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Searching for Neutrinoless Double Beta Decay at SNOLAB

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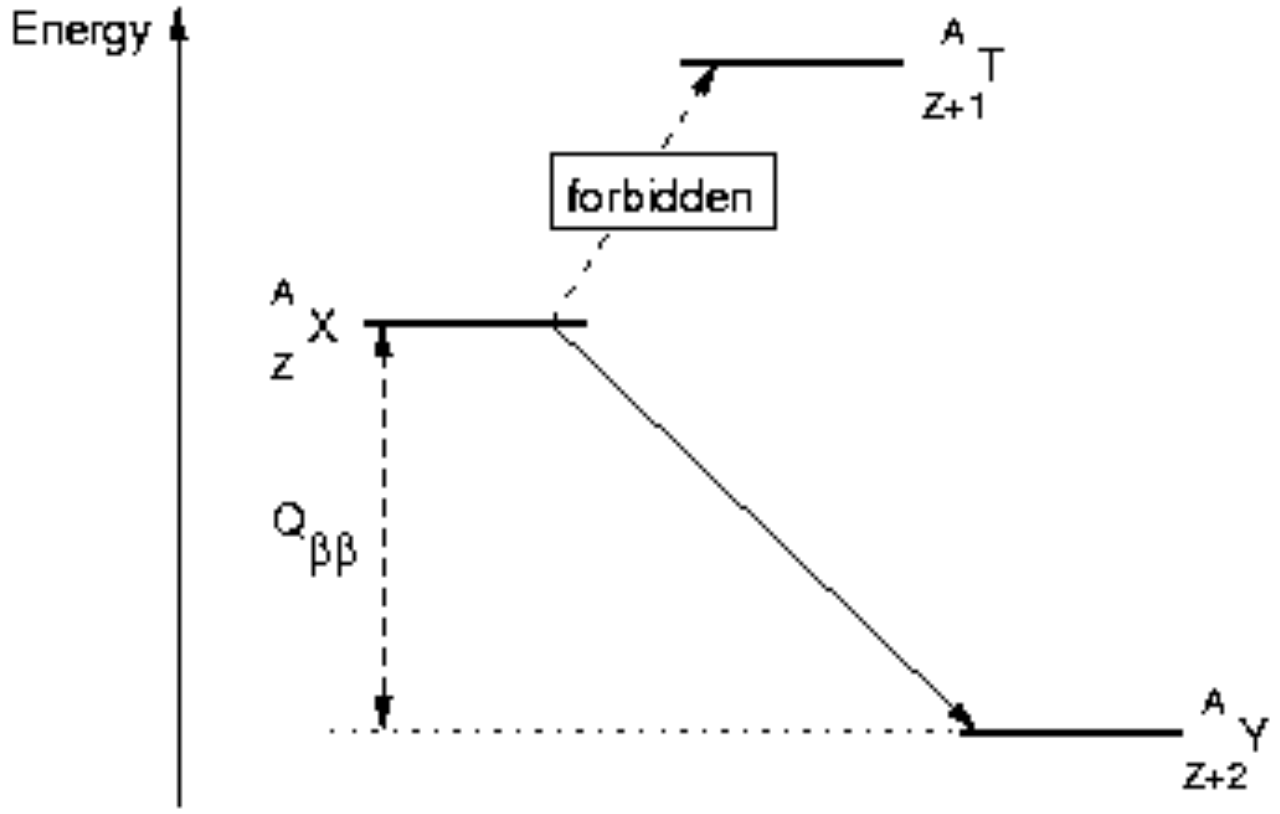
SNOLAB

