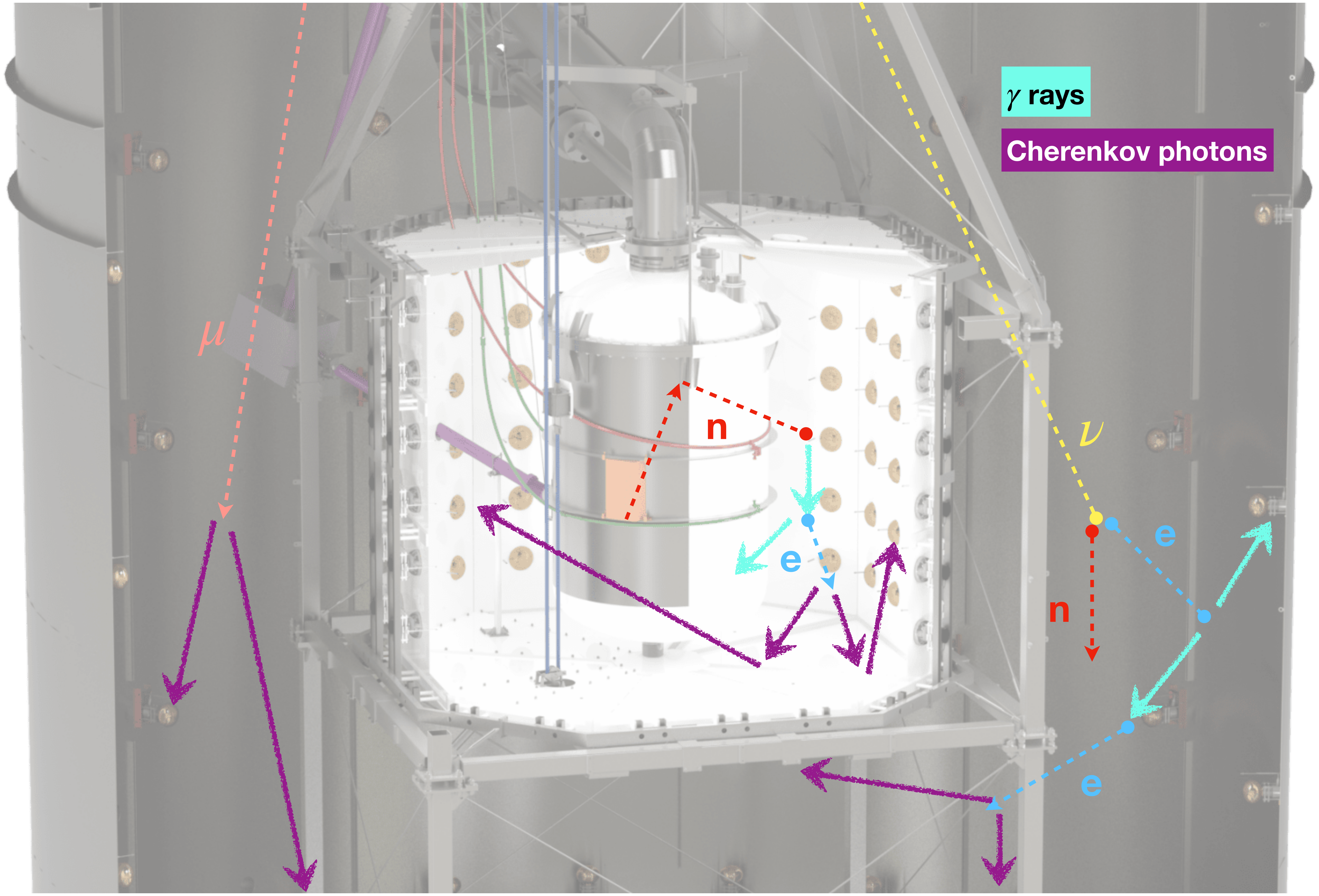
- Energy range: [0.01, 100] GeV (we focused on the low energy region)
- Cosmic ray protons interacting in the atmosphere
- $\nu_e : \nu_\mu : \nu_\tau \simeq 1 : 2 : 0$ before oscillations

The XENONnT Experiment

Water Cherenkov Vetoes Working Principle

- **Neutron Veto (120 PMTs)**
  - Neutron capture in pure water (~200 μs):

    $$H + n \rightarrow {}^{2}H^{*} \rightarrow {}^{2}H + \gamma \text{ (2.2 MeV)}$$
  - >99% reflectivity for optical and UV photons, 34 t of pure water
  - Region of interest: ~MeV
- **Muon veto (84 PMTs)**
  - >99% for $\lambda > 400$ nm, 666 t of pure water
  - Region of interest: ~GeV
- Neutrino region of interest: MeV – GeV

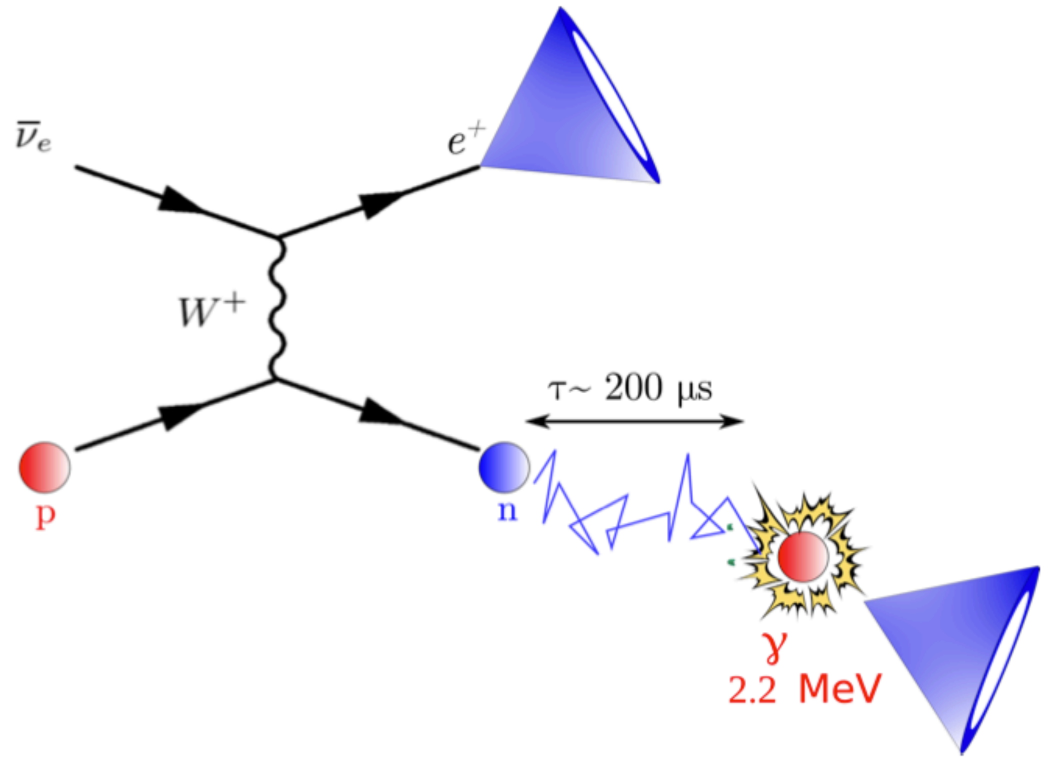


Core-collapse Supernova Neutrinos

Flux, cross section and expected rate

- 27 $M_\odot$
- LS220 EoS
- 10 kpc
- No oscillations

Inverse beta decay cross section

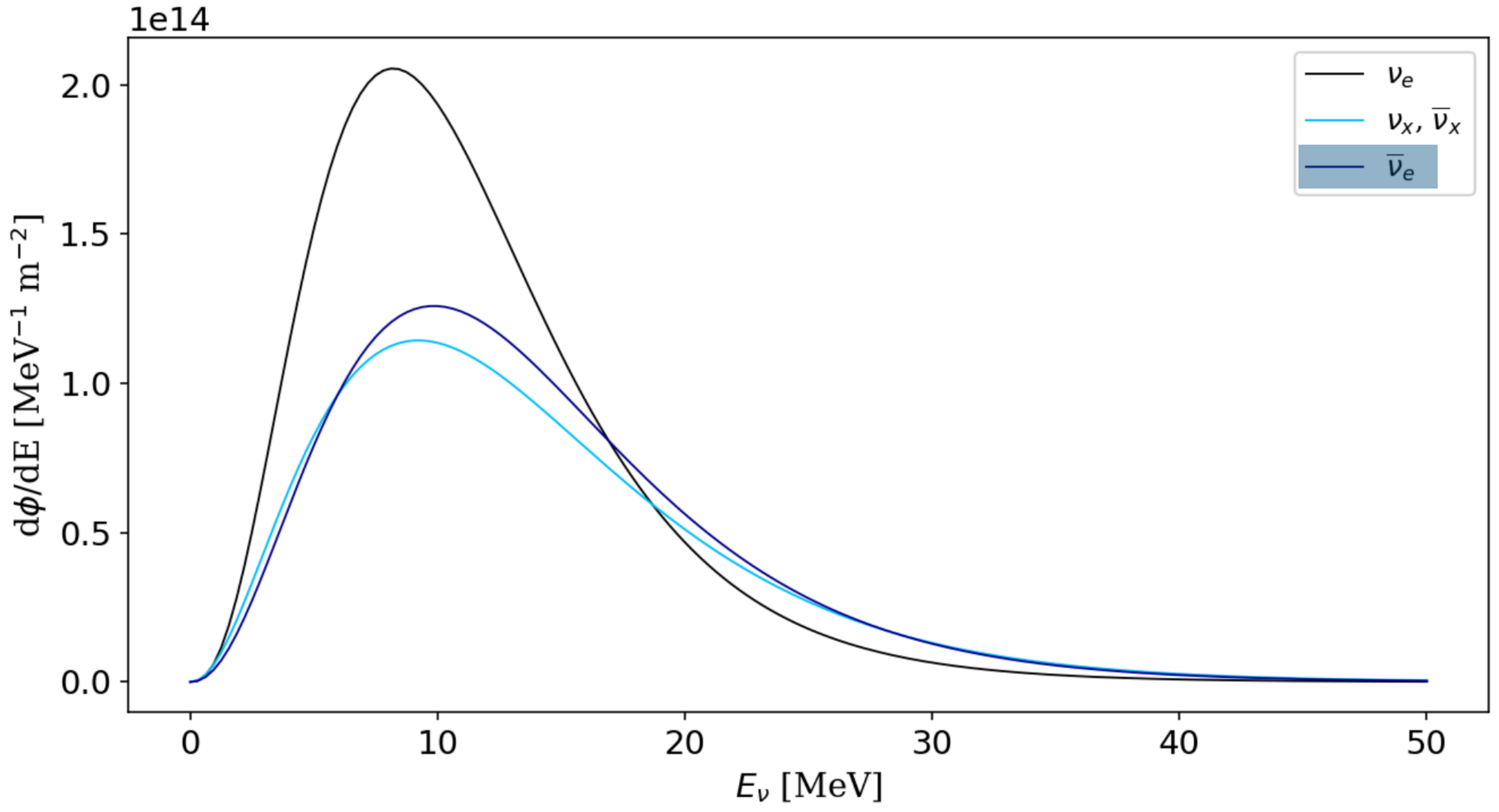


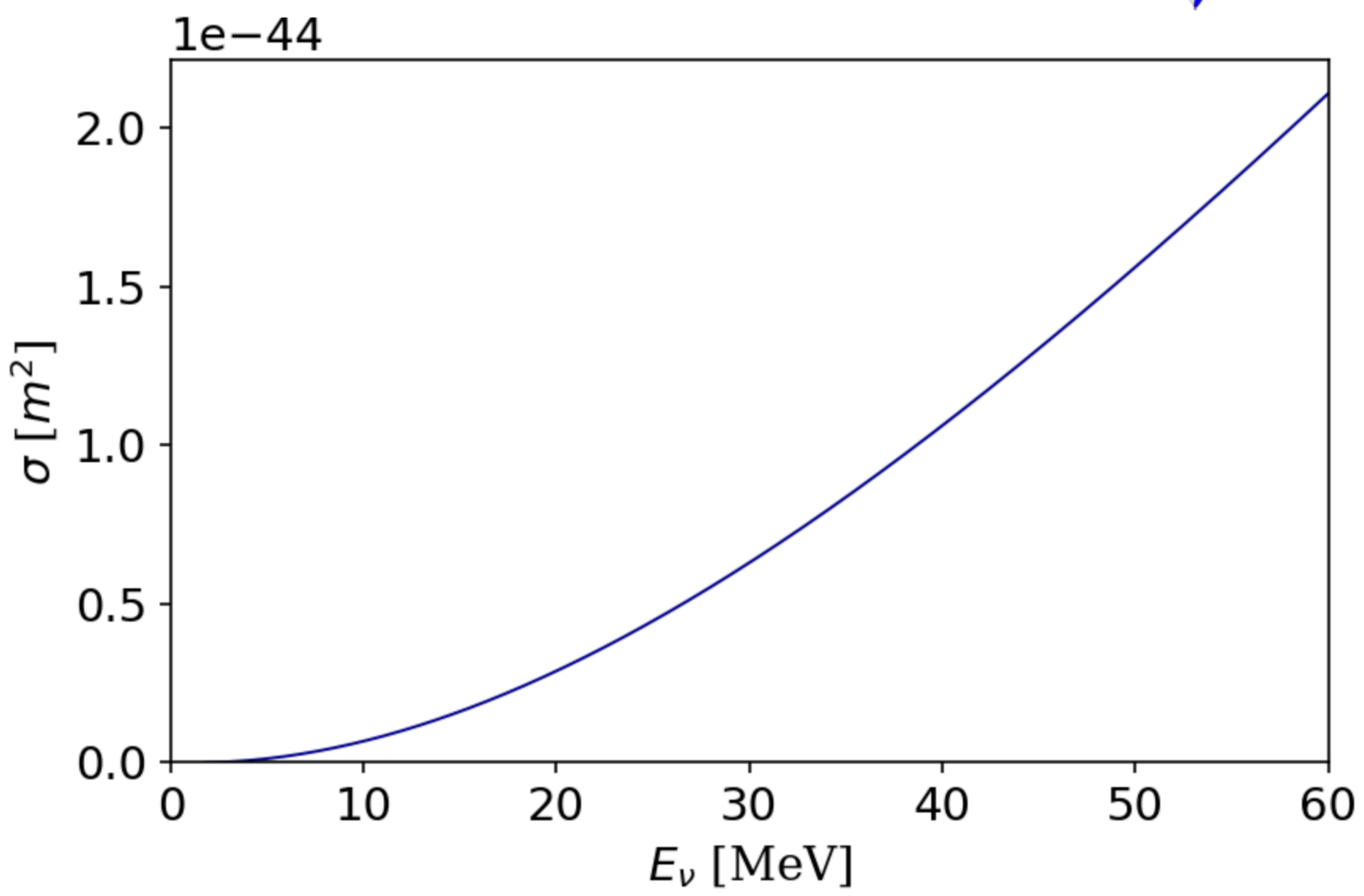
Expected inverse beta decay events

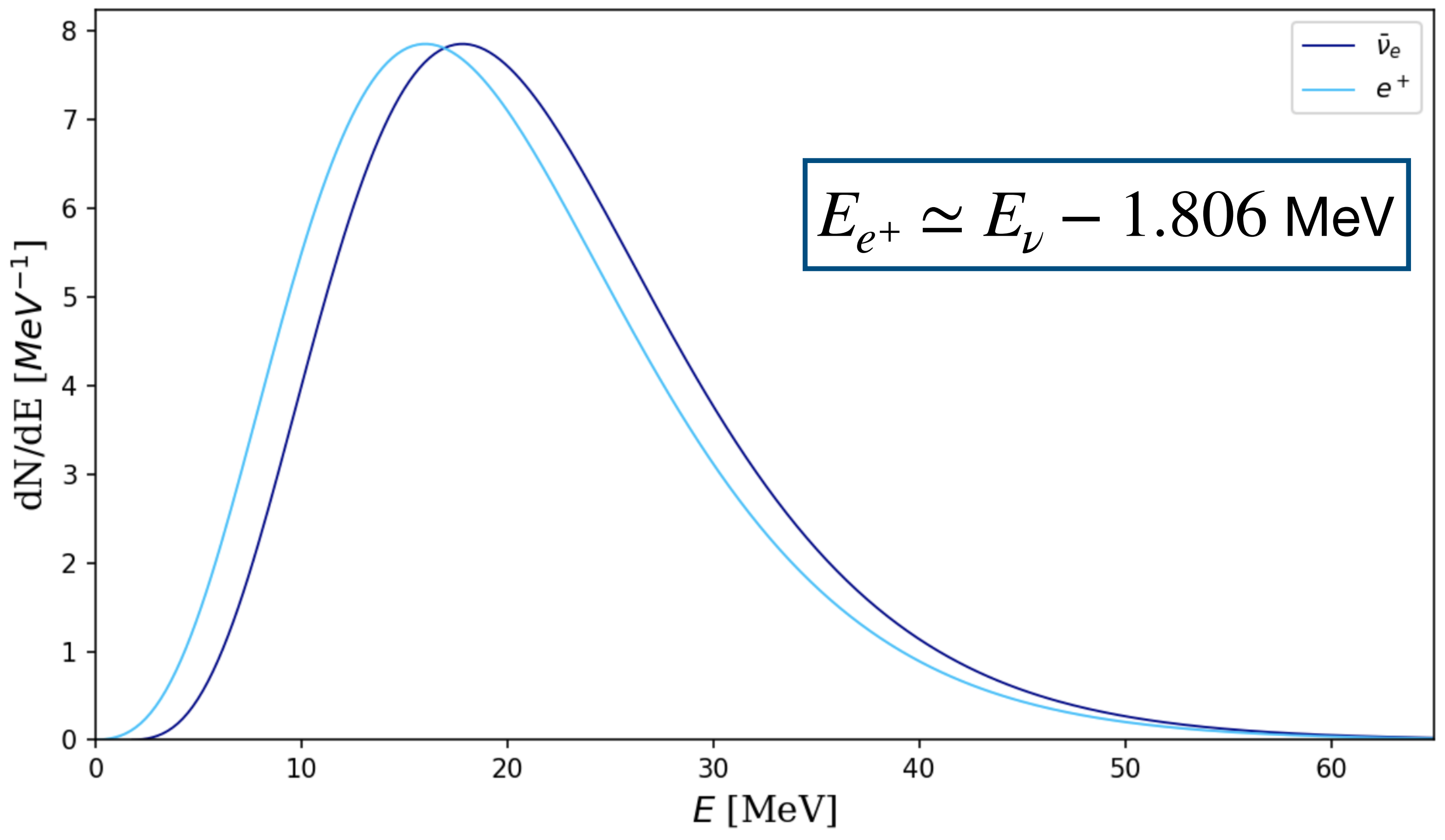
700 tonnes of pure water in the water tank

$$\frac{dN_i^{\nu}}{dE_i} = N_{H_2O} f_p \frac{d\Phi_i^{\bar{\nu}_e}(E_i)}{dE_i} \sigma_i(E_i)$$

