Low-Threshold Neutrino Detection

2026 Neutrino Summer School

Phil Barbeau, Duke University

Signatures challenging to detect

- Start with *Thresholdless*
  - Neutrino-electron Elastic Scattering
  - Coherent **Elastic** Neutrino-Nucleus Scattering (CEvNS)
  - Neutrino Capture on **radioactive** Nuclei
- Next Lecture: Low-Threshold Neutrino Detection
  - Neutrino Capture on **stable** nuclei
  - Neutral Current **Inelastic** Scattering

Neutrino Capture on Radioactive Nuclei

Ordinary Beta Decay $A_N^Z \rightarrow A_{N-1}^{Z+1} + e^- + \bar{\nu}_e$

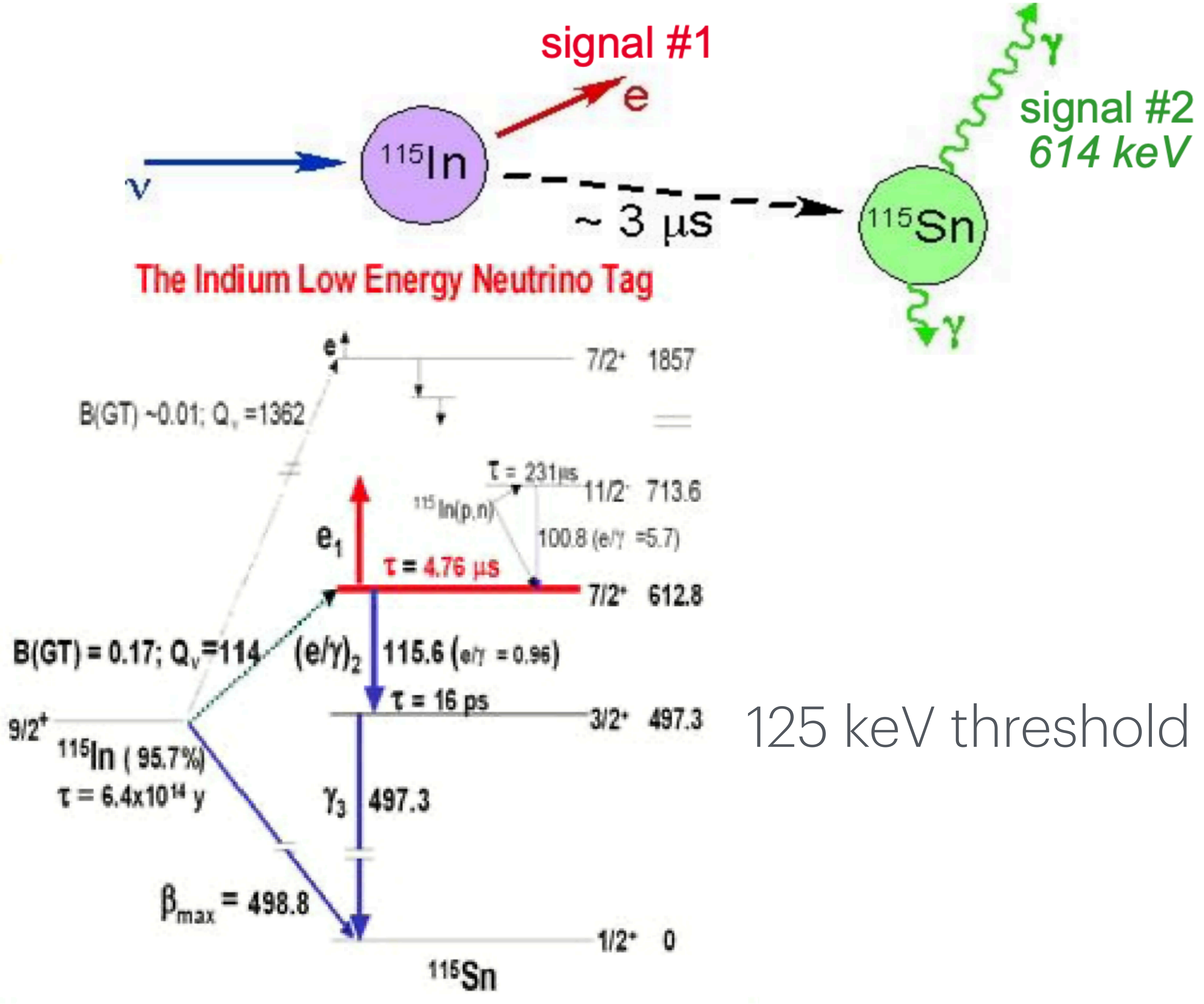
Neutrino Capture $\nu_e + A_N^Z \rightarrow e^- + A_{N-1}^{Z+1}$

Cross section related to beta decay amplitude

Reaction exothermic: no threshold
(dependent on and quantum numbers of daughter)

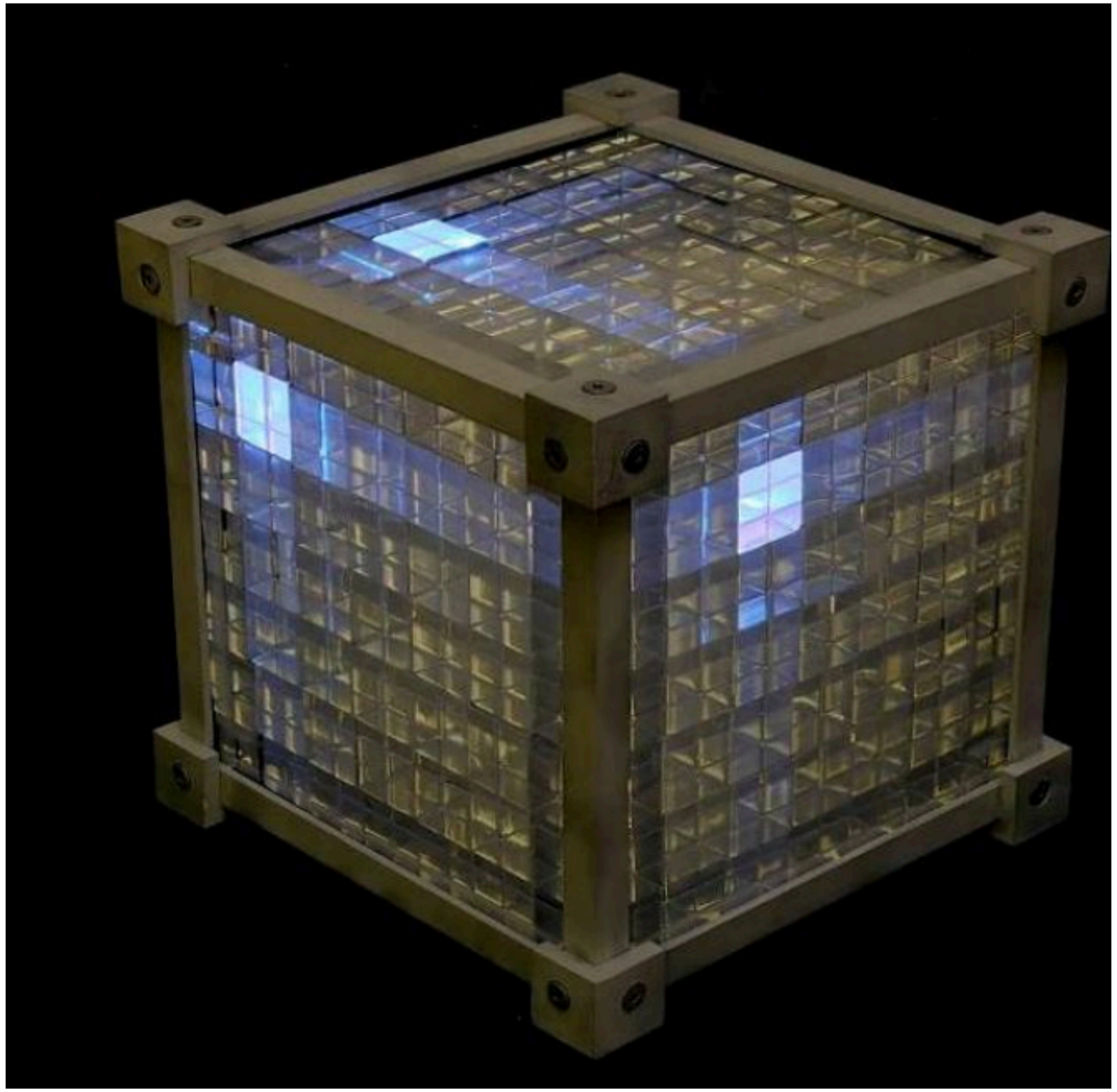
Neutrino Capture on Radioactive Nuclei

Indium-115 (10^{14} yr half-life) with LENS for Solar ν's



125 keV threshold

Rhagavan Optical Lattice



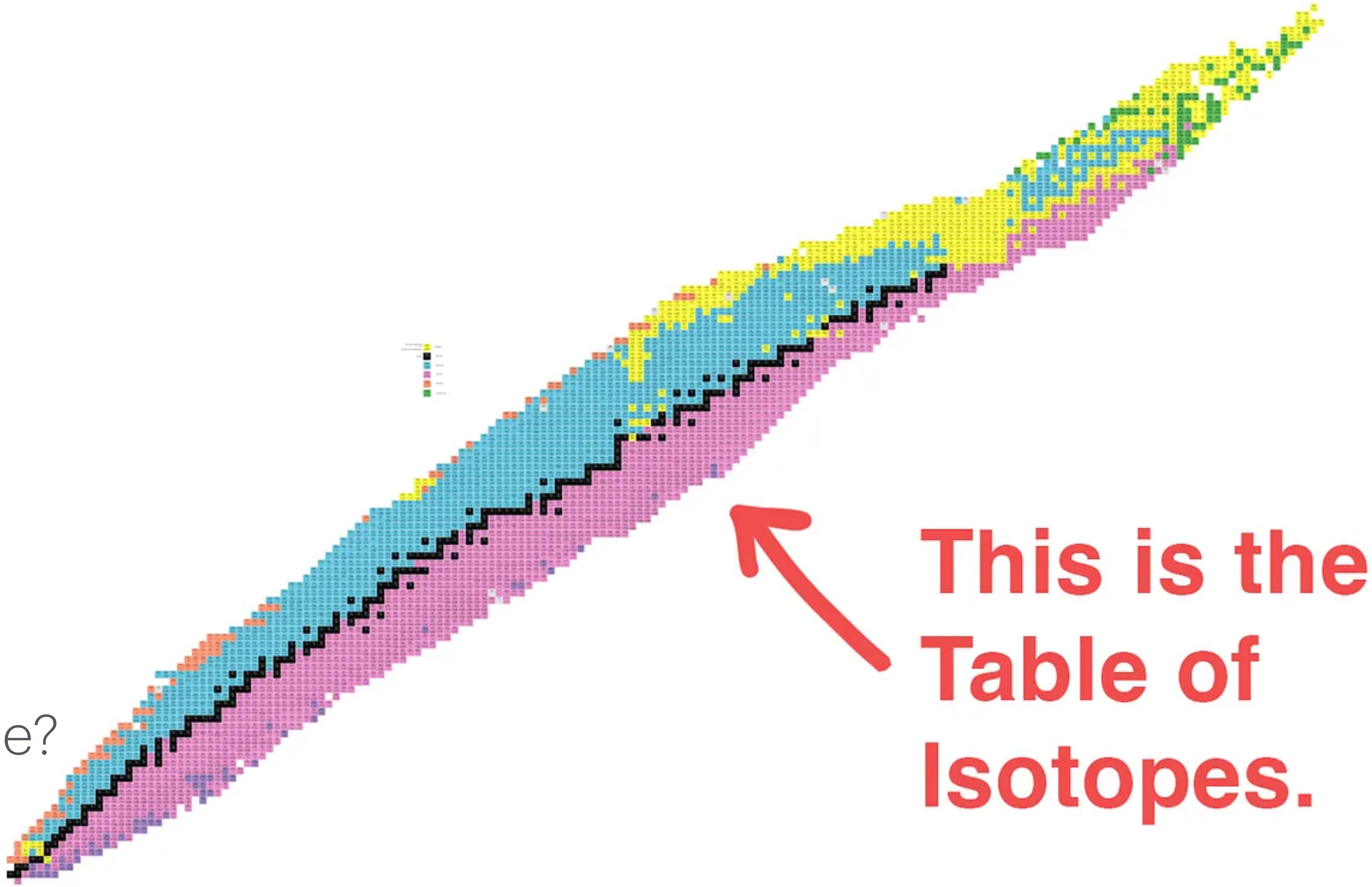
Neutrino Capture on Radioactive Nuclei

How Many Targets?

- ^{115}In
- ^{175}Yb
  - 301 keV threshold
  - 50 ns 1+ half-life of ^{175}Lu
  - 72 keV secondary signal

Challenge: can you find a better one?

Go hunting: www.nndc.bnl.gov



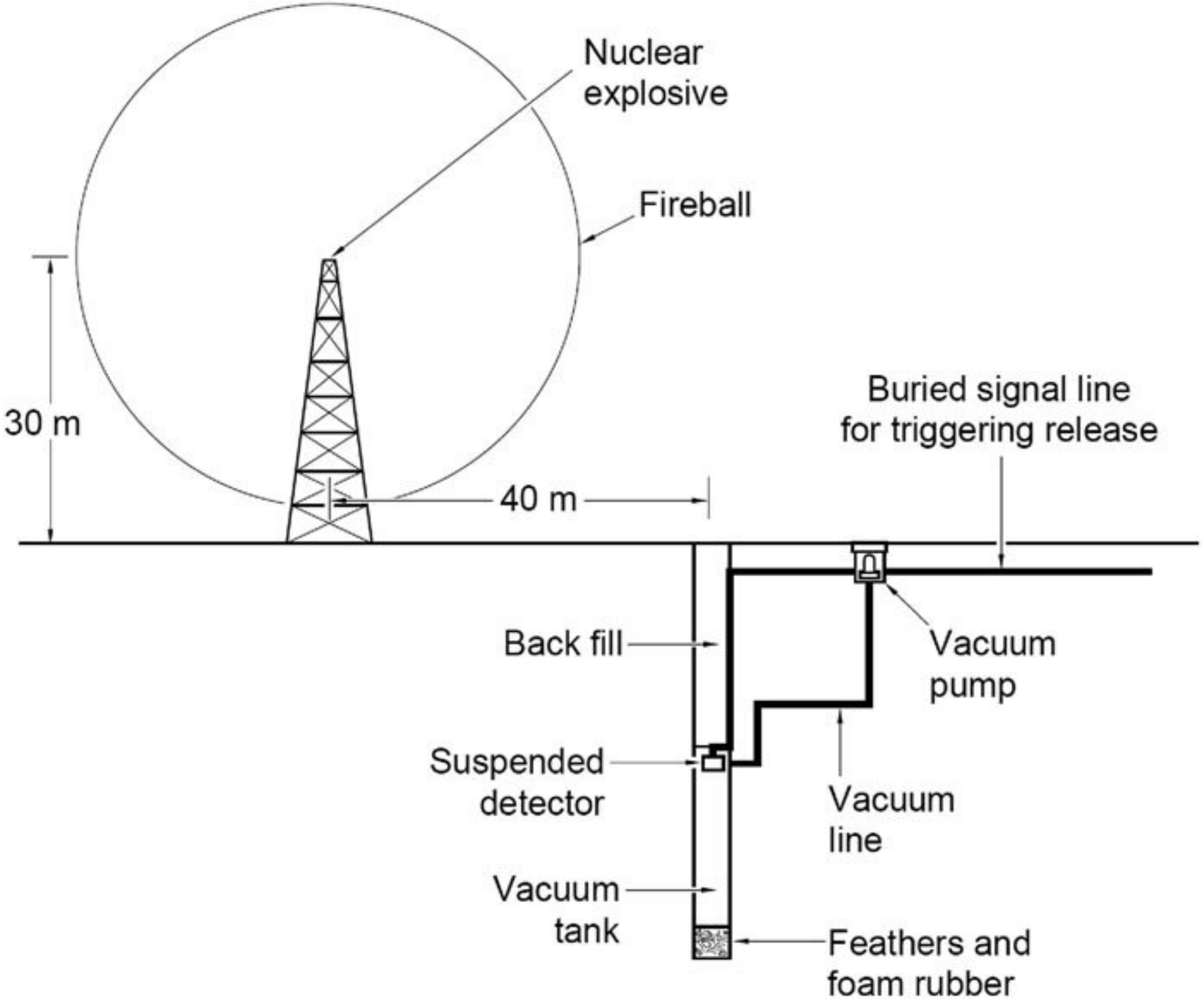
This is the Table of Isotopes.

Inverse Beta Decay

Search for low energy antineutrinos (e.g. Geoneutrinos)

Ordinary Beta Decay:

Interchange particles:



Inverse Beta Decay

Search for low energy antineutrinos (e.g. Geoneutrinos)

Ordinary Beta Decay:

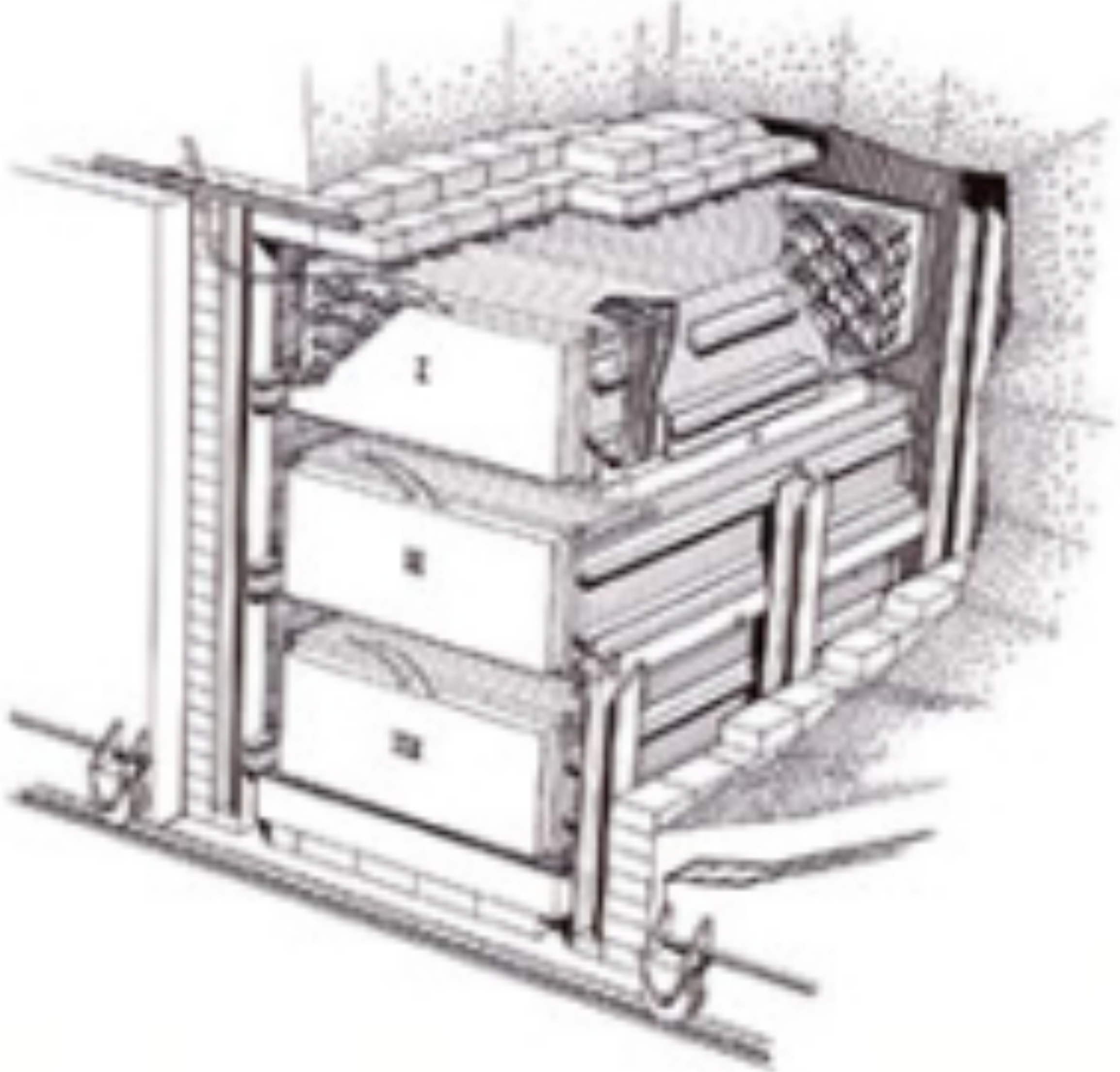
$$(A, Z-1) \rightarrow (A, Z) + e^- + \bar{\nu} + Q_\beta$$

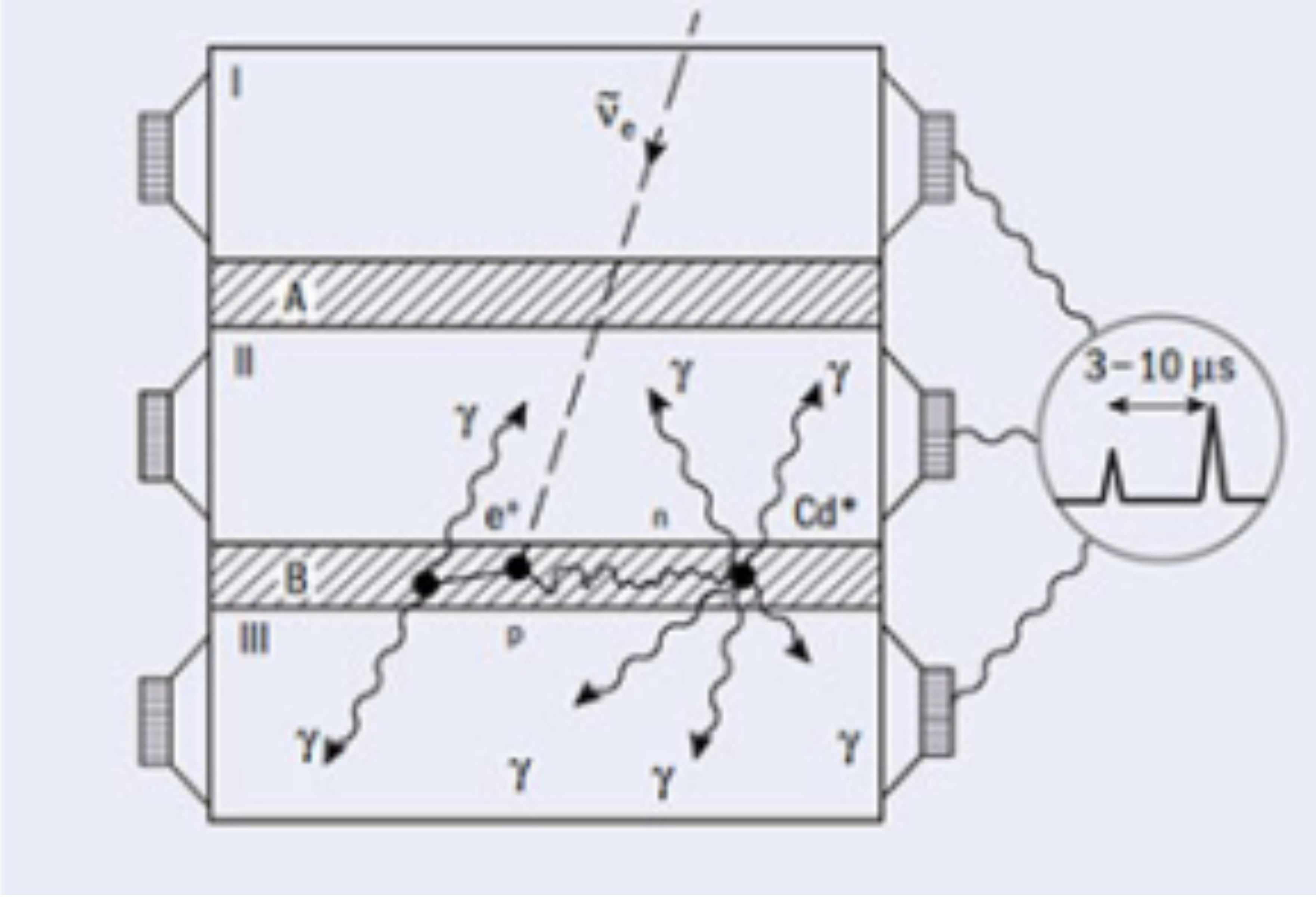
Inverse Beta Decay

Interchange particles:

$$\boxed{e^+} + (A, Z-1) \leftarrow (A, Z) + \bar{\nu} + Q_\beta + \boxed{1.02\ \text{MeV}}$$