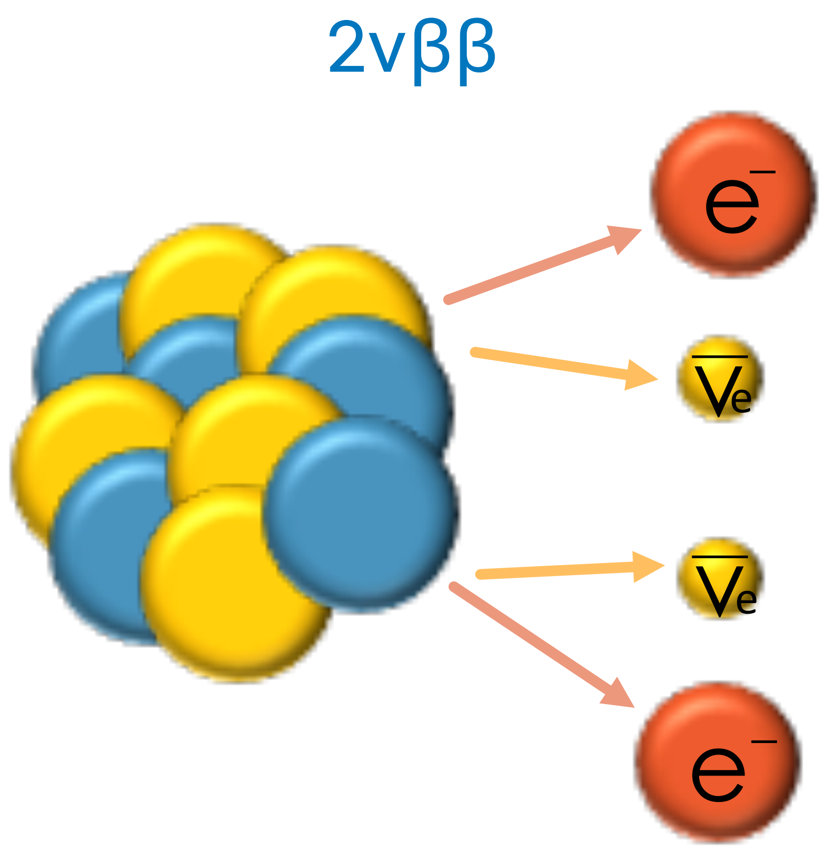
Double Beta Decay

What we DO know about Neutrinos

- Fermion: spin 1/2, electrically neutral
- Only experience the weak force, rarely interacting with anything
- They come in three flavors associated with three other fundamental particles
  - electron, muon and tau
- They change, or oscillate, from one type to another
- Most abundant massive particles in the universe, 340/cm^3

Double Beta Decay





- M. Goeppert-Mayer
- Physical Review 48 (1935) 512

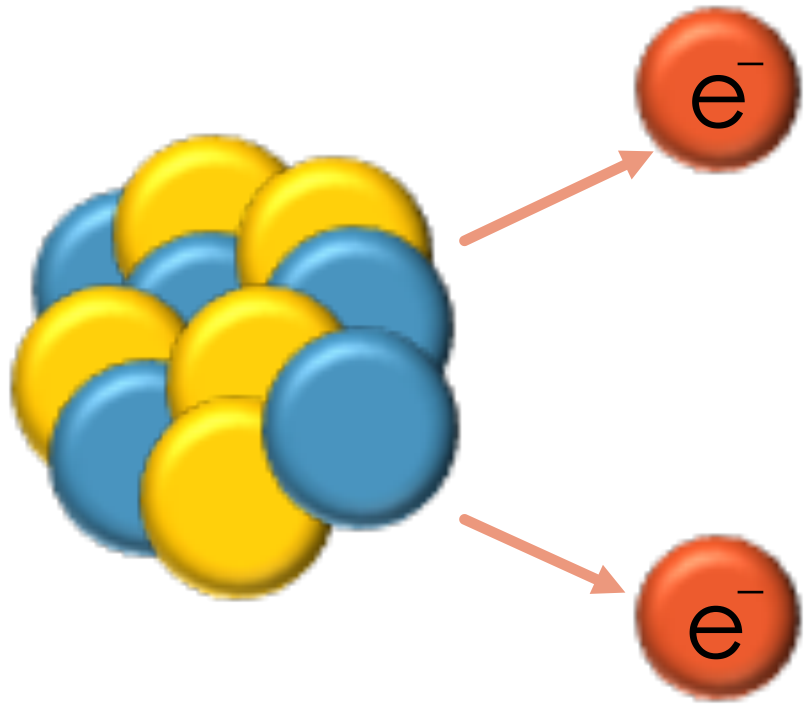
- Candidate isotopes: Even-even nuclei where single β decay is forbidden

- Allowed in Standard Model
- Observed in 12 isotopes

Neutrinoless Double Beta Decay

- E. Majorana
- Nuovo Cimento 14, 171 (1937)