Time-integrated differential flux





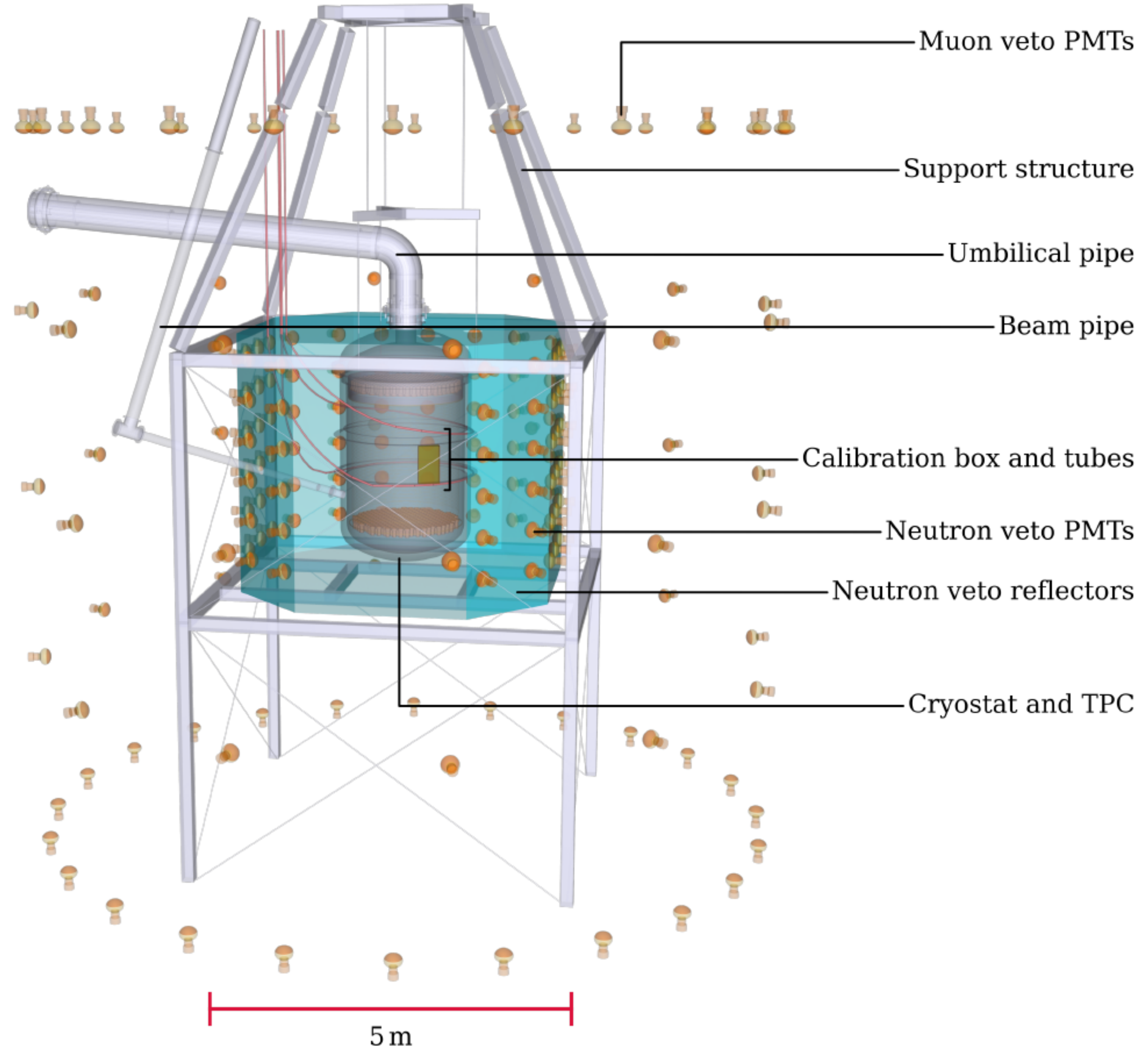


XENONnT Simulation Framework

GEANT4 Model, NV and MV HitSim

GEANT4 XENONnT Vetoes Model

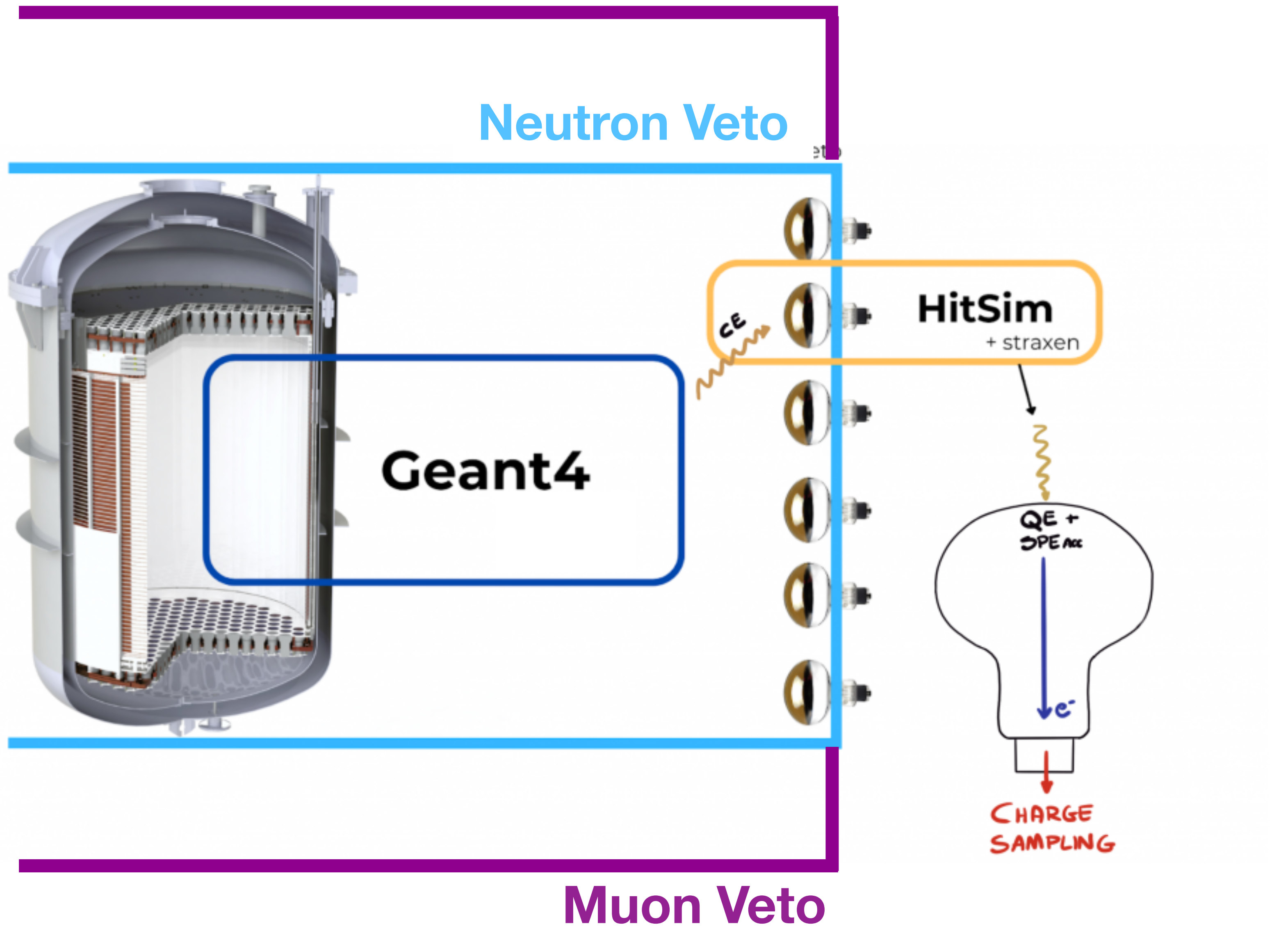
MC simulation of particle transport and interactions in matter.



Neutron and Muon Veto Hitlet Simulators

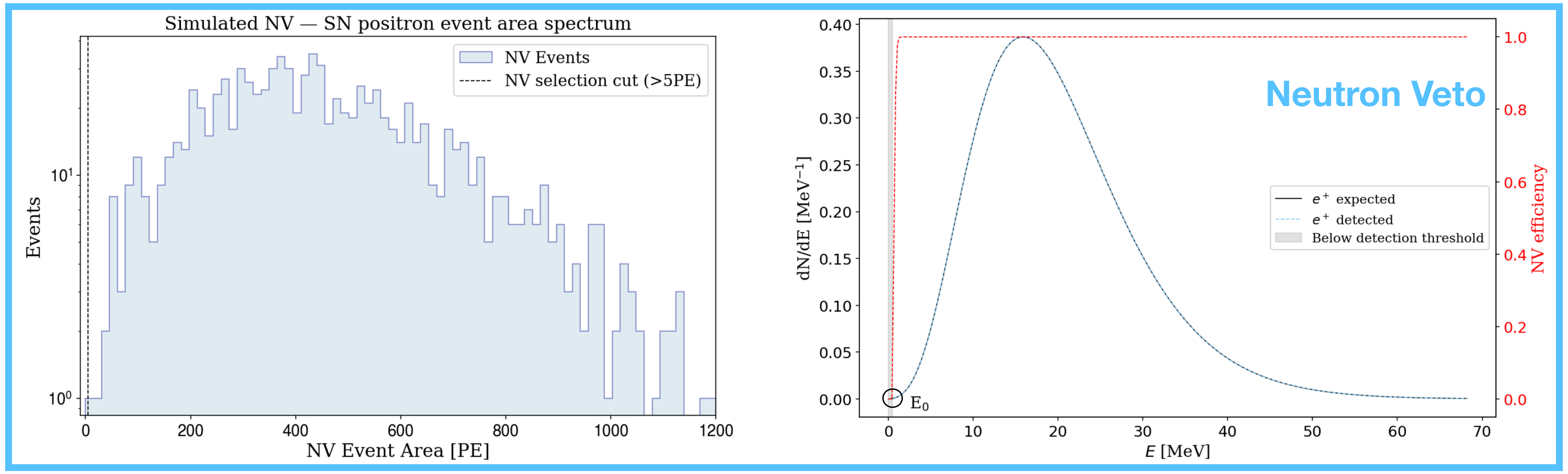
Simulations of PMT response to incident Cherenkov photons and subsequent hitlet and event generation.

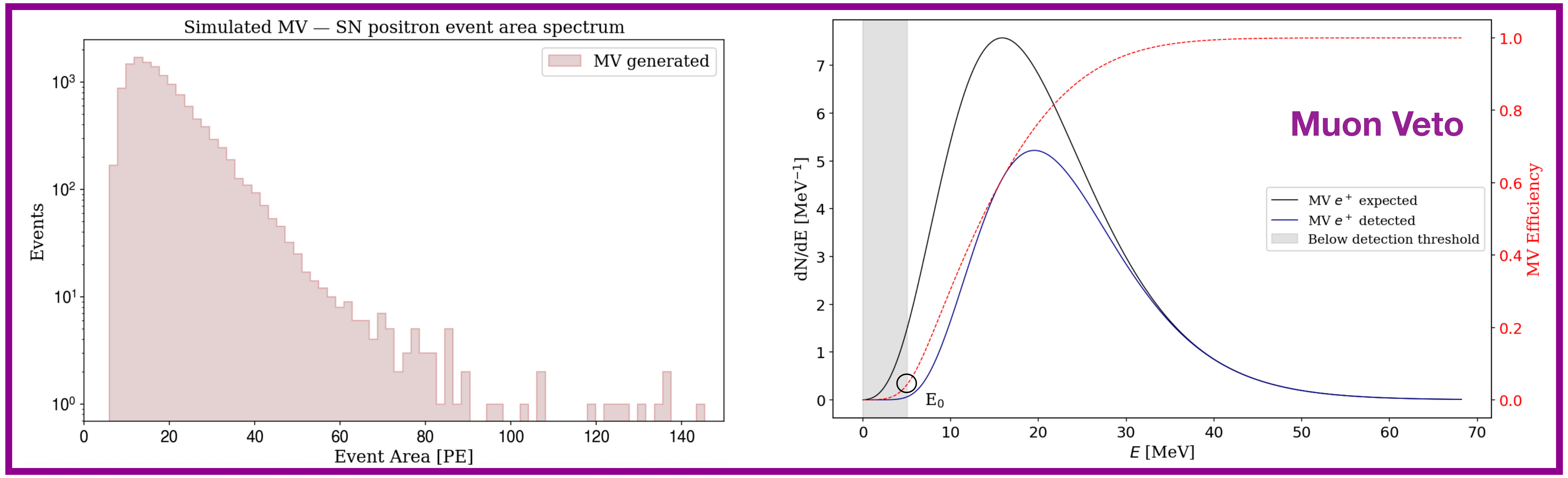
Same time and charge information as real data: same processing



Supernova Neutrinos

Positron spectrum and energy-dependent efficiency





Positron energy-dependent efficiency model

$\varepsilon^{NV}_{e^+,\ total} = 100\,\%$

From best fit parameters the effective detector threshold is: $E_0 = 0.508 \pm 0.007$ MeV

$\varepsilon^{MV}_{e^+,\ total} = (67.6 \pm 0.3)\,\%$

From best fit parameters the effective detector threshold is: $E_0 = 5.0 \pm 0.2$ MeV

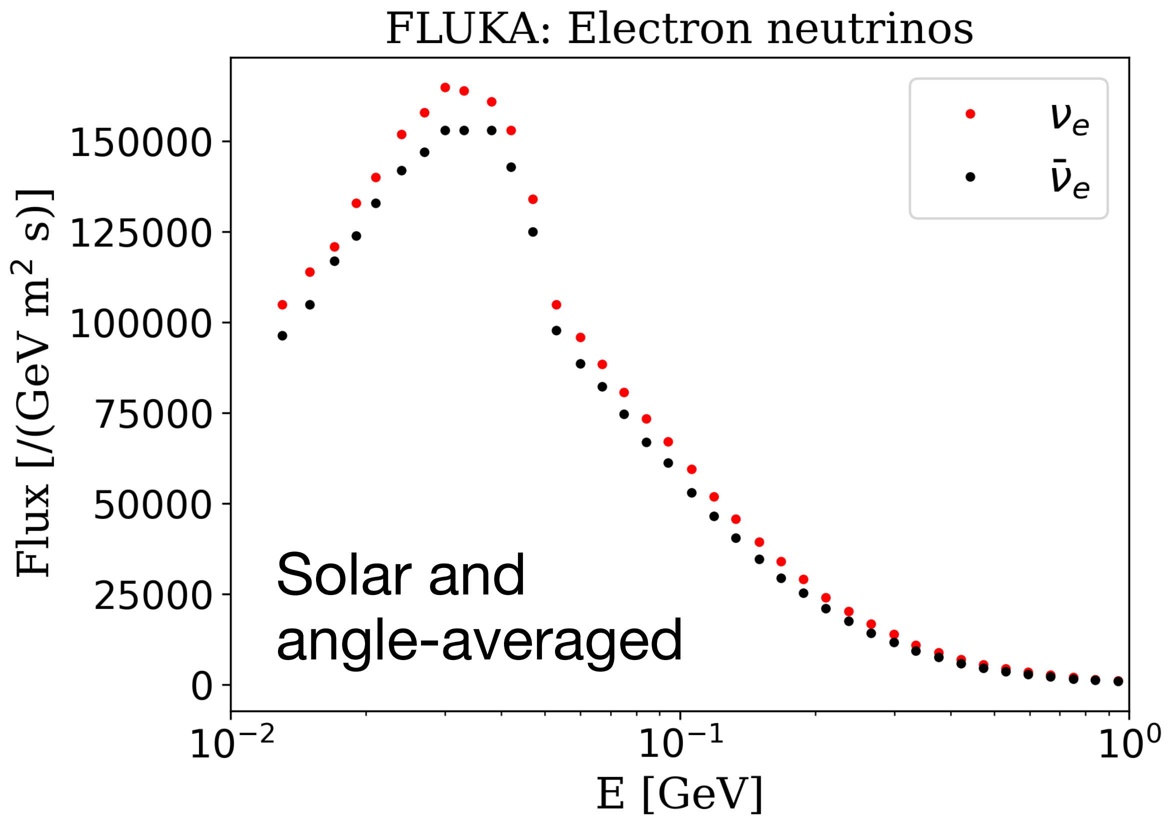
	Exp. NV	Det. NV	Exp. MV	Det. MV
LS220, 27 solar M	8.3	8.3	161.6	108.0