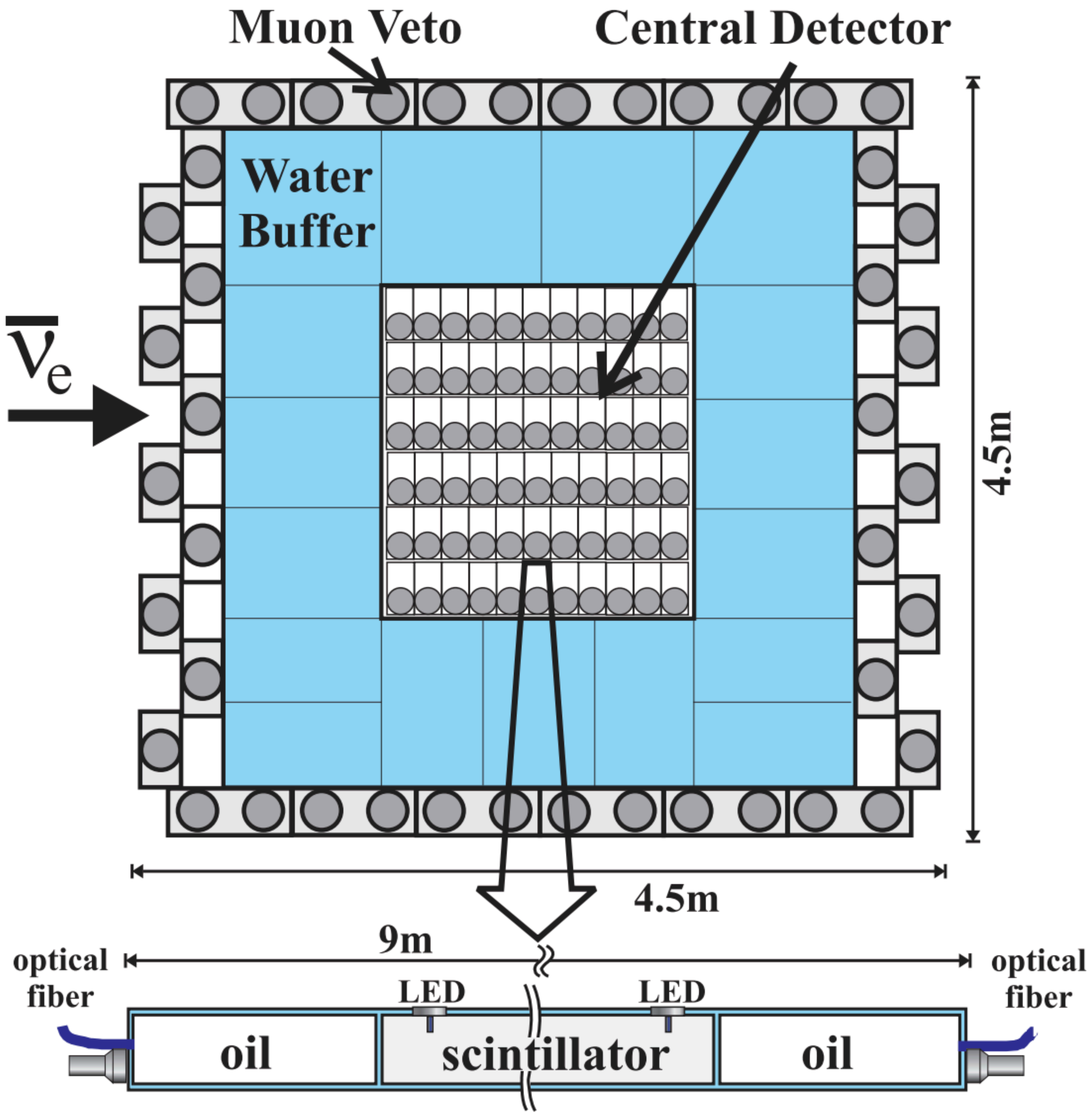
Reines and Cowen at Savannah River

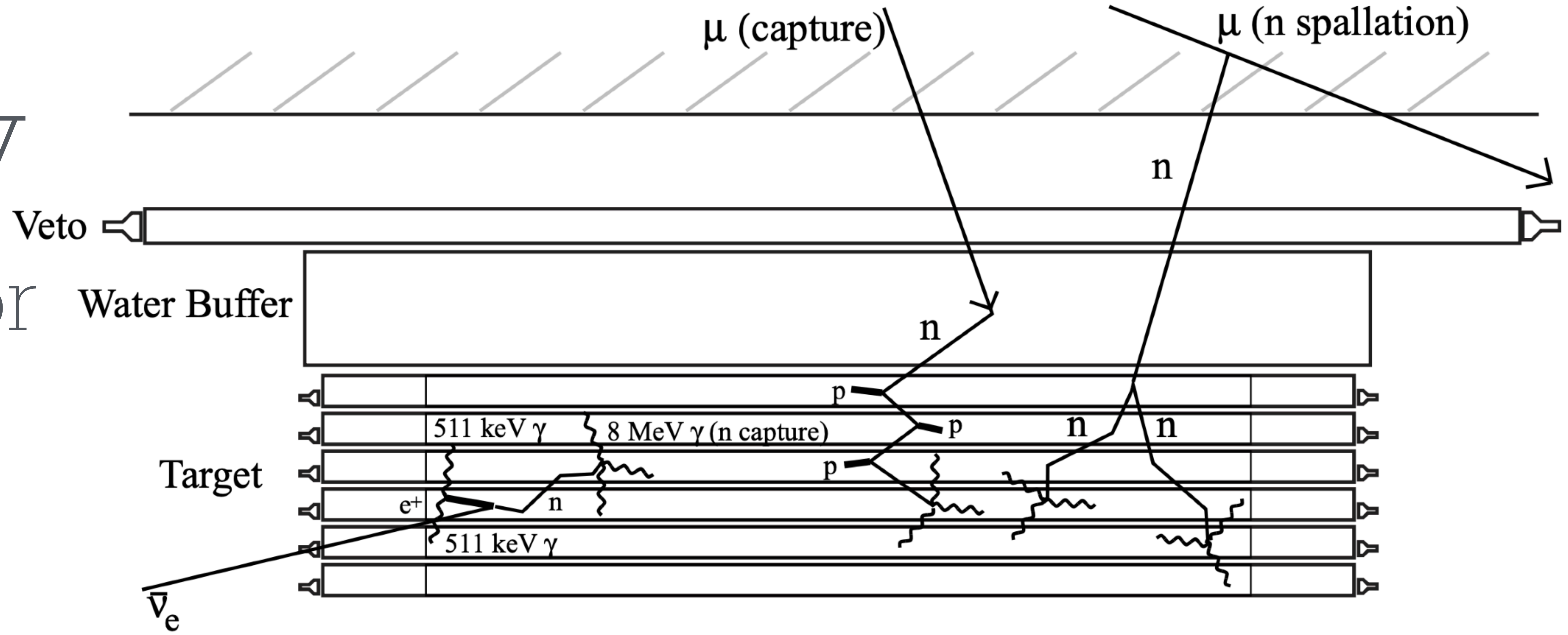


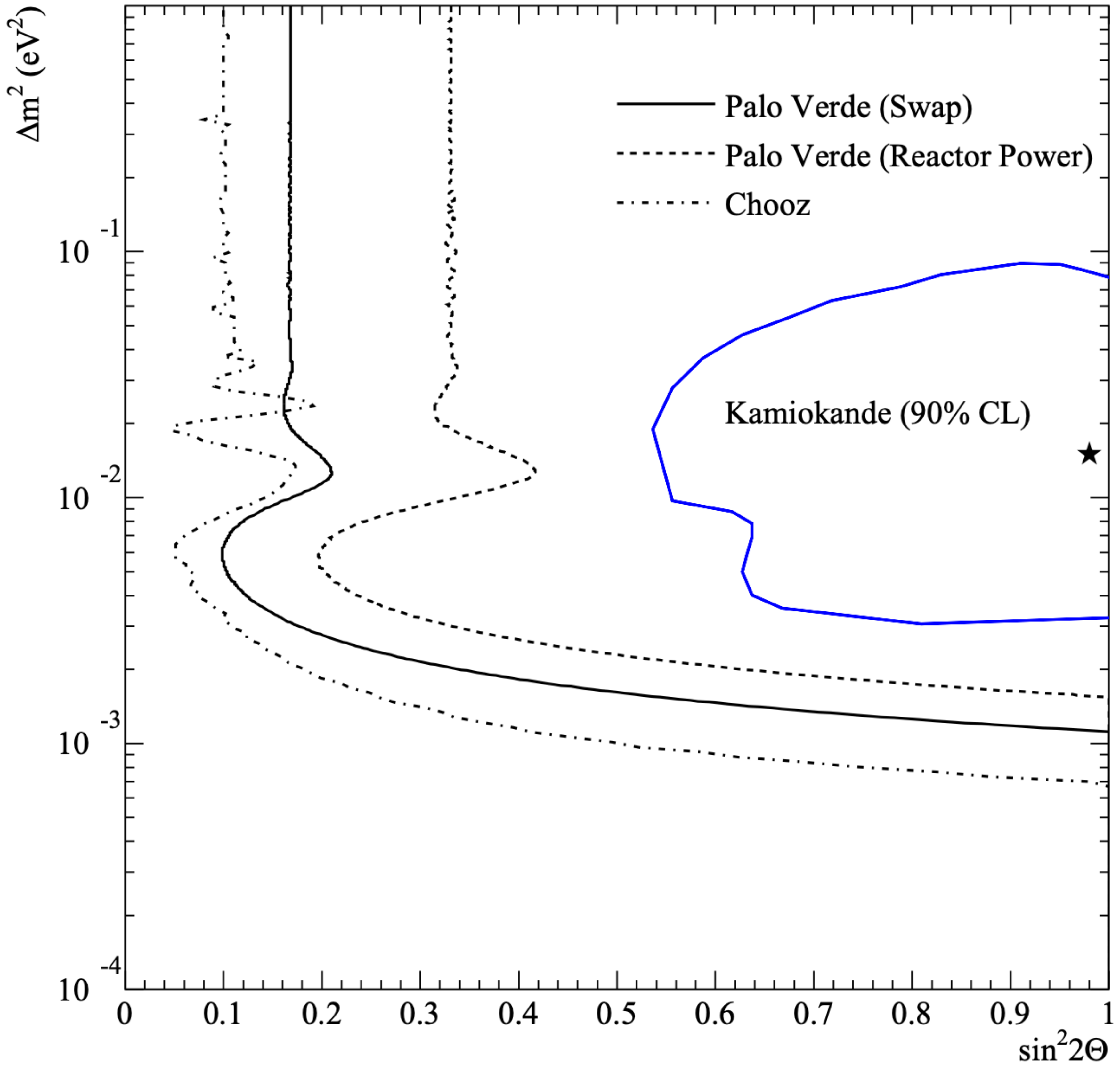


Inverse Beta Decay

Palo Verde Gd-Liquid Scintillator

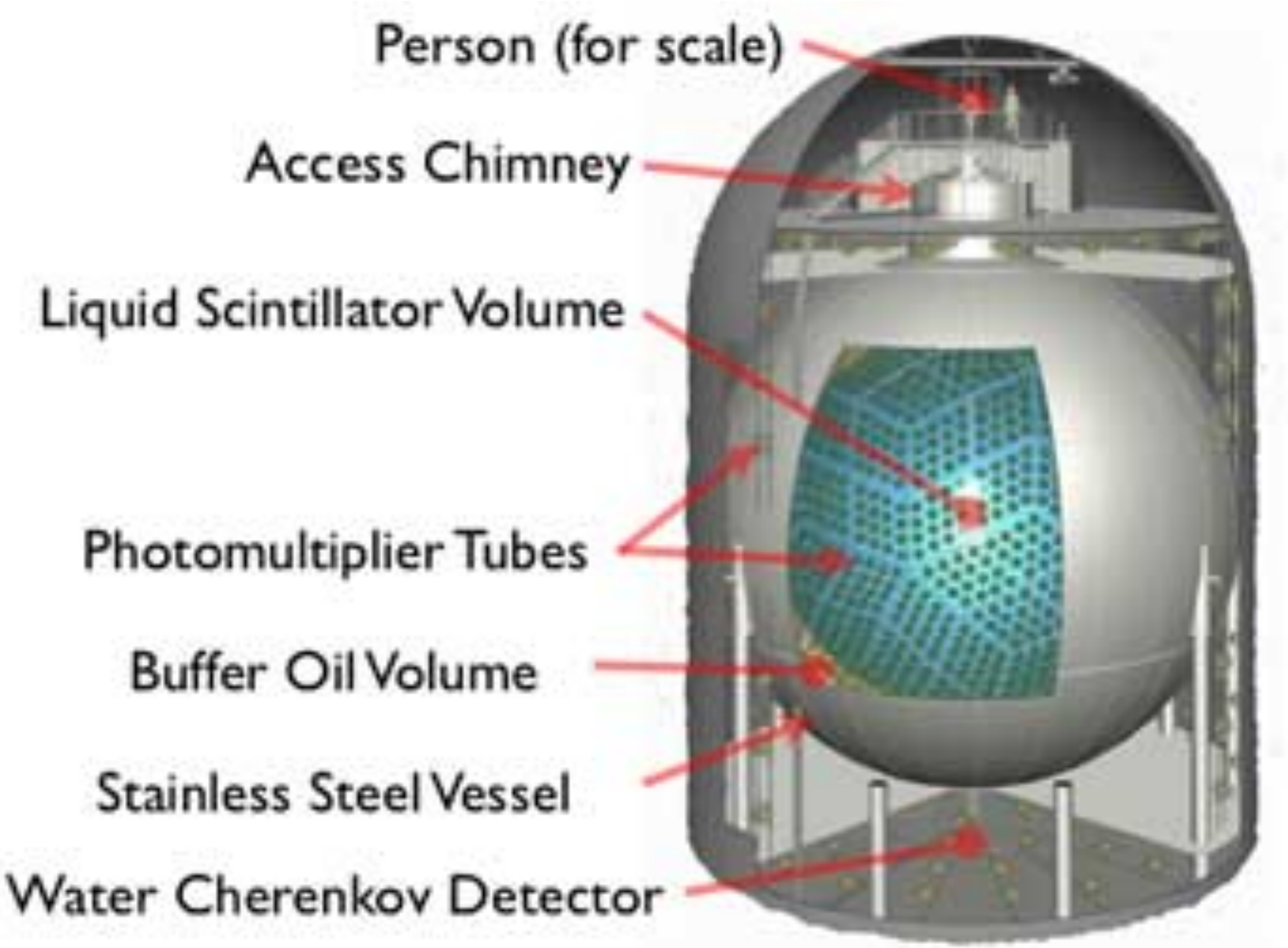




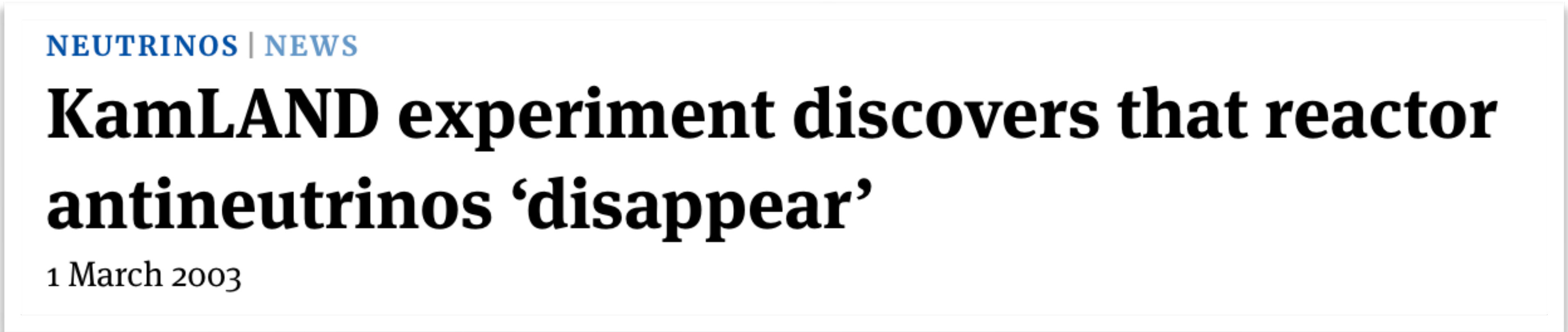


Inverse Beta Decay

Kamland water Cherenkov




CERNCOURIER


NEUTRINOS | NEWS

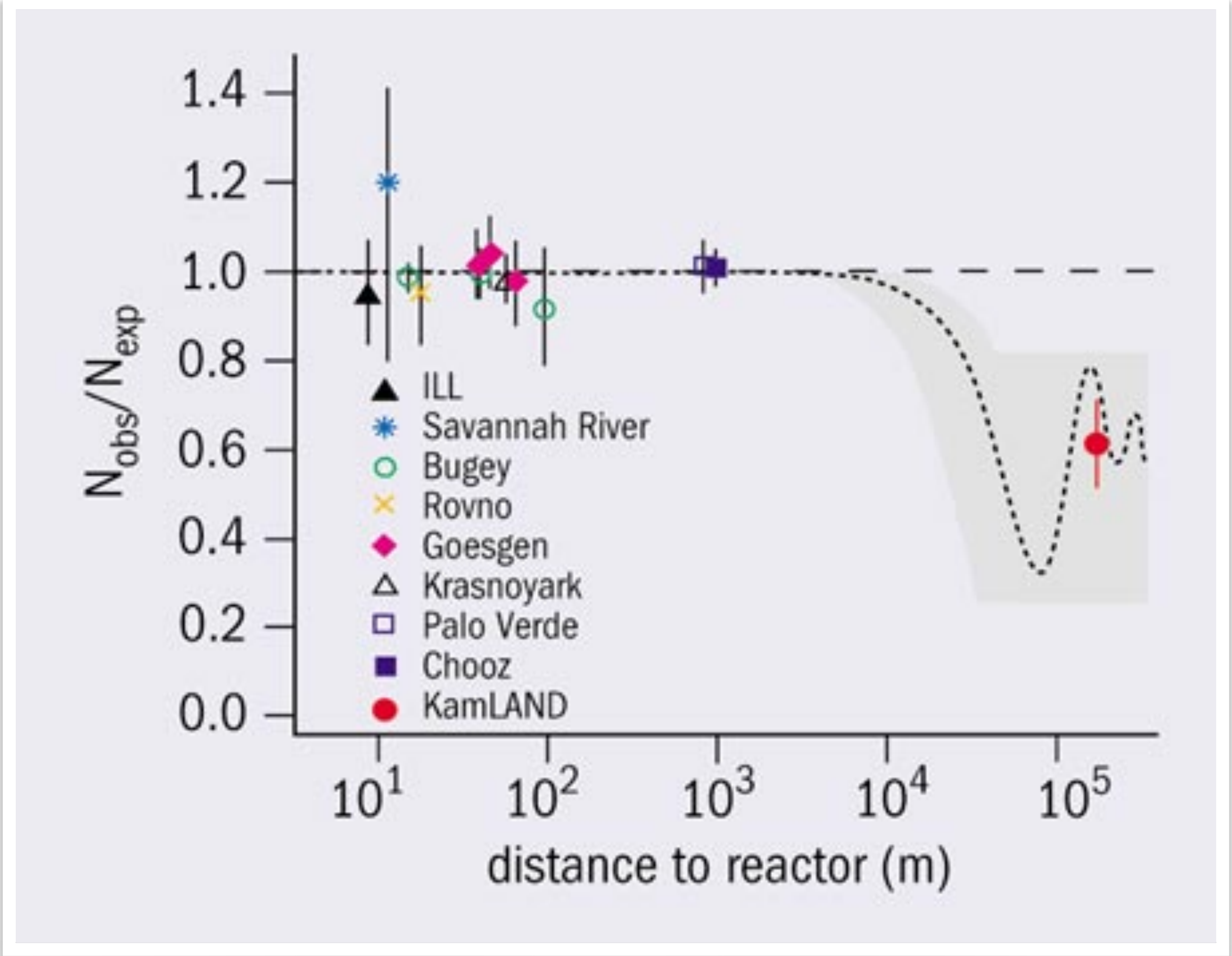
KamLAND experiment discovers that reactor antineutrinos 'disappear'