0νββ

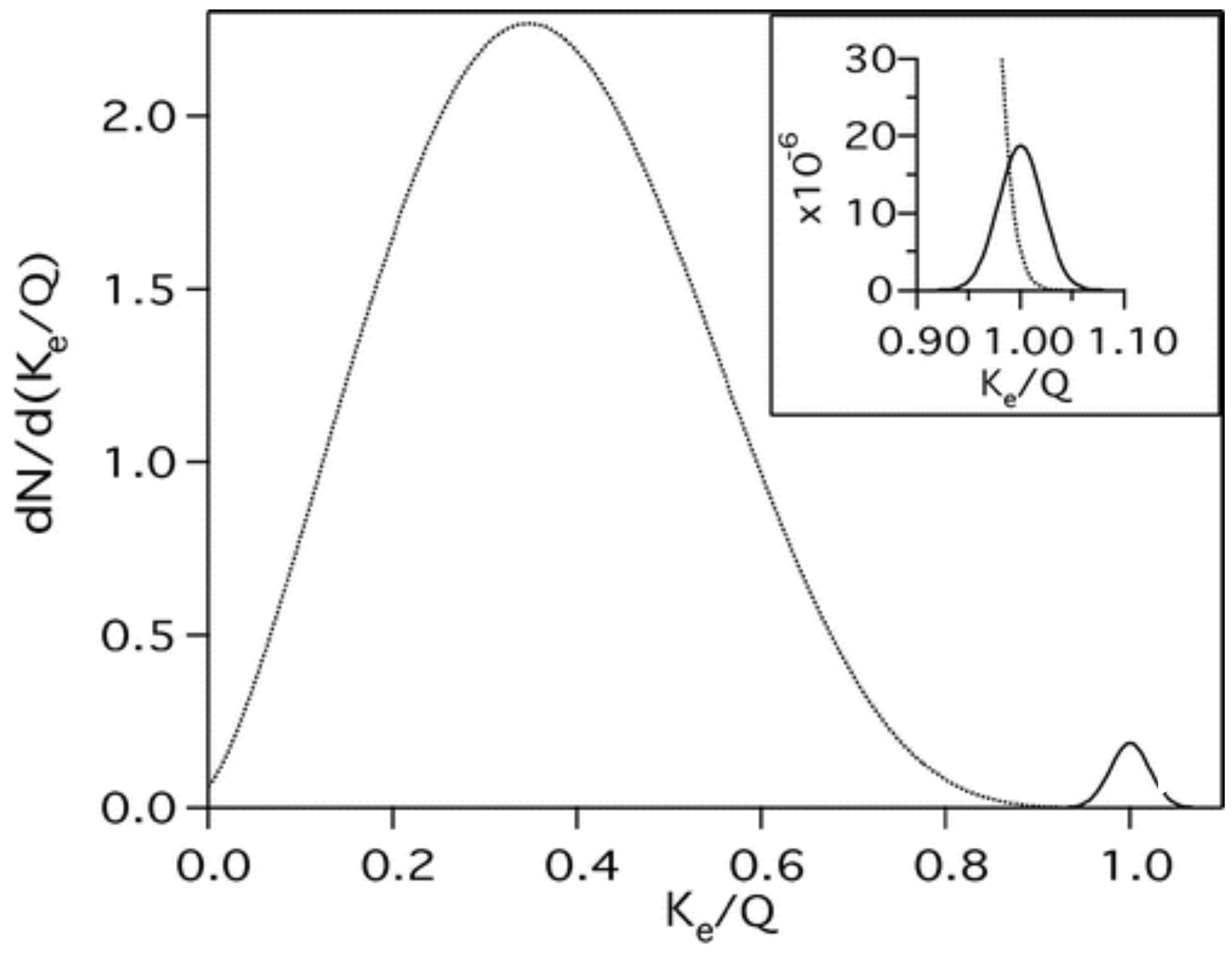


$$\nu \equiv \bar{\nu}$$

- Not yet observed
- Implies non-conservation of lepton number
- Implies neutrinos are Majorana particles