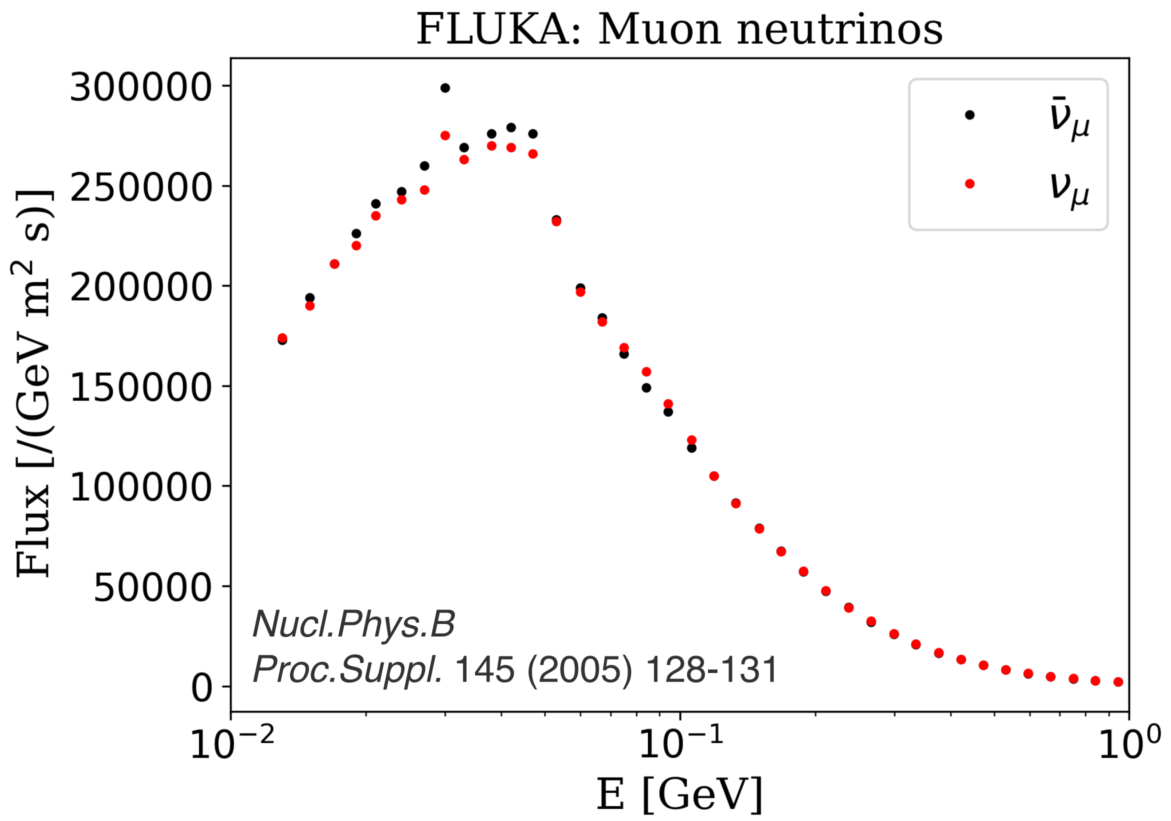
(Other SN models have been studied, e.g. LS220 11.2 $M_\odot$ at 10 kpc: ~60 MV+NV detected positron events)

Atmospheric Neutrinos

Flux, cross section and expected rate

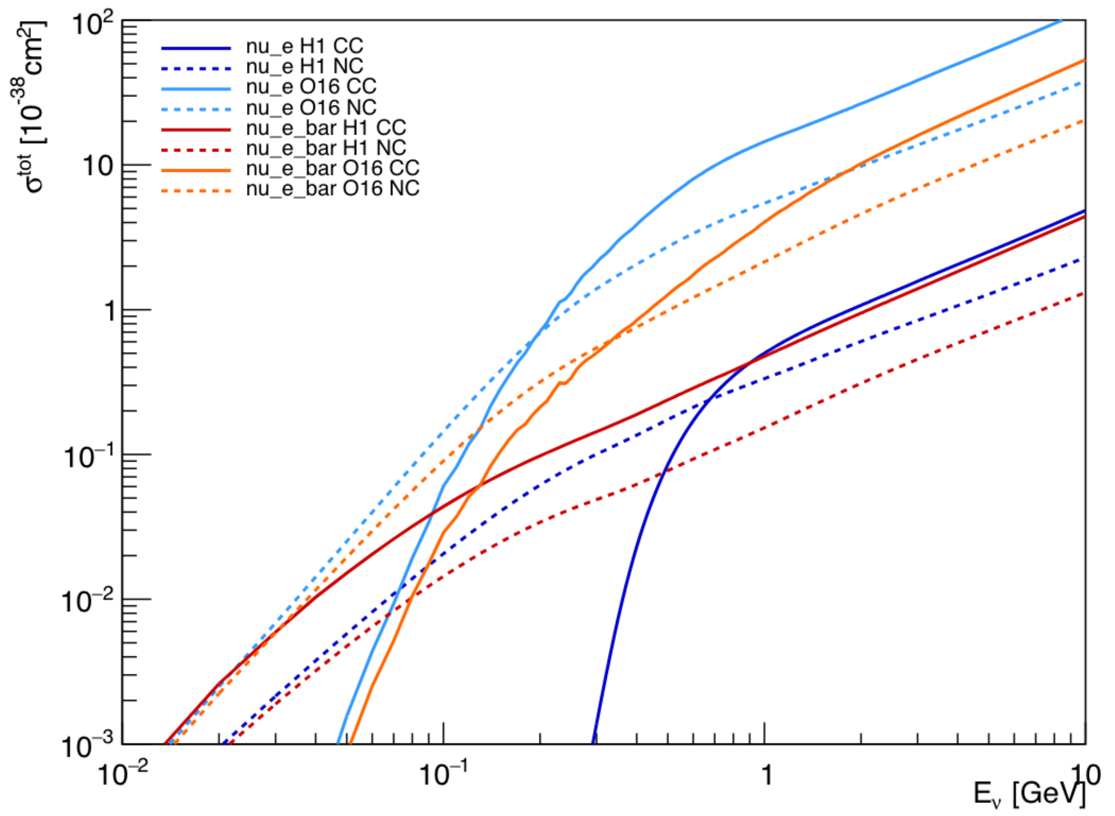
Differential LNGS flux



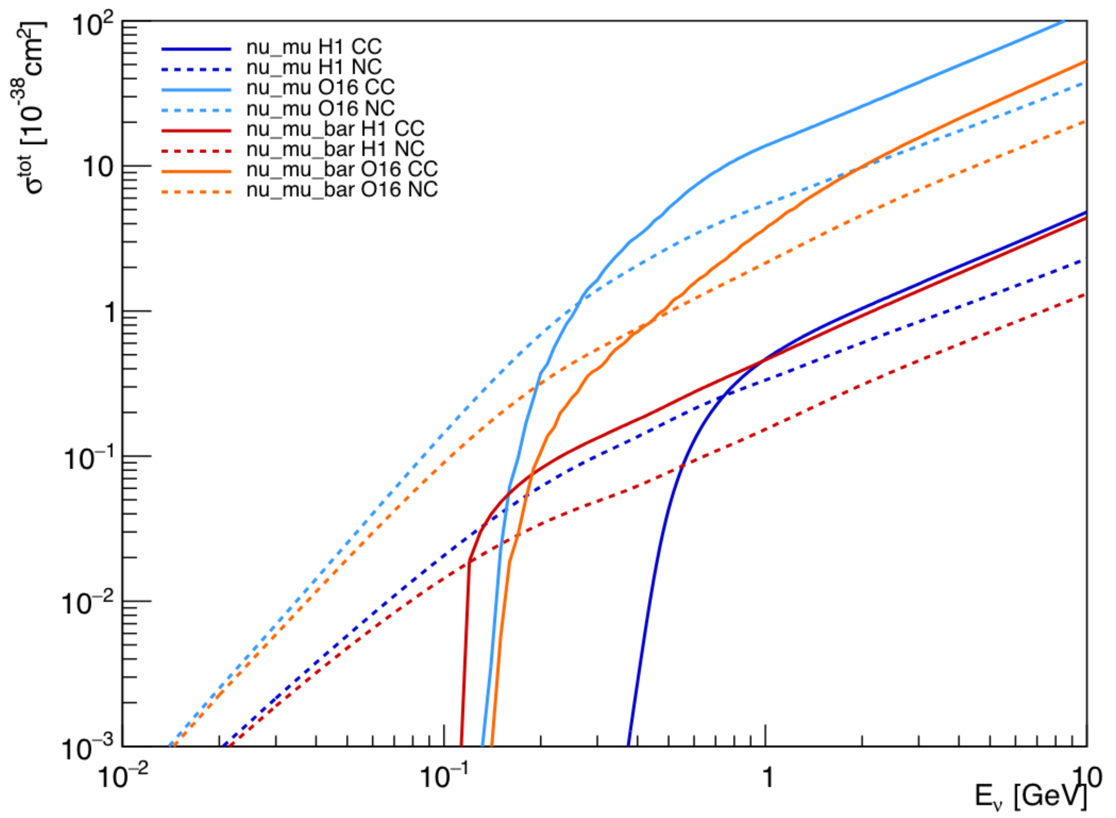


Cross sections

GENIE total LFG-NAV σ: ν_e & $\bar{\nu}_e$



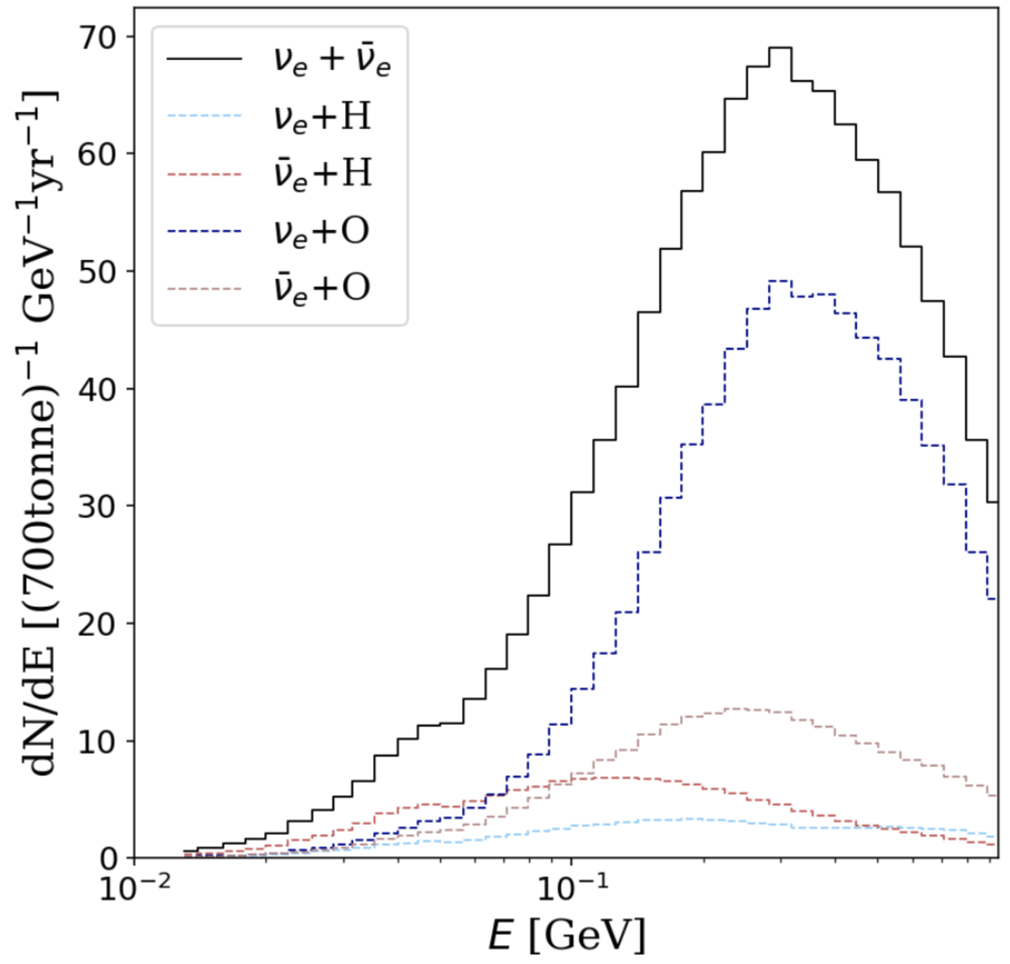
GENIE total LFG-NAV σ: ν_μ & $\bar{\nu}_\mu$

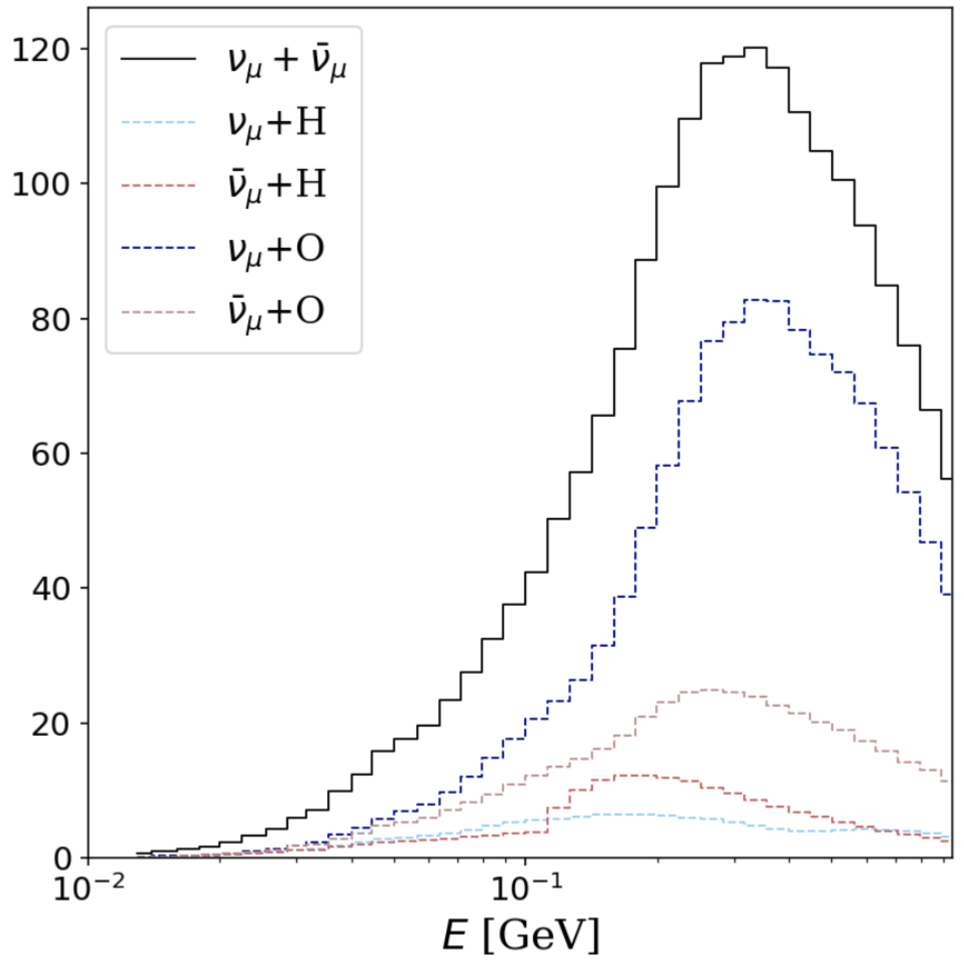


Expected atmospheric ν annual rate

700 tonnes of pure water in the water tank

$$\frac{dN_i^{\nu_x}}{dE_i} = \Delta t \frac{d\Phi_i^{\nu_x}(E_i)}{dE_i dt} \left(N_H \sigma_i^H(E_i) + N_O \sigma_i^O(E_i)\right)$$





Atmospheric Neutrinos

GENIE Neutrino MC Generator

- The ROOT-based GENIE generator is a "canonical" **neutrino interaction physics Montecarlo**, whose validity extends to all nuclear targets and neutrino flavors from MeV to PeV energy scales.
- **Muon and electron neutrino and antineutrino simulations with a water target** using the best theoretical model implemented in GENIE so far and the FLUKA flux.
- Interactions: CC quasi-elastic, NC elastic, CC and NC resonant pion production and CC and NC multinucleon processes.