1 March 2003


NEUTRINOS | NEWS

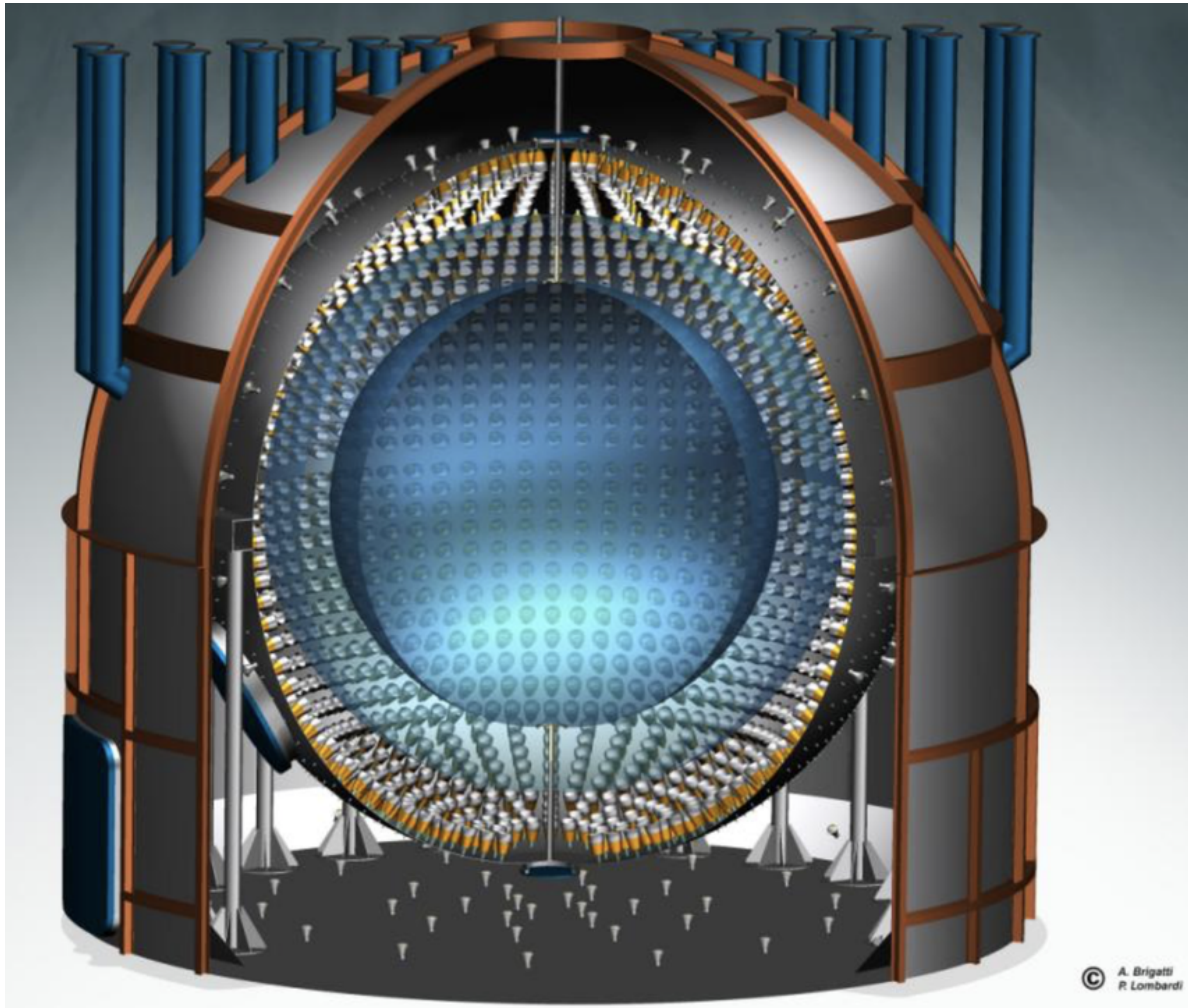
KamLAND detects geoneutrinos

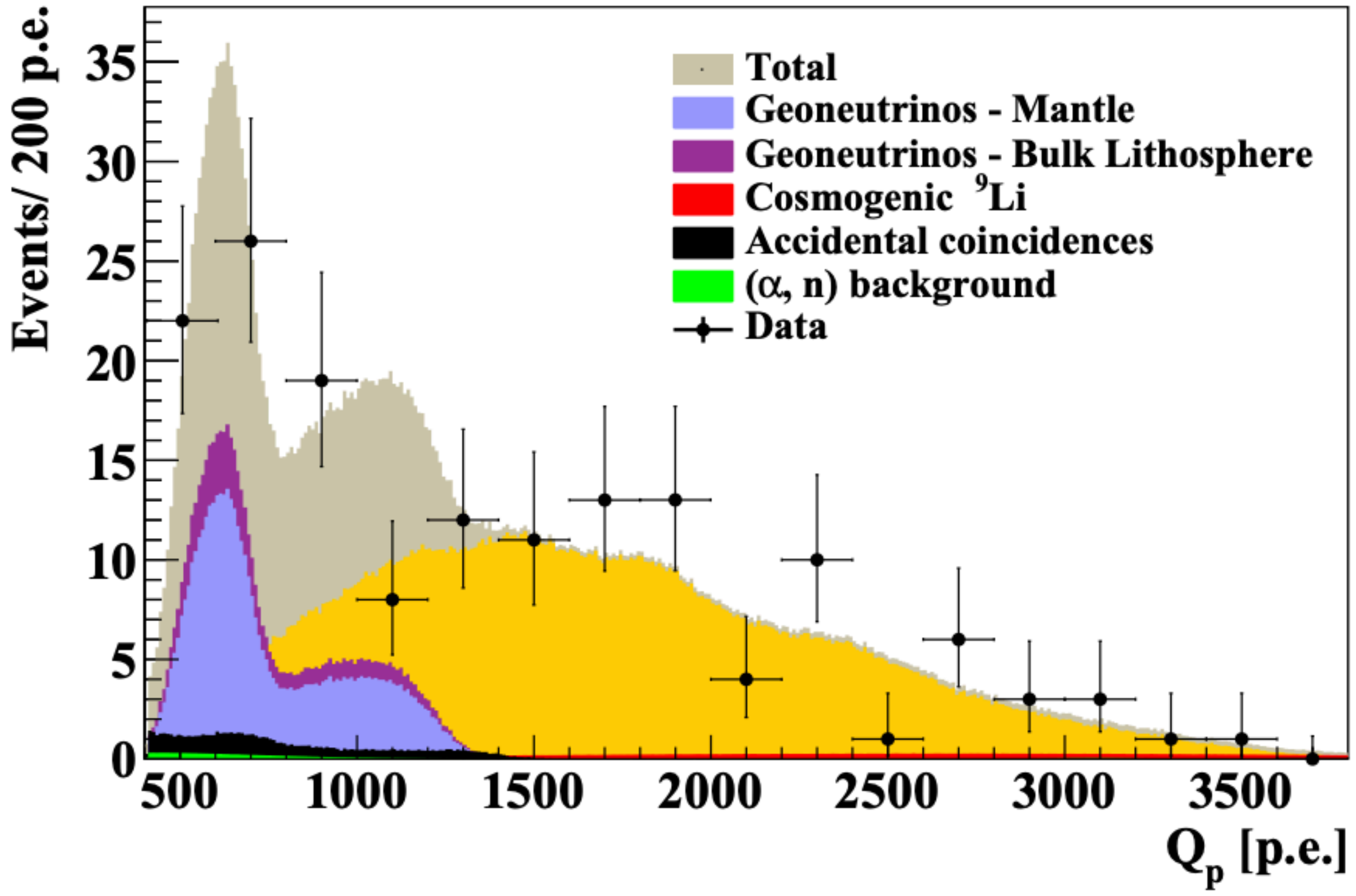
22 August 2005



Inverse Beta Decay

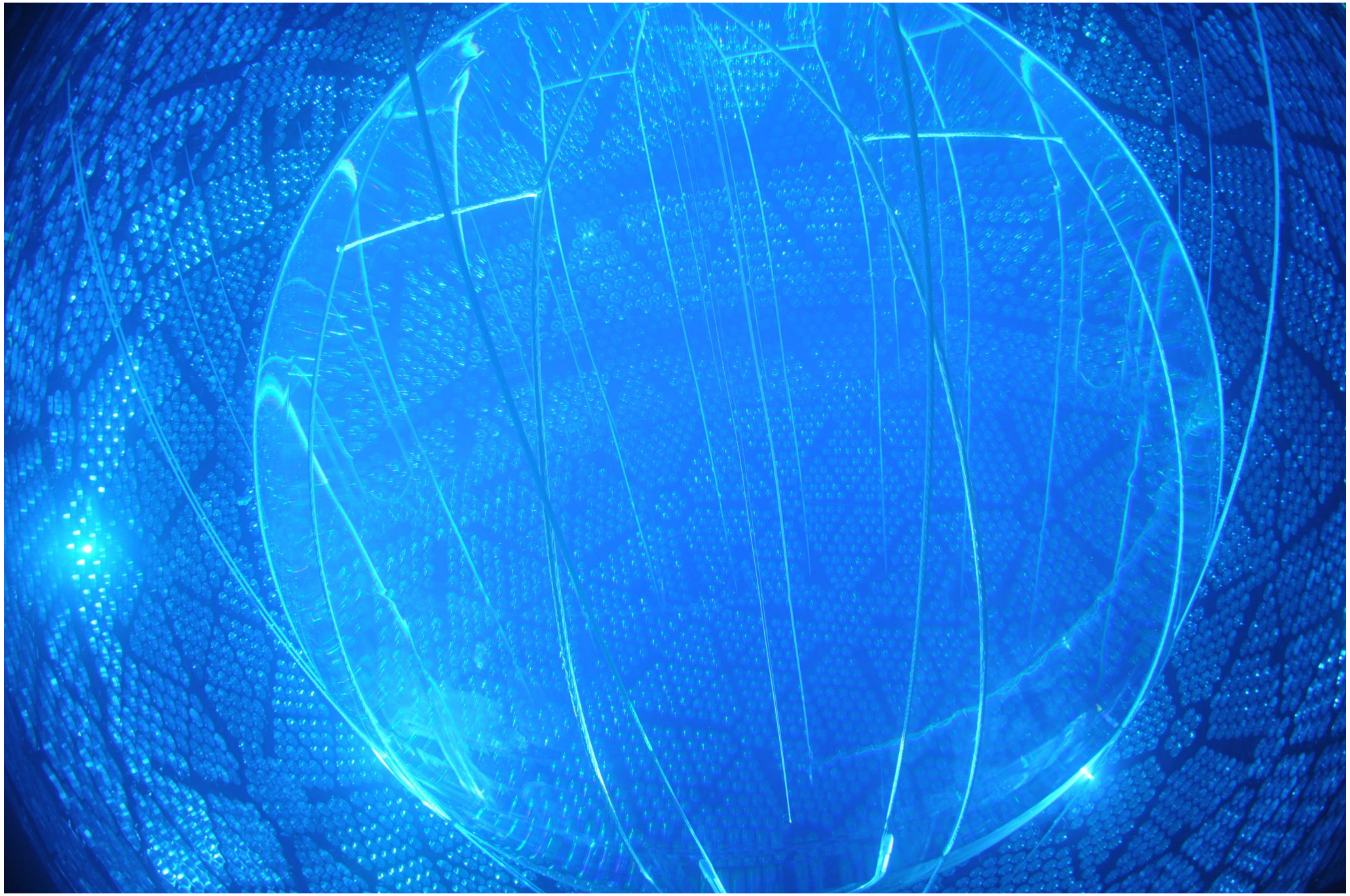
Borexino Liquid Scintillator

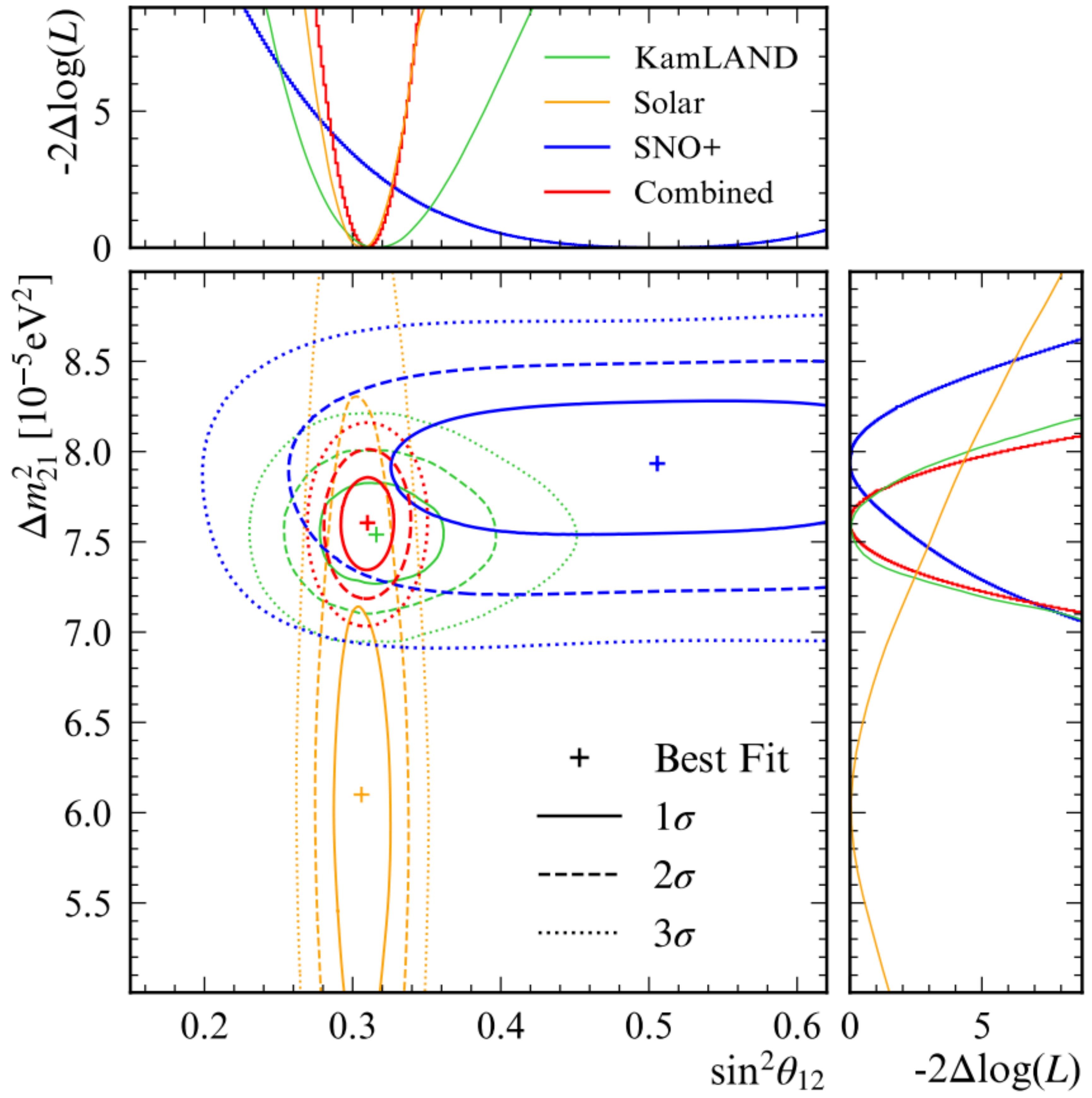


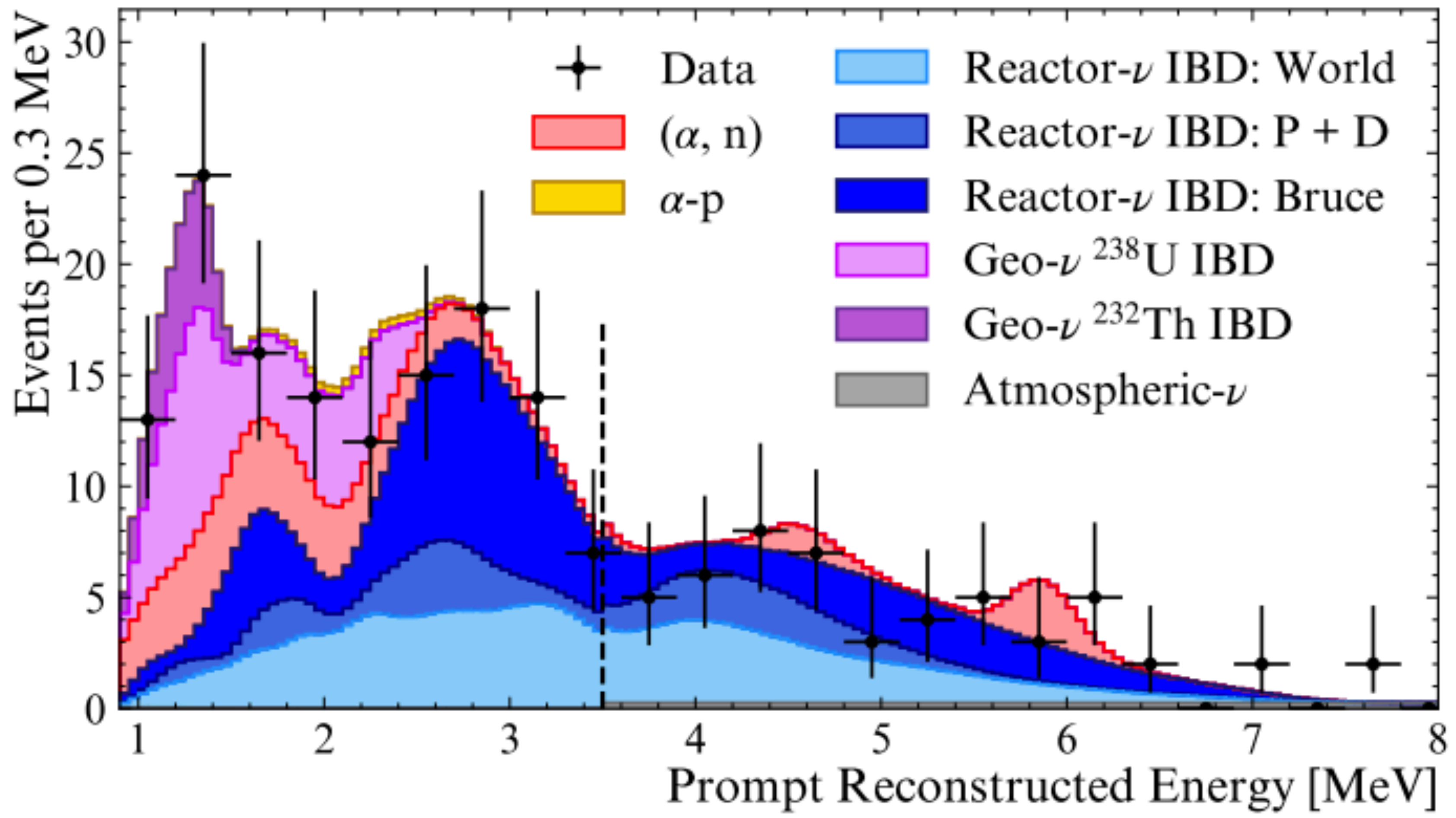


Inverse Beta Decay

SNO+ Liquid Scintillator

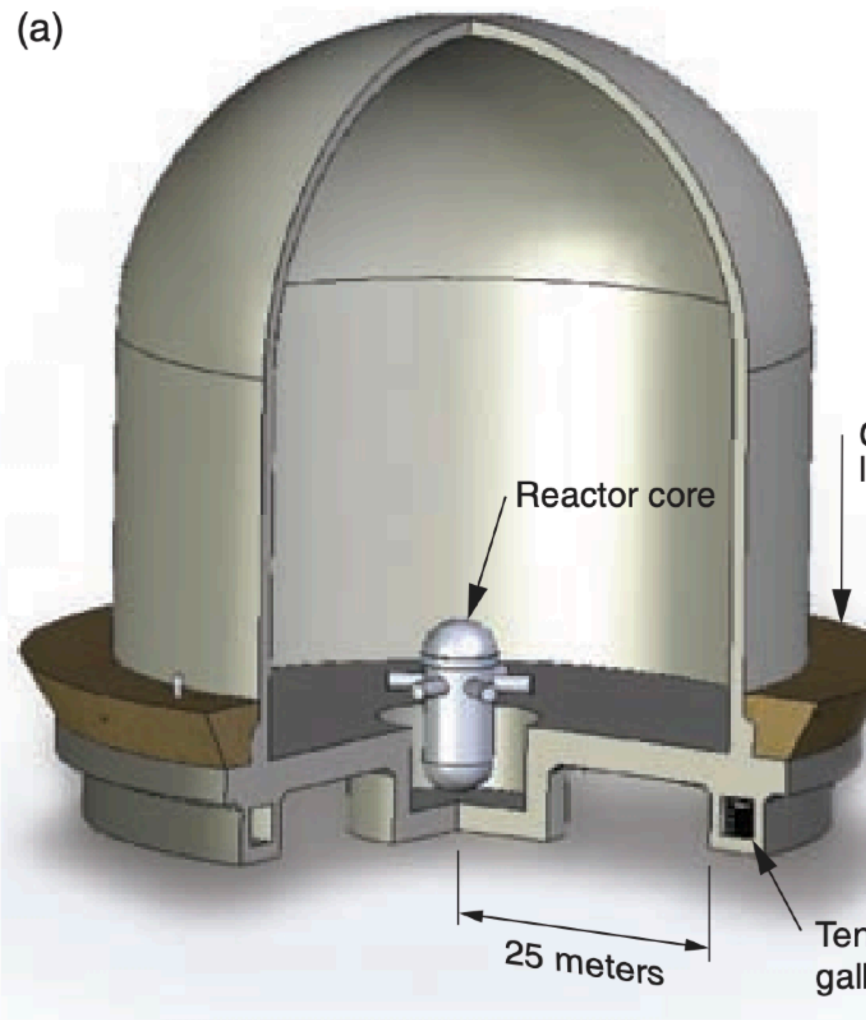


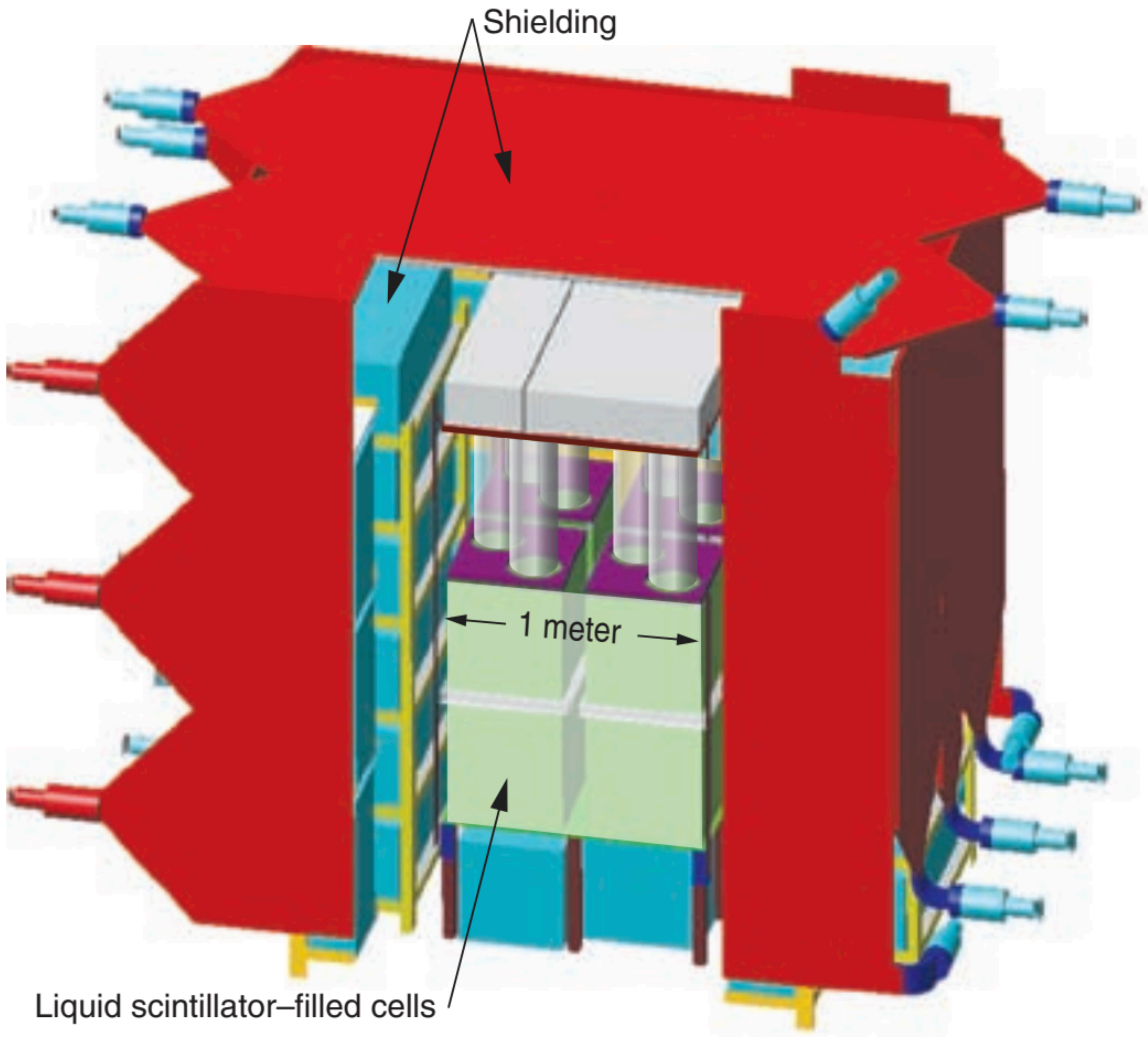




Inverse Beta Decay

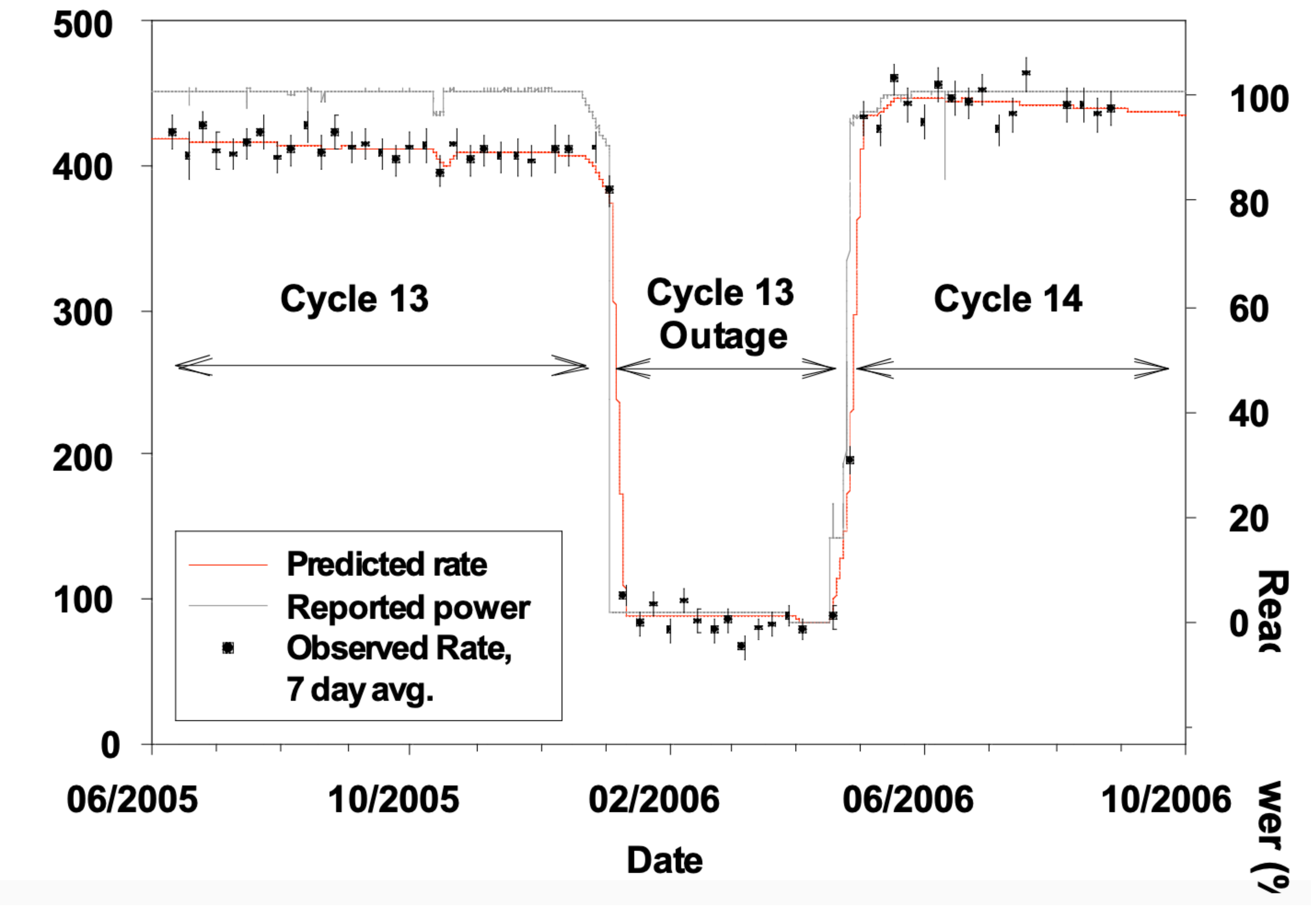
SONGS Gd-Scintillator





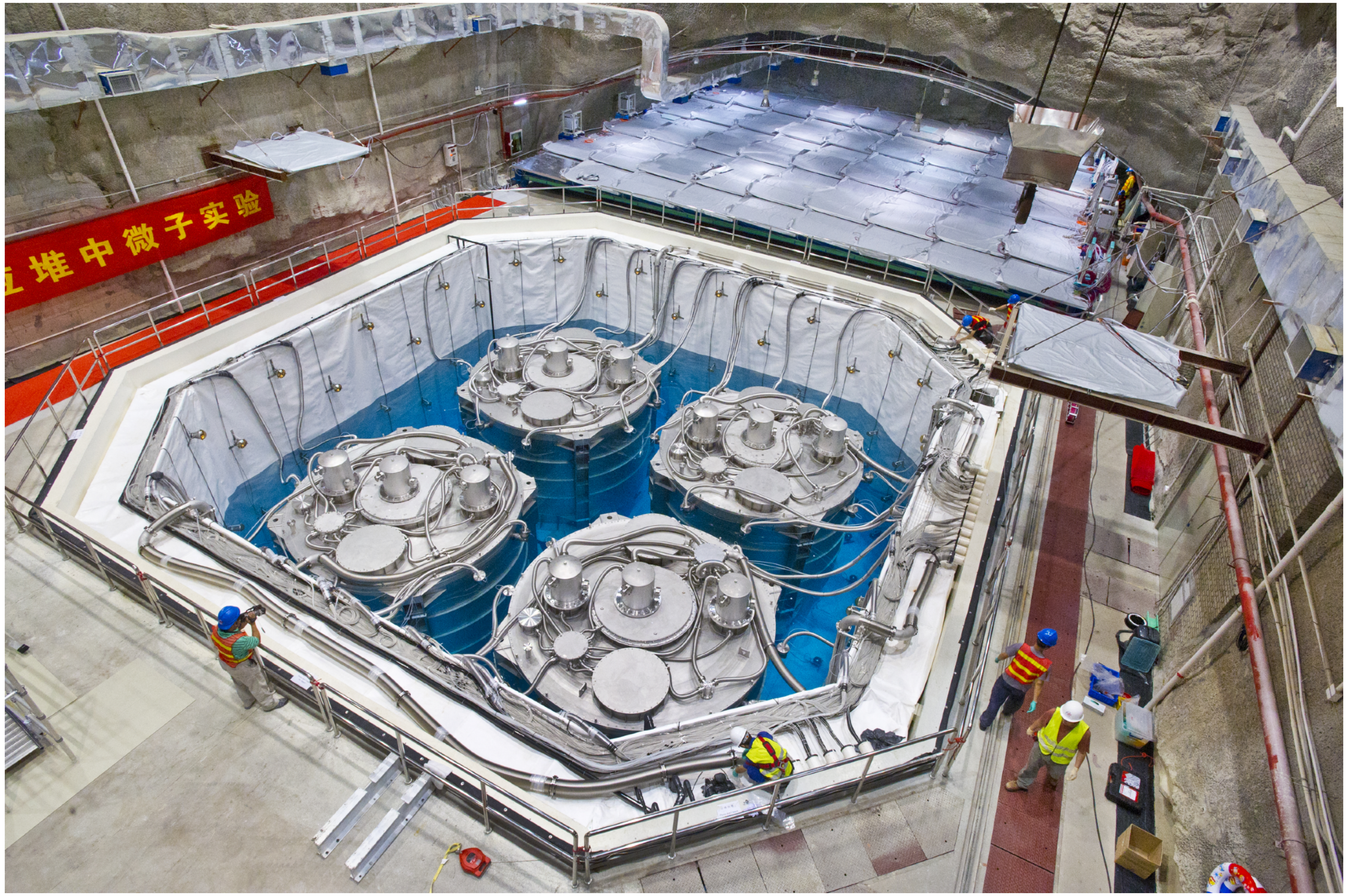
Burnup of 1.5 tons of ^{235}U

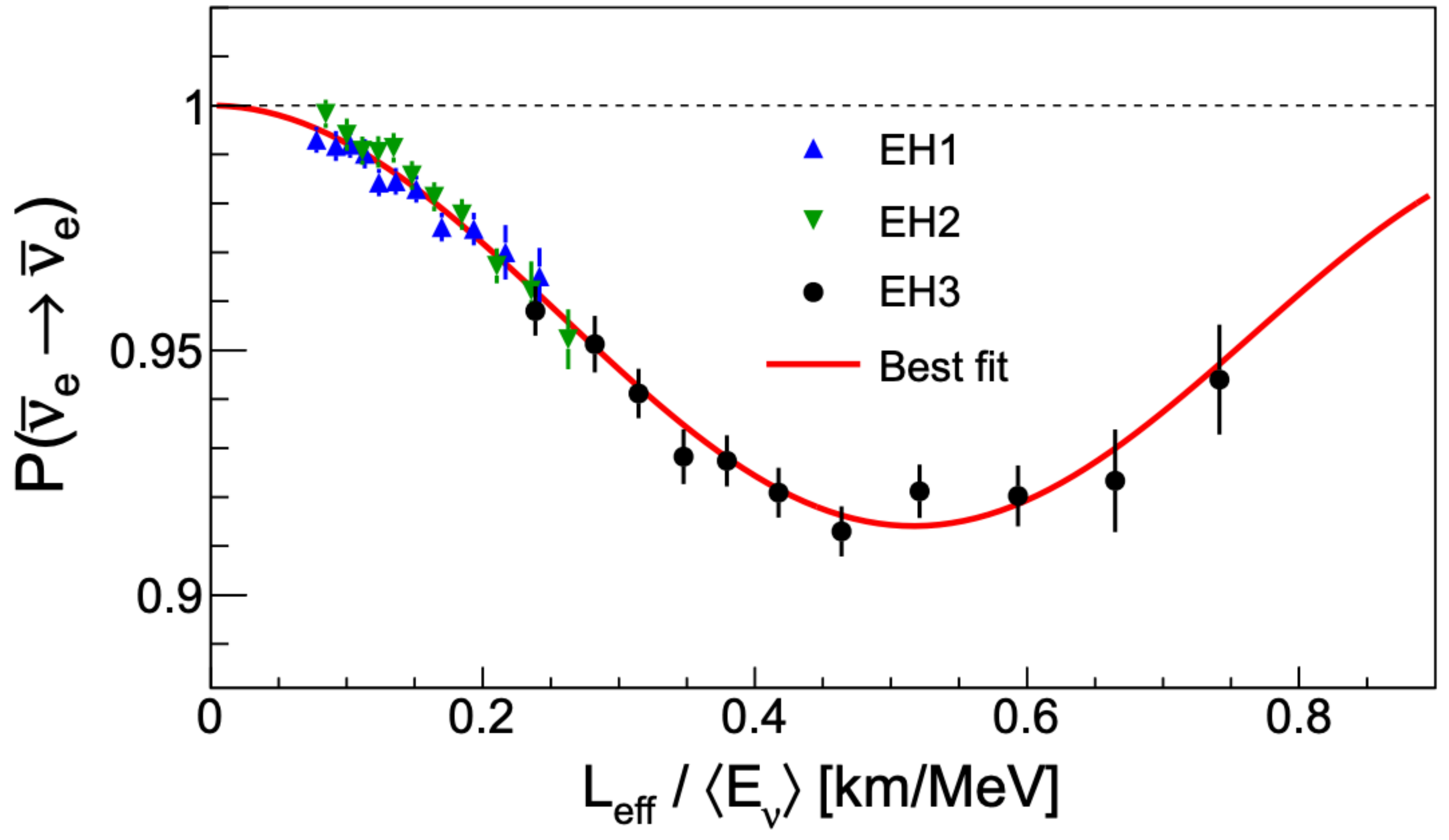
Production of 250 kg of ^{239}Pu

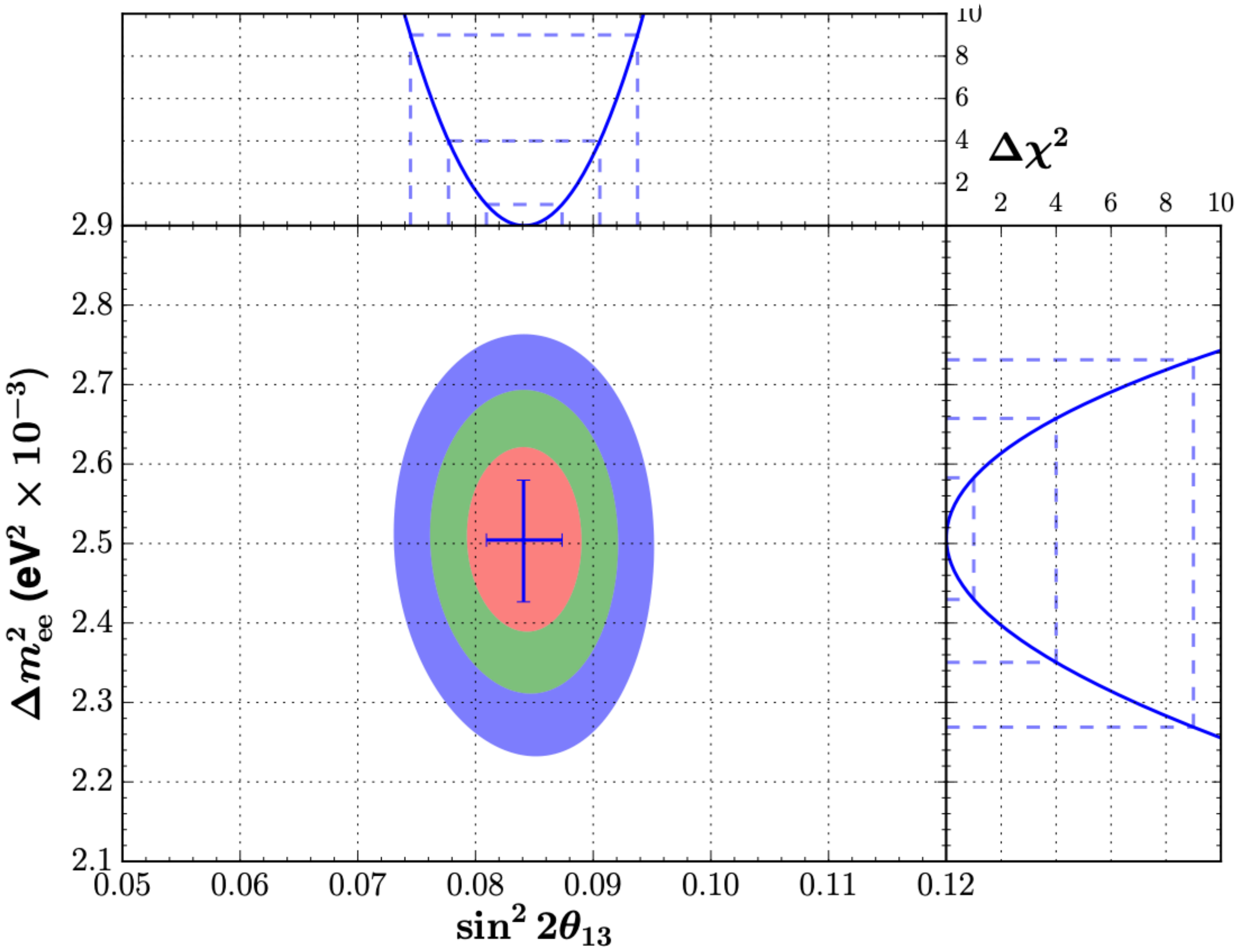


Inverse Beta Decay

Daya Bay Gd-Liquid Scintillator



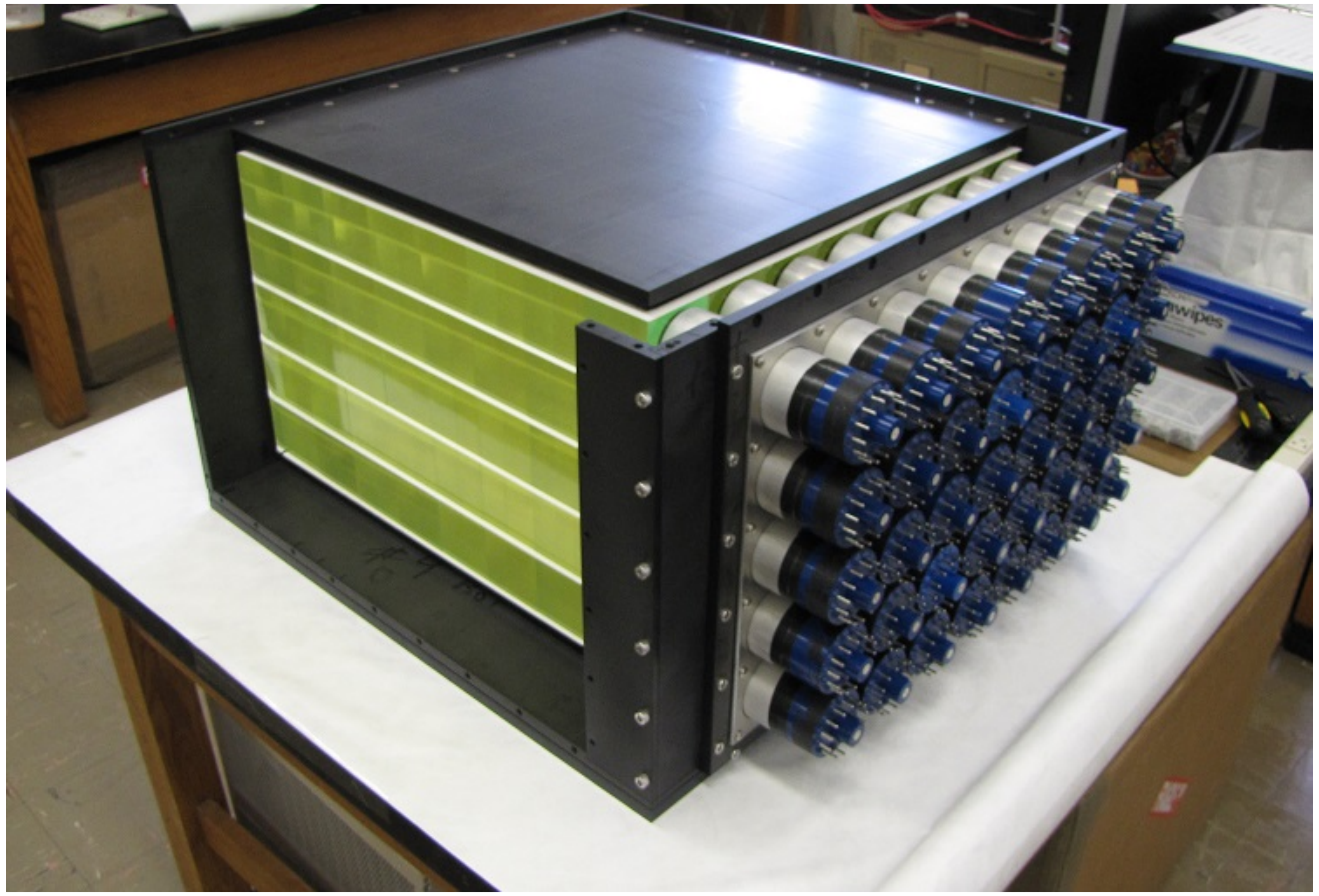




Inverse Beta Decay

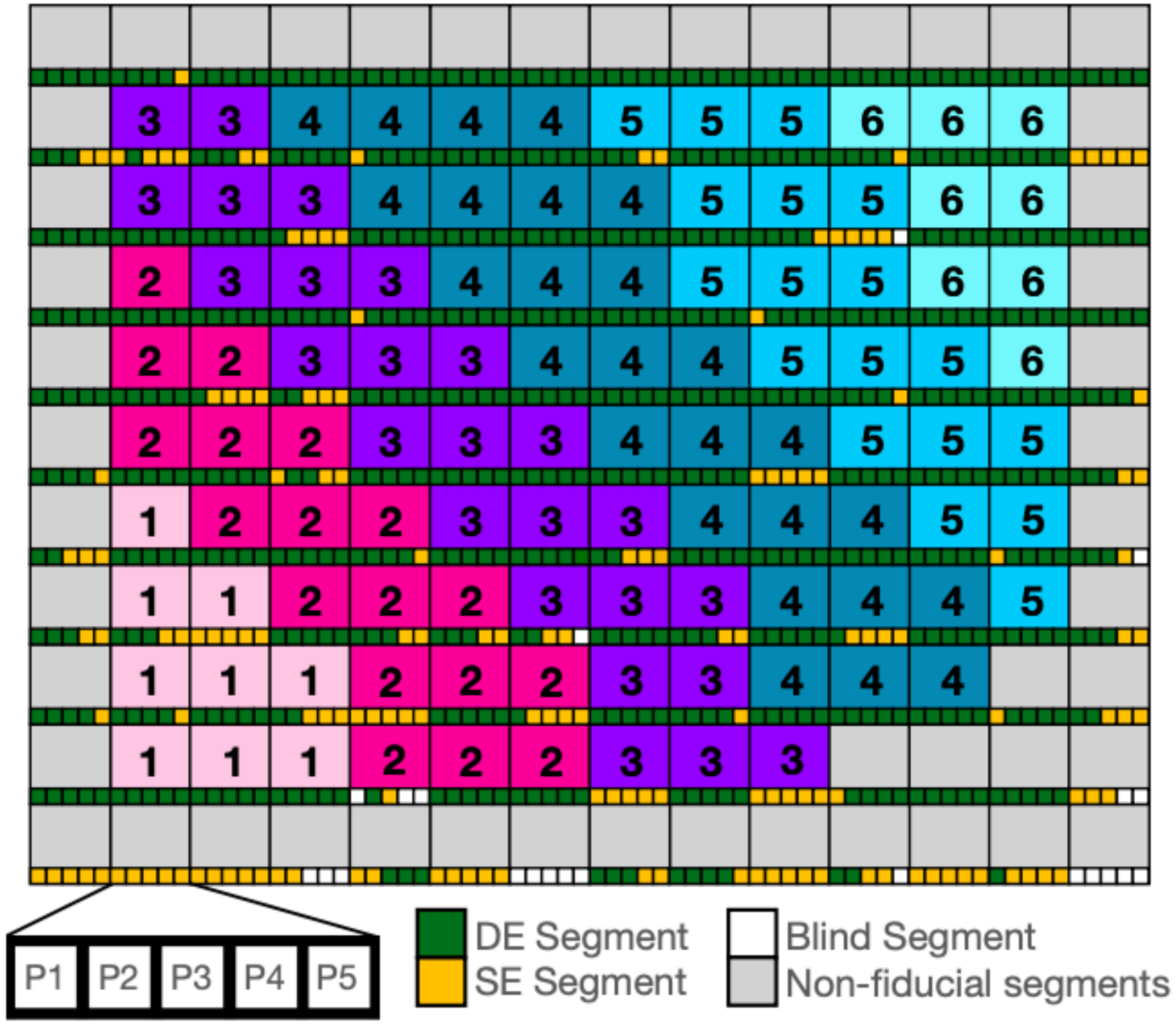
Mini-Chandler (Mobile Neutrino Lab)