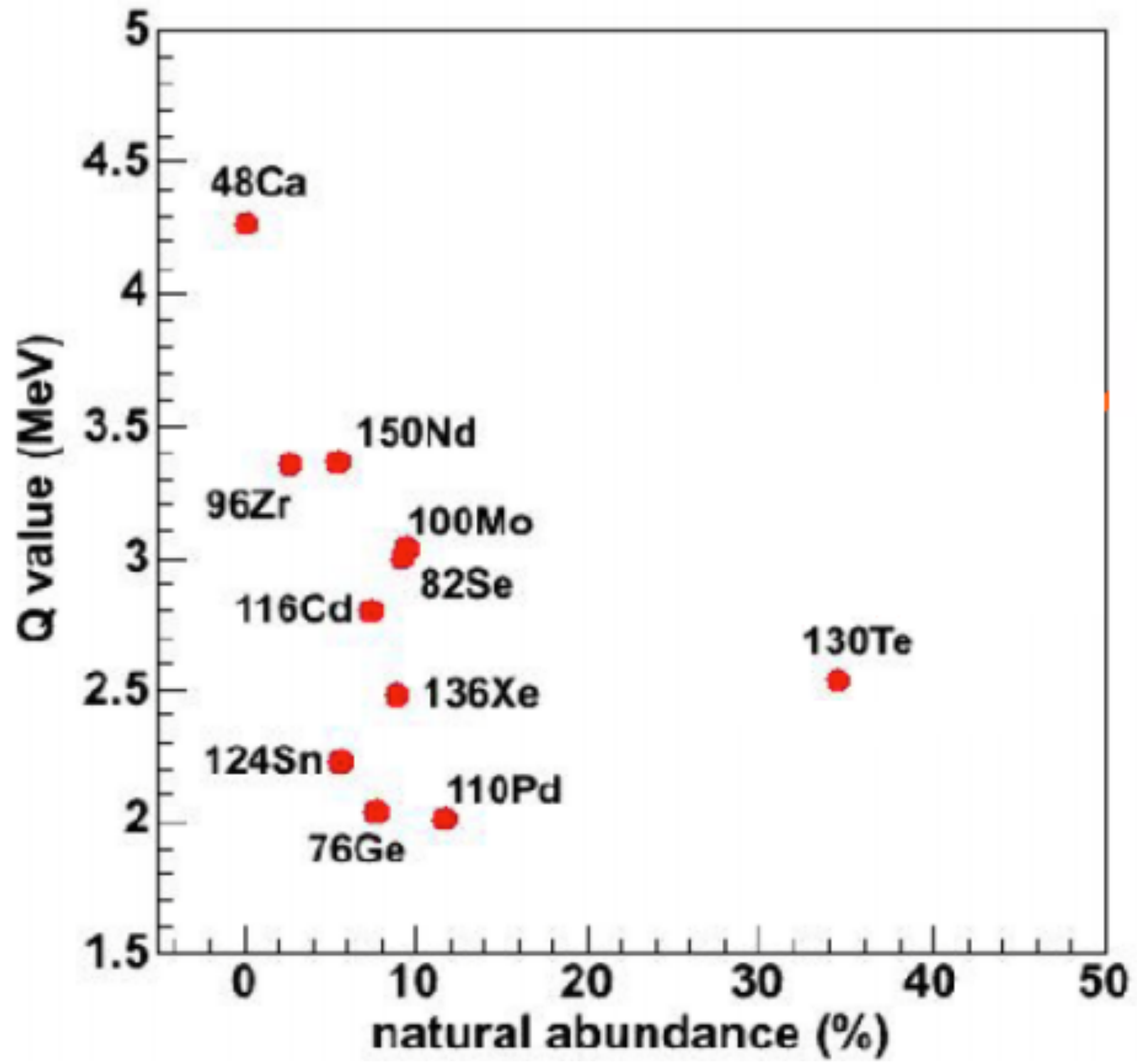
Neutrinoless Double Beta Decay

- Key experimental signature for 0νββ is a peak in visible energy at the Q-value of the nucleus, smeared by detector resolution.
- Requirements:
  - Large source mass
  - Good energy resolution
  - Low backgrounds