Example interaction: CC resonant pion production ($E_\nu = 690\,\mathrm{MeV}$)

$$\nu_e + {}^{16}\mathrm{O}\,(n) \;\rightarrow\; e^- + \Delta^+ + {}^{15}\mathrm{O} \;\rightarrow$$

$$e^- + (n + \pi^+) + {}^{15}\mathrm{O}* \xrightarrow{\text{de-excitation}}$$

$$e^- + n + \pi^+ + \gamma + {}^{15}\mathrm{O} \xrightarrow{\text{FSI}}$$

$$e^- + p + n + \pi^+ + \gamma + X \text{ (nuclear remnant)}$$

Implementation of a GENIE-to-GEANT4 bridge:

- GENIE output adaptation
- Multi-particle vertex generator in GEANT4

Atmospheric Neutrinos

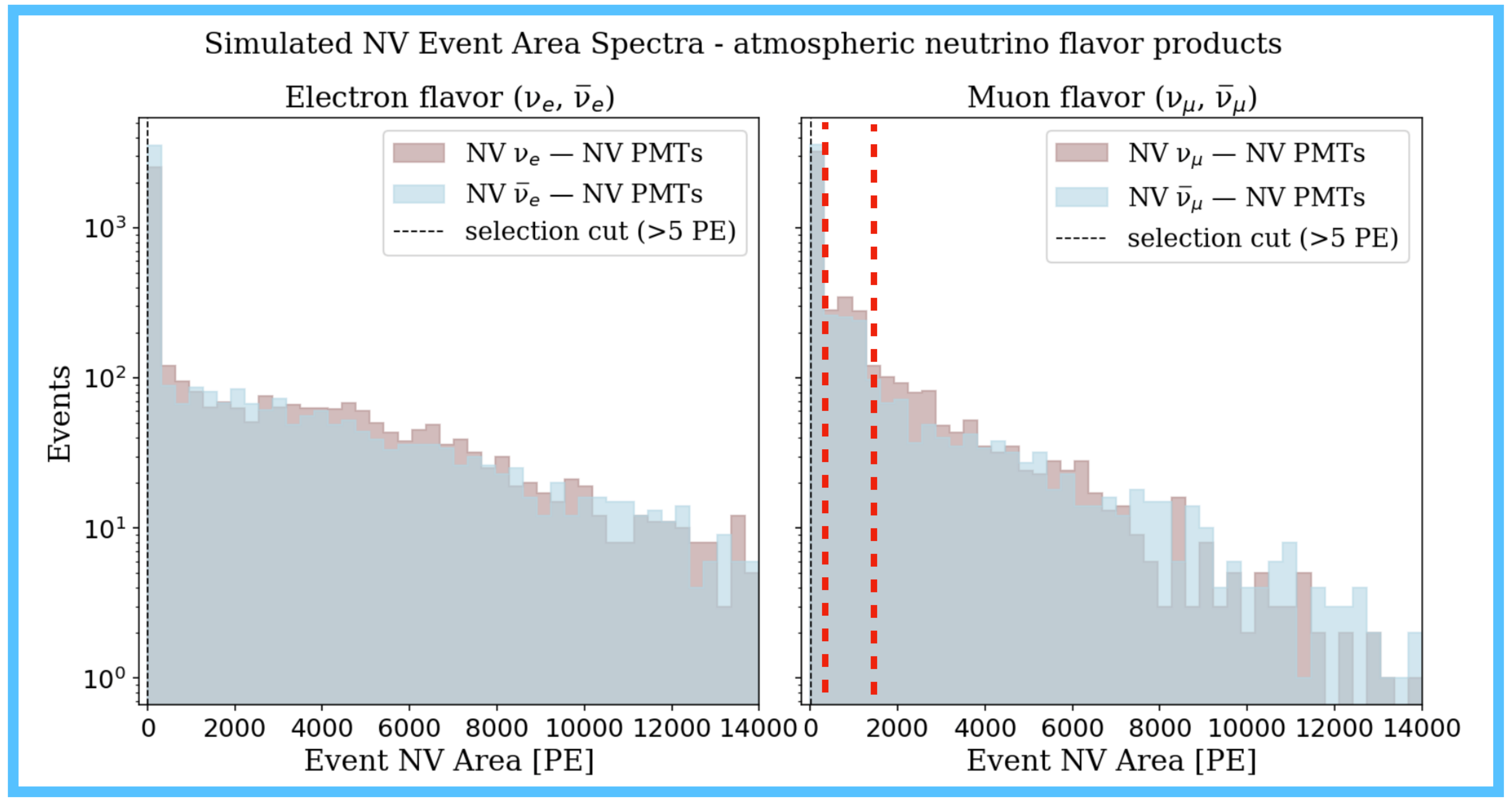
Neutrino-induced spectra and detection efficiency

Muon decay bump at about 50 MeV: 1000 PEs in the NV and 50 PEs in the MV

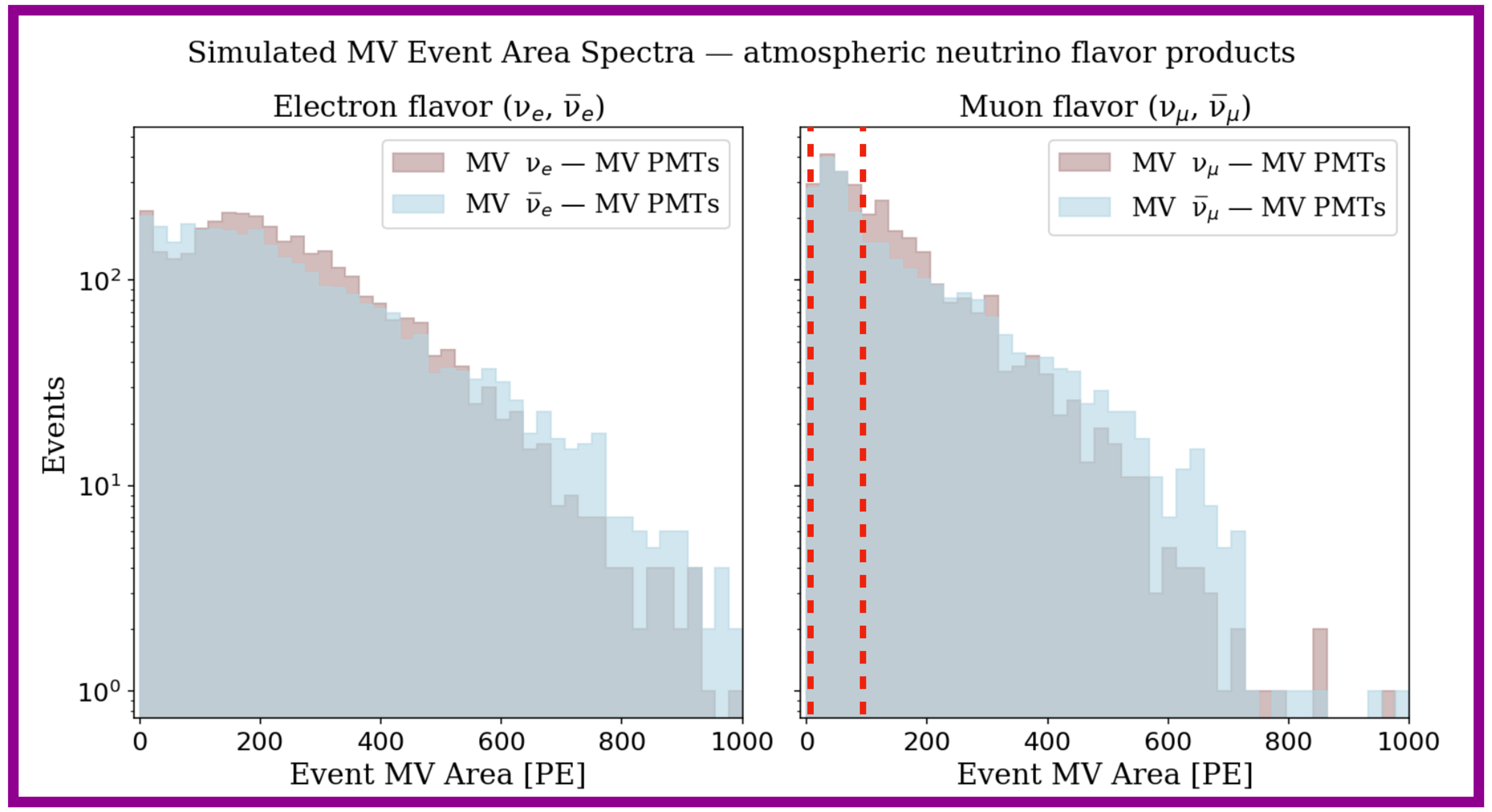
Flavor	ε_{NV} (%)	ε_{MV} (%)
ν_e	87.0 ± 0.7	69.0 ± 0.7
$\bar{\nu}_e$	83.7 ± 0.7	65.4 ± 0.7
ν_μ	83.7 ± 0.7	62.6 ± 0.7
$\bar{\nu}_\mu$	79.8 ± 0.8	57.2 ± 0.7

Flavor	Exp. NV	Det. NV	Exp. MV	Det. MV
ν_e	1.2	1.1	24.3	16.8
$\bar{\nu}_e$	0.4	0.3	7.9	5.2
ν_μ	2.1	1.7	40.8	25.6
$\bar{\nu}_\mu$	0.8	0.6	15.3	8.7
Total [yr^{-1}]	4.5	3.7	88.3	56.3

Neutron Veto

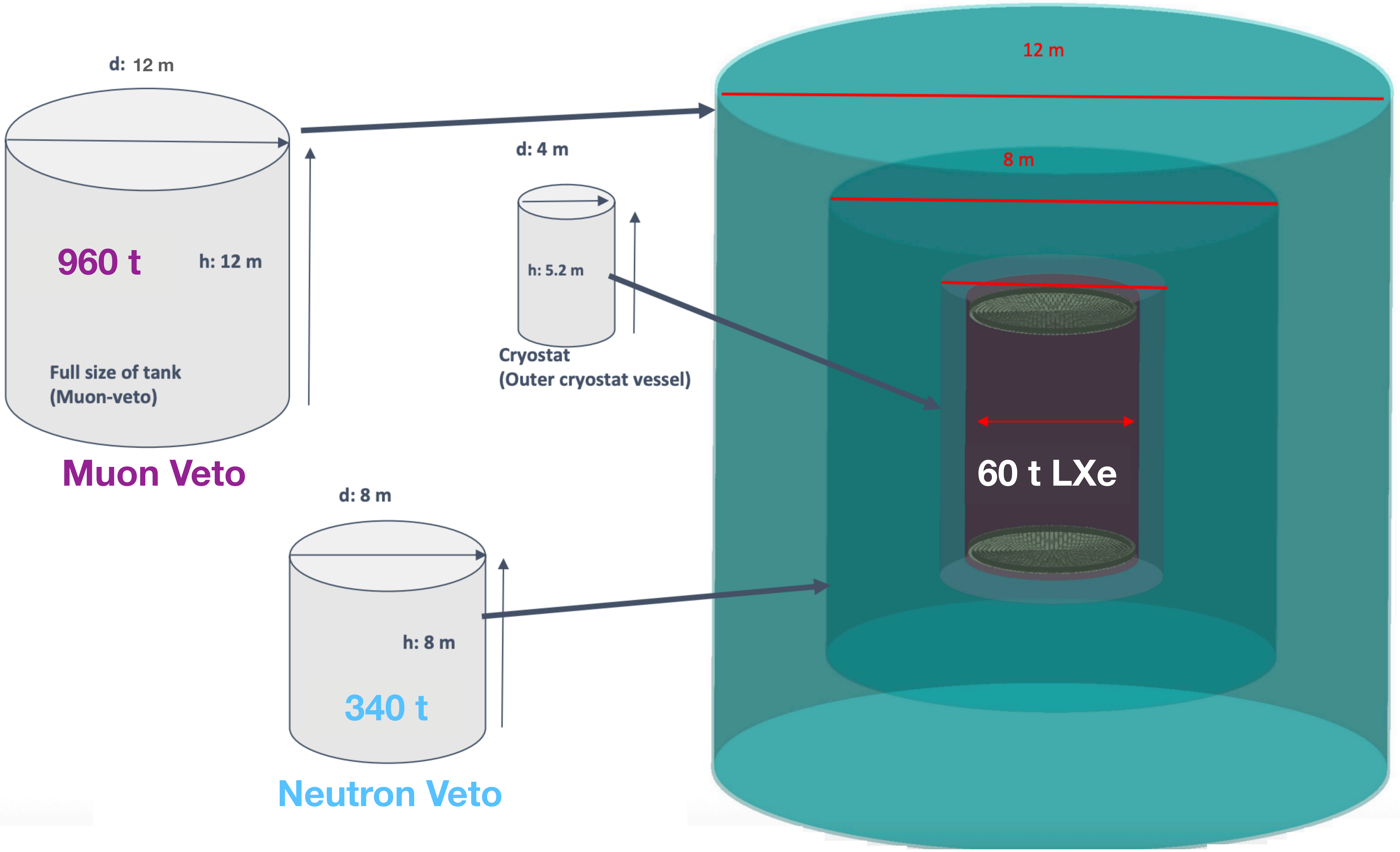


Muon Veto



The XLZD Observatory

- Low background **next generation** dark matter and neutrino observatory with a 60 t LXe target
- Construction may start in ~2030
- **One proposed configuration**
  - Dual-phase time projection chamber within the cryostat: 60 tonnes of LXe
  - Neutron Veto: 340 tonnes of pure water
  - Muon Veto: 960 tonnes of pure water



The XLZD projection

SN and atmospheric neutrino detection

Supernova neutrino

NV+MV: at least 100 detected IBD positrons up to 15 kpc

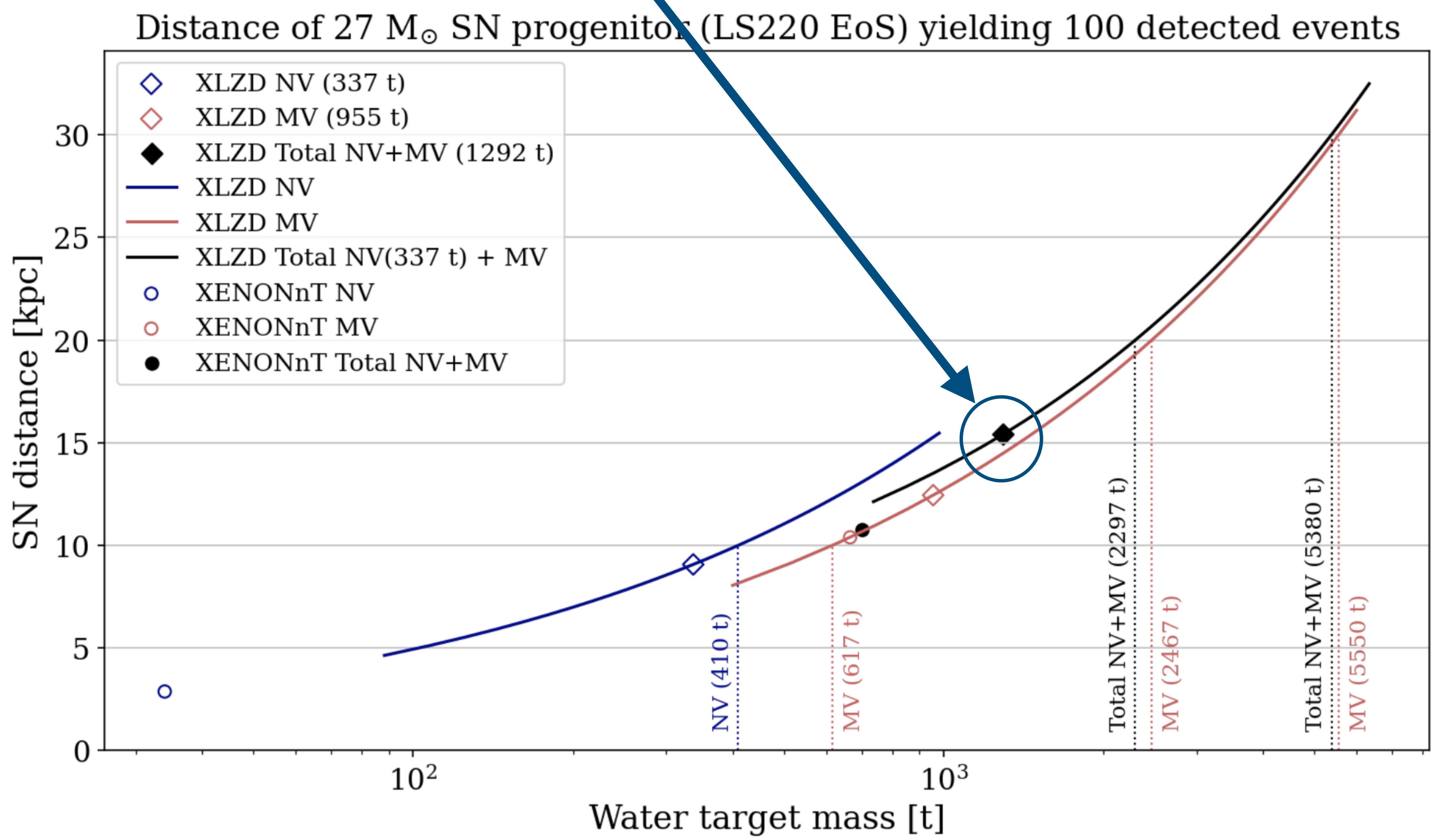
XLZD benchmark configuration

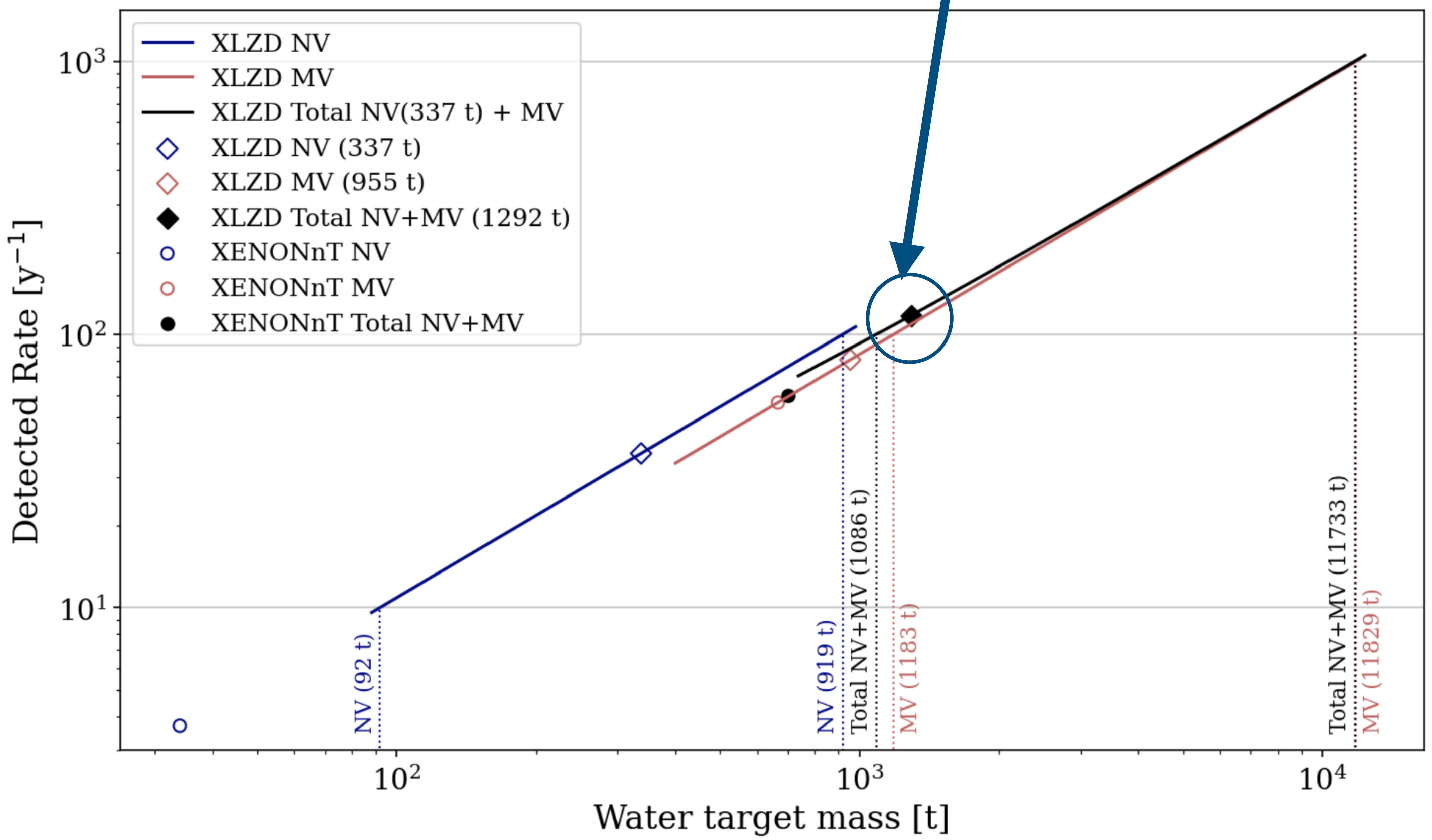
The XENONnT vetoes efficiencies are assumed