Li-Doped Plastic Scintillator Rhagavan Optical Lattice



Inverse Beta Decay

Prospect: Li-Doped Liquid Scintillator

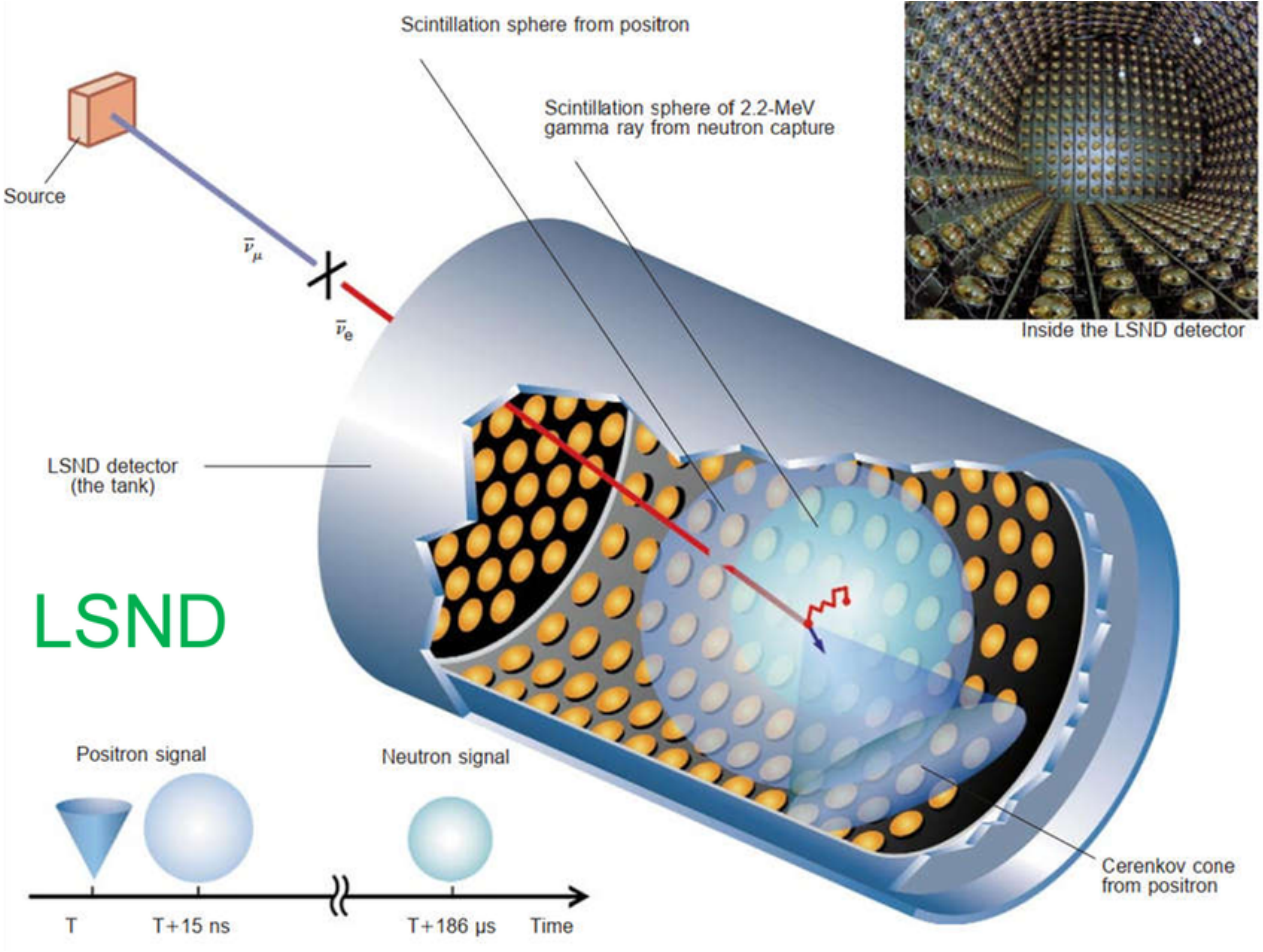


	3	3	4	4	4	4	5	5	5	6	6	6	
	3	3	3	4	4	4	4	5	5	5	6	6	
	2	3	3	3	4	4	4	5	5	5	6	6	
	2	2	3	3	3	4	4	4	5	5	5	6	
	2	2	2	3	3	3	4	4	4	5	5	5	
	1	2	2	2	3	3	3	4	4	4	5	5	
	1	1	2	2	2	3	3	3	4	4	4	5	
	1	1	1	2	2	2	3	3	4	4	4		
	1	1	1	2	2	2	3	3	3				

Inverse Beta Decay - Higher Energy

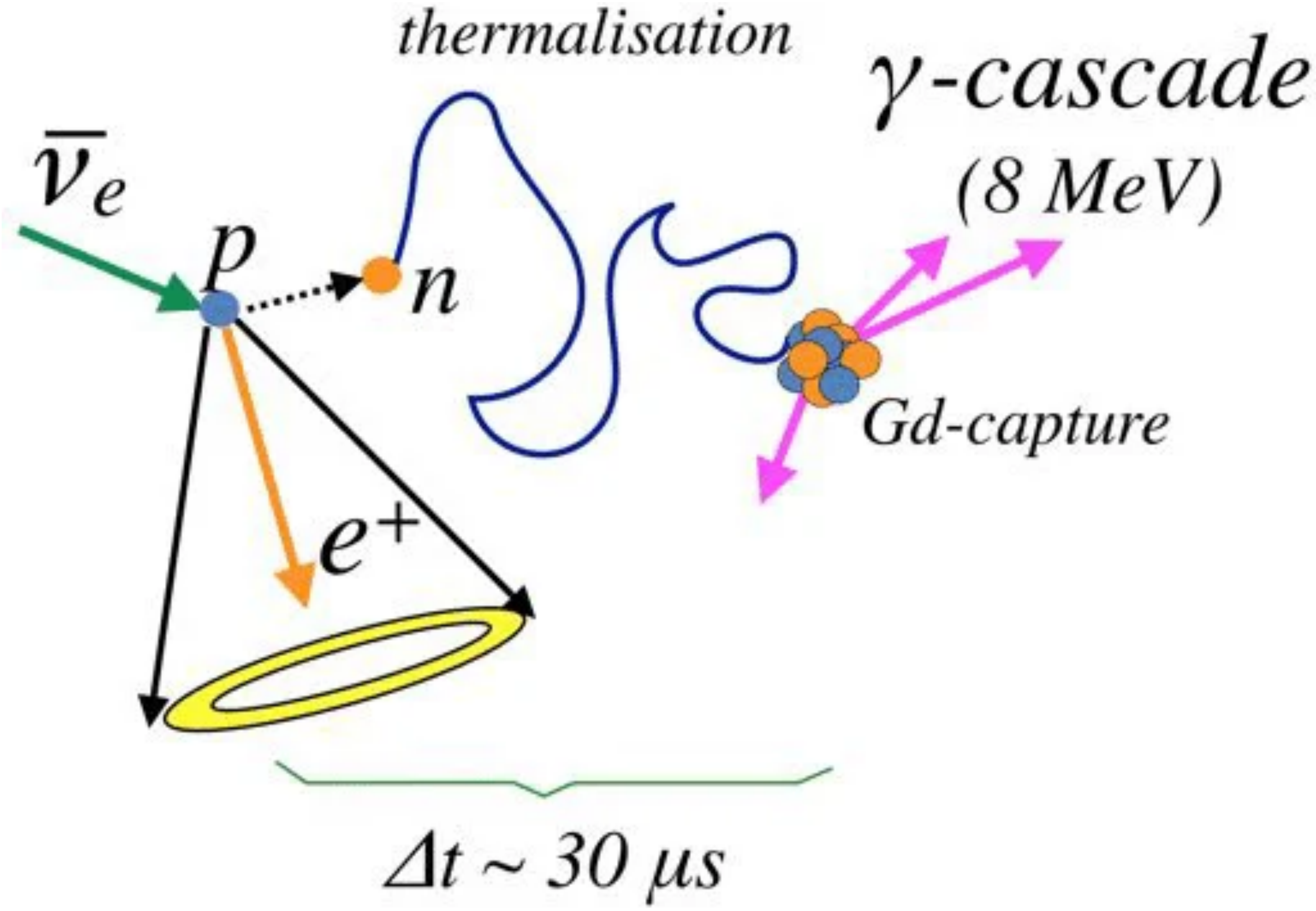
LSND

Plus CC and NC on C (Will come back to this with Karmen)



Final Note about IBD

Directionality



The kinematics of the process dictate that the neutrino carries the neutrino energy

But the neutron carries the neutrino momentum *IF you can get it before thermalization*

Also: this a precisely known cross section, as it is translatable to neutron decay, a very well-measured rate

Neutrino Capture

Deuterium at Reactors

$\bar{\nu}_e + d \rightarrow n + n + e^+$ 1.4 MeV threshold

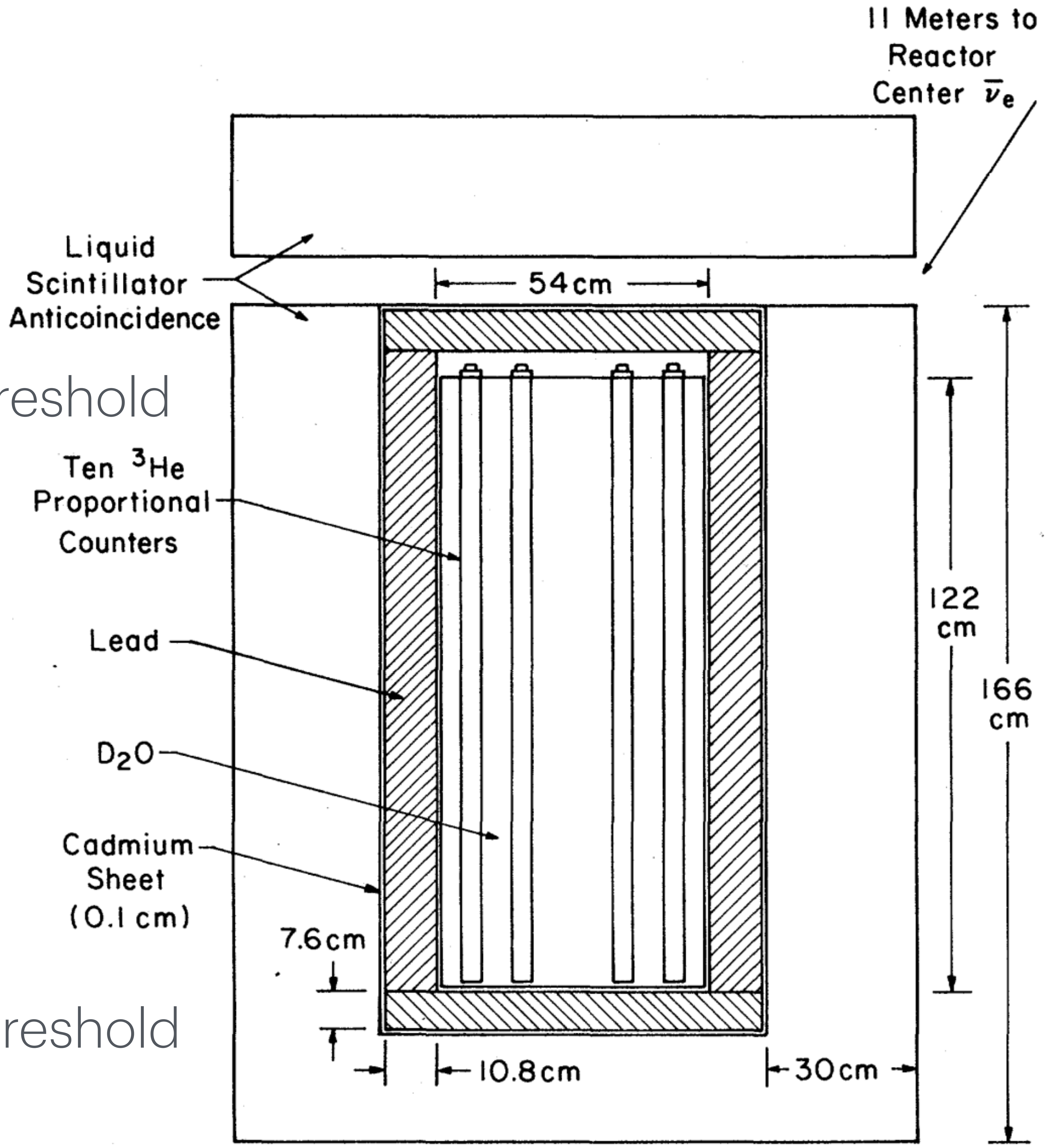
^{3}He tubes for detection of thermal neutrons

$(1.5 \pm 0.4) \times 10^{-45}\ \mathrm{cm}^2/\bar{\nu}_e$

Also measured Neutral Current rate

$\bar{\nu}_e + d \rightarrow n + p + \bar{\nu}_e$ 2.2 MeV threshold

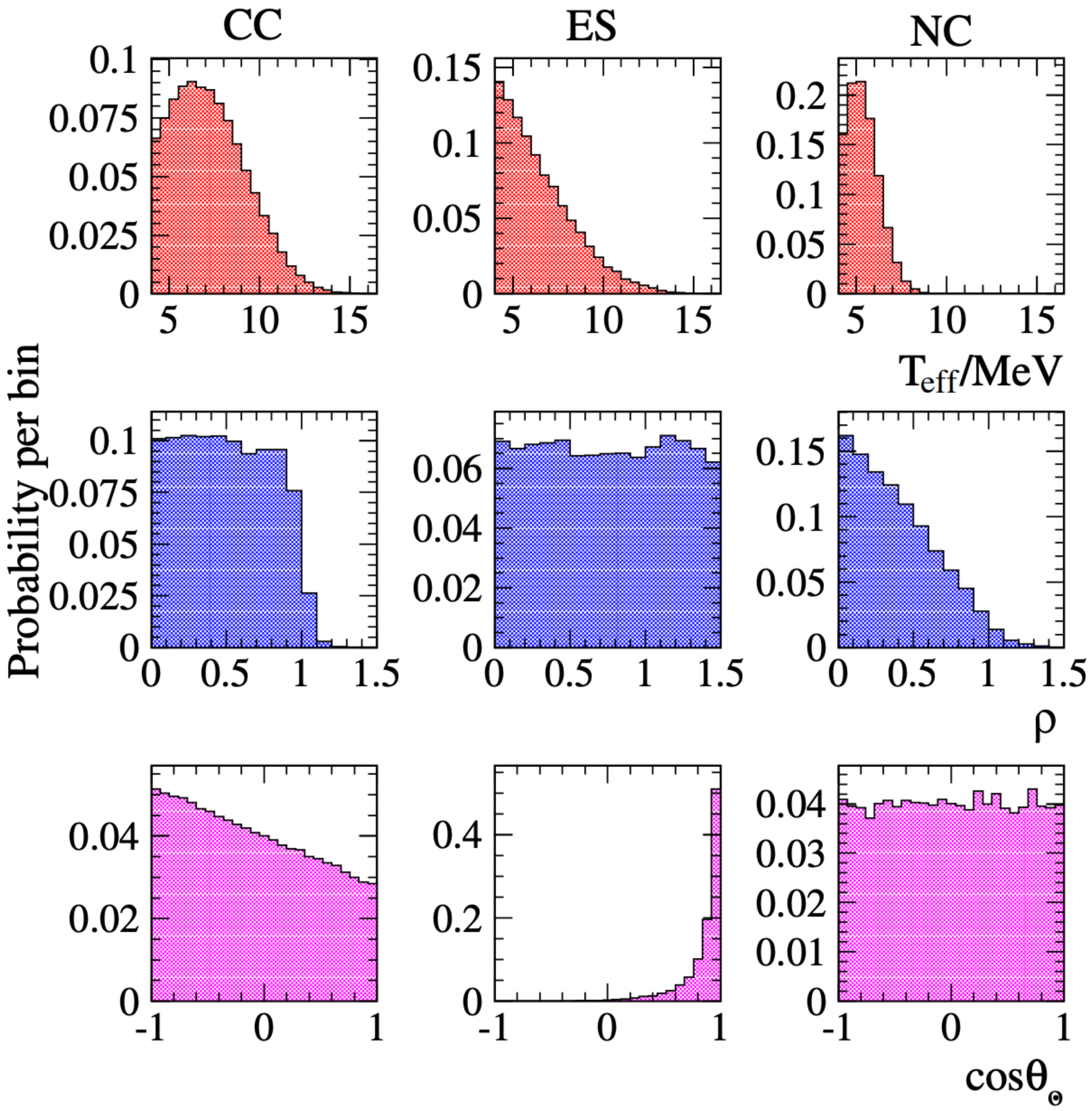
$(3.8 \pm 0.9) \times 10^{-45}\ \mathrm{cm}^2/\bar{\nu}_e$



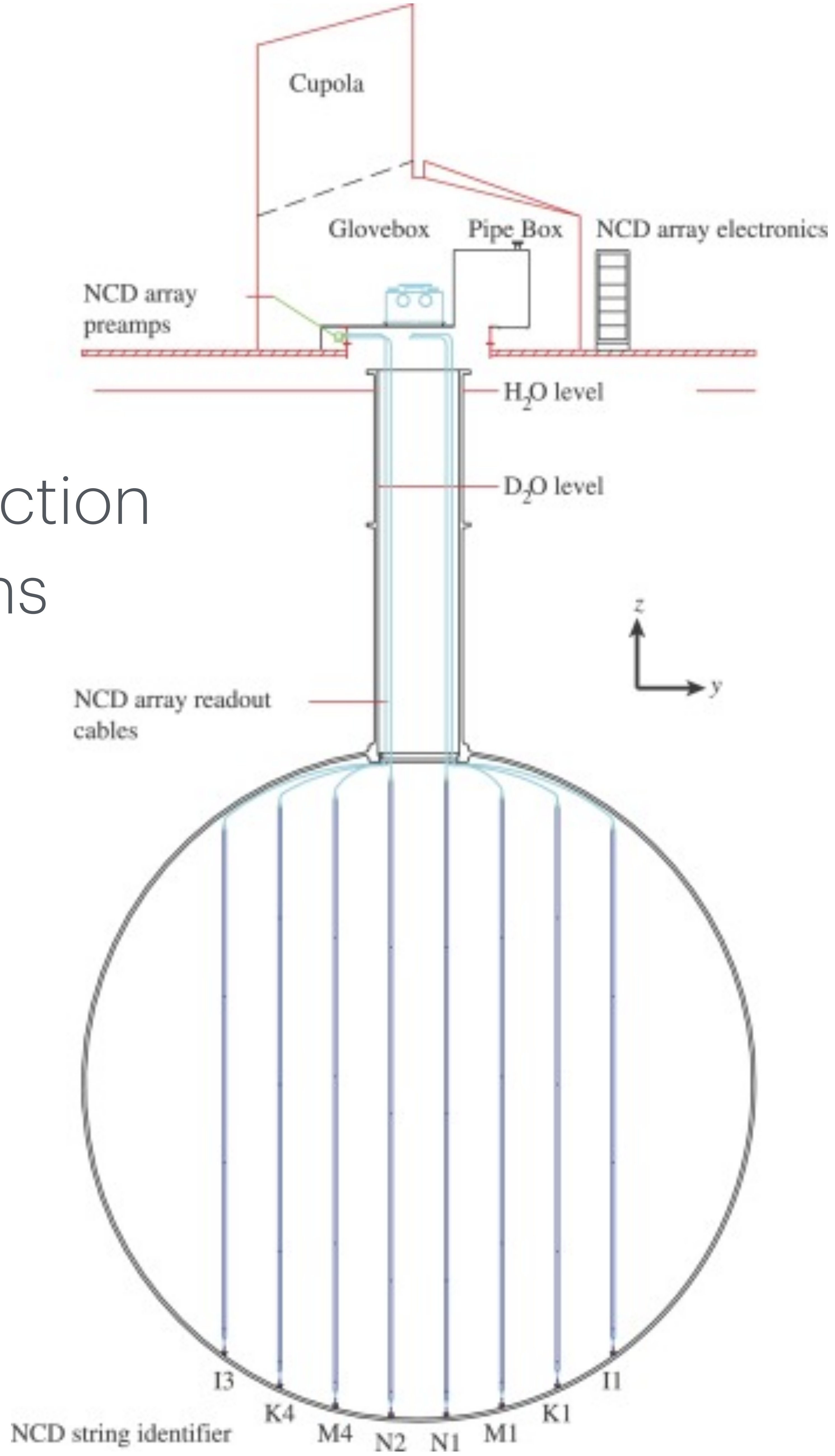
Phys. Rev. Lett. **43**, 96 – **Published 9 July, 1979**