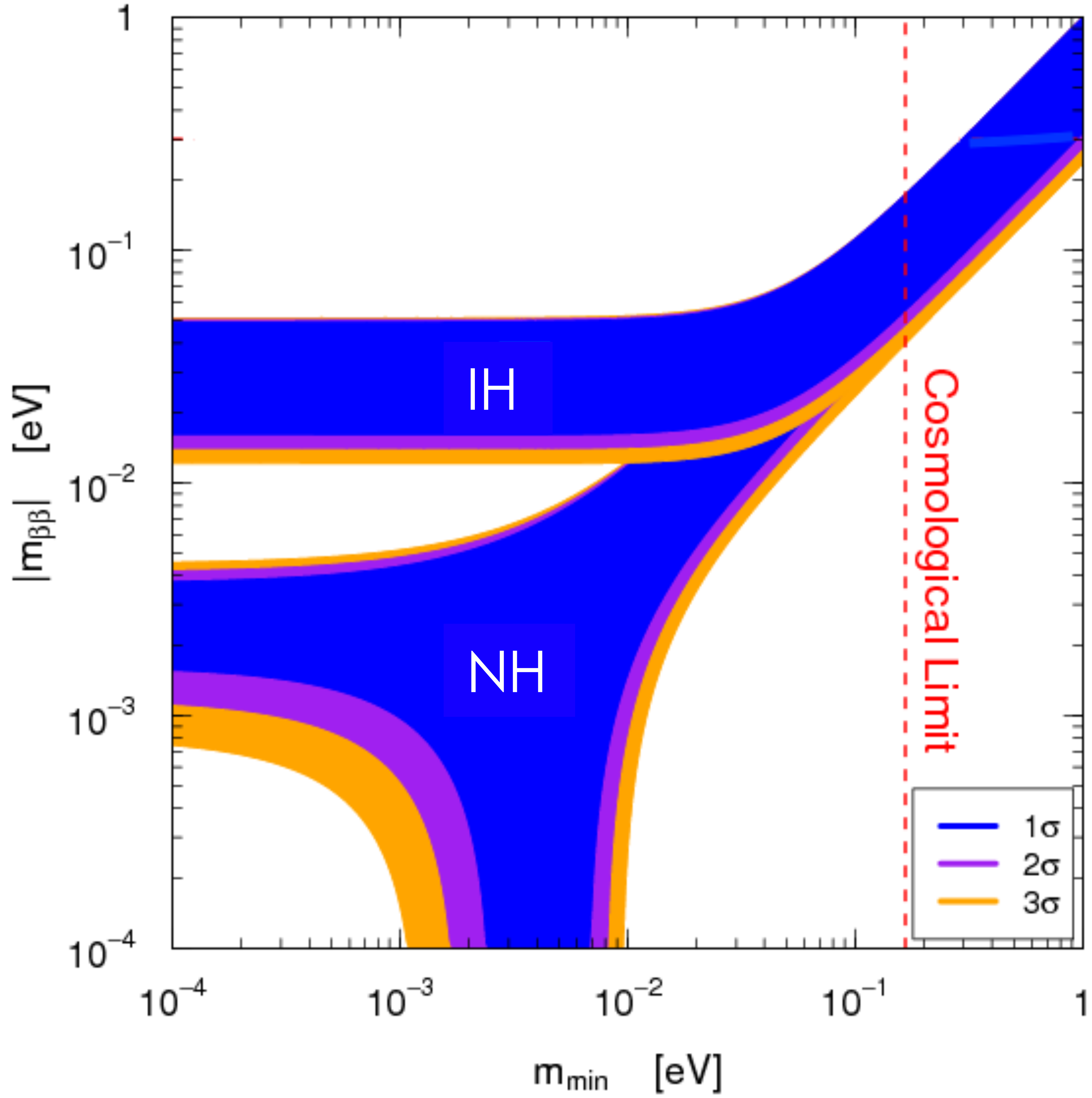


Chose Isotope based on:

- 2νββ half-life
- Q-value
- Natural Abundance
- Detector Compatibility



Neutrinoless Double Beta Decay



The rate of $0\nu\beta\beta$ is given by

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}|M^{0\nu}|^2\langle m_{\beta\beta}\rangle^2$$