Atmospheric neutrino

NV: 38 detected from 45 expected

MV : 81 detected from 127 expected





Summary and Conclusions

27 $M_\odot$, LS220 EoS core-collapse SN model at 10 kpc

LNGS angle- and solar-averaged flux

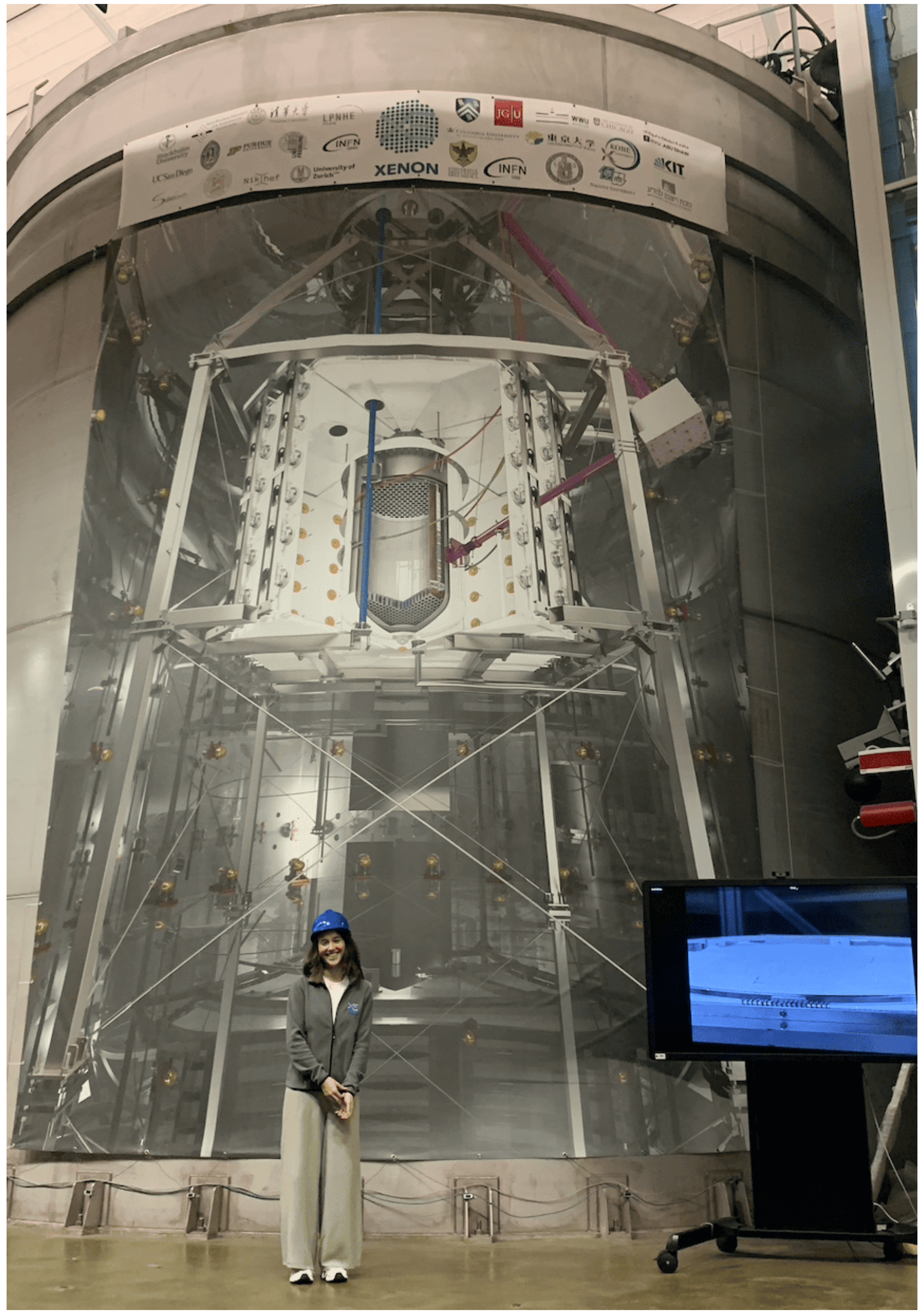
Study of XENONnT Vetoes performance and signal description:

- Core-collapse supernova neutrino burst IBD interactions in pure water
- Atmospheric electron and muon neutrino annual interaction rate in pure water

XENONnT	Exp. NV+MV	Det. NV	NV Efficiency	Det. MV	MV Efficiency
Supernova neutrino IBD	170	8	100 %	108	68 %
Atmospheric neutrinos	93	4	~84 %	56	~64 %

XLZD Vetoes projection from XENONnT performance:

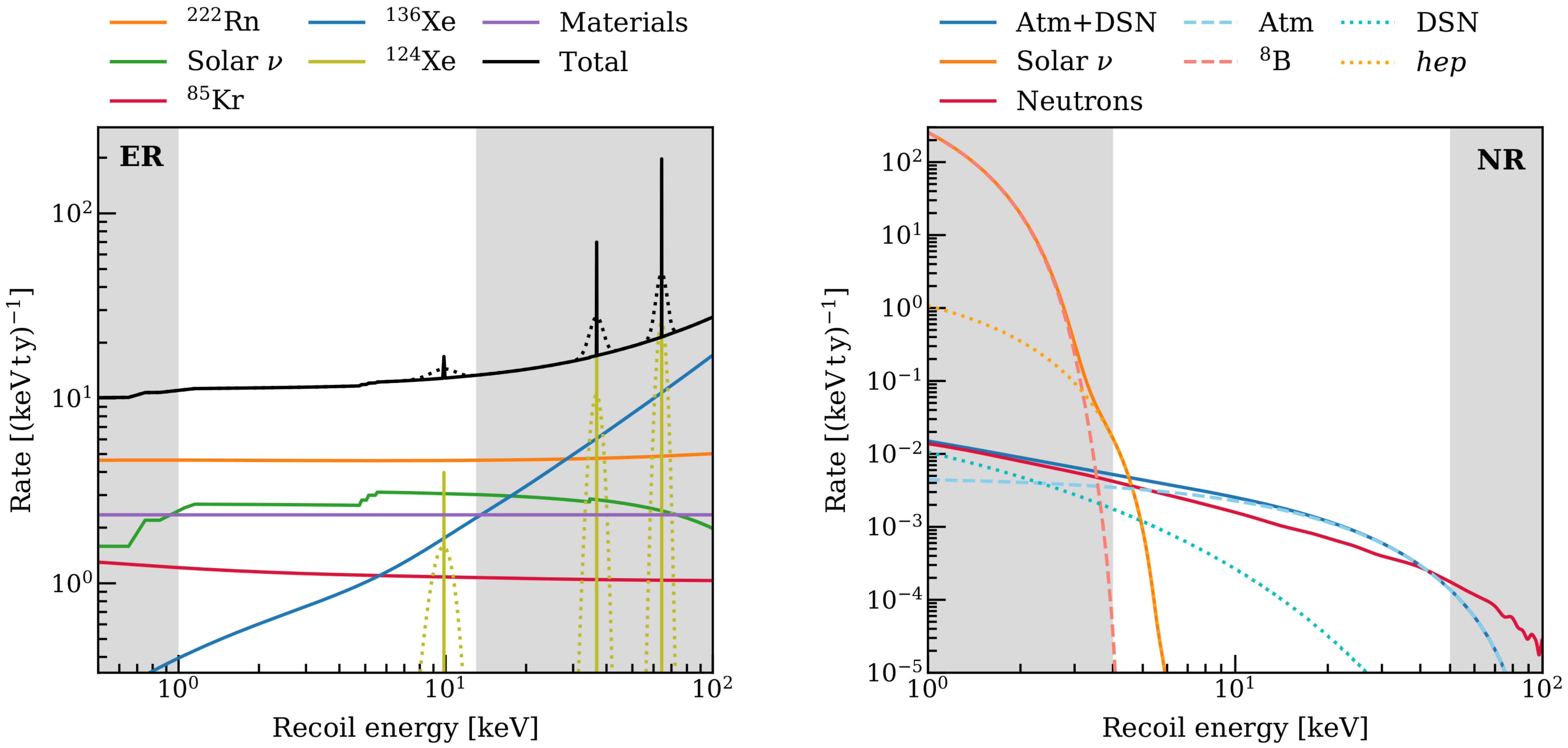
- Detection of at least 100 IBD positrons up to ~15 kpc supernova distance
- Total detected annual rate of 118 atmospheric neutrino-induced events in NV+MV



Participation at the XENONnT vetoes reassembly: XENONnT 2025 Upgrade

Back-up

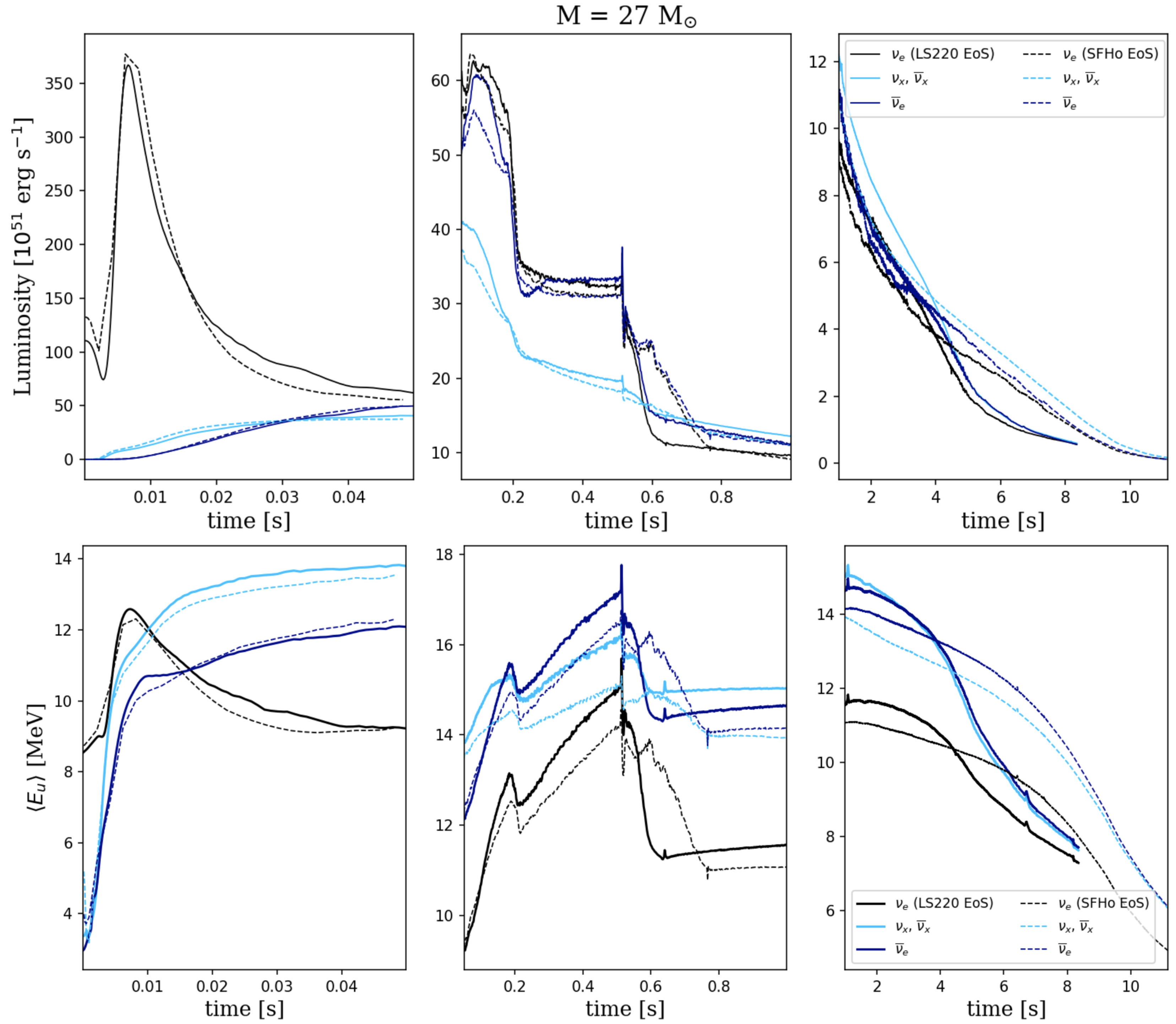
XENONnT Backgrounds



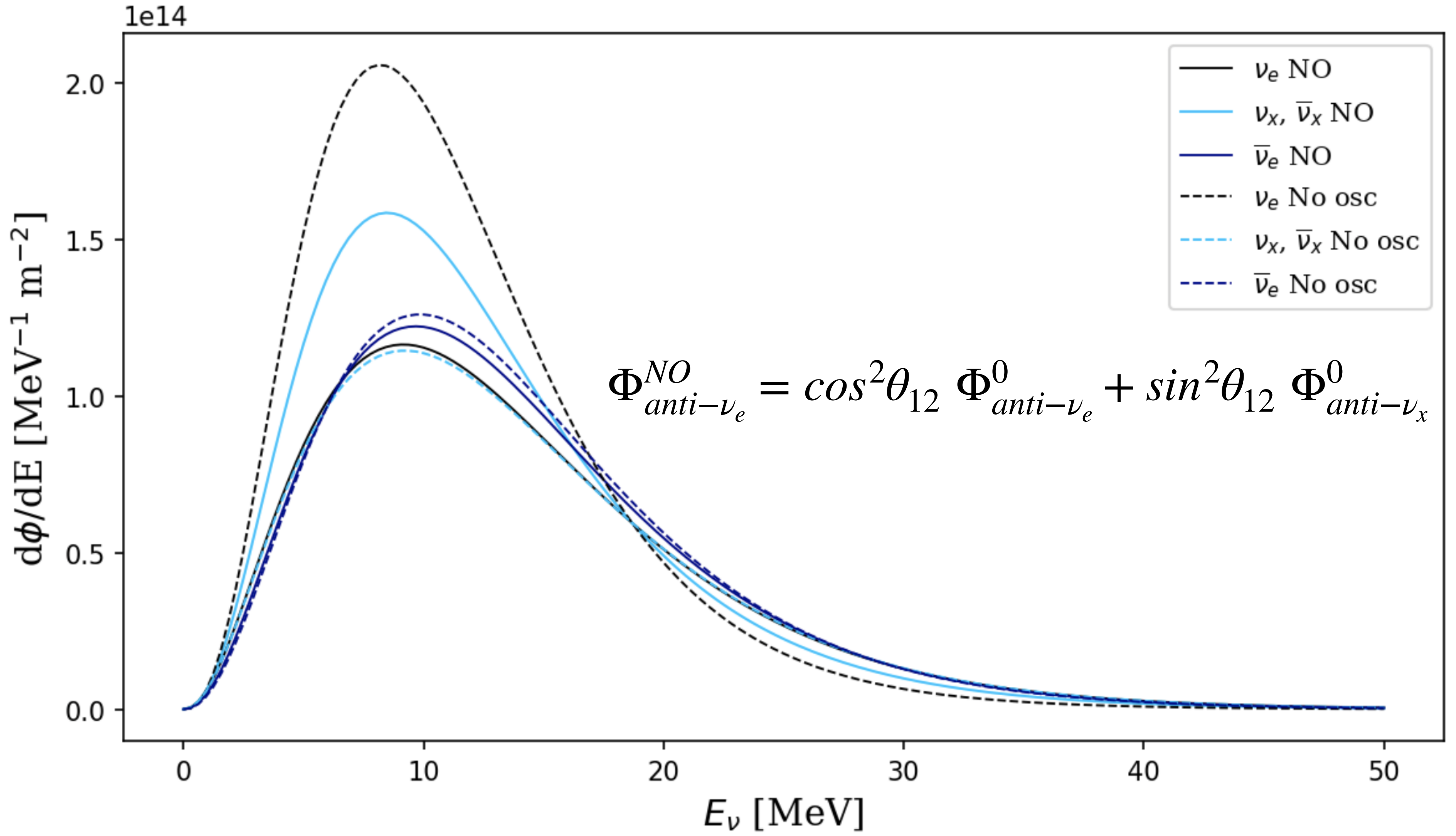
- Upper limit on the WIMP-nucleon SI σ: 1.7×10^{-47} cm^2 at 30 GeV/c^2 (PRL 135 (2025) 22, 221003)