Neutrino Capture

Deuterium in SNO for Solar



^{3}He tubes for detection of thermal neutrons



Neutrino Capture - Radiochemistry

Homestake Neutrino Experiment

$$^{37}\mathrm{Cl} + \nu_e \rightarrow {}^{37}\ \mathrm{Ar} + e^-$$

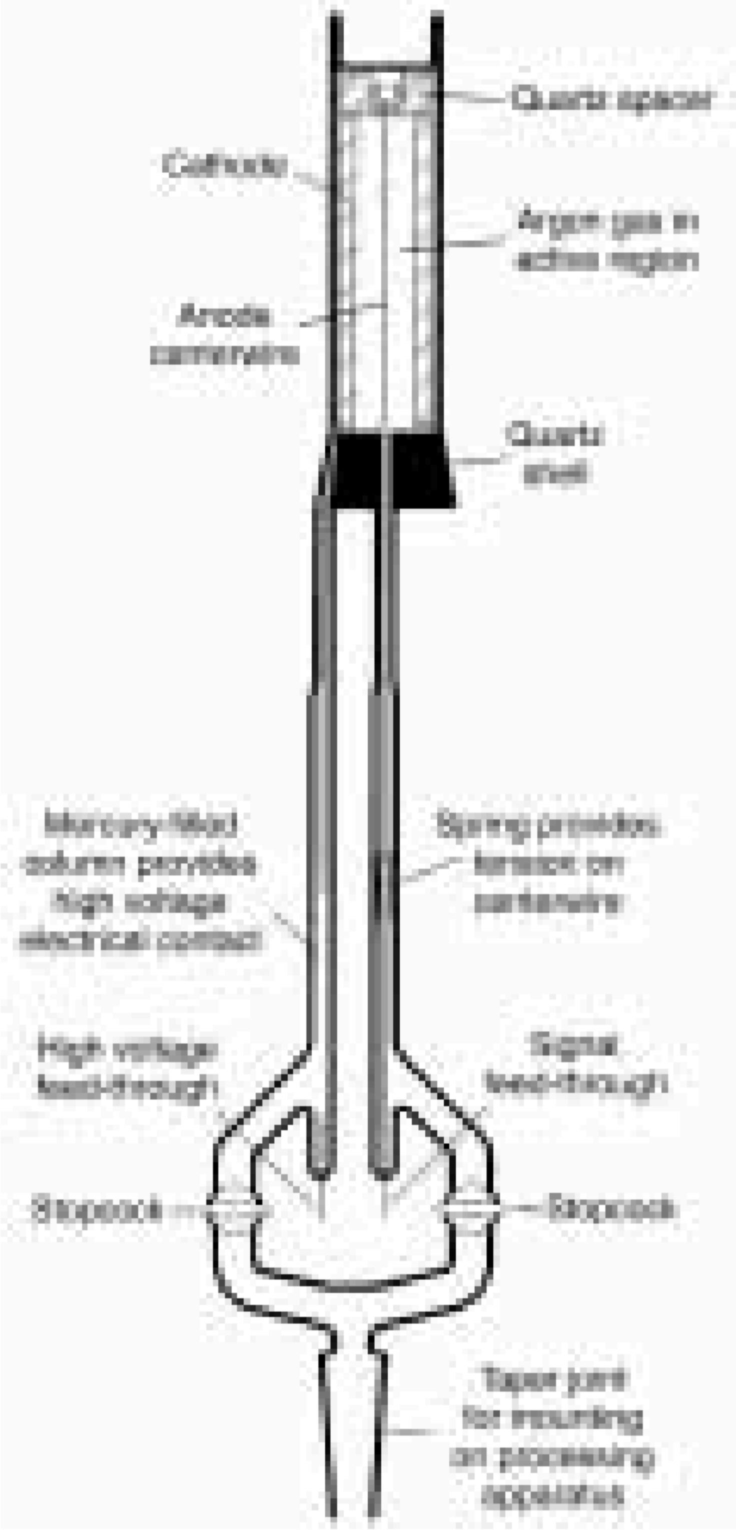
814 keV threshold

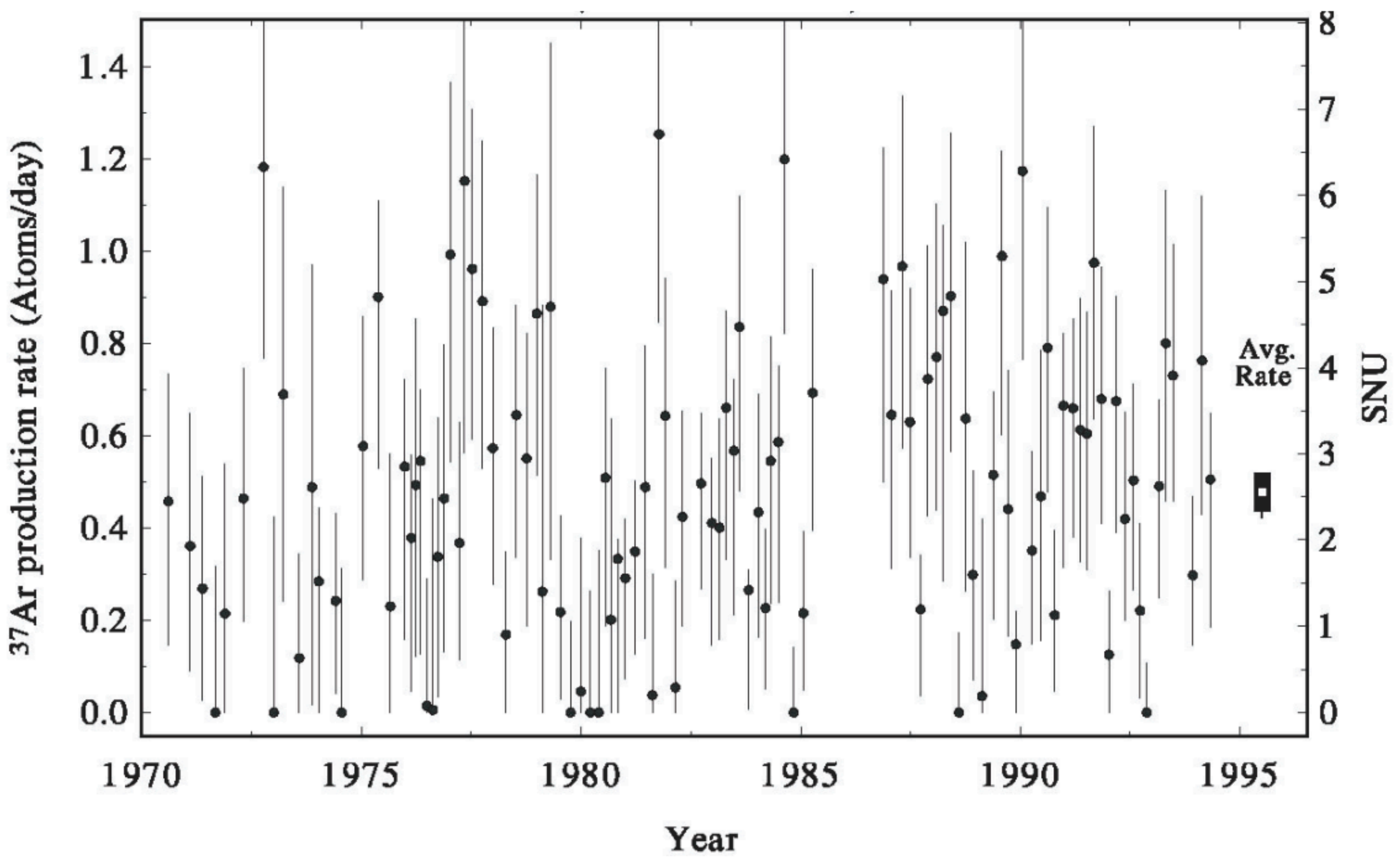
35 day half-life

Ar bubbled through Detergent, collecting ^{37}Ar

37Ar beta decay counted in low-background proportional counters

Bottle of gas flown back every week for decades





Neutrino Capture - Radiochemistry

Gallex, Sage & BEST

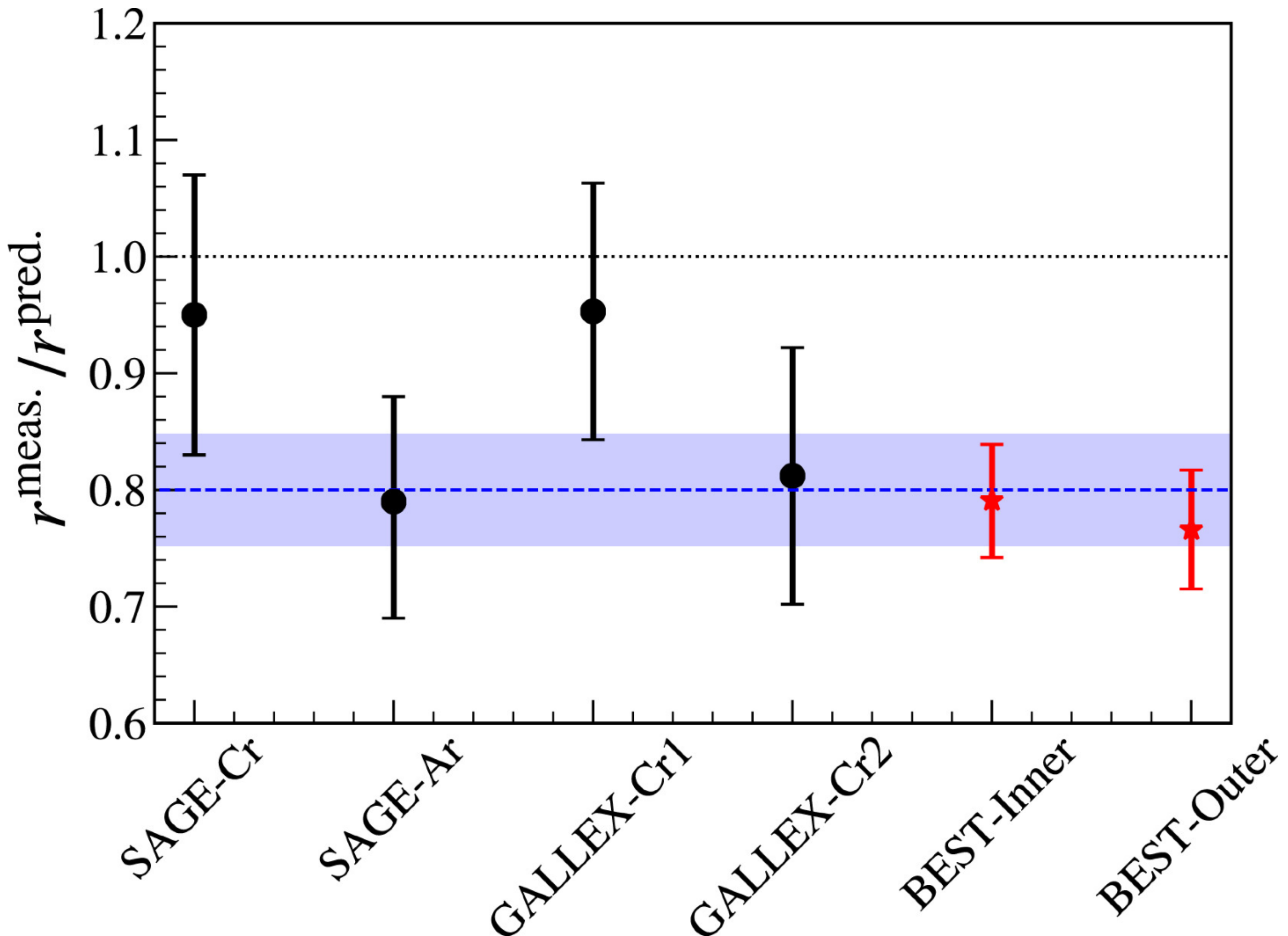
$^{71}Ga(\nu_e, e^-)^{71}Ge$

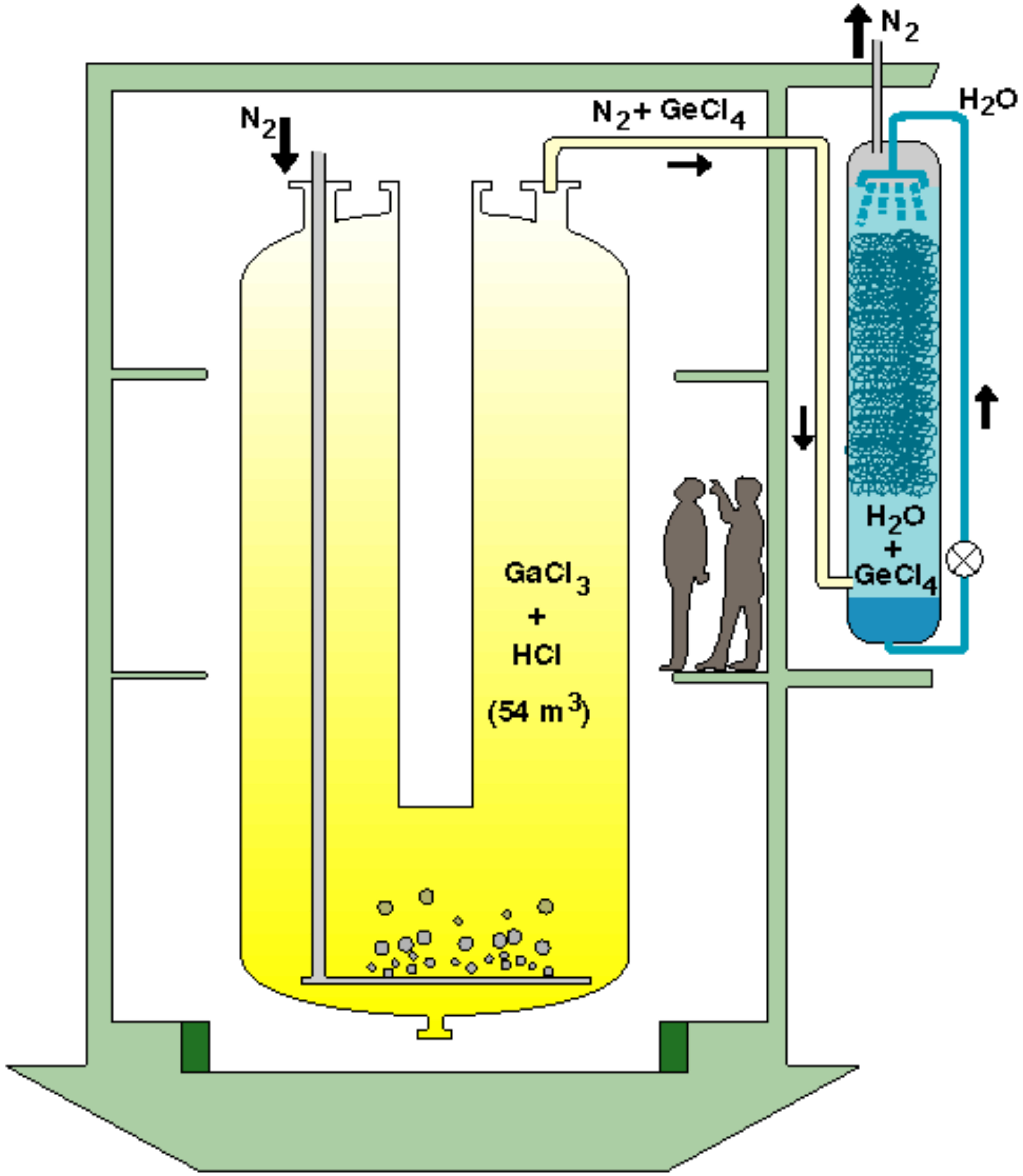
233 keV threshold

11.4 day half-life

$^{71}Ga\ (p,n)\ ^{71}Ge$

Biggest Background





Neutrino Capture - Radiochemistry

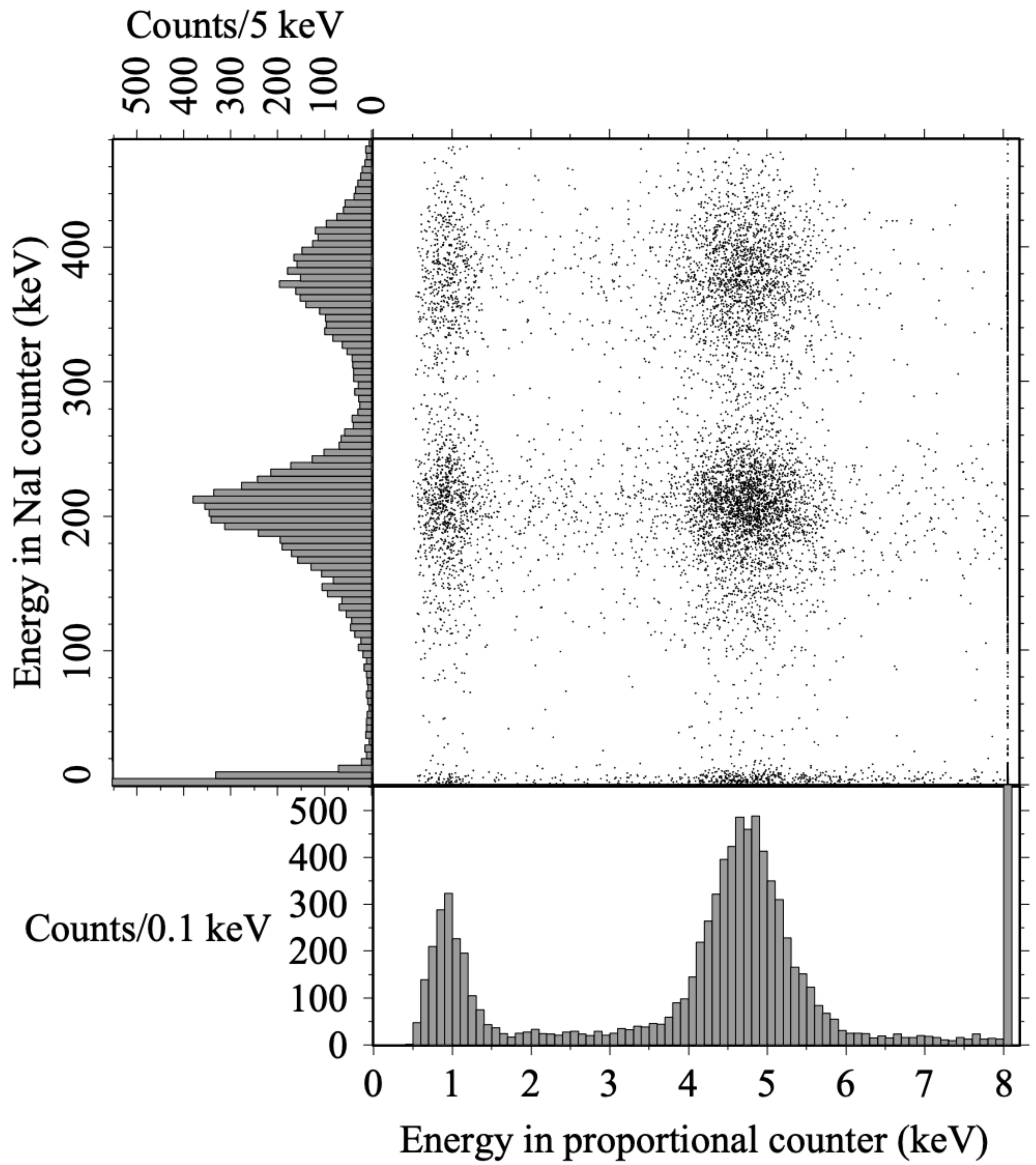
LAMPF $127I(\nu_e, e^-)127Xe$

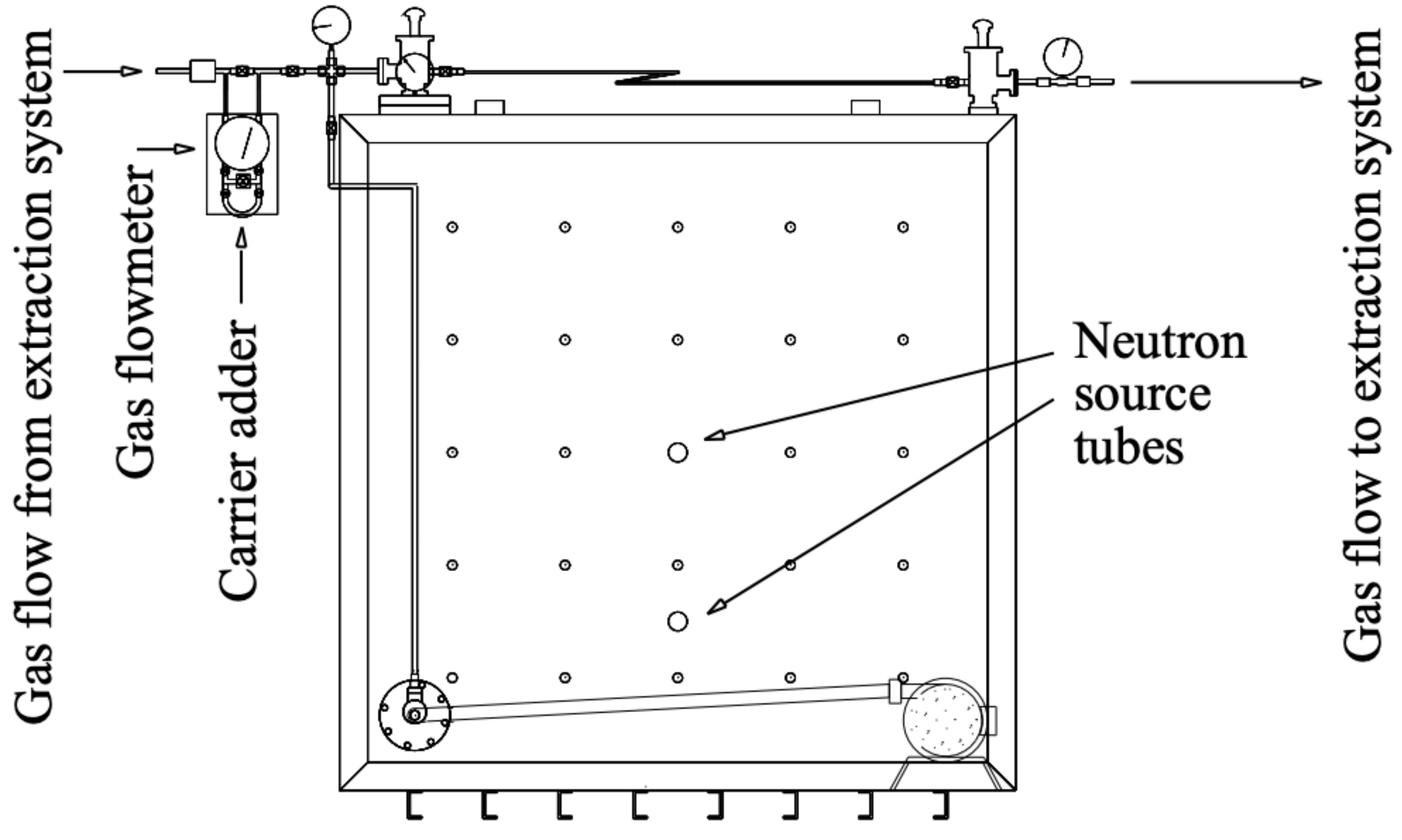
789 keV

36.4 d half-life

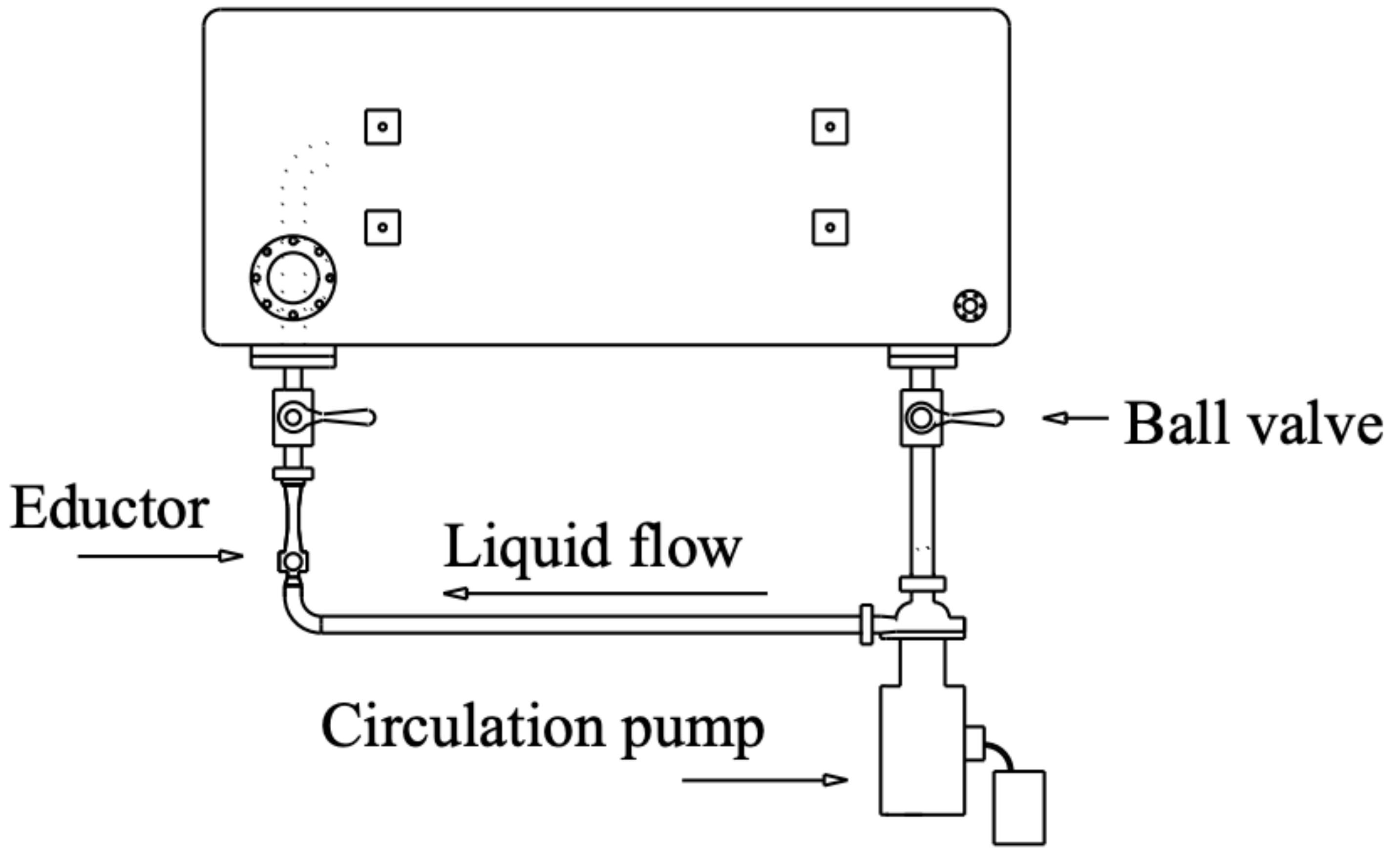
2,220 L of NaI solution

^{127}Xe extraction





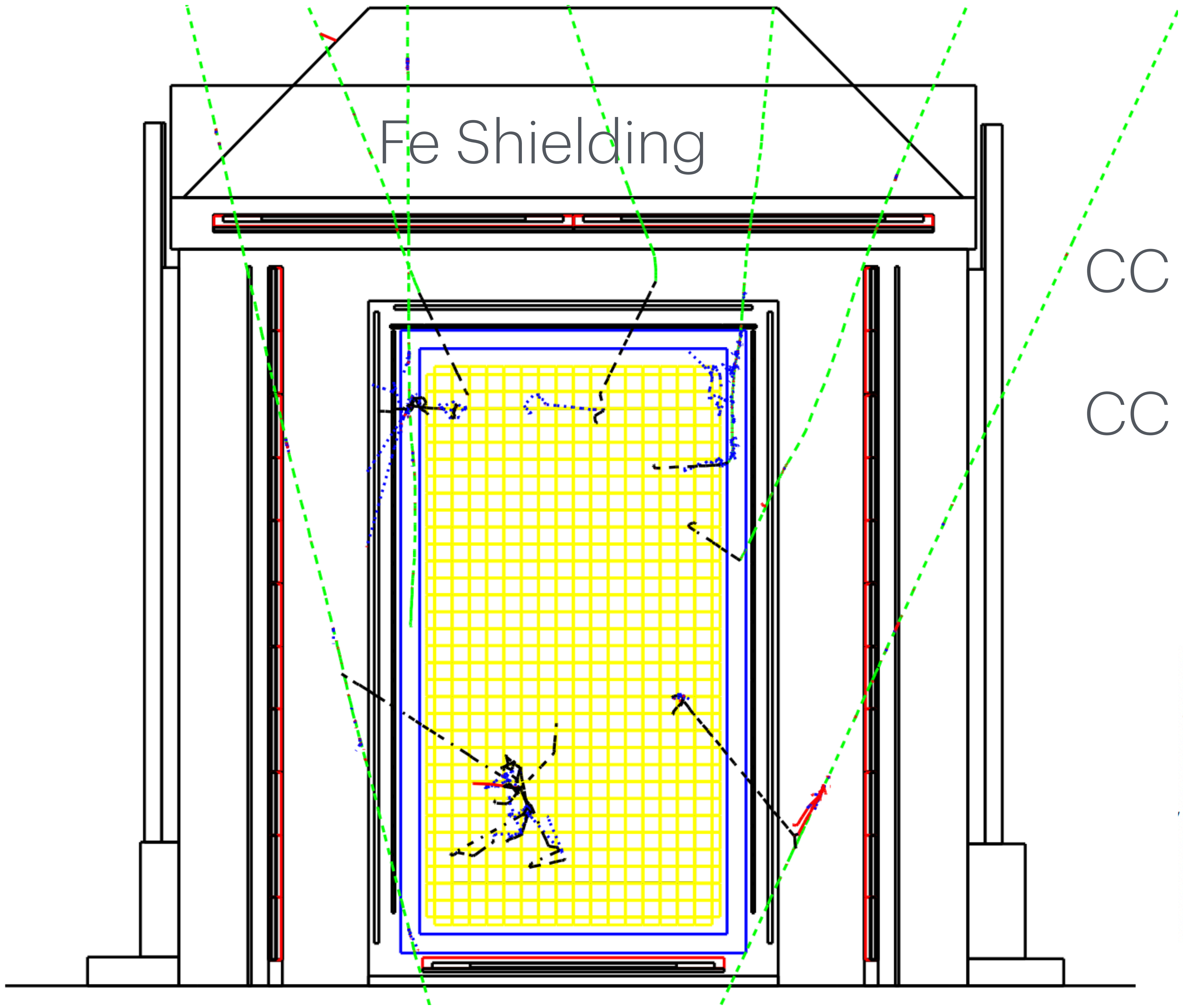
Front view



Top view

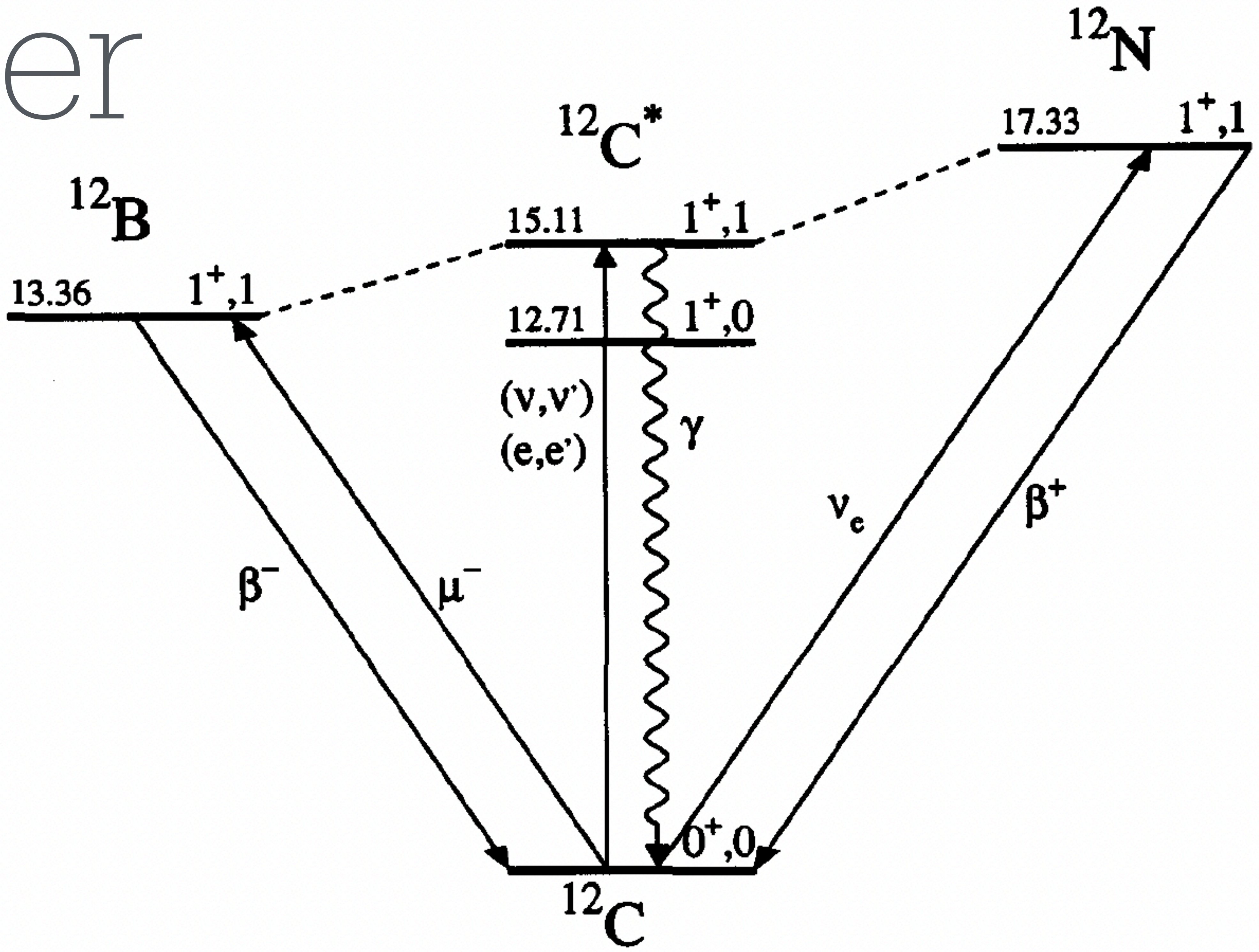
Neutrino Capture - Heavier

Karmen - ISIS spallation Neutron SOurce



CC and NC on C

CC on Fe

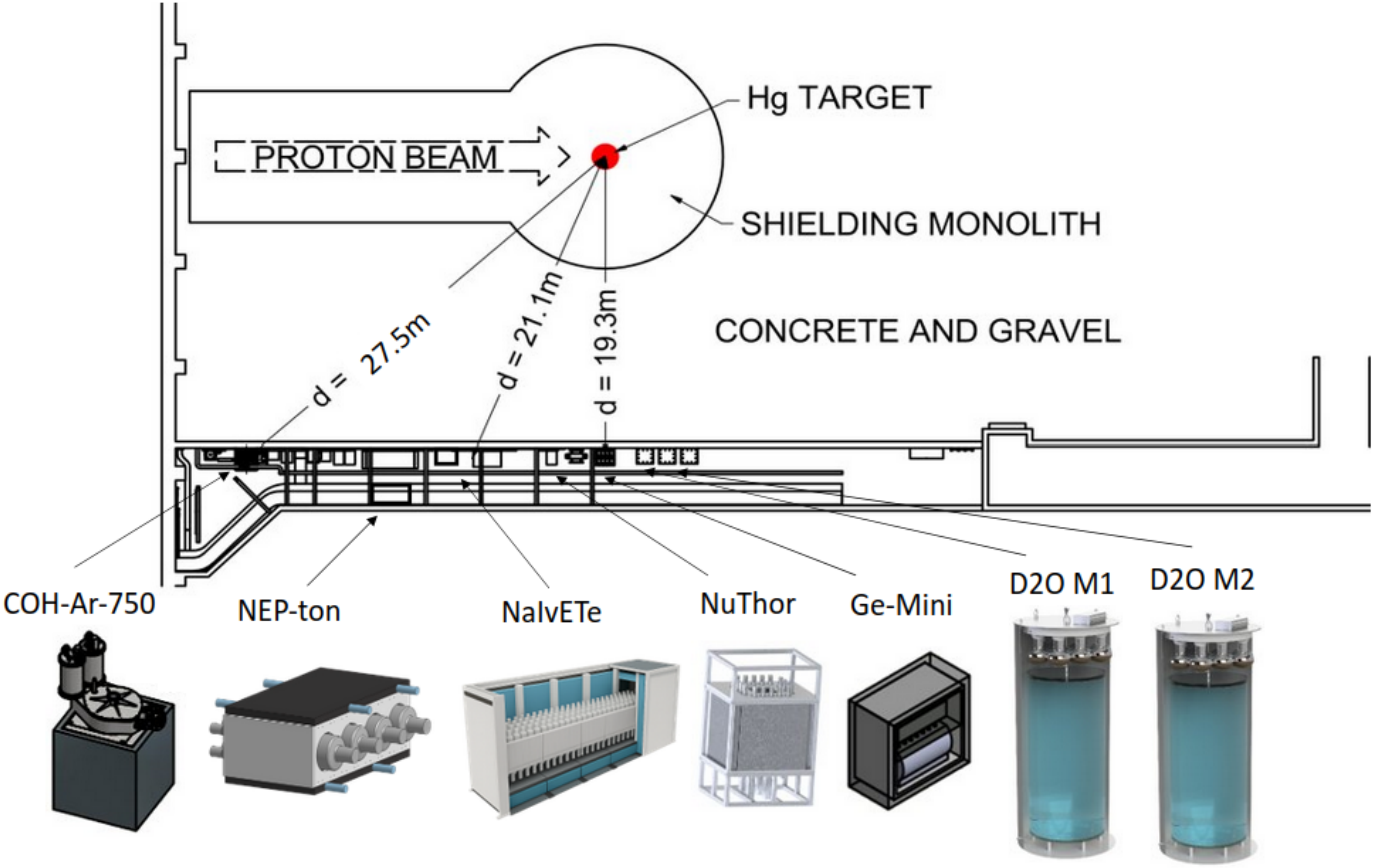


$$+ \ C^{12}_{\text{g.s.}} \rightarrow (e^-, \mu^-) + N^{12}_{\text{g.s.}} \qquad \text{(Exclusive Charged Current)}$$

$$+ \ C^{12}_{\text{g.s.}} \rightarrow (e^-, \mu^-) + N^{*12} \qquad \text{(Inclusive Charged Current)}$$

$$\nu + \ C^{12}_{\text{g.s.}} \rightarrow \nu + C^{*12} \qquad \text{(Neutral Current)}$$

Return to "Neutrino Alley"



D2O: Reducing Flux Uncertainty

- Deuterium ν_e charged-current cross section calculated with few percent theoretical uncertainties
- 549 kg of heavy water deployed to the SNS in 2023
- Goal: reduce flux normalization uncertainty to 3-5% level within 5 years—**analysis underway!**
- Second module w/H_2O to study non-deuterium neutrino scattering

D cross section one of the

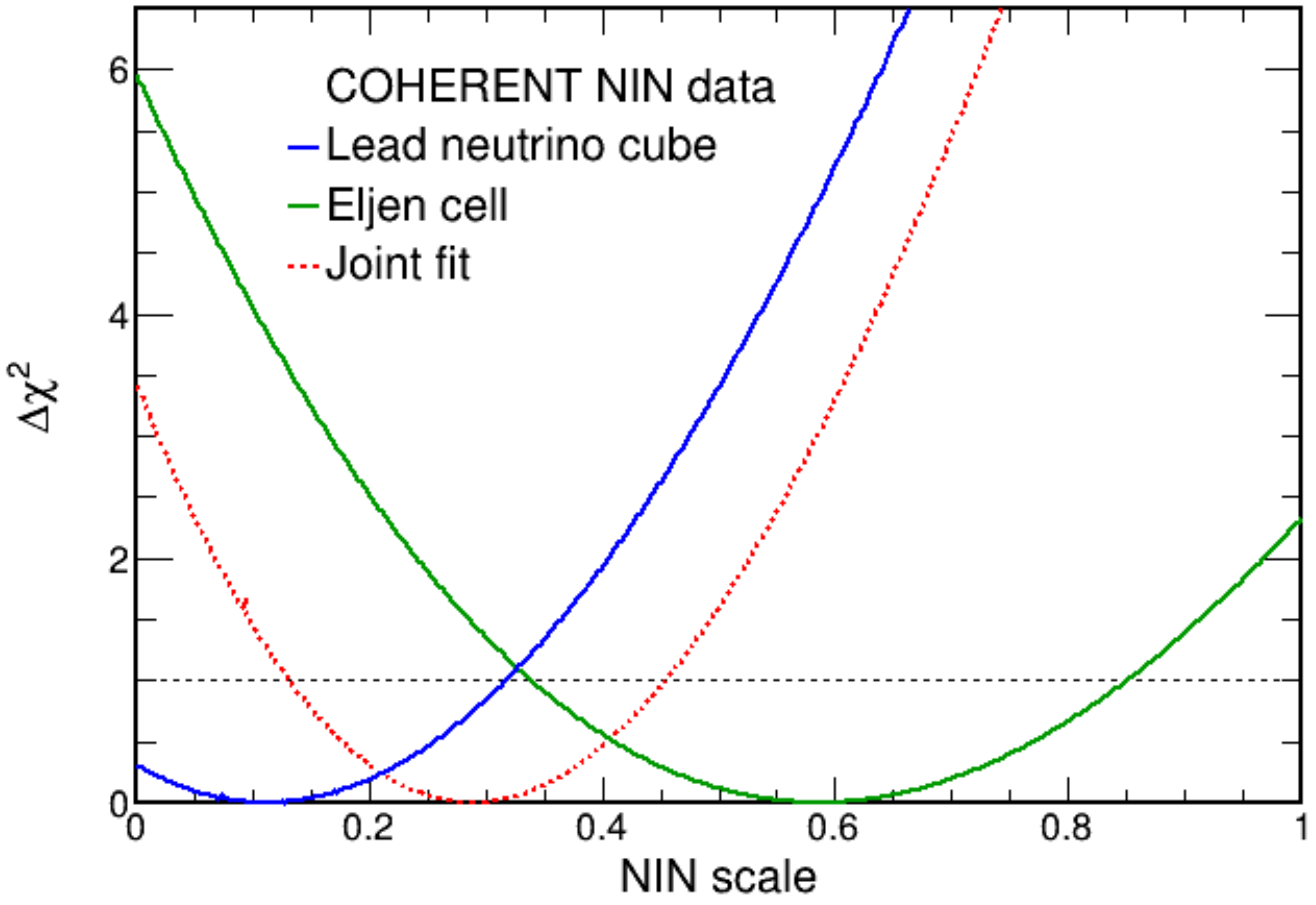
more precisely calculated

Neutrino Induced Backgrounds

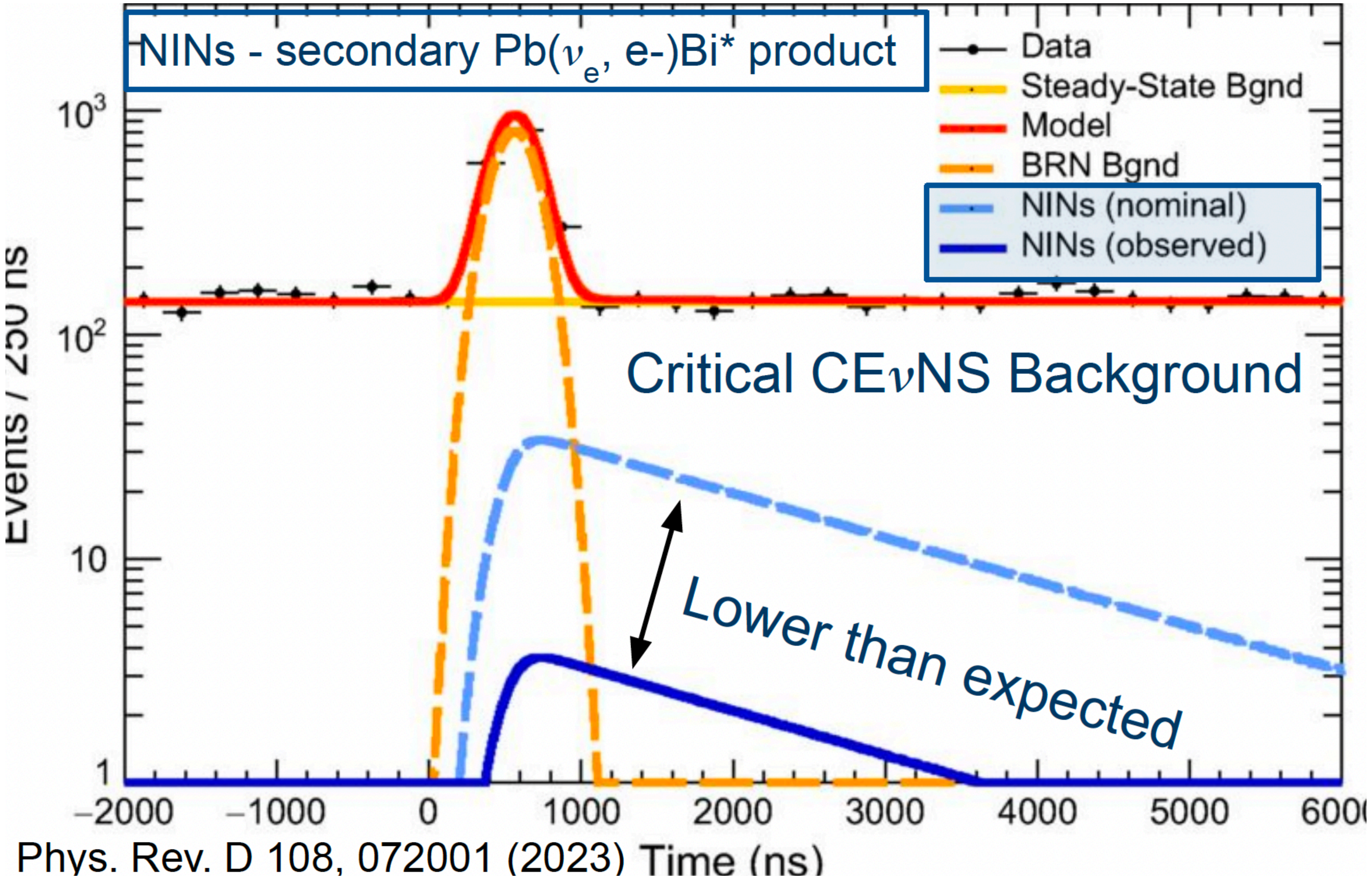
- CEvNS detectors surrounded by tons of lead
- Charged-current scattering can generate neutrino-induced neutrons (NINs)