$T_{1/2}$: half-life
G: phase space factor
M: nuclear matrix element
$m_{\beta\beta}$: effective neutrino mass

$$\langle m_{\beta\beta}\rangle = |\sum_i U^2_{ei} m_i|$$

SNOLAB

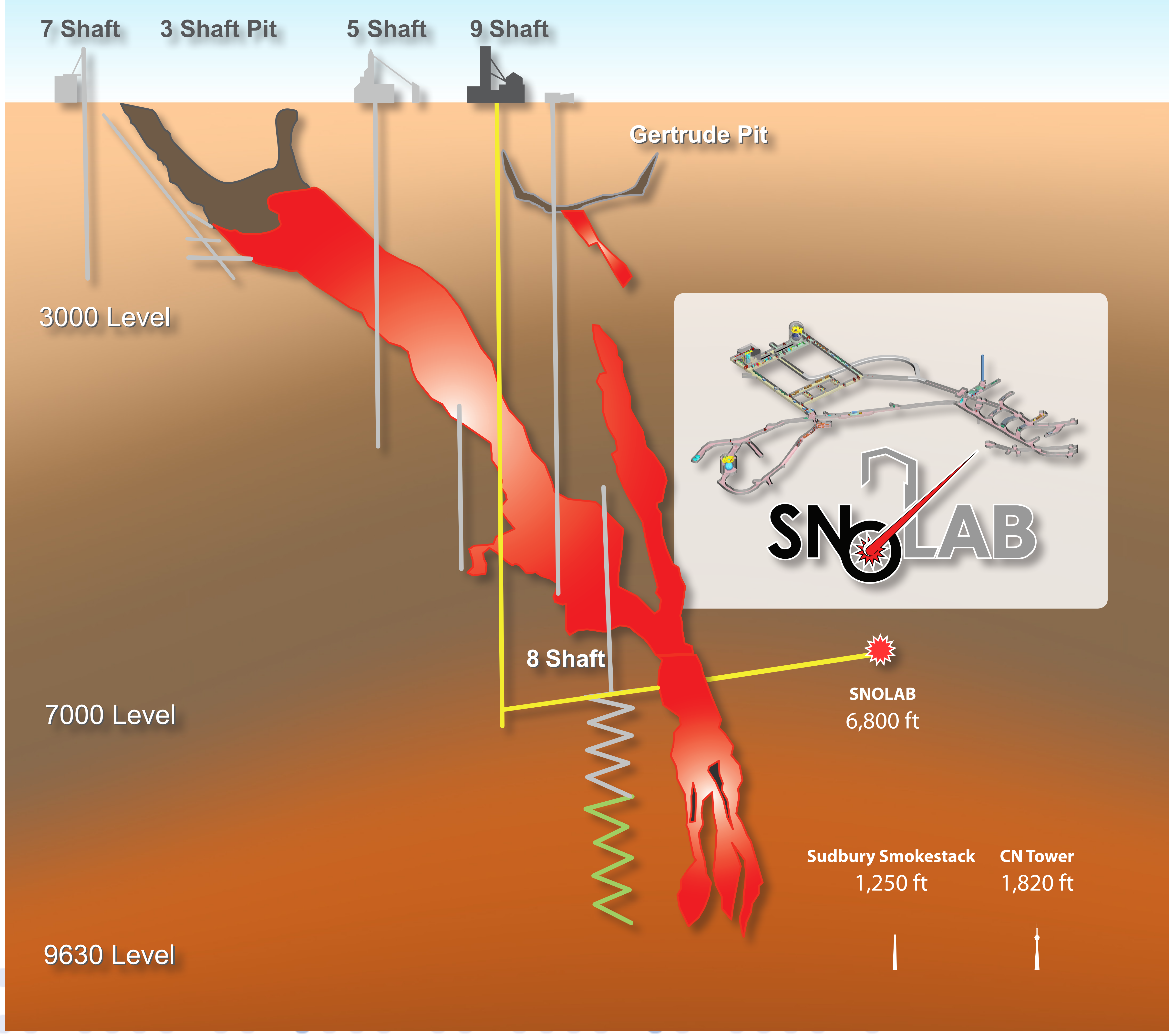
SNOLAB

SNOLAB is located on the traditional territory of the Robinson-Huron Treaty of 1850, shared by the Indigenous people of the surrounding Atikameksheng Anishnawbek First Nation as part of the larger Anishinabek Nation.

We acknowledge those who came before us and honour those who are the caretakers of this land and the waters.