Supernova models

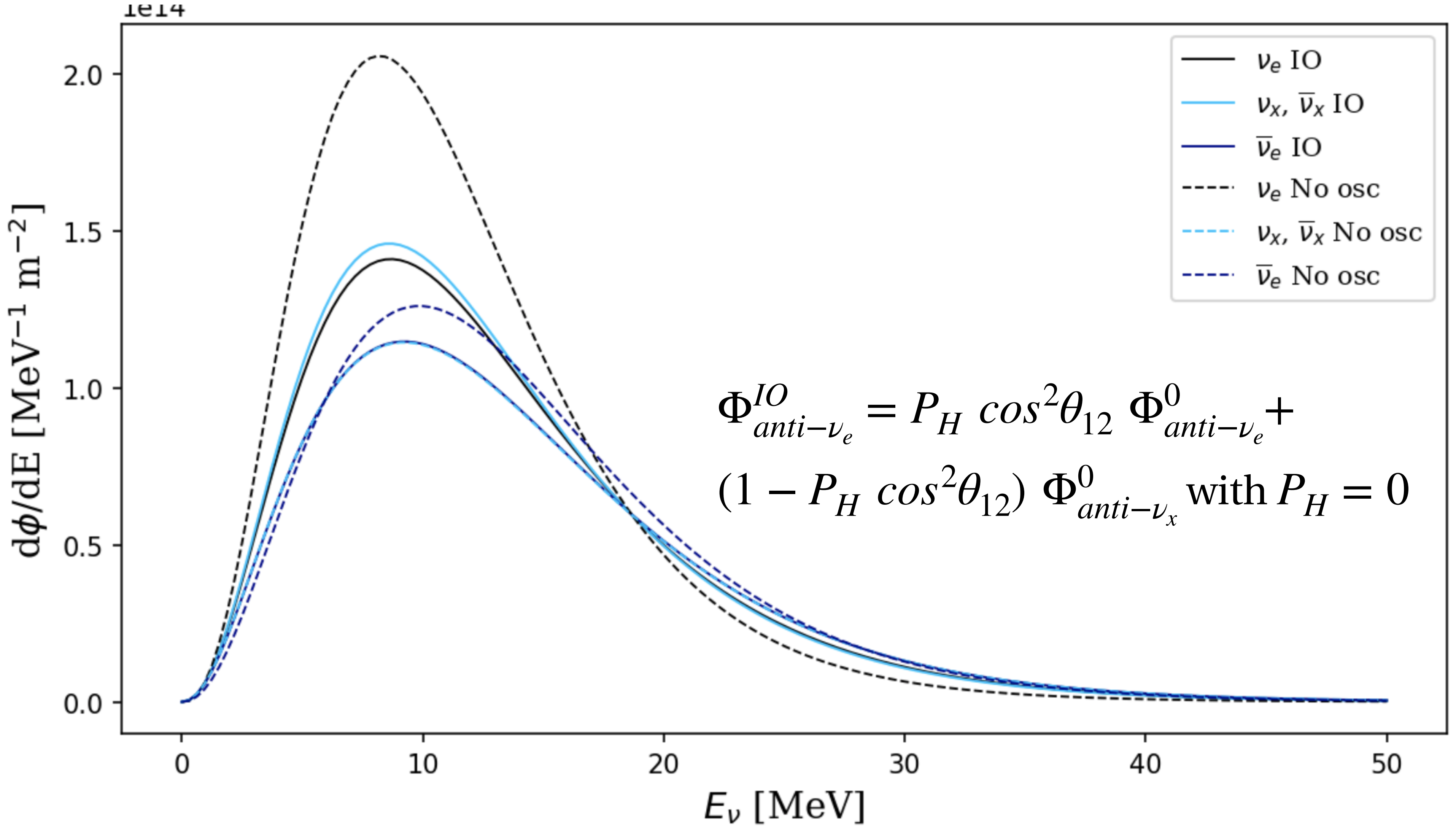
$$\Phi_{\nu_\beta}(E) = \int_0^T \frac{L_{\nu_\beta}(t_{pb})\ \varphi_{\nu_\beta}(E, t_{pb})}{4\pi d^2 \left\langle E_{\nu_\beta}(t_{pb})\right\rangle}\, dt_{pb}$$



Model	Exp. NV	Det. NV	Exp. MV	Det. MV	Eff. MV
LS220, 11.2 $M_\odot$	4.3	4.3	84.2	52.4	62 ± 5 %
LS220, 27 $M_\odot$	8.3	8.3	161.6	108.0	67 ± 4 %
SFHo, 27 $M_\odot$	8.6	8.6	167.5	109.5	65 ± 4 %
LS220, 27 $M_\odot$, NO osc.	8.1	8.1	159.5	107.3	67 ± 4 %
LS220, 27 $M_\odot$, IO osc.	7.9	7.9	155.1	106.0	68 ± 4 %

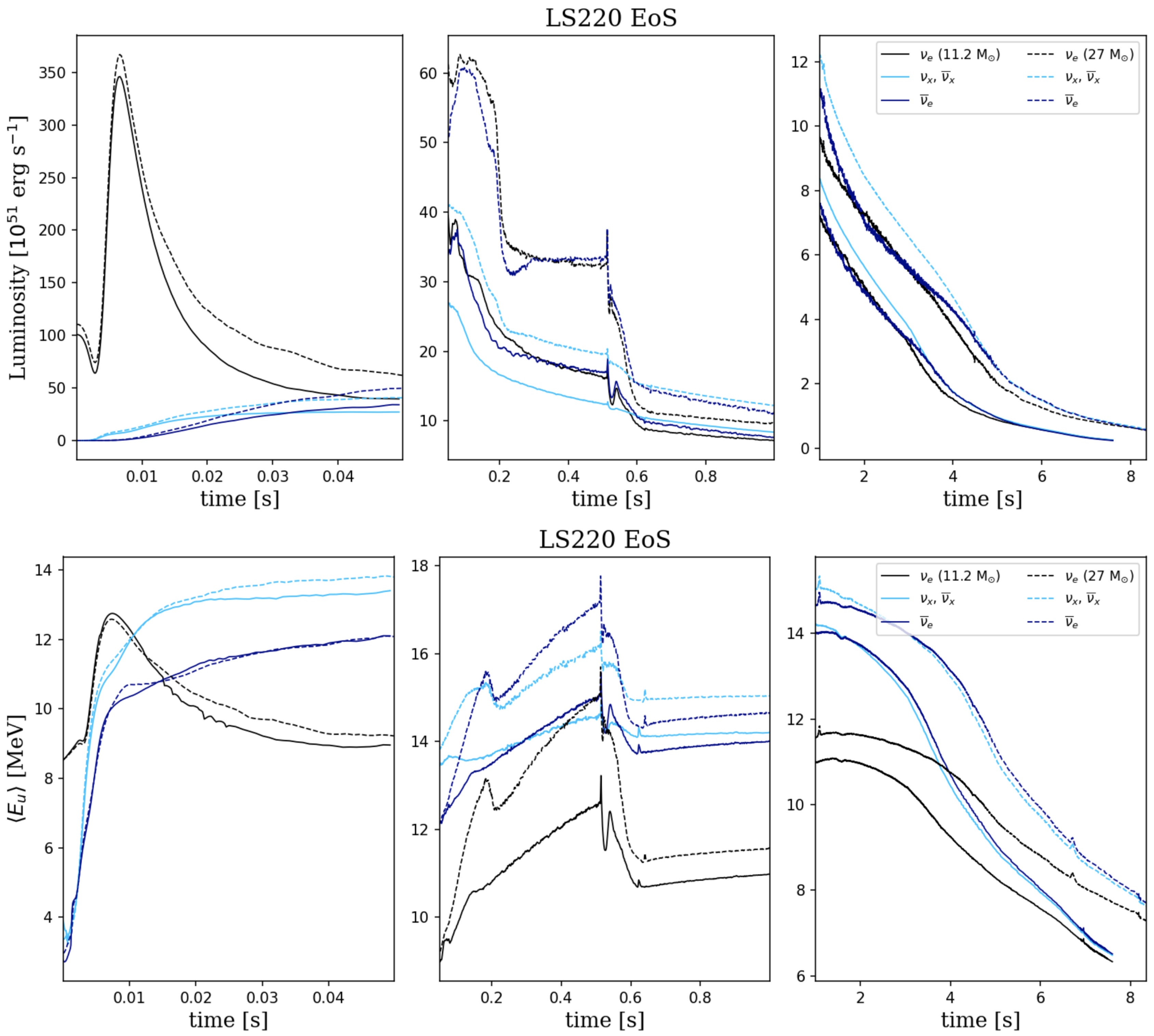


$$\Phi^{NO}_{anti-\nu_e} = cos^2\theta_{12}\ \Phi^0_{anti-\nu_e} + sin^2\theta_{12}\ \Phi^0_{anti-\nu_x}$$



$$\Phi^{IO}_{anti-\nu_e} = P_H\ cos^2\theta_{12}\ \Phi^0_{anti-\nu_e} + (1 - P_H\ cos^2\theta_{12})\ \Phi^0_{anti-\nu_x} \text{ with } P_H = 0$$

Supernova models



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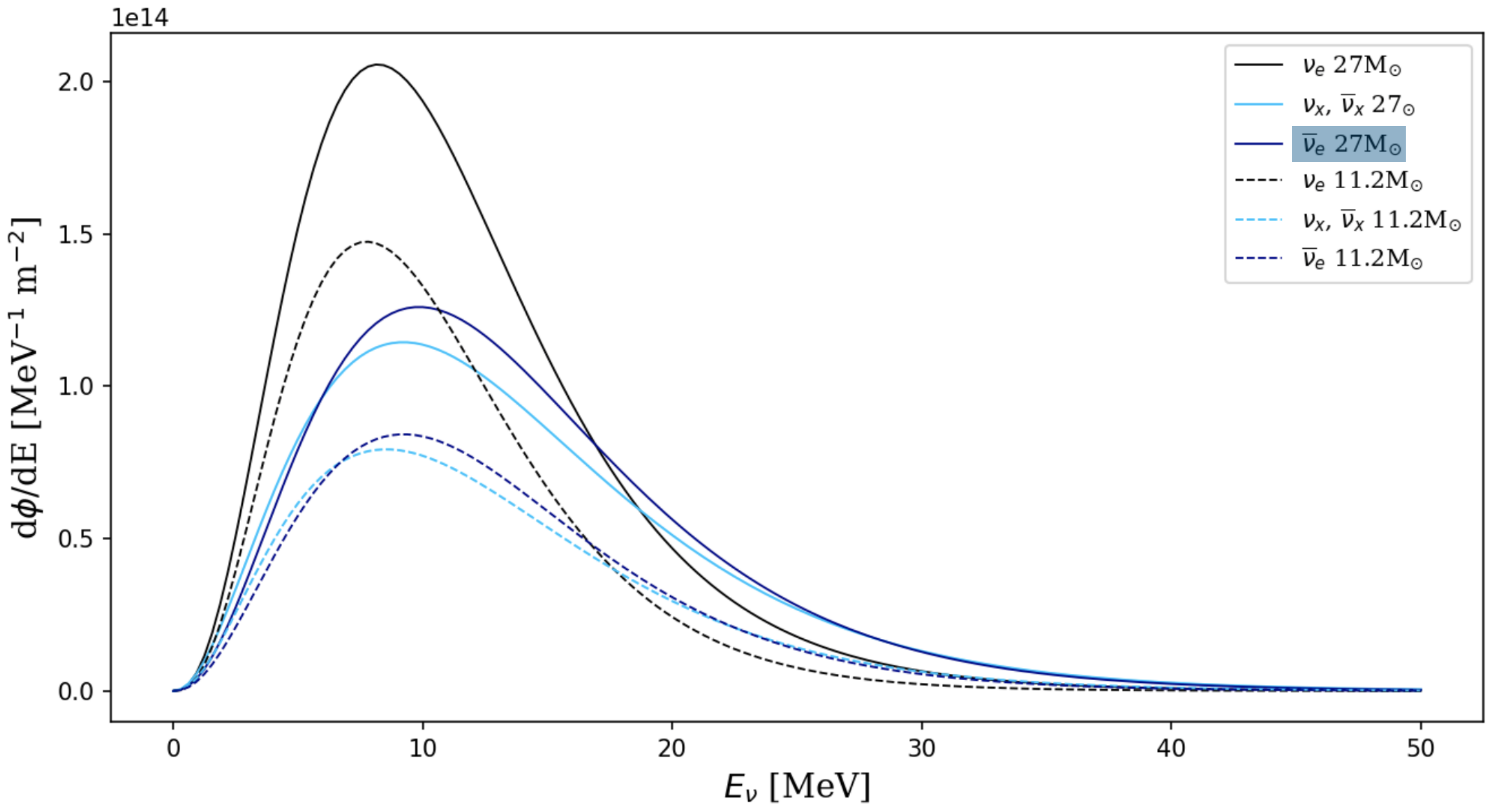
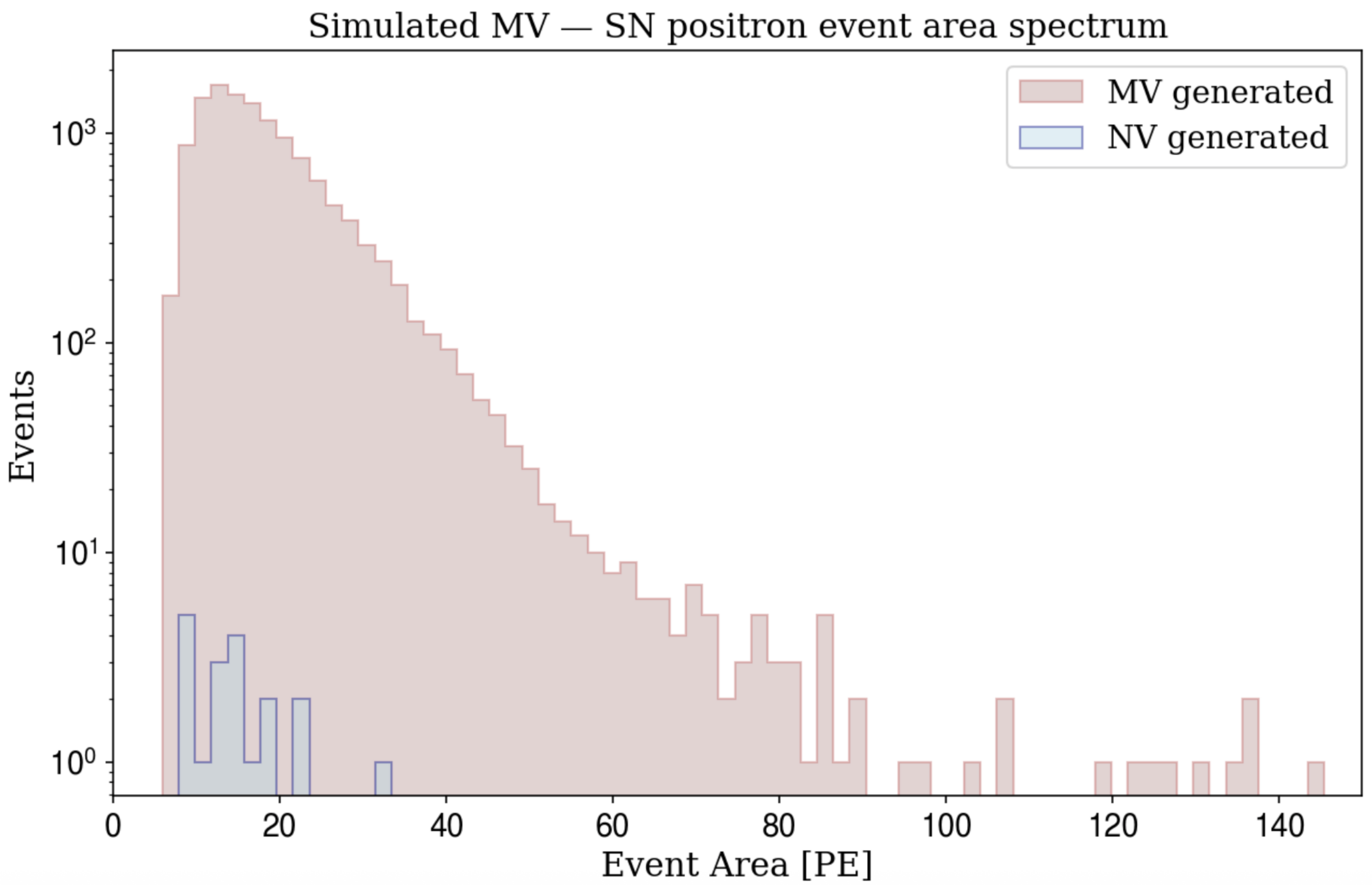
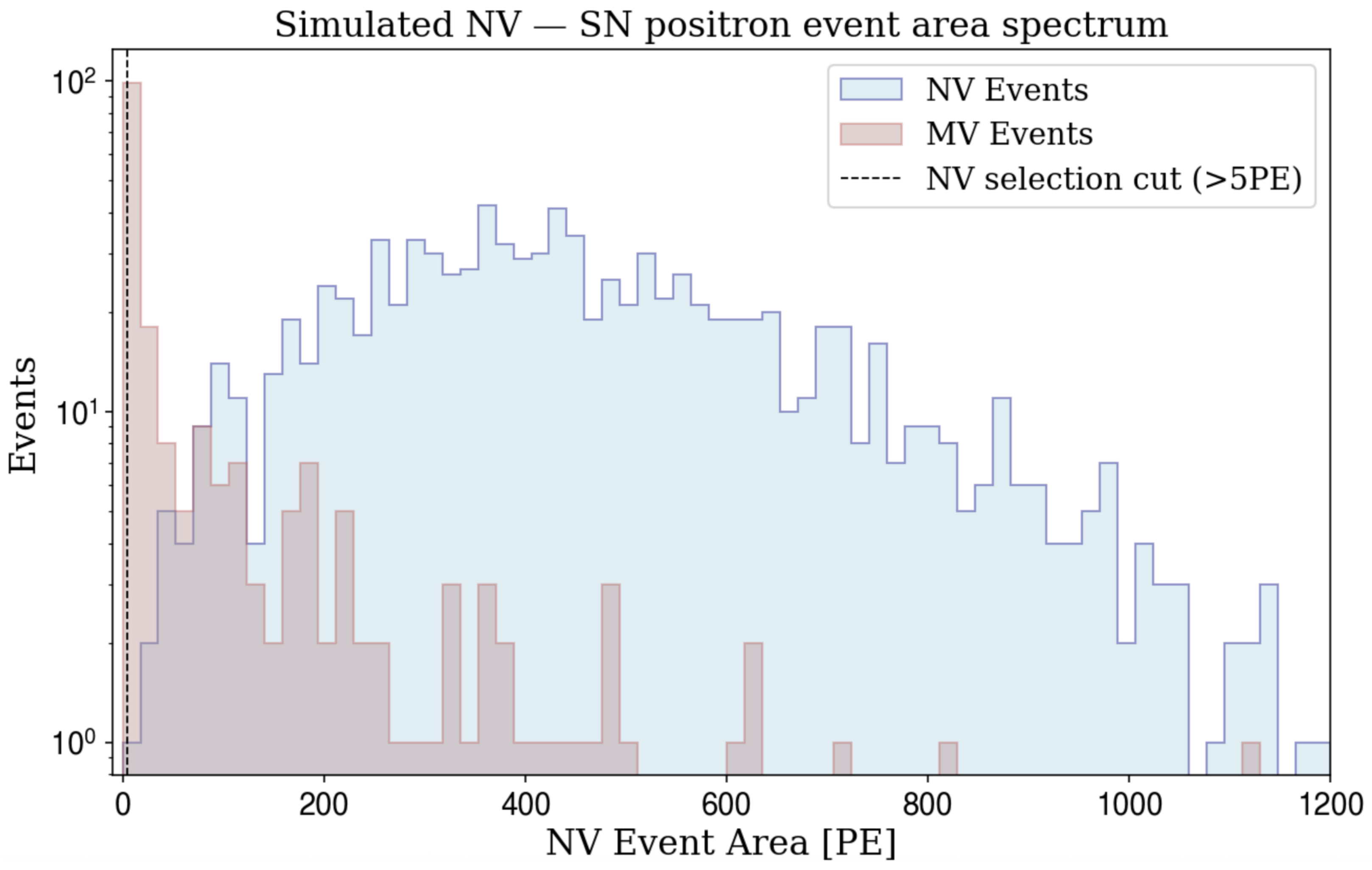
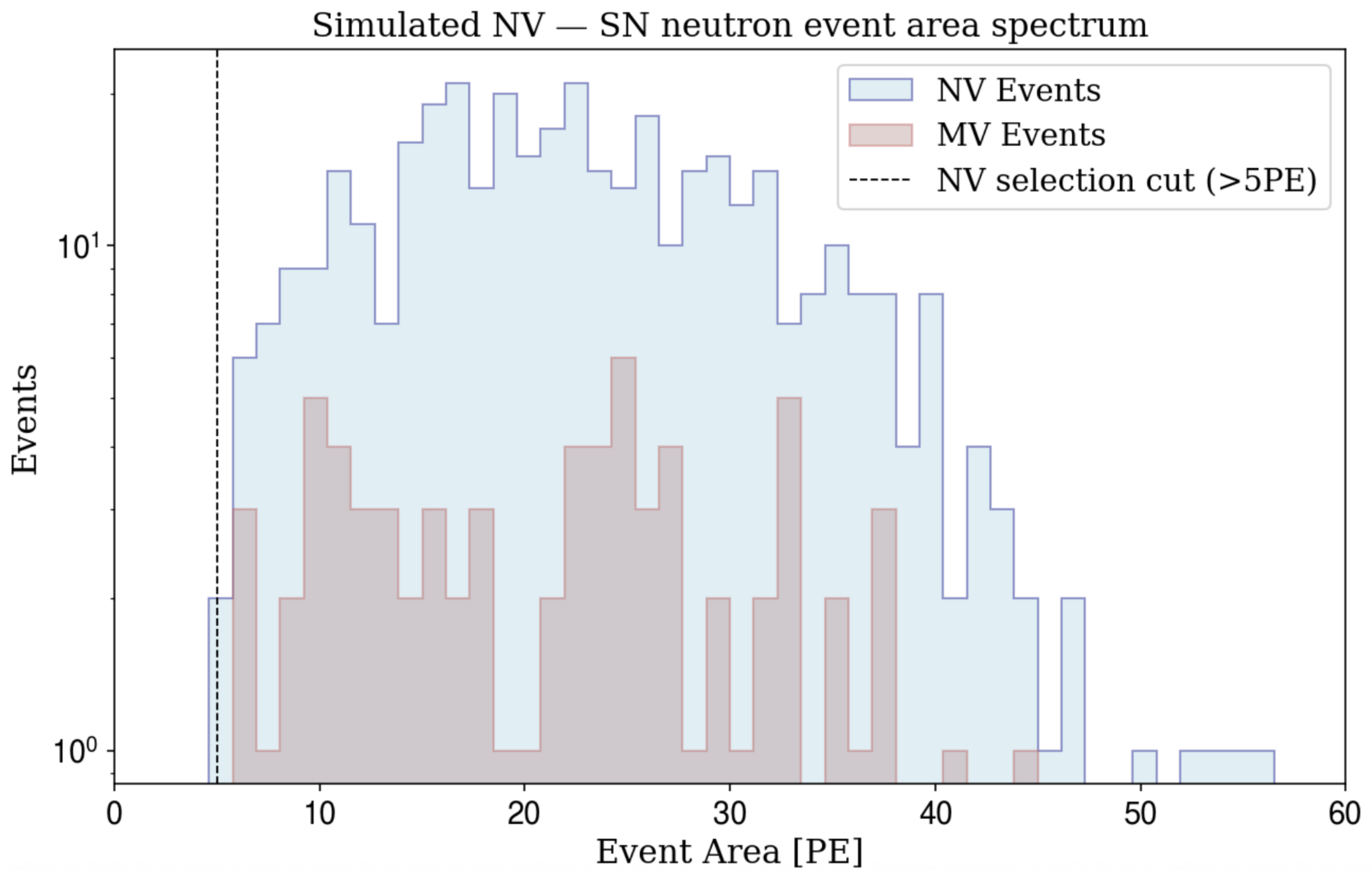
$$\Phi_{\nu_\beta}(E) = \int_0^T \frac{L_{\nu_\beta}(t_{pb})\,\varphi_{\nu_\beta}(E, t_{pb})}{4\pi d^2 \langle E_{\nu_\beta}(t_{pb})\rangle}\, dt_{pb}$$