$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow e^- + {}^{208-x}\mathrm{Bi} + x\mathrm{n}$$

- Expected to be smaller than CEvNS, but unmeasured, large theoretical uncertainties
- Collaboration deployed two detectors to study this process
- Initial results see suppression in NIN production - **not a major background for CEvNS detectors**



Neutrino Induced Backgrounds


NINs - secondary Pb(ν_e, e-)Bi* product

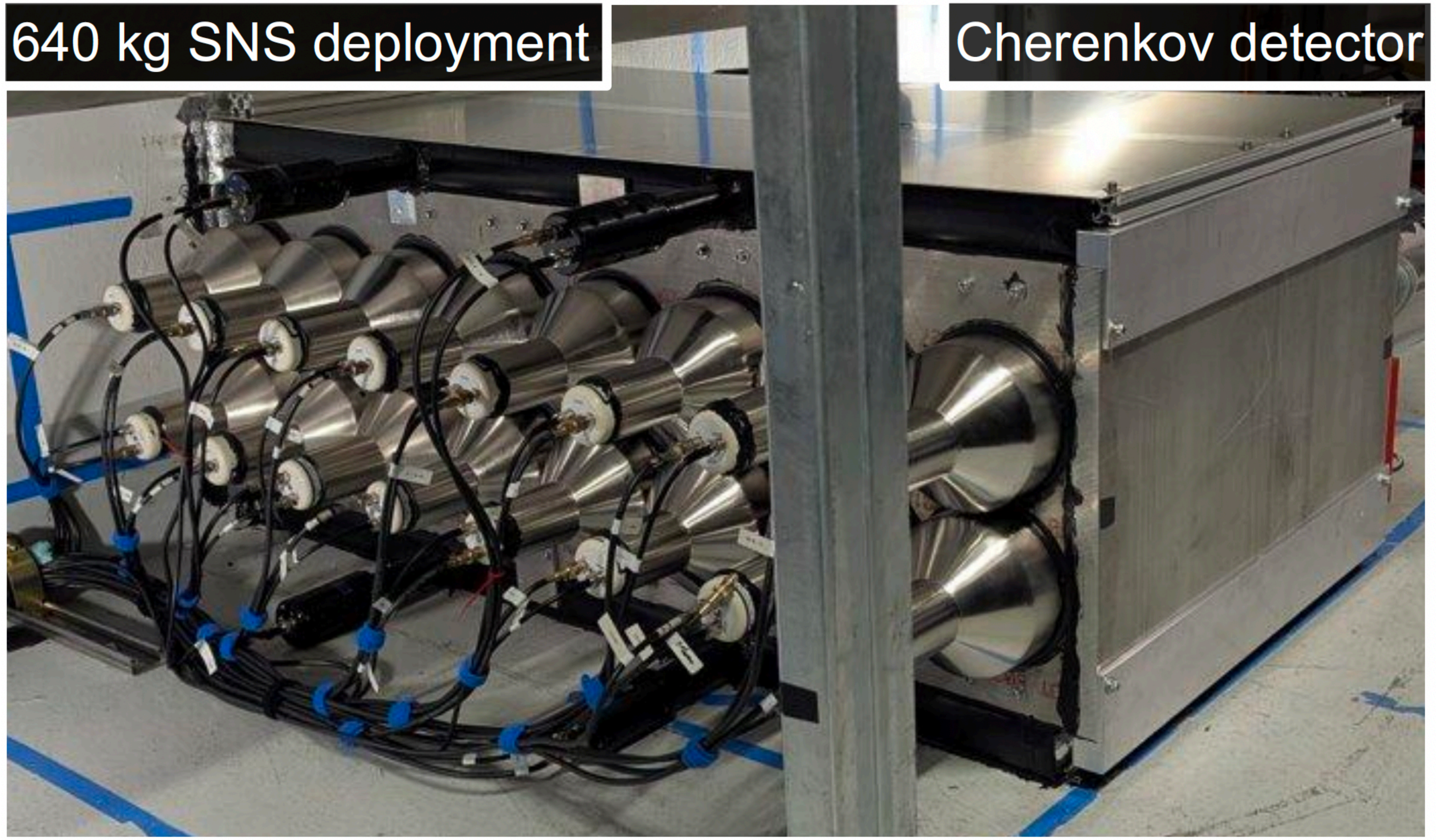
Critical CEνNS Background

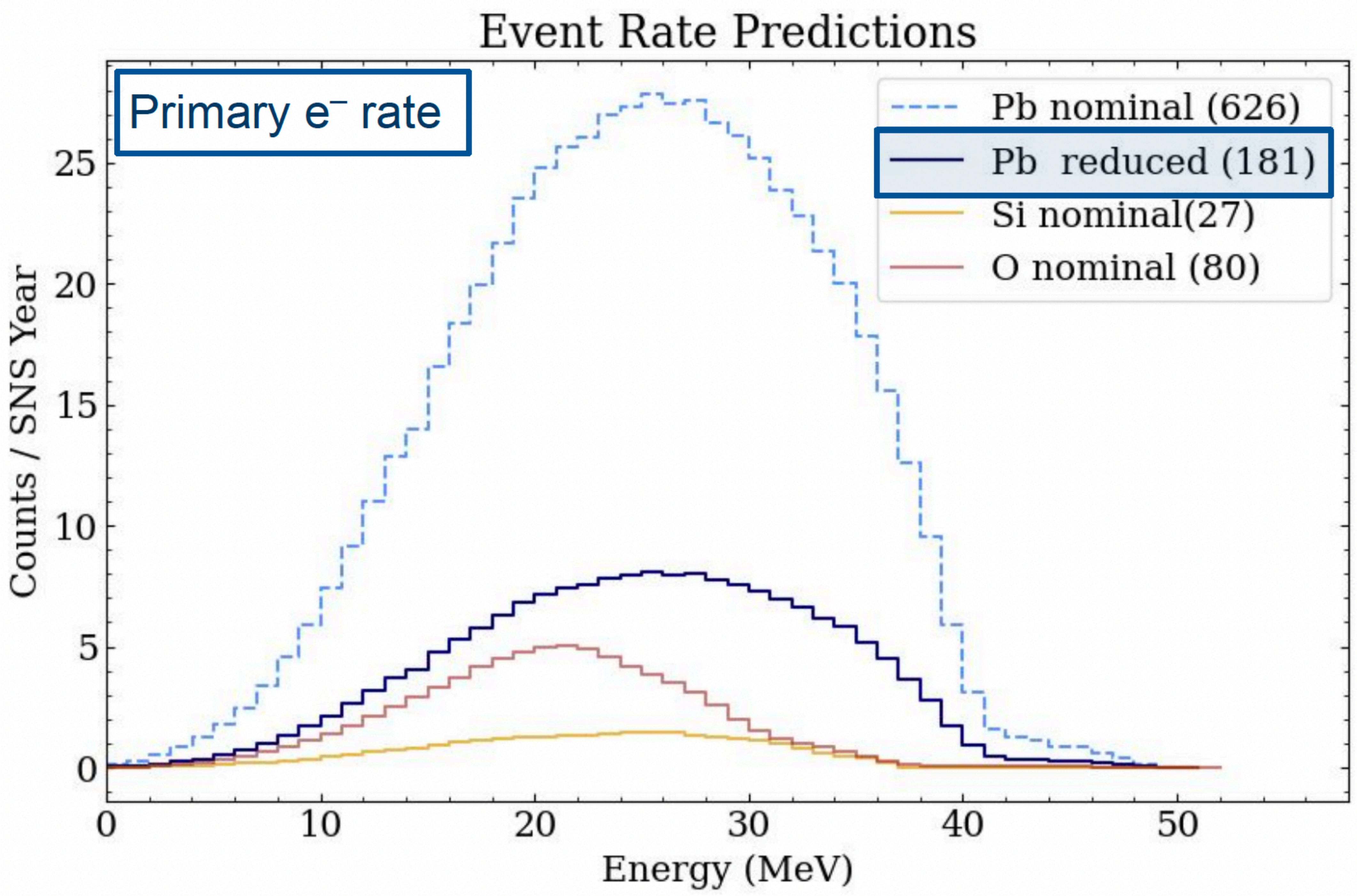
Lower than expected

Phys. Rev. D 108, 072001 (2023)

Direct Pb CC Detectors

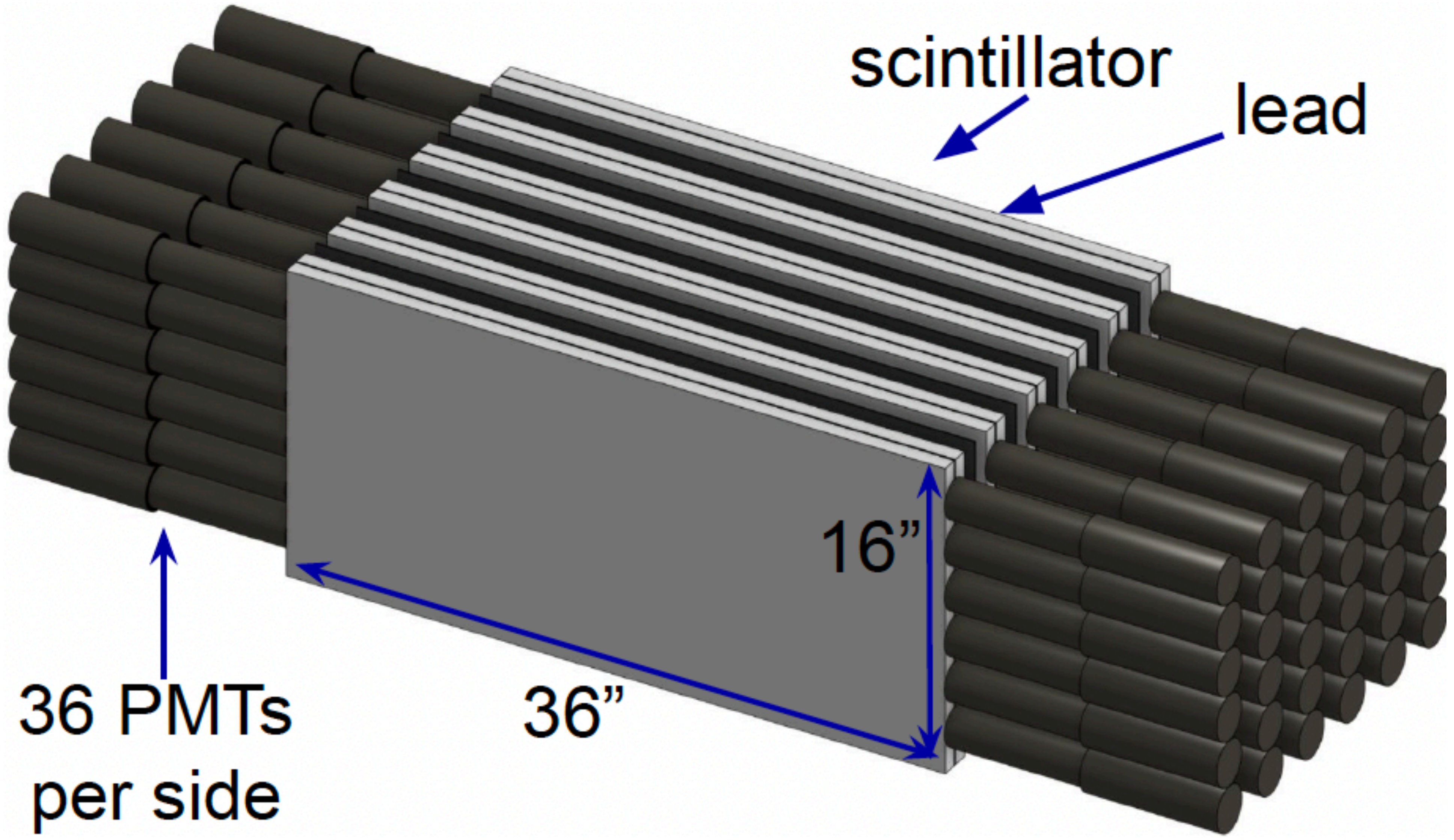
NEP-Ton Pb-Glass Cherenkov Detector

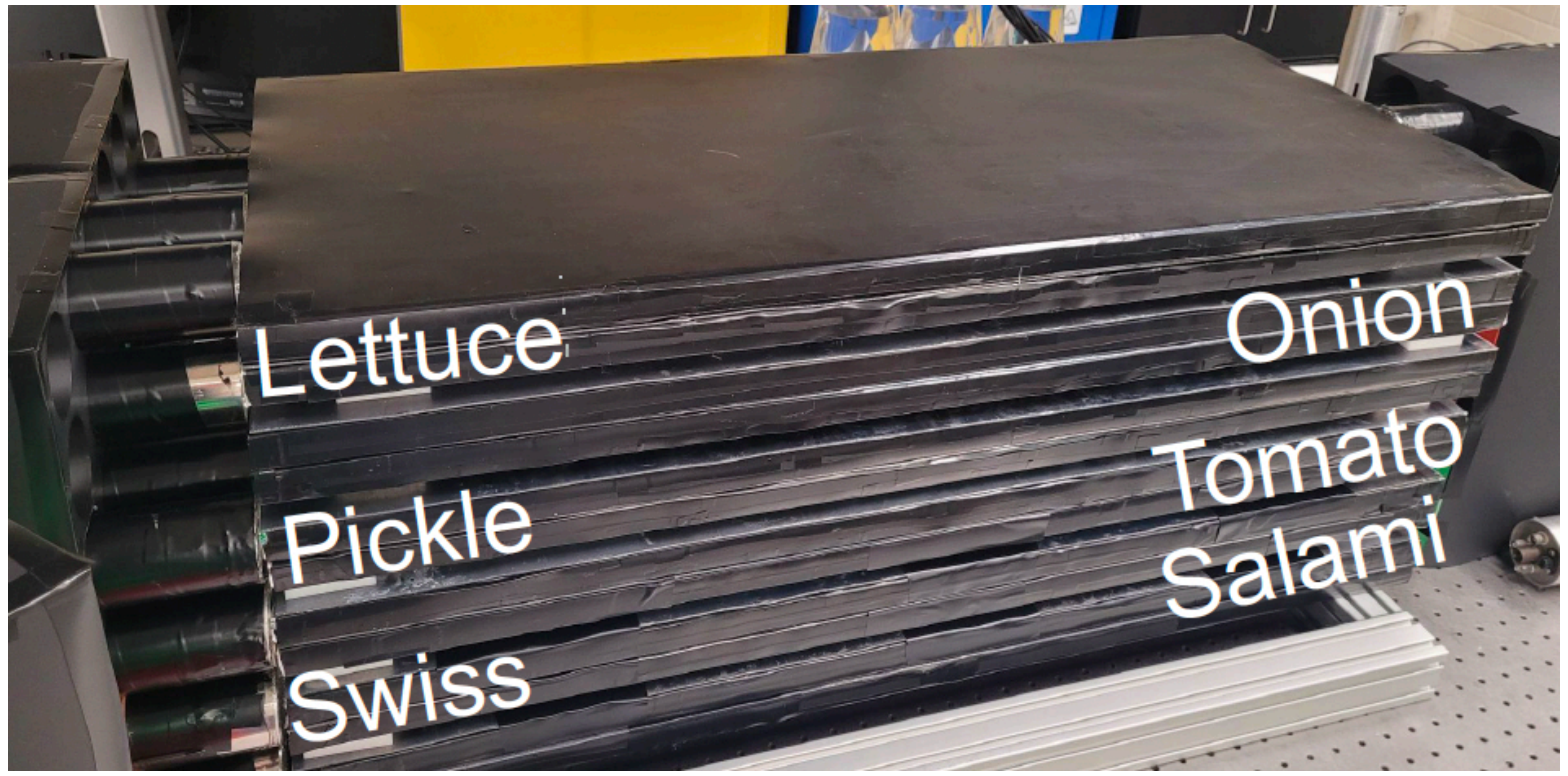




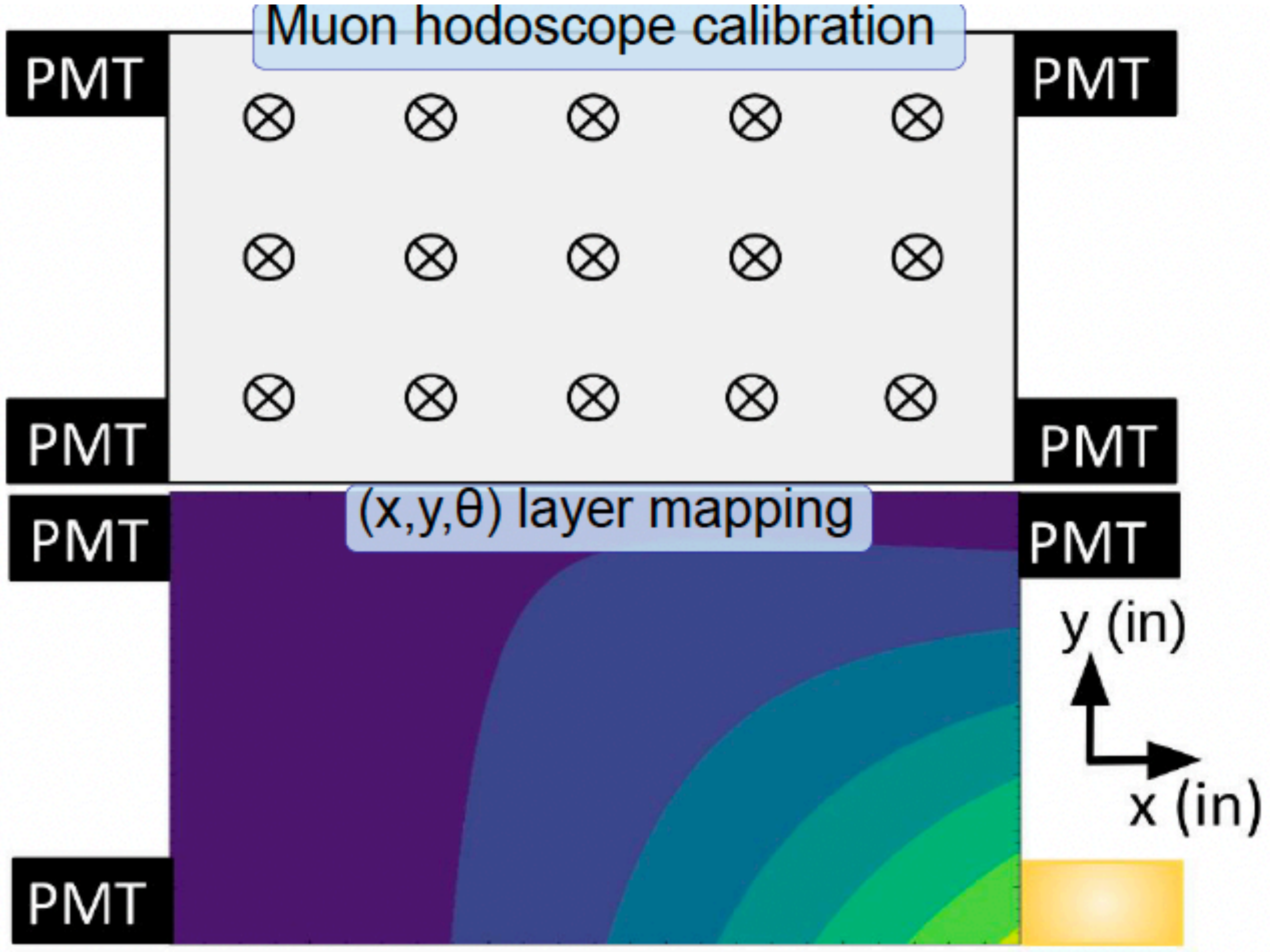
Direct Pb CC Detectors

Metal-Sandwich Scintillator



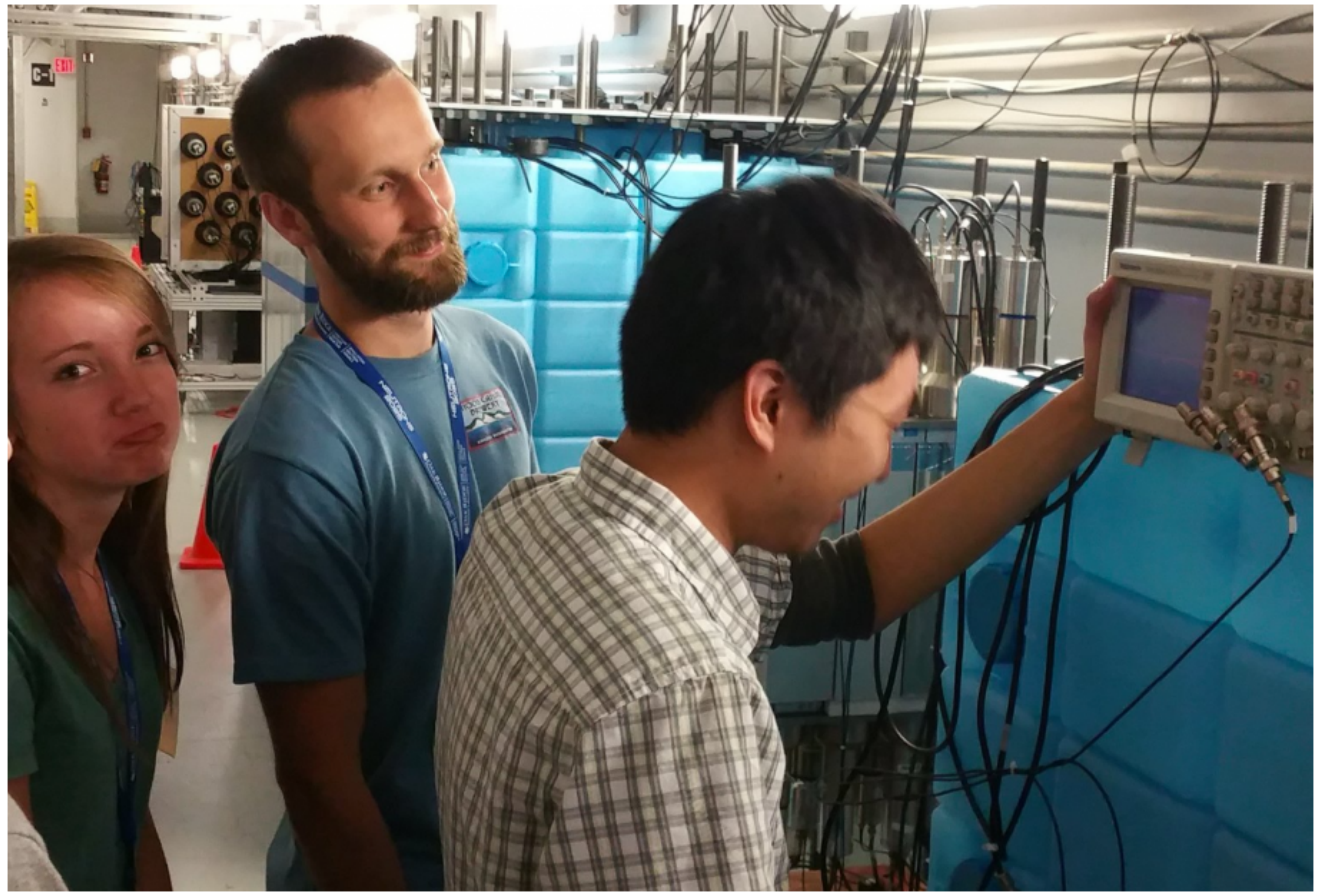


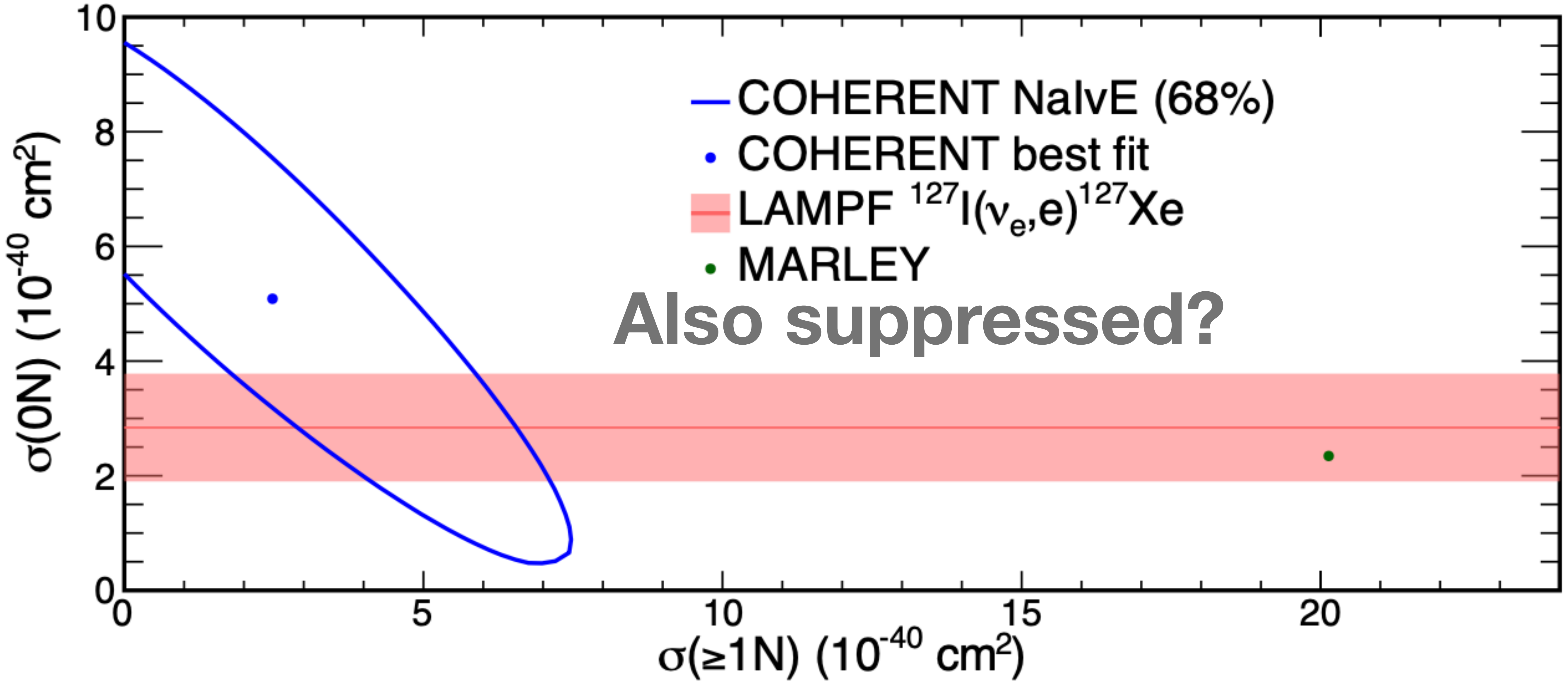
Directional measurement



Opens possibility of other targets (Fe, W, etc.)