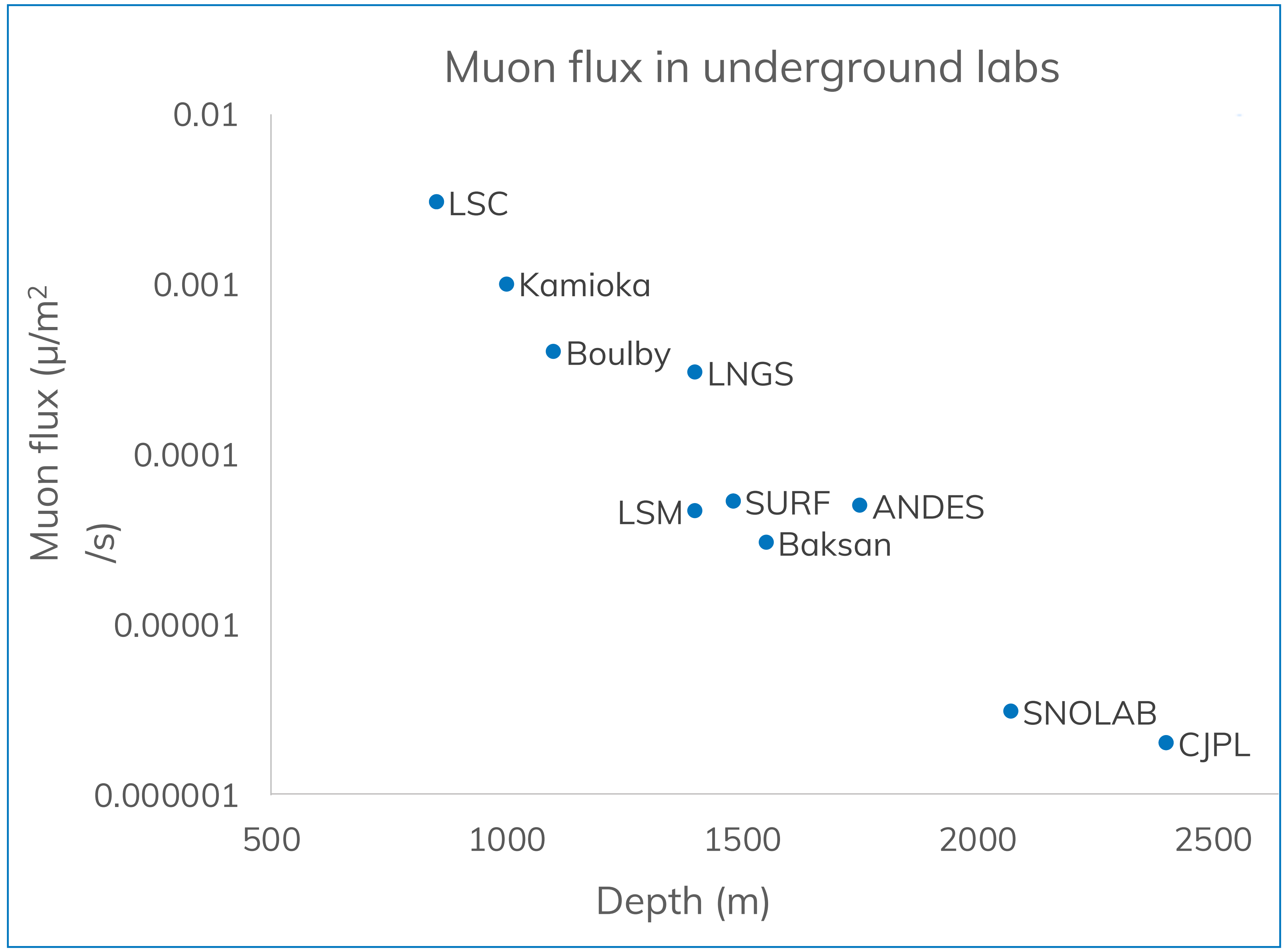
https://en.wikipedia.org/wiki/SNOLAB

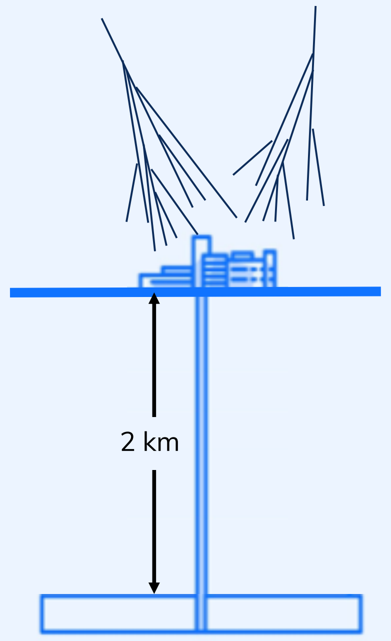
CREIGHTON MINE



About SNOLAB

SNOLAB is a science laboratory specializing in neutrino and dark matter physics. It's located 2 km underground in the active Vale Creighton nickel mine near Sudbury, Ontario, Canada.