IBD positron and neutron spectra

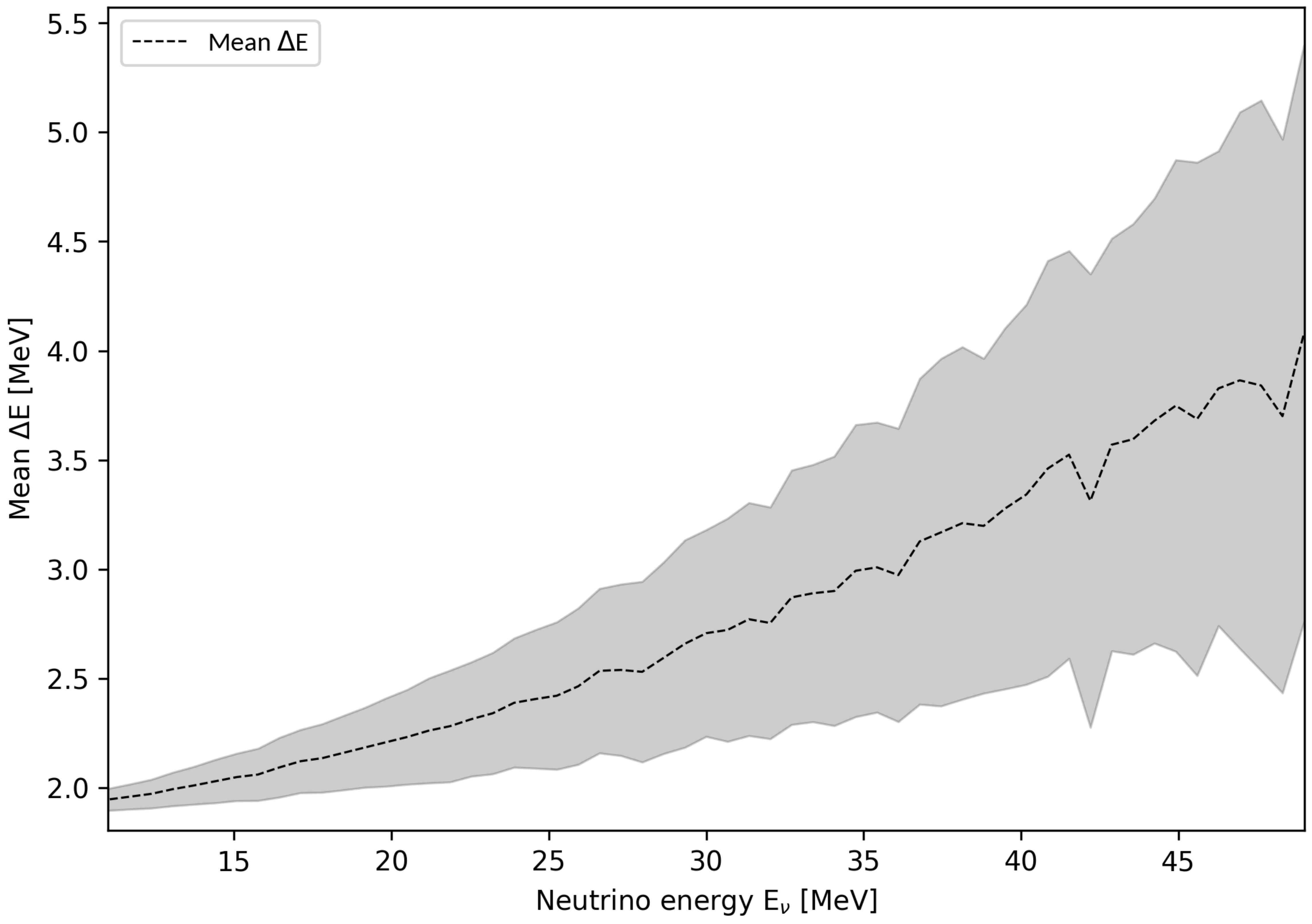




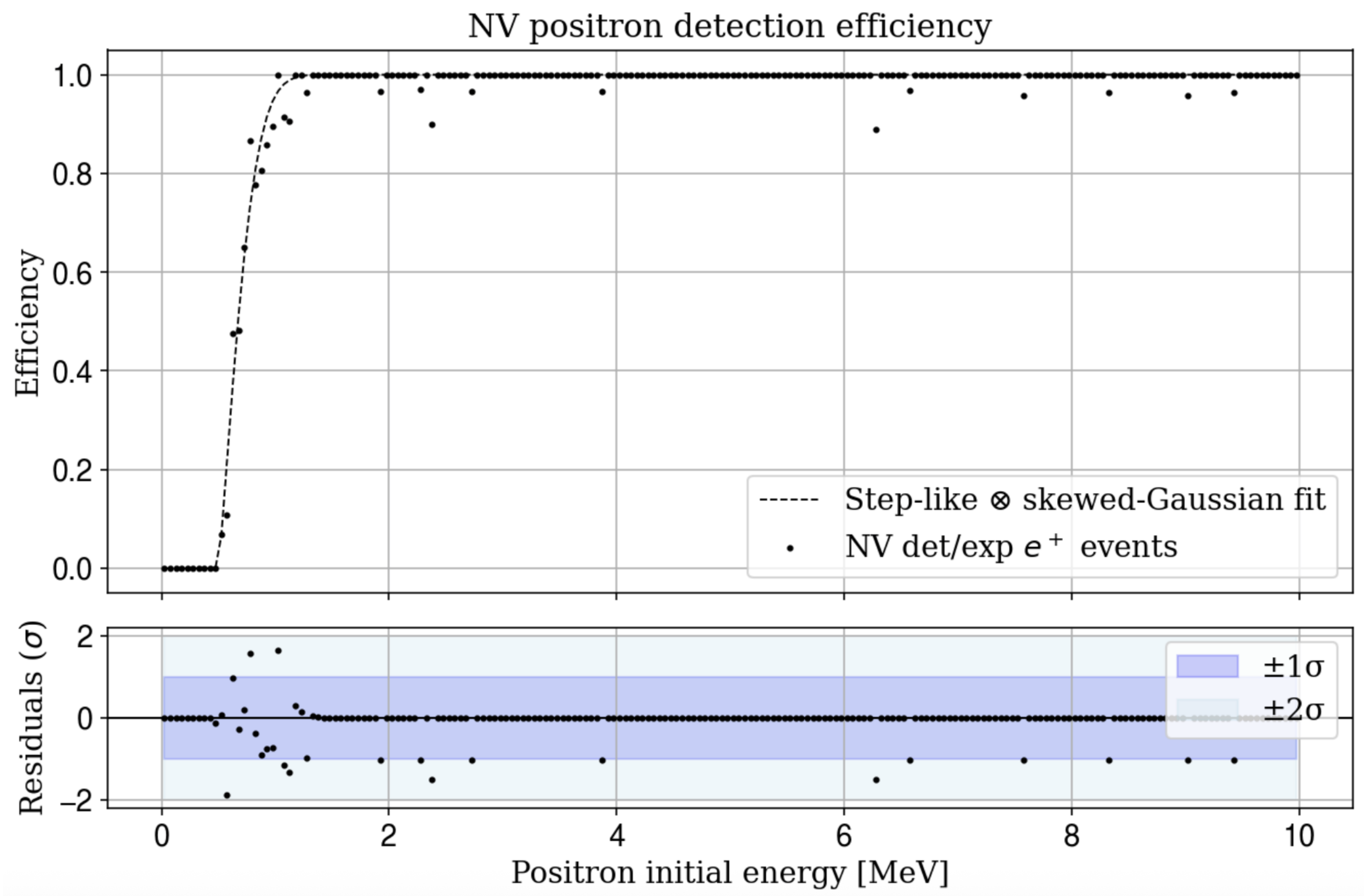


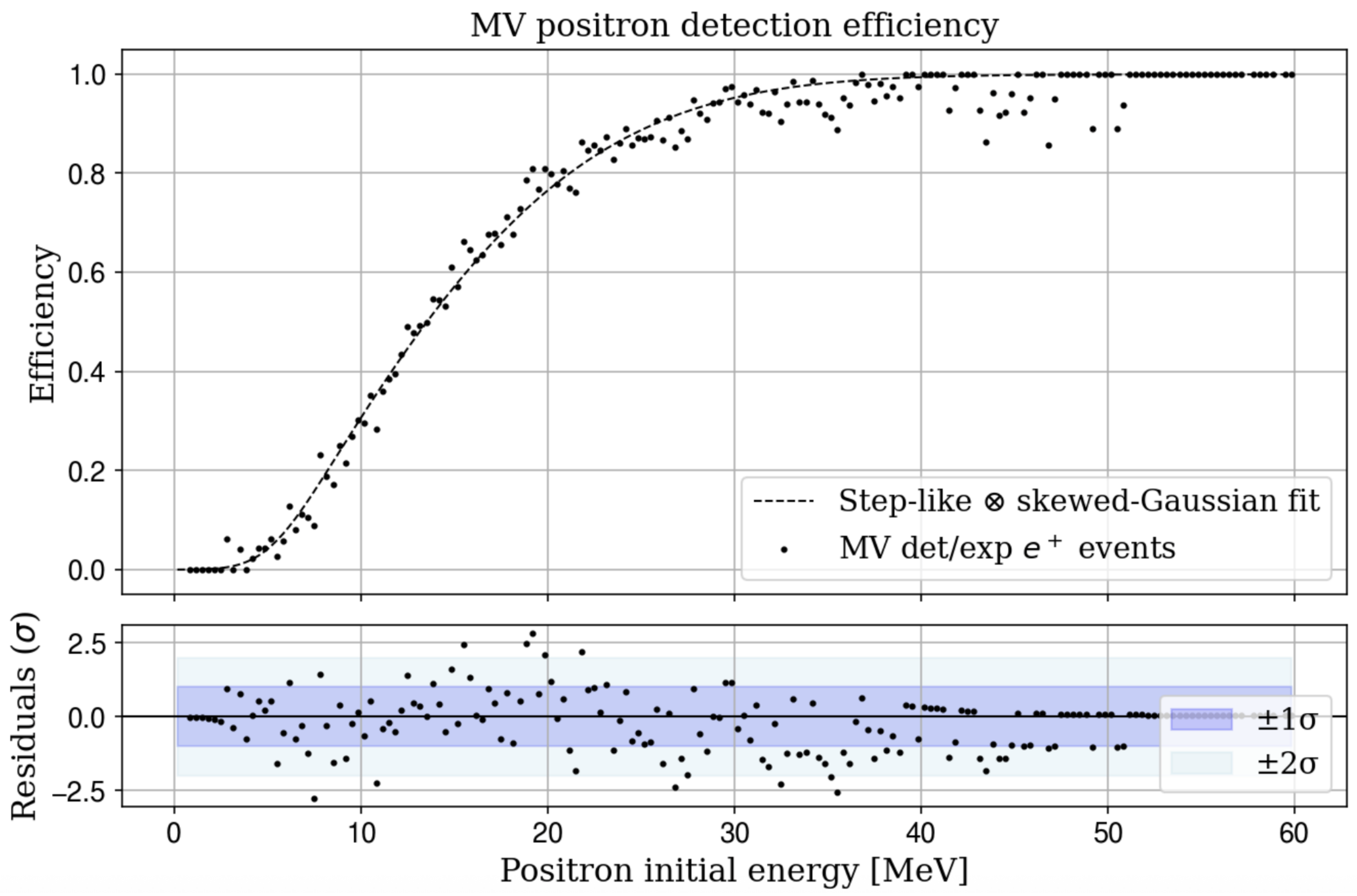
IBD positron spectrum approximation

$$\langle E_\nu - E_{e^+} \rangle = 2.4 \pm 0.6 \text{ MeV}$$



Energy-dependent efficiency fit





$$\eta(E;\sigma,\alpha) = \eta_{\max}\int_{-\infty}^{+\infty} H(E'-E_0)\, g_{\text{skew}}(E-E';\sigma,\alpha)\,\mathrm{d}E' =$$