Direct ^{127}I Measurement: NaIvE-185



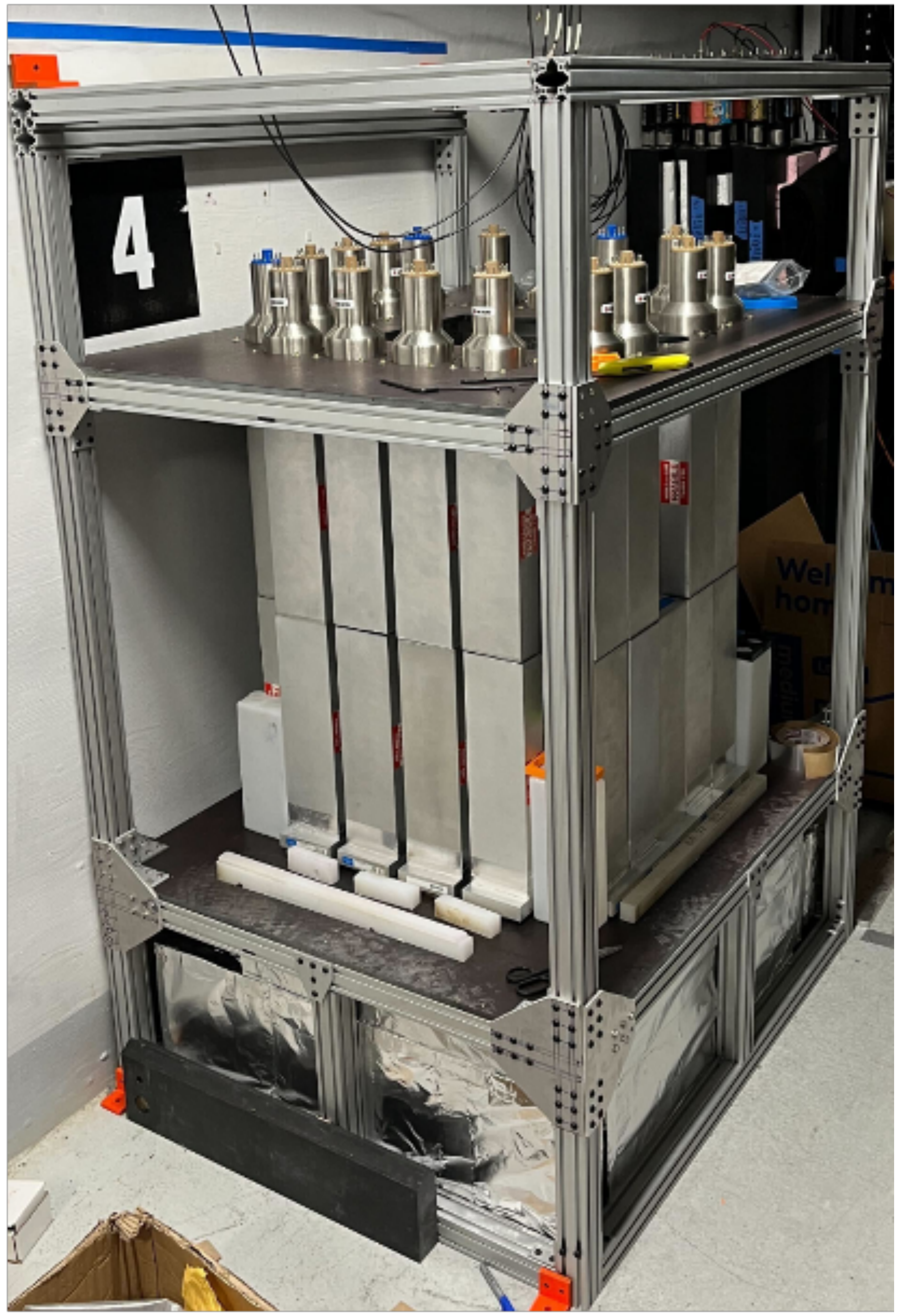


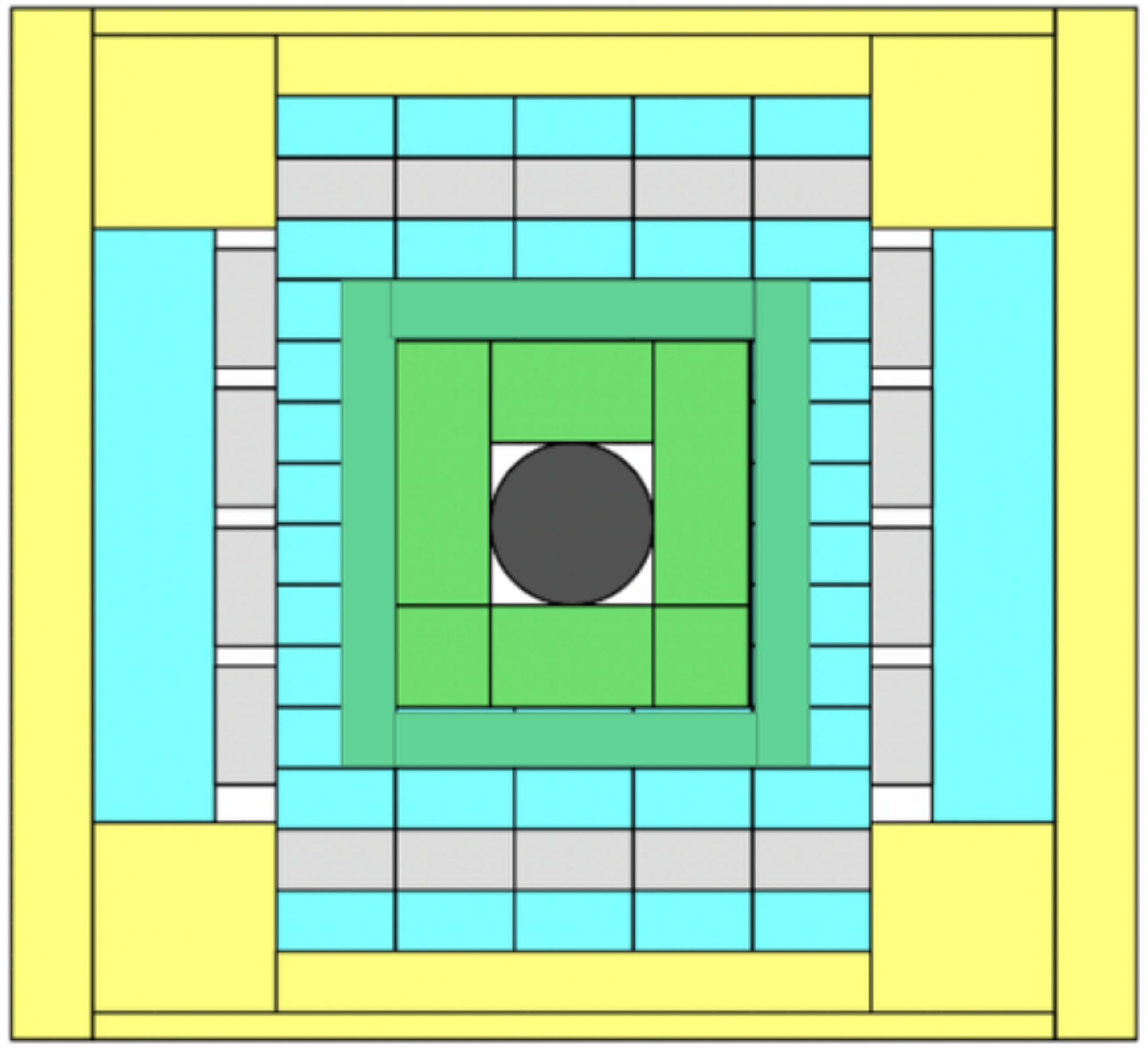
Also suppressed?

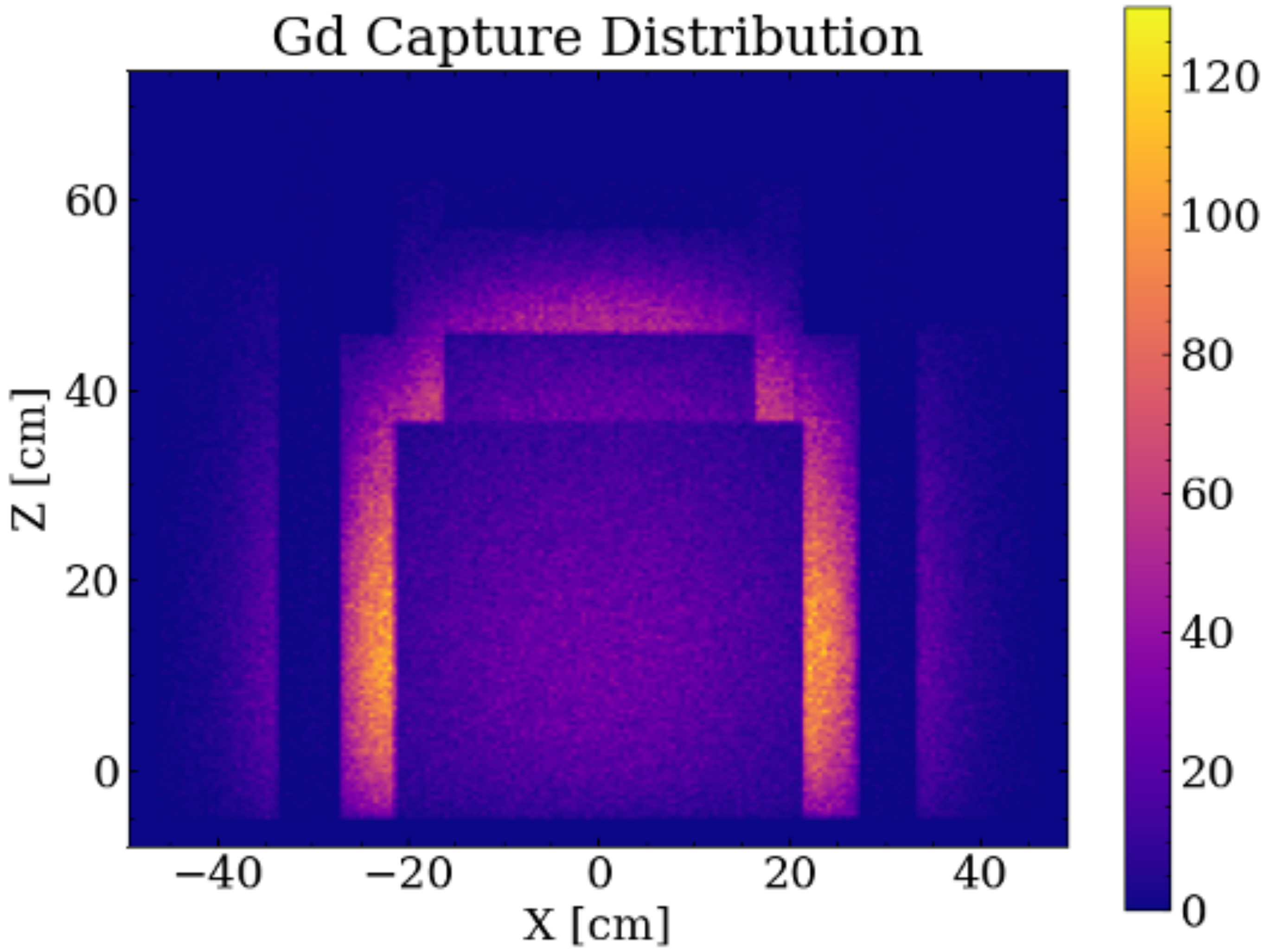
NU THOR

A first measurement of neutrino-induced fission

- Unique opportunity at ORNL— intense ν_e source + 52 kg of ^{232}Th
- Neutrino-induced fission first predicted in 1971[1]
  - Charged-current interaction induces a ^{232}Th fission
- Signature is large number of fission neutrons following neutrino pulse
- 2.4σ result in Tyler Johnson's PhD thesis, **~3.5x exposure!**

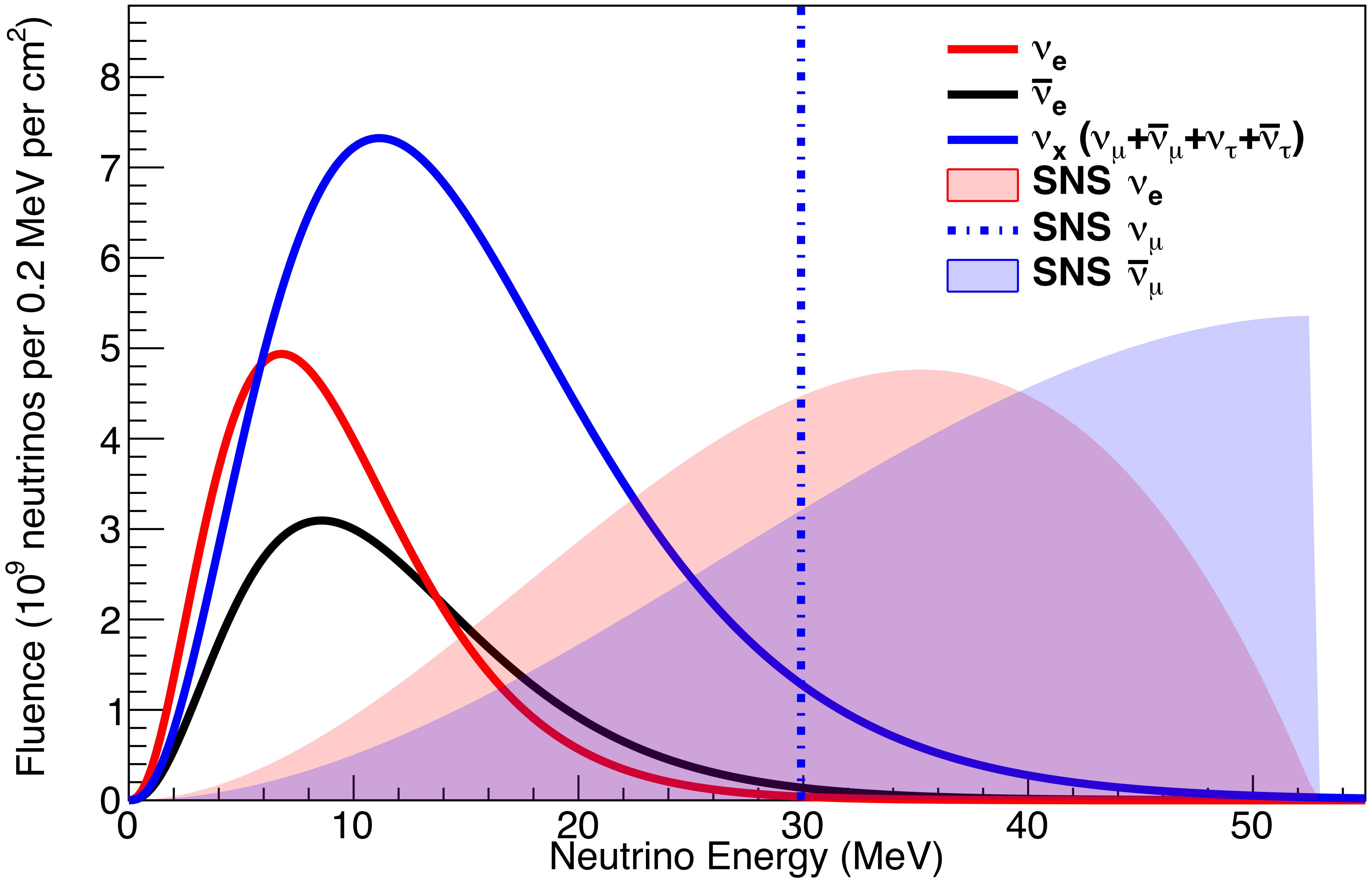




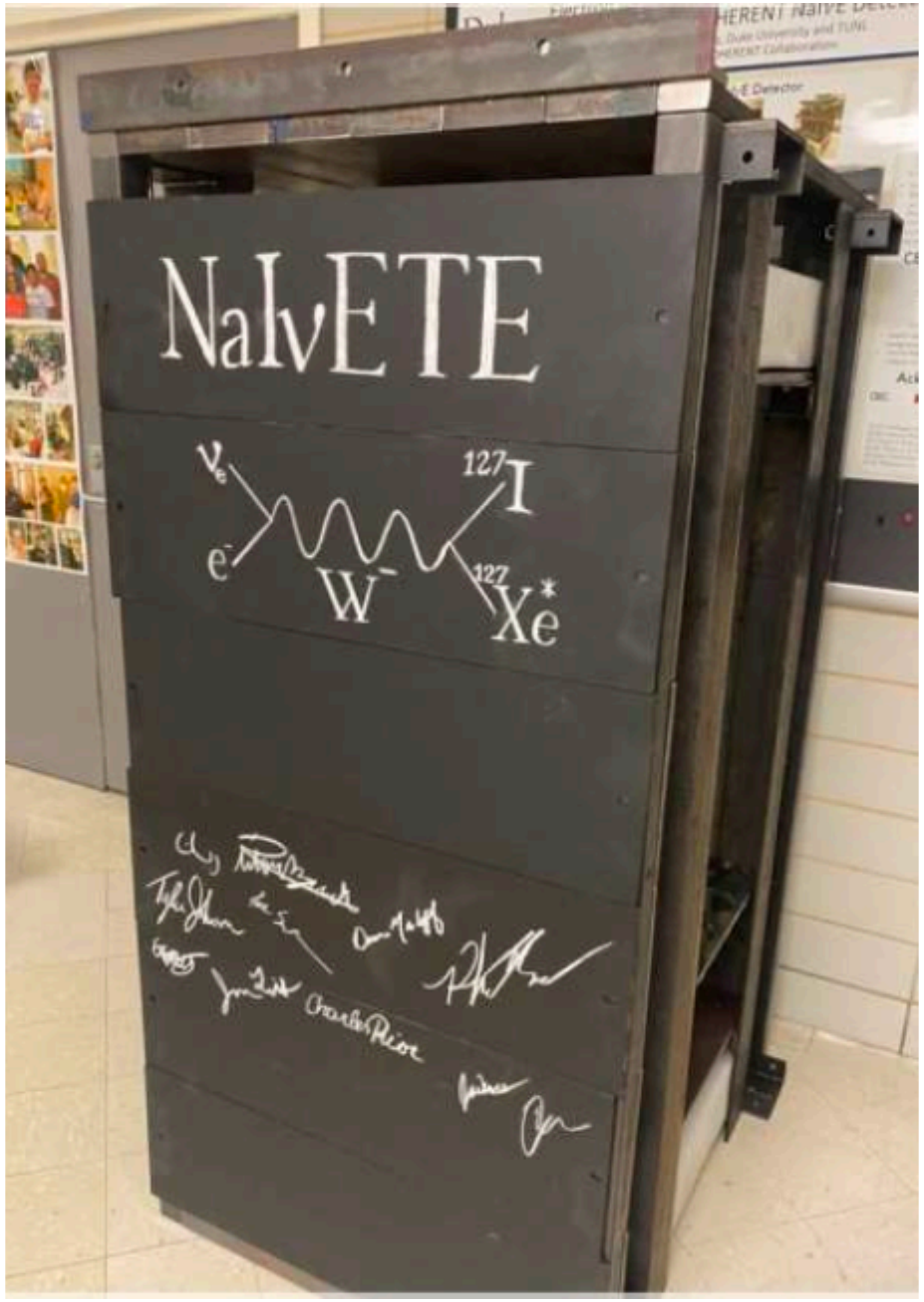


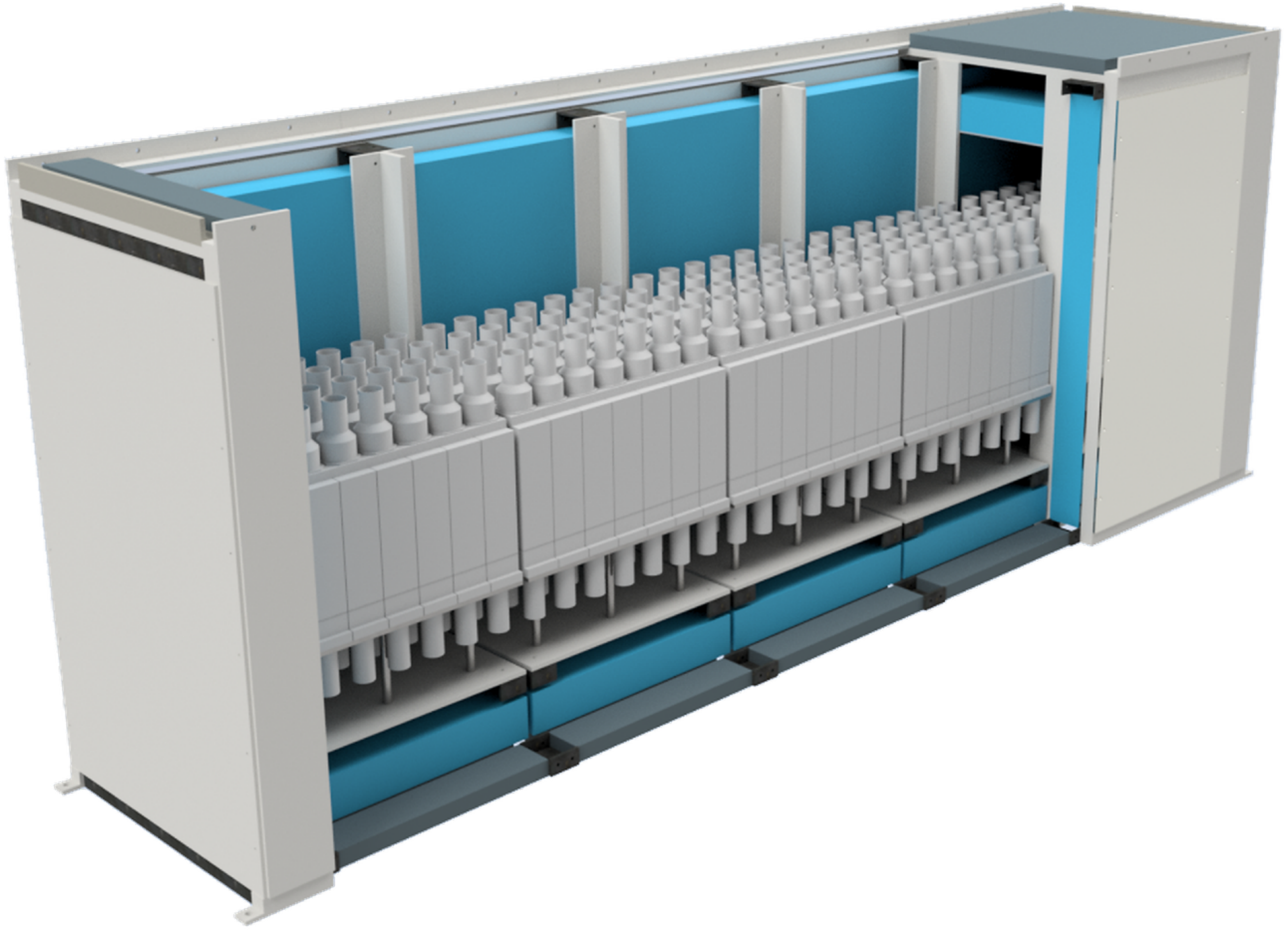
SNS: The Supernova Simulator

- Neutrino flux normalization
- Neutrino-induced backgrounds
- Calibrating SN neutrino detectors
- Make novel measurements of neutrino-nucleus cross sections



Direct ^{127}I & ^{23}Na CC Measurement: NaIvE-Te

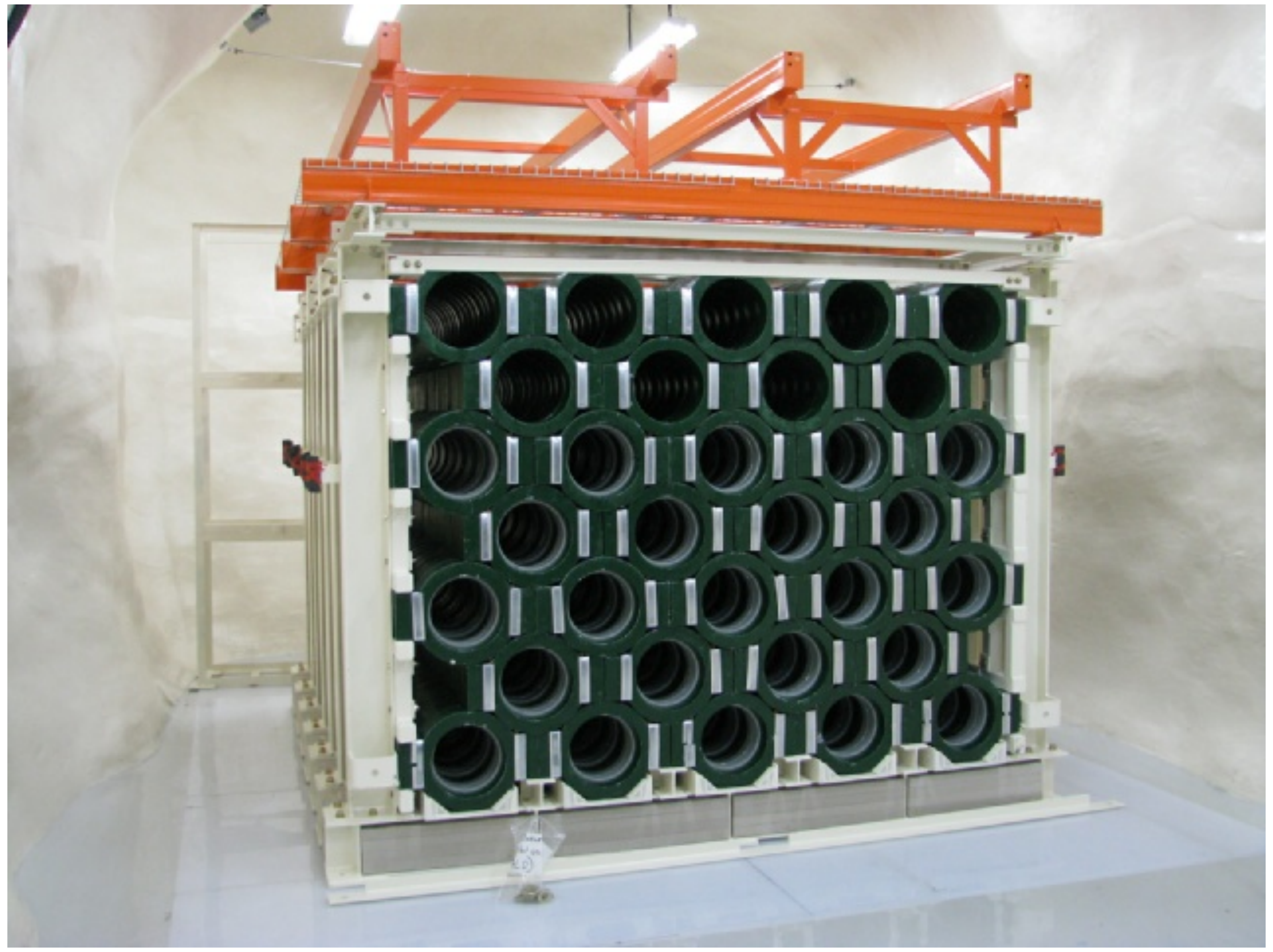




Calibrating Supernova Neutrino Detectors

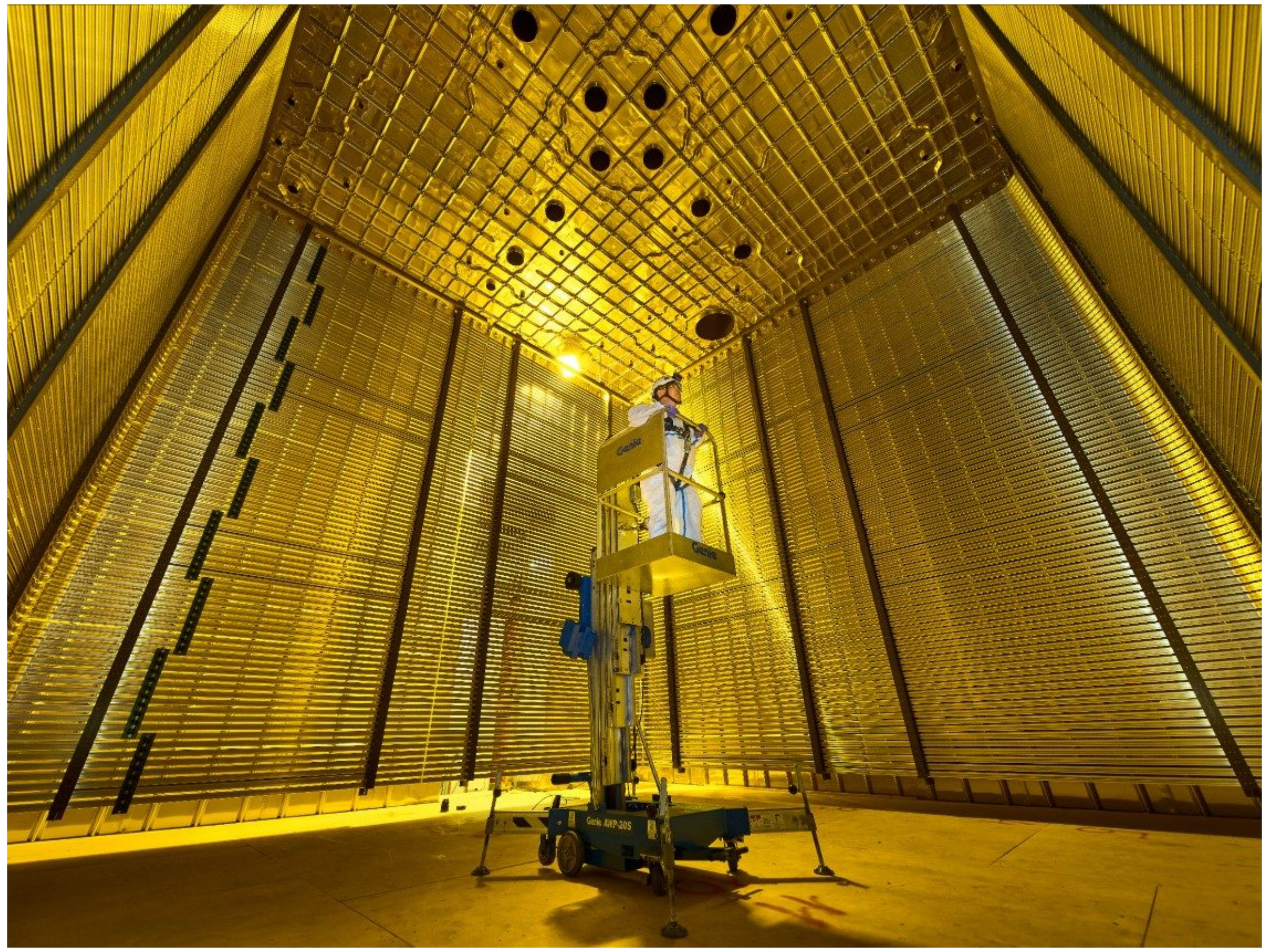
Lead, Argon, and Oxygen

HALO



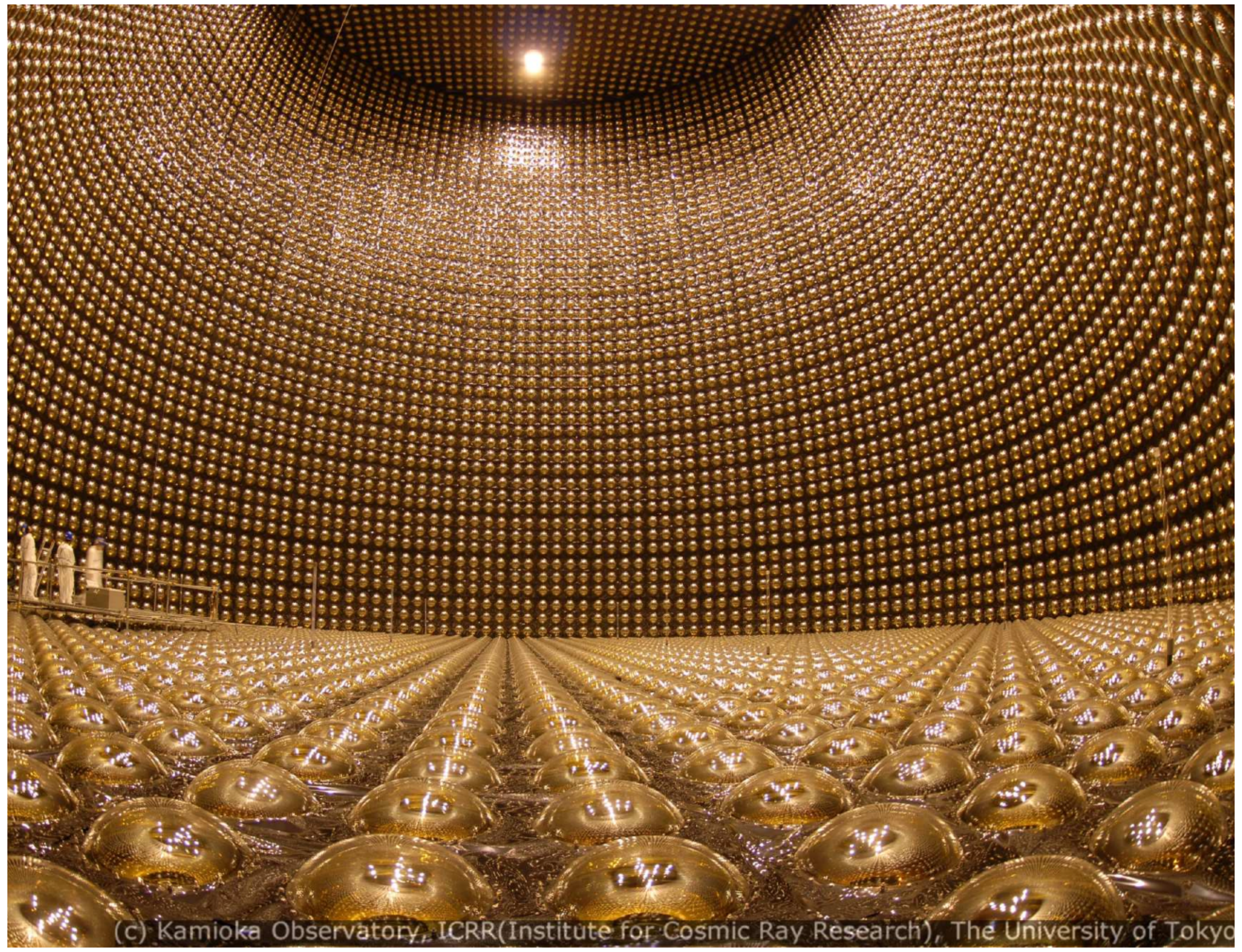
$$\nu_e + {}^{208}\mathrm{Pb} \rightarrow e^- + {}^{208}\mathrm{Bi}^*$$

DUNE



$$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$$

Super-K/Hyper-K



(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Toky

$$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^*$$

Calibrating Supernova Neutrino Detectors

Lead, Argon, and Oxygen

HALO DUNE Super-K/Hyper-K

$\nu_e + {}^{208}\mathrm{Pb} \rightarrow e^- + {}^{208}\mathrm{Bi}^*$

$\nu_e + {}^{40}\mathrm{Ar} \rightarrow e^- + {}^{40}\mathrm{K}^*$

$\nu_e + {}^{16}\mathrm{O} \rightarrow e^- + {}^{16}\mathrm{F}^*$

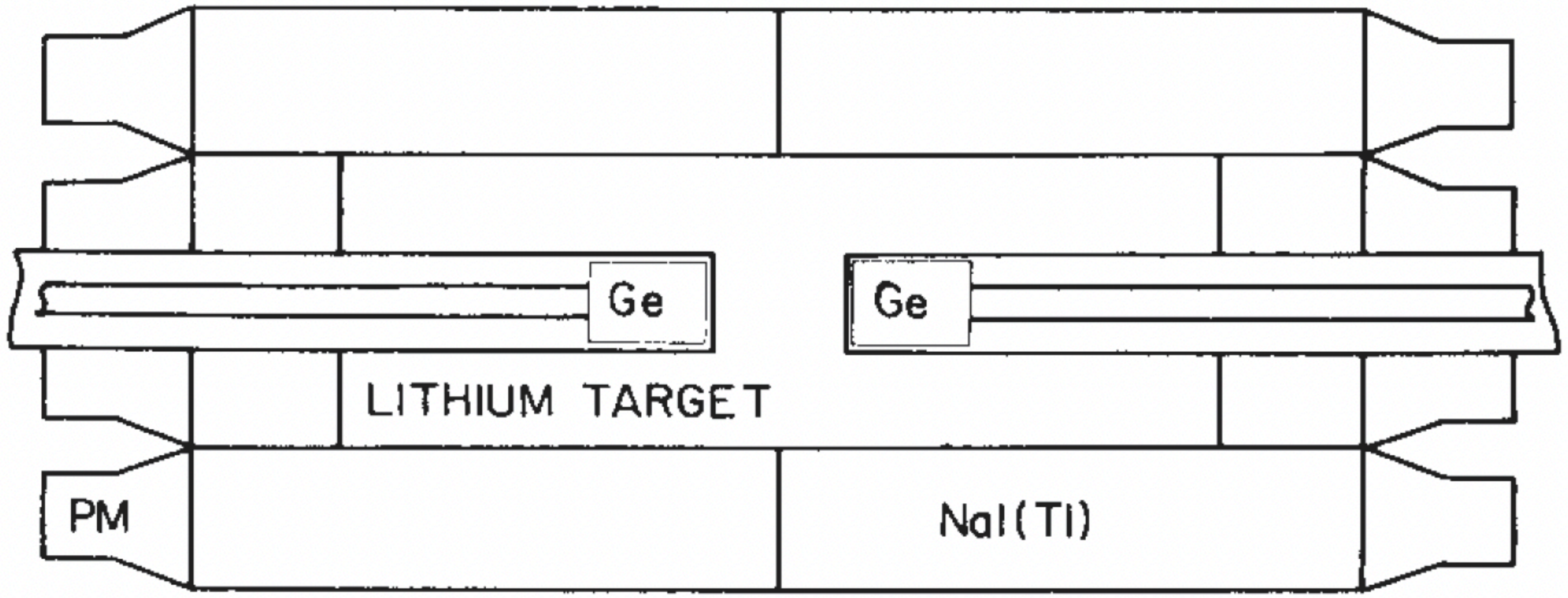
Now for some unproven, but very interesting techniques

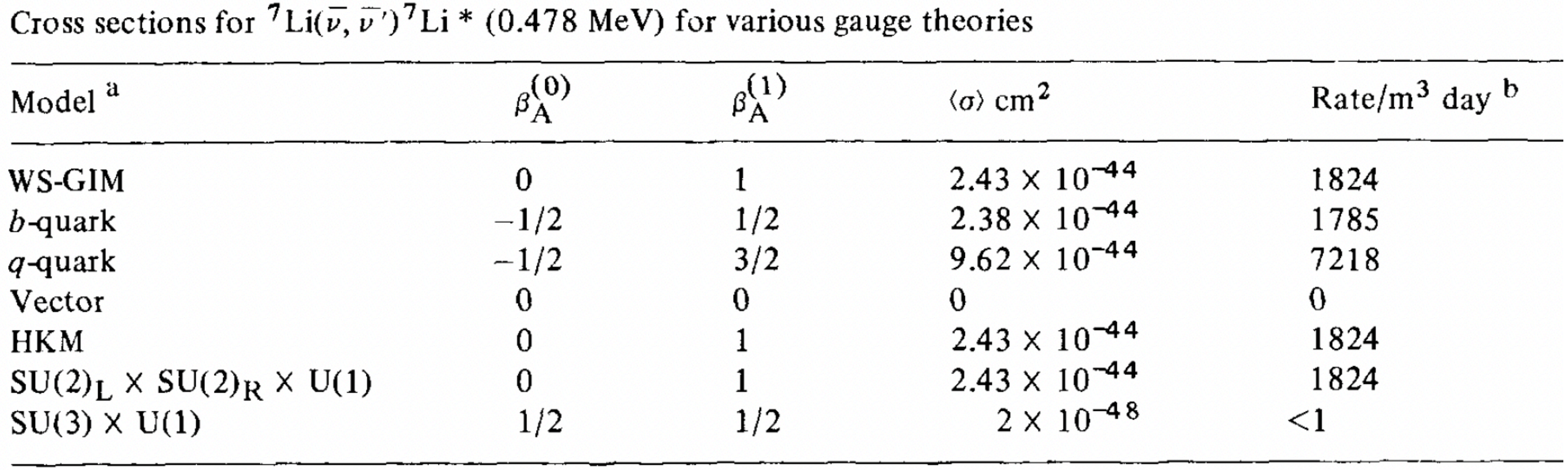
Neutral Current Excitation

^{7}Li example for reactor neutrinos

$$^7\mathrm{Li}(\bar{\nu}, \bar{\nu}')^7\mathrm{Li}^*\,(0.478\ \mathrm{MeV})$$

At low energy, dominated by Gamow-Teller operator




Cross sections for $^7\mathrm{Li}(\bar{\nu}, \bar{\nu}')^7\mathrm{Li}^*$ (0.478 MeV) for various gauge theories

Model [a]	$\beta_A^{(0)}$	$\beta_A^{(1)}$	$\langle\sigma\rangle$ cm^2	Rate/m^3 day [b]
WS-GIM	0	1	2.43×10^{-44}	1824
b-quark	−1/2	1/2	2.38×10^{-44}	1785
q-quark	−1/2	3/2	9.62×10^{-44}	7218
Vector	0	0	0	0
HKM	0	1	2.43×10^{-44}	1824
$SU(2)_L \times SU(2)_R \times U(1)$	0	1	2.43×10^{-44}	1824
$SU(3) \times U(1)$	1/2	1/2	2×10^{-48}	<1

F. T. Avignone, III, T. W. Donnelly, NIM 179, (1981) 163-169

Resonant Orbital Electron Capture

Search for low energy antineutrinos (e.g. Geoneutrinos)

Ordinary Beta Decay:

$$(A, Z-1) \rightarrow (A, Z) + e^- + \bar{\nu} + Q_\beta$$

Resonant Orbital Electron Capture

Interchange initial and final states:

$$(A, Z-1) \leftarrow (A, Z) + e^- + \bar{\nu} + Q_\beta$$

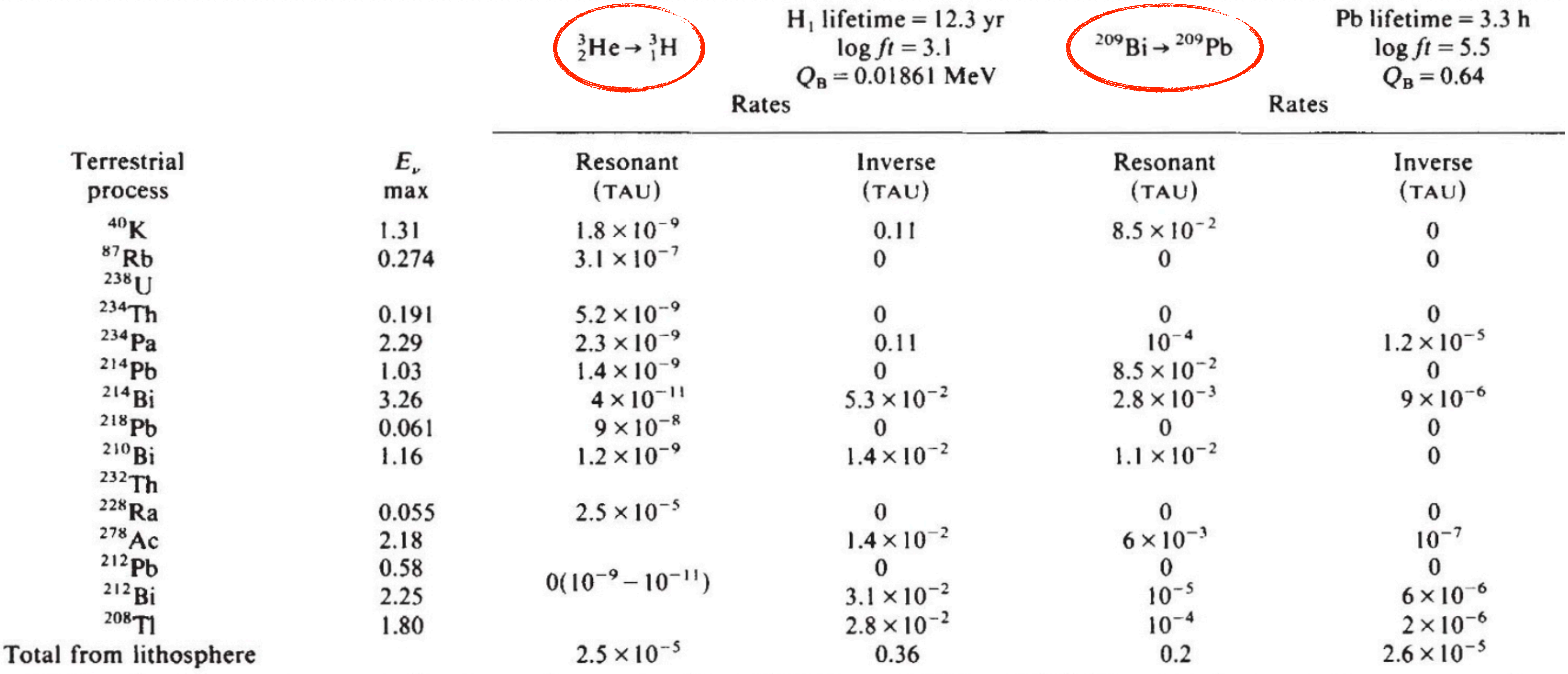
L. A. Mikaelyan, B. G. Tsinoev, A. A. Borovoi, Yad. Fiz. 6 349-352 (1967)

$$E_{\bar{\nu}\ res} = E_0 + E_i$$

Inverse Beta Decay

Interchange particles:

$$e^+ + (A, Z-1) \leftarrow (A, Z) + \bar{\nu} + Q_\beta + 1.02\ \mathrm{MeV}$$



		${}^{3}_{2}\mathrm{He} \rightarrow {}^{3}_{1}\mathrm{H}$	H_1 lifetime = 12.3 yr log $ft = 3.1$ $Q_B = 0.01861$ MeV	${}^{209}\mathrm{Bi} \rightarrow {}^{209}\mathrm{Pb}$	Pb lifetime = 3.3 h log $ft = 5.5$ $Q_B = 0.64$
		Rates		Rates	
Terrestrial process	E_ν max	Resonant (TAU)	Inverse (TAU)	Resonant (TAU)	Inverse (TAU)
${}^{40}\mathrm{K}$	1.31	1.8×10^{-9}	0.11	8.5×10^{-2}	0
${}^{87}\mathrm{Rb}$	0.274	3.1×10^{-7}	0	0	0
${}^{238}\mathrm{U}$					
${}^{234}\mathrm{Th}$	0.191	5.2×10^{-9}	0	0	0
${}^{234}\mathrm{Pa}$	2.29	2.3×10^{-9}	0.11	10^{-4}	1.2×10^{-5}
${}^{214}\mathrm{Pb}$	1.03	1.4×10^{-9}	0	8.5×10^{-2}	0
${}^{214}\mathrm{Bi}$	3.26	4×10^{-11}	5.3×10^{-2}	2.8×10^{-3}	9×10^{-6}
${}^{218}\mathrm{Pb}$	0.061	9×10^{-8}	0	0	0
${}^{210}\mathrm{Bi}$	1.16	1.2×10^{-9}	1.4×10^{-2}	1.1×10^{-2}	0
${}^{232}\mathrm{Th}$					
${}^{228}\mathrm{Ra}$	0.055	2.5×10^{-5}	0	0	0
${}^{278}\mathrm{Ac}$	2.18	$0(10^{-9} - 10^{-11})$	1.4×10^{-2}	6×10^{-3}	10^{-7}
${}^{212}\mathrm{Pb}$	0.58		0	0	0
${}^{212}\mathrm{Bi}$	2.25		3.1×10^{-2}	10^{-5}	6×10^{-6}
${}^{208}\mathrm{Tl}$	1.80		2.8×10^{-2}	10^{-4}	2×10^{-6}
Total from lithosphere		2.5×10^{-5}	0.36	0.2	2.6×10^{-5}

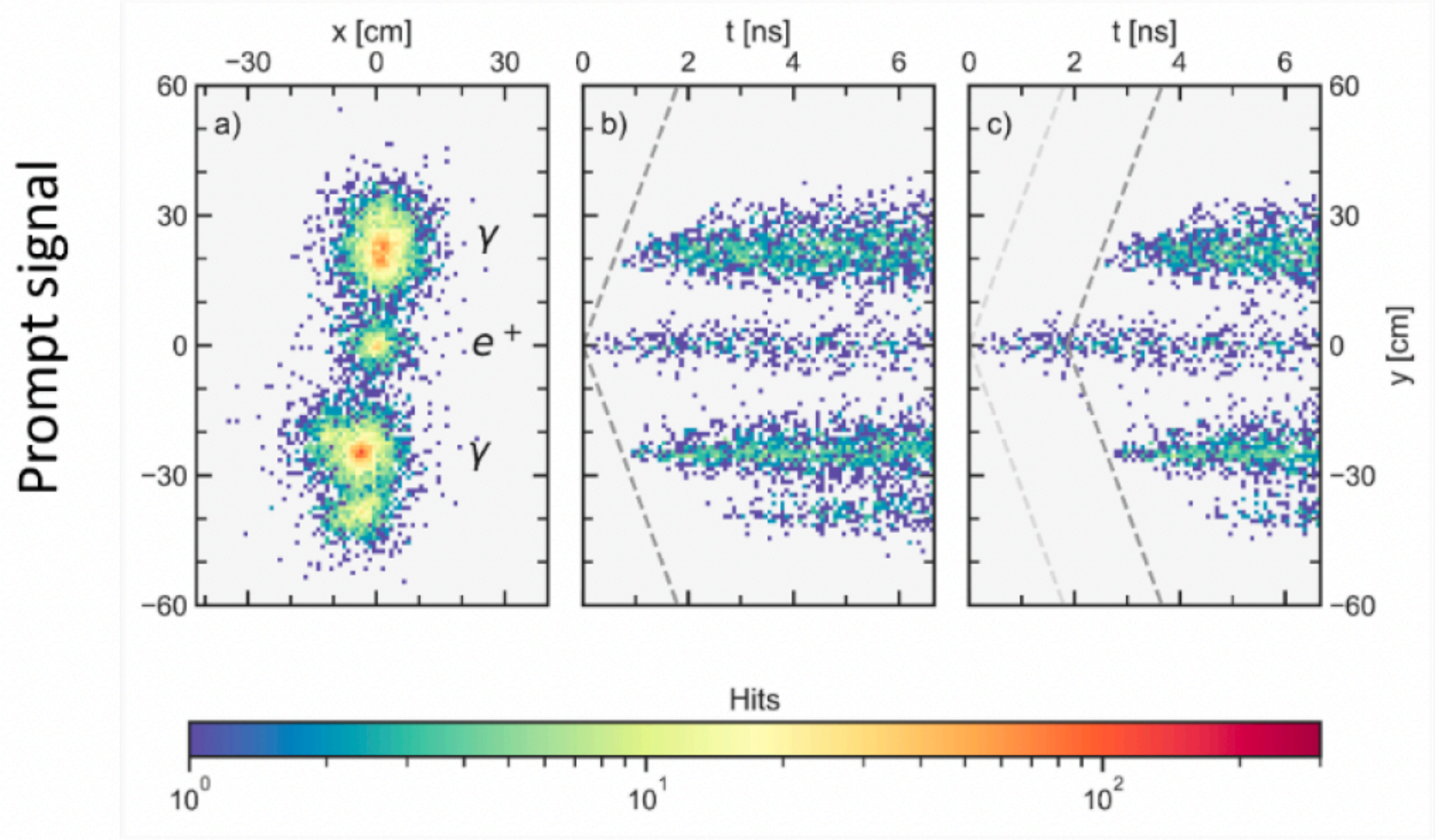
L. Krauss, S. L. Glashow, D. N. Schramm, Nature vol. 310, 19, July 1984

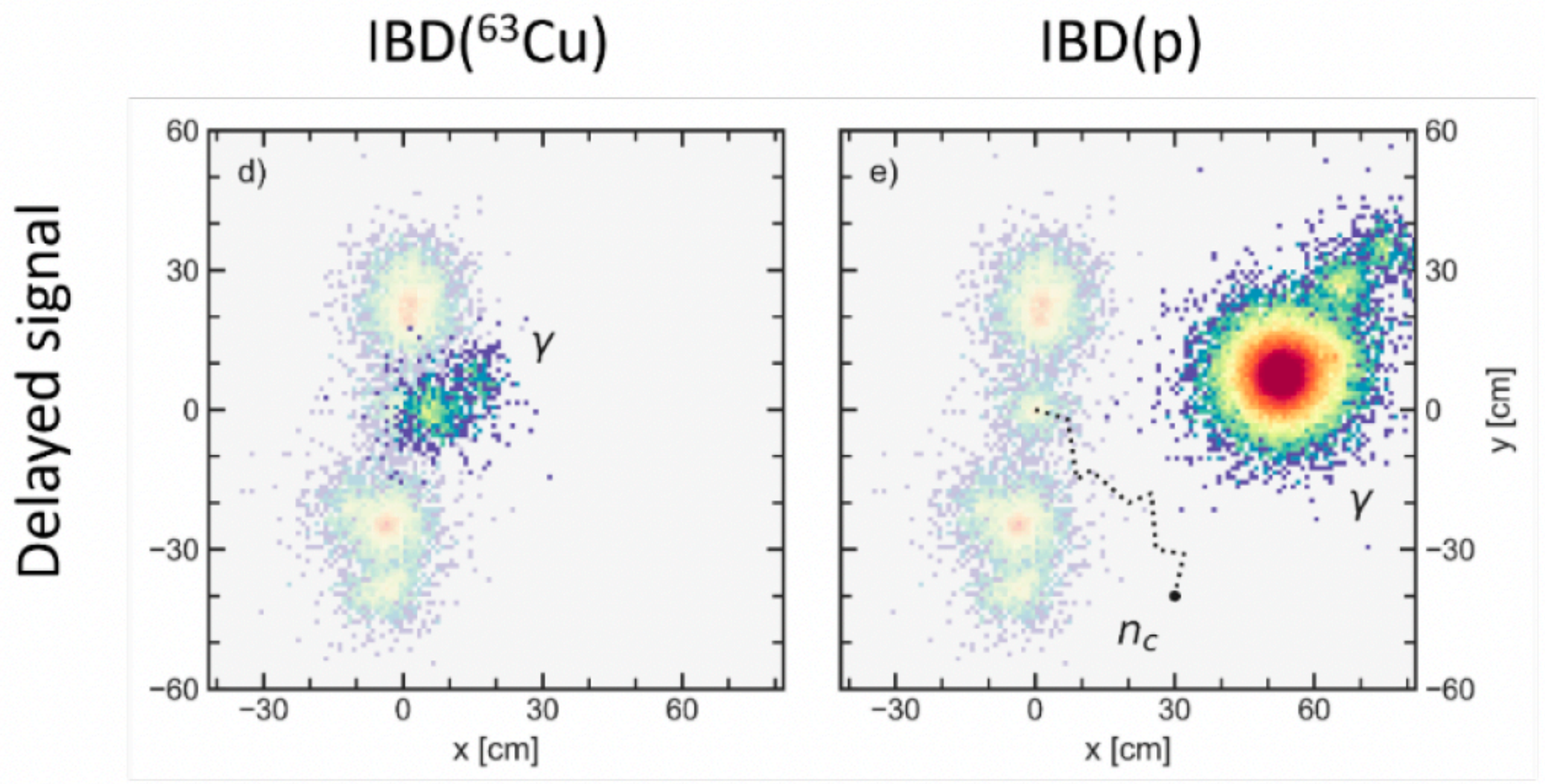
Table 3 Antineutrino targets with product lifetime ≥1 day and $Q_{\mathrm{ns}} < 2$ MeV (in order of increasing log *ft*)

Target process	Q_{B} (MeV) (ground state transition)	log *ft*	Product lifetime	Interaction rate (TAU)	Sensitivity to terrestrial decay
${}^{3}_{2}\mathrm{He} \to {}^{3}_{1}\mathrm{H}$	0.0186	3.1	12 yr	0.32	${}^{238}\mathrm{U}$, ${}^{40}\mathrm{K}$, ${}^{232}\mathrm{Th}$
${}^{33}_{16}\mathrm{S} \to {}^{33}_{15}\mathrm{P}$	0.248	5.0	25 day	0.002	${}^{232}\mathrm{Th}$, ${}^{238}\mathrm{U}$, ${}^{87}\mathrm{Rb}$
${}^{35}_{17}\mathrm{Cl} \to {}^{35}_{16}\mathrm{S}$	0.167	5.0	88 day	0.004	${}^{232}\mathrm{Th}$, ${}^{238}\mathrm{U}$, ${}^{87}\mathrm{Rb}$
${}^{121}_{51}\mathrm{Sb} \to {}^{121}_{50}\mathrm{Sn}$	0.383	5.0	27 h	0.01	${}^{40}\mathrm{K}$, ${}^{238}\mathrm{U}$
${}^{64}_{30}\mathrm{Zn} \to {}^{64}_{29}\mathrm{Cu} \to {}^{64}_{28}\mathrm{N_i}$	0.573	5.3	Stable	0.02	${}^{40}\mathrm{K}$, ${}^{238}\mathrm{U}$, ${}^{232}\mathrm{Th}$
${}^{77}_{34}\mathrm{Se} \to {}^{77}_{33}\mathrm{As}$	0.68	5.7	1.6 day		
${}^{175}_{71}\mathrm{Lu} \to {}^{175}_{70}\mathrm{Vb}$	0.467	6.3	5.5 day	$\sim 10^{-2}$	
${}^{169}_{69}\mathrm{Tm} \to {}^{169}\mathrm{Er}$	0.34	6.4	9.4 day		
${}^{185}_{75}\mathrm{Re} \to {}^{185}_{74}\mathrm{W}$	0.49	6.5	75 day		
${}^{177}_{72}\mathrm{Hf} \to {}^{177}_{71}\mathrm{Lu}$	0.497	6.6	6.7 day		
${}^{63}_{29}\mathrm{Cu} \to {}^{63}_{28}\mathrm{Ni}$	0.067	6.7	92 yr	0.04* (0.15–0.2 MeV)	${}^{87}\mathrm{Rb}$, ${}^{232}\mathrm{Th}$
${}^{153}_{63}\mathrm{Eu} \to {}^{153}_{62}\mathrm{Sm}$	0.801	7.2	2 day		
${}^{199}_{80}\mathrm{Hg} \to {}^{199}_{79}\mathrm{Au}$	0.46	7.5	3.15 day		
${}^{151}_{63}\mathrm{Eu} \to {}^{151}_{62}\mathrm{Sm}$	0.076	7.6	87 yr	0.15 (0.15–0.23 MeV)	${}^{87}\mathrm{Rb}$, ${}^{232}\mathrm{Th}$
${}^{141}_{59}\mathrm{Pr} \to {}^{141}_{58}\mathrm{Ce}$	0.58	7.7	33 day		
${}^{161}_{66}\mathrm{Dy} \to {}^{161}_{65}\mathrm{Tb}$	0.58	7.8	7 day		
${}^{155}_{64}\mathrm{Gd} \to {}^{155}_{63}\mathrm{Eu}$	0.248	8.2	1.8 yr		
${}^{14}_{7}\mathrm{N} \to {}^{14}_{6}\mathrm{C}$	0.156	9.0	5×10^{3} yr		
${}^{85}_{37}\mathrm{Rb} \to {}^{85}_{36}\mathrm{Kr}$	0.67	9.1	10.7 yr		
${}^{113}_{49}\mathrm{In} \to {}^{113}_{48}\mathrm{Cd}$	0.58	9.2	14 yr		
${}^{39}_{19}\mathrm{K} \to {}^{39}_{18}\mathrm{Ar}$	0.565	9.9	269 yr		
${}^{204}_{82}\mathrm{Pb} \to {}^{204}_{81}\mathrm{Tl}$	0.765	9.9	3.8 yr		
${}^{79}_{35}\mathrm{Br} \to {}^{79}_{34}\mathrm{Se}$	0.154	10.8	6.5×10^{4} yr	0.08 (0.25 MeV)	${}^{87}\mathrm{Rb}$, ${}^{232}\mathrm{Th}$
${}^{107}_{47}\mathrm{Ag} \to {}^{107}_{46}\mathrm{Pd}$	0.035	10.8	7×10^{6} yr		

IBD on Cu

LiquidO





$$\bar{\nu}_e + {}^{63}Cu \rightarrow {}^{63}Ni^* + e^+$$

$$e^+ + e^- \rightarrow 2\gamma$$

$${}^{63}Ni^* \rightarrow {}^{63}Ni + \gamma$$

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

$$e^+ + e^- \rightarrow 2\gamma$$

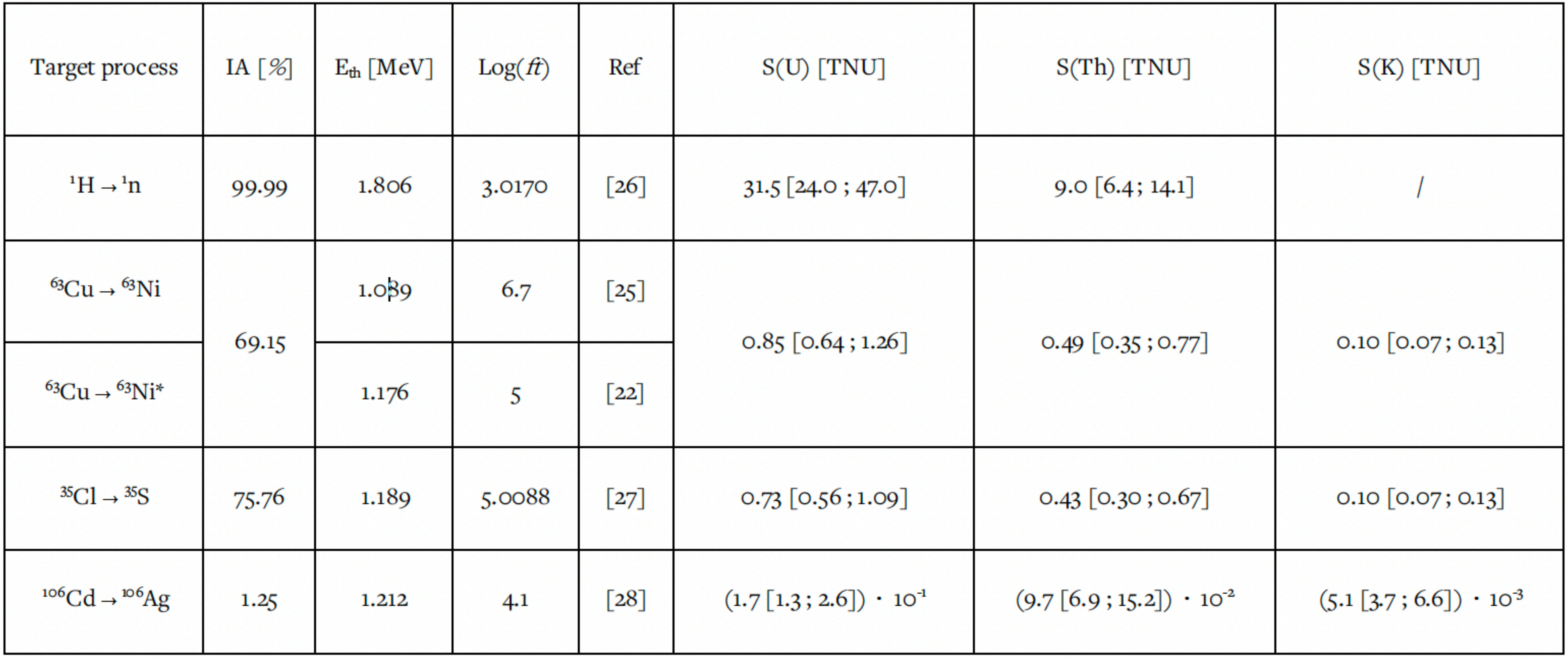
$$n + p \rightarrow d + \gamma$$

$$n + {}^{63}Cu \rightarrow {}^{64}Cu + \gamma's$$

$$n + {}^{65}Cu \rightarrow {}^{66}Cu + \gamma's$$

Neutrino Capture…again

LiquidO for Geoneutrinos



Target process	IA [%]	E_{th} [MeV]	Log(ft)	Ref	S(U) [TNU]	S(Th) [TNU]	S(K) [TNU]
$^{1}\mathrm{H} \rightarrow {}^{1}\mathrm{n}$	99.99	1.806	3.0170	[26]	31.5 [24.0 ; 47.0]	9.0 [6.4; 14.1]	/
$^{63}\mathrm{Cu} \rightarrow {}^{63}\mathrm{Ni}$	69.15	1.089	6.7	[25]	0.85 [0.64 ; 1.26]	0.49 [0.35 ; 0.77]	0.10 [0.07; 0.13]
$^{63}\mathrm{Cu} \rightarrow {}^{63}\mathrm{Ni}^{*}$		1.176	5	[22]			
$^{35}\mathrm{Cl} \rightarrow {}^{35}\mathrm{S}$	75.76	1.189	5.0088	[27]	0.73 [0.56 ; 1.09]	0.43 [0.30 ; 0.67]	0.10 [0.07; 0.13]
$^{106}\mathrm{Cd} \rightarrow {}^{106}\mathrm{Ag}$	1.25	1.212	4.1	[28]	$(1.7\ [1.3 ; 2.6]) \cdot 10^{-1}$	$(9.7\ [6.9 ; 15.2]) \cdot 10^{-2}$	$(5.1\ [3.7 ; 6.6]) \cdot 10^{-3}$

Signatures challenging to detect

- Start with *Thresholdless*
  - Neutrino-electron Elastic Scattering
  - Coherent **Elastic** Neutrino-Nucleus Scattering (CEvNS)
  - Neutrino Capture on **radioactive** Nuclei
- Next Lecture: Low-Threshold Neutrino Detection
  - Neutrino Capture on **stable** nuclei
  - Neutral Current **Inelastic** Scattering


SNO+
IceCube
Super-Kamiokande
DUNE
MINERvA
NOvA
COHERENT
JUNO
ν
KamLAND
RENO
Borexino
HALO
LZ
DEAP-3600
XMASS
GERDA