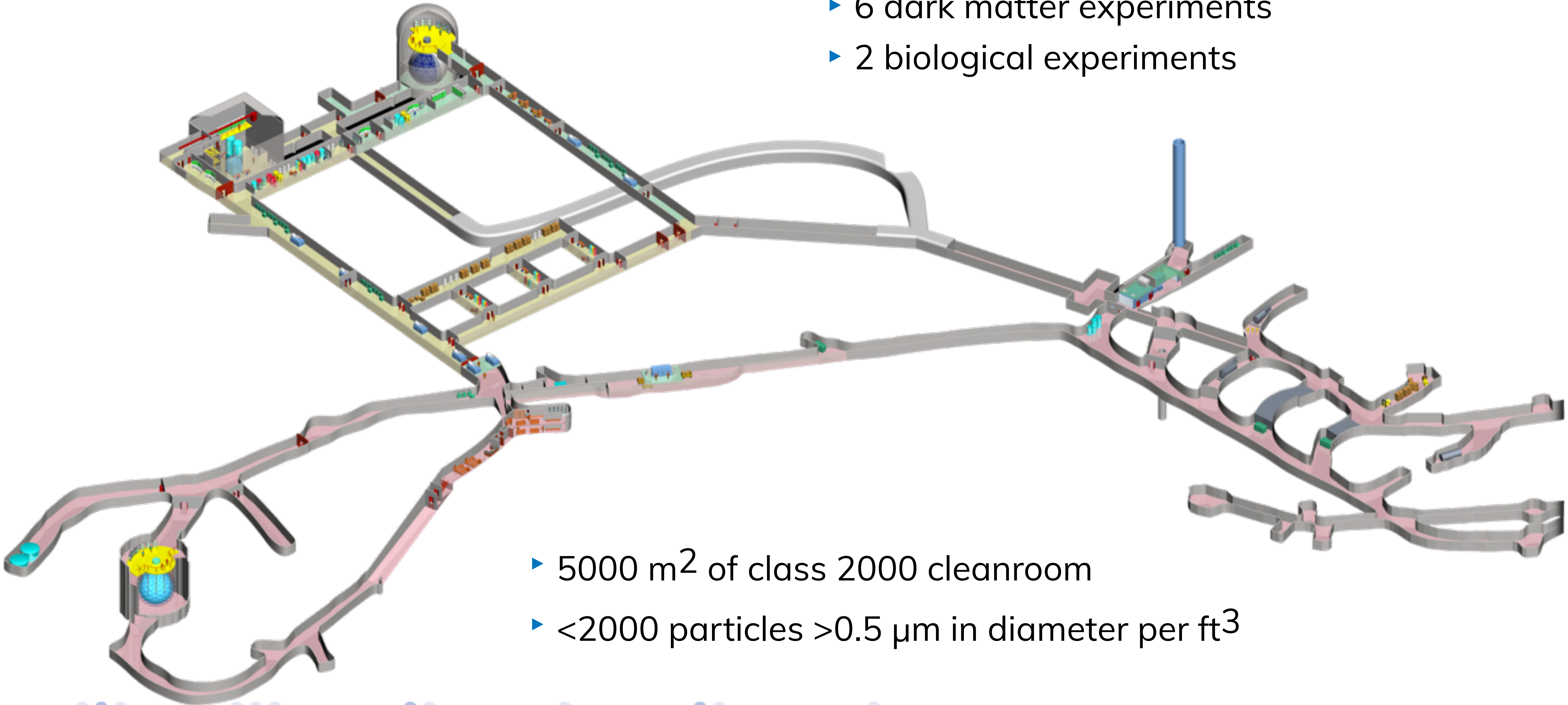


2 km of rock reduces the cosmic radiation by a factor of ~50 million!

SNOLAB Layout

SNOLAB is home to:

- 2 neutrino experiments
- 6 dark matter experiments
- 2 biological experiments