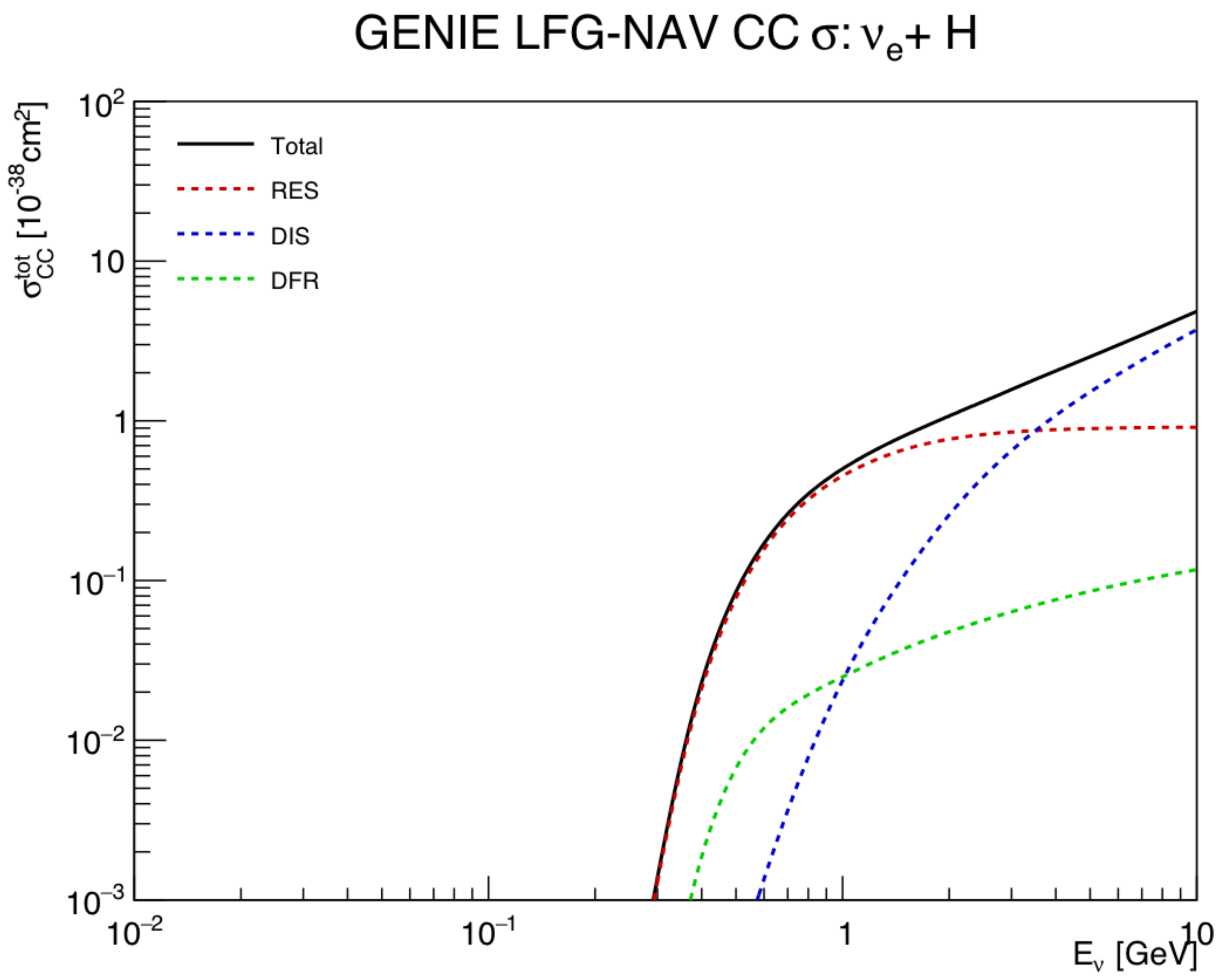
$$\eta_{\max}\left(\Phi\left(\frac{E-E_0}{\sigma}\right) - 2T\left(\frac{E-E_0}{\sigma},\alpha\right)\right)$$

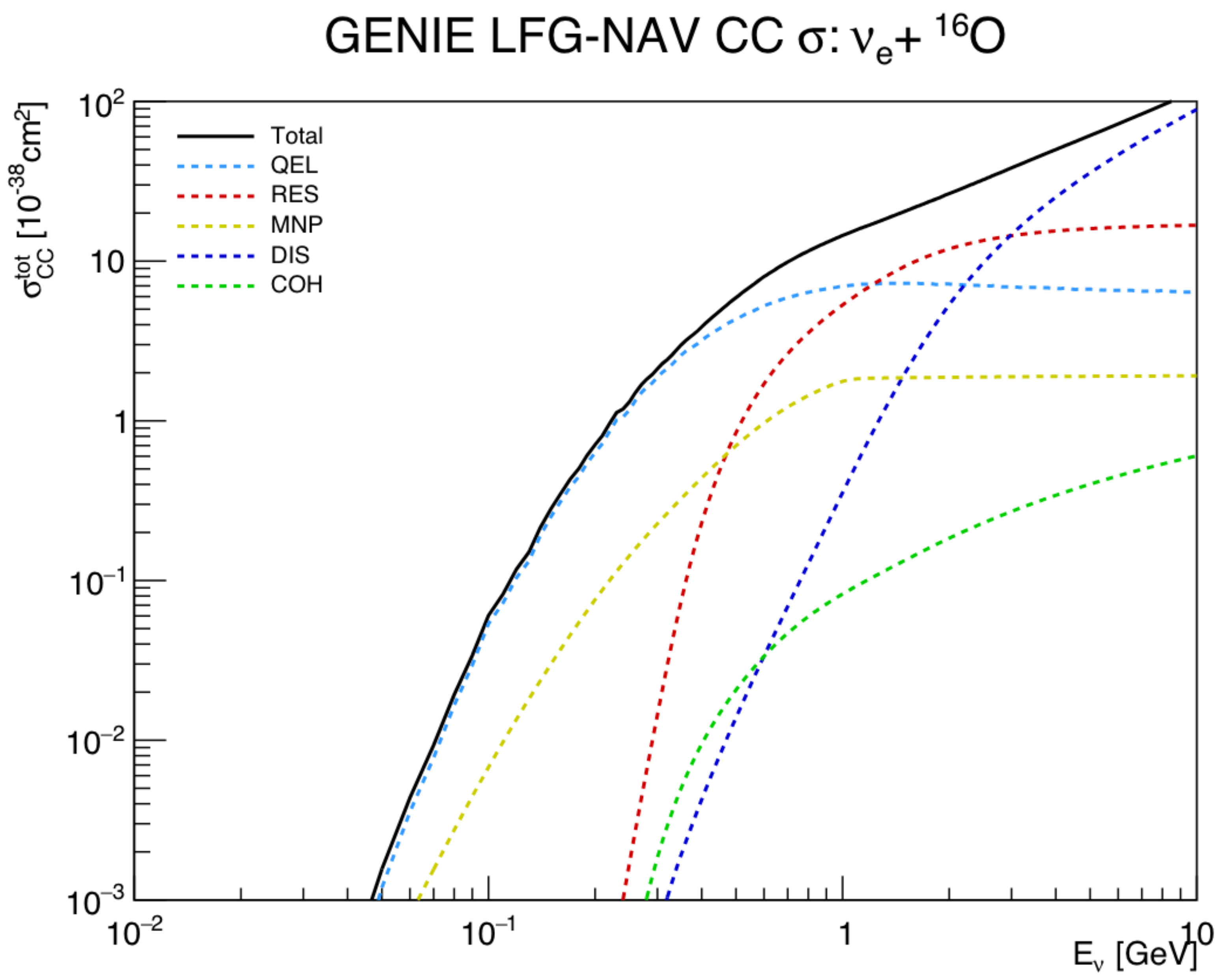
where $\Phi(x)$ is the cumulative gaussian distribution and $T(x)$ is the Owen's T function

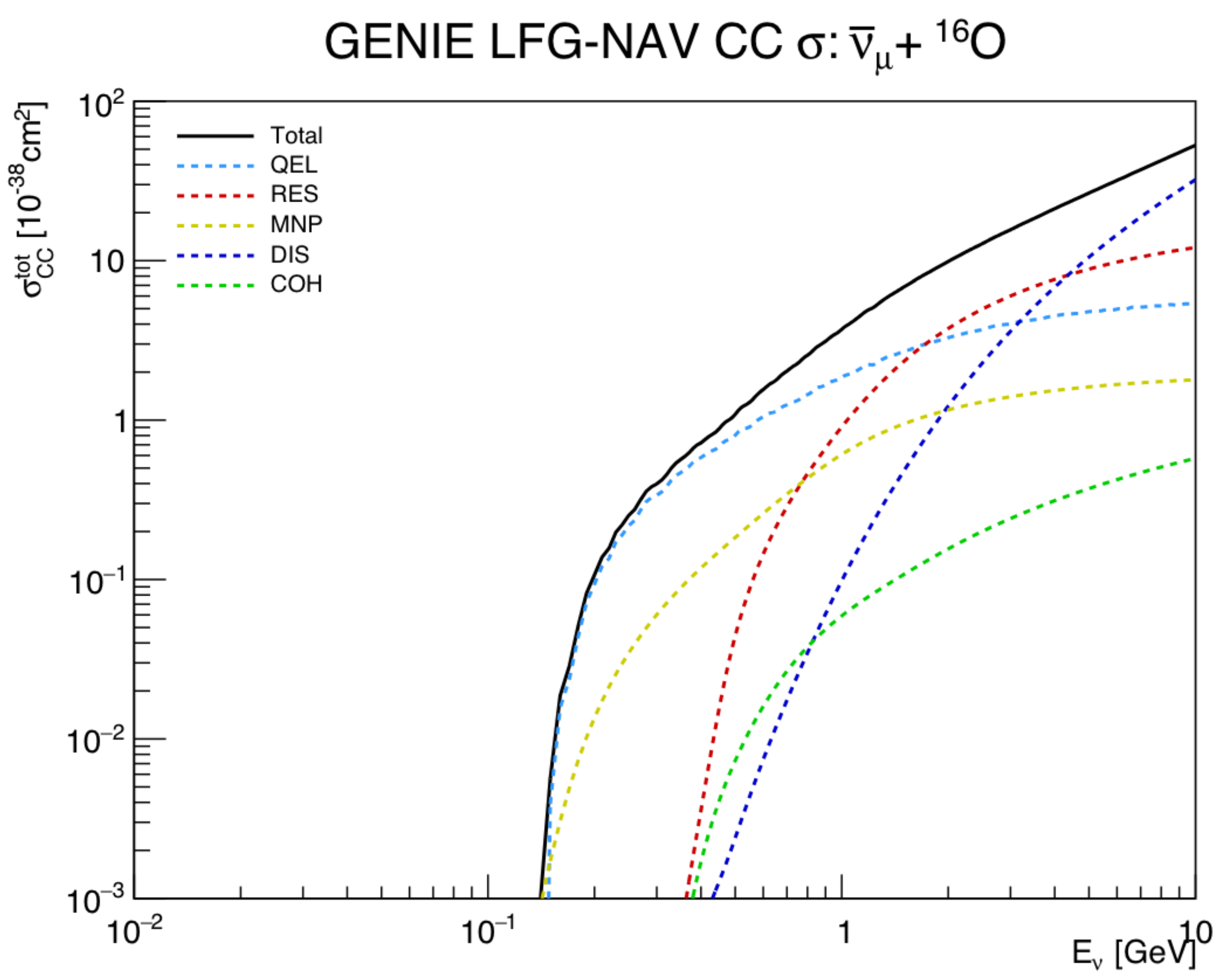
$$\mu = E_0 + \sqrt{\frac{2}{\pi}}\frac{\alpha\sigma}{\sqrt{1+\alpha^2}}$$

Fit parameter	Neutron Veto	Muon Veto
E_0 (MeV)	0.508 ± 0.007	5.0 ± 0.2
σ (MeV)	0.243 ± 0.009	12.6 ± 0.3
α	11 ± 12	7 ± 3

GENIE interaction cross sections







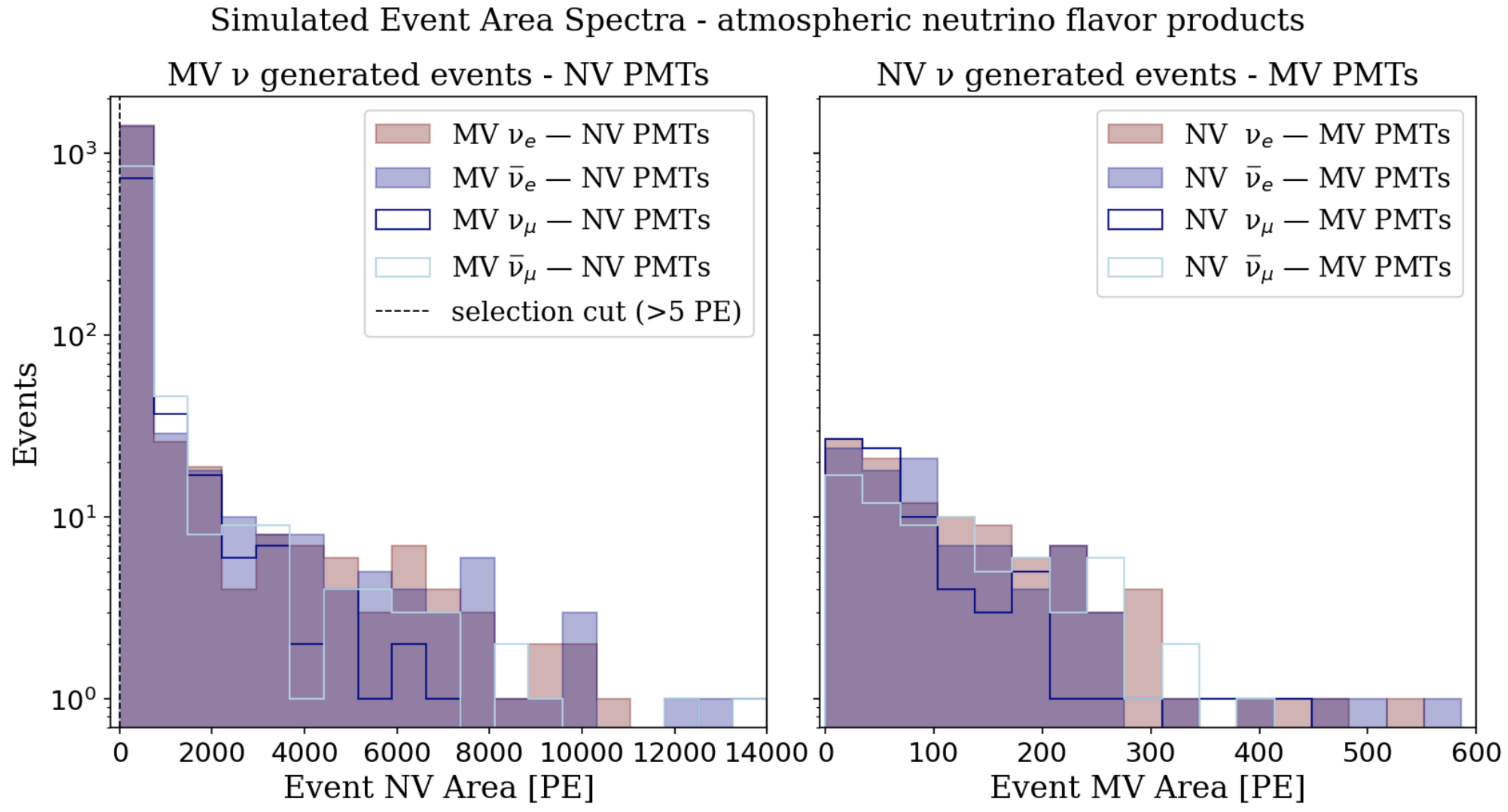
Int.	QES			RES			MNP			DIS		
$+H_2O$	Tot.	CC	NC	Tot.	CC	NC	Tot.	CC	NC	Tot.	CC	NC
ν_e	75%	59%	41%	15%	73%	27%	10%	73%	27%	<1%	37%	63%
$\bar{\nu}_e$	83%	57%	43%	7%	57%	43%	9%	70%	30%	<1%	38%	62%
ν_μ	77%	54%	46%	13%	66%	34%	9%	68%	32%	<1%	31%	69%
$\bar{\nu}_\mu$	84%	51%	49%	6%	44%	56%	9%	64%	36%	<1%	31%	69%

Atmospheric external events

Flavor	ε_{NV} (%)	ε_{MV} (%)
ν_e	87.0 ± 0.7	69.0 ± 0.7
$\bar{\nu}_e$	83.7 ± 0.7	65.4 ± 0.7
ν_μ	83.7 ± 0.7	62.6 ± 0.7
$\bar{\nu}_\mu$	79.8 ± 0.8	57.2 ± 0.7

$\varepsilon_{NV}^{ext} = (1.3 \pm 0.2)\,\%$

Flavor	Exp. NV	Det. NV (int)	Exp. MV	Det. MV (int)	Det. NV (ext)
ν_e	1.2	1.1	24.3	16.8	0.3
$\bar{\nu}_e$	0.4	0.3	7.9	5.2	0.1
ν_μ	2.1	1.7	40.8	25.6	0.7
$\bar{\nu}_\mu$	0.8	0.6	15.3	8.7	0.2
Total [yr^{-1}]	4.5	3.7	88.3	56.3	1.3



GENIE Neutrino Generator

Example interaction: CC resonant pion production

1764848695 NOTICE gevdump : [n] <gEvDump.cxx::main (177)> : ** Event: 66

Model+tune: G18_10a_02_11b

GENIE GHEP Event Record [print level: 3]

Idx	Name	Ist	PDG	Mother		Daughter		Px	Py	Pz	E	m	
0	nu_e	0	12	-1	-1	5	5	0.000	0.000	0.690	0.690	0.000	
1	O16	0	1000080160	-1	-1	2	4	0.000	0.000	0.000	14.895	14.895	
2	neutron	11	2112	1	-1	6	6	0.067	-0.167	-0.049	0.923	**0.940	M = 0.904
3	O15	2	1000080150	1	-1	12	12	-0.072	0.168	0.046	13.966	*13.971	M = 13.965
4	gamma	1	22	1	-1	-1	-1	0.005	-0.001	0.003	0.006	0.000	
5	e-	1	11	0	-1	-1	-1	-0.105	0.027	0.008	0.108	0.001	P = (0.966,-0.247,-0.071)
6	Delta+	3	2214	2	-1	7	8	0.172	-0.194	0.634	1.504	**1.232	M = 1.340
7	neutron	14	2112	6	-1	9	10	-0.025	-0.321	0.234	1.020	0.940	FSI = 2
8	pi+	14	211	6	-1	11	11	0.197	0.128	0.400	0.484	0.140	FSI = 1
9	proton	1	2212	7	-1	-1	-1	0.076	-0.038	-0.097	0.947	0.938	
10	neutron	1	2112	7	-1	-1	-1	-0.140	-0.281	0.233	1.017	0.940	
11	pi+	1	211	8	-1	-1	-1	0.197	0.128	0.400	0.484	0.140	
12	HadrBlob	15	2000000002	3	-1	-1	-1	-0.034	0.165	0.144	13.022	**0.000	M = 13.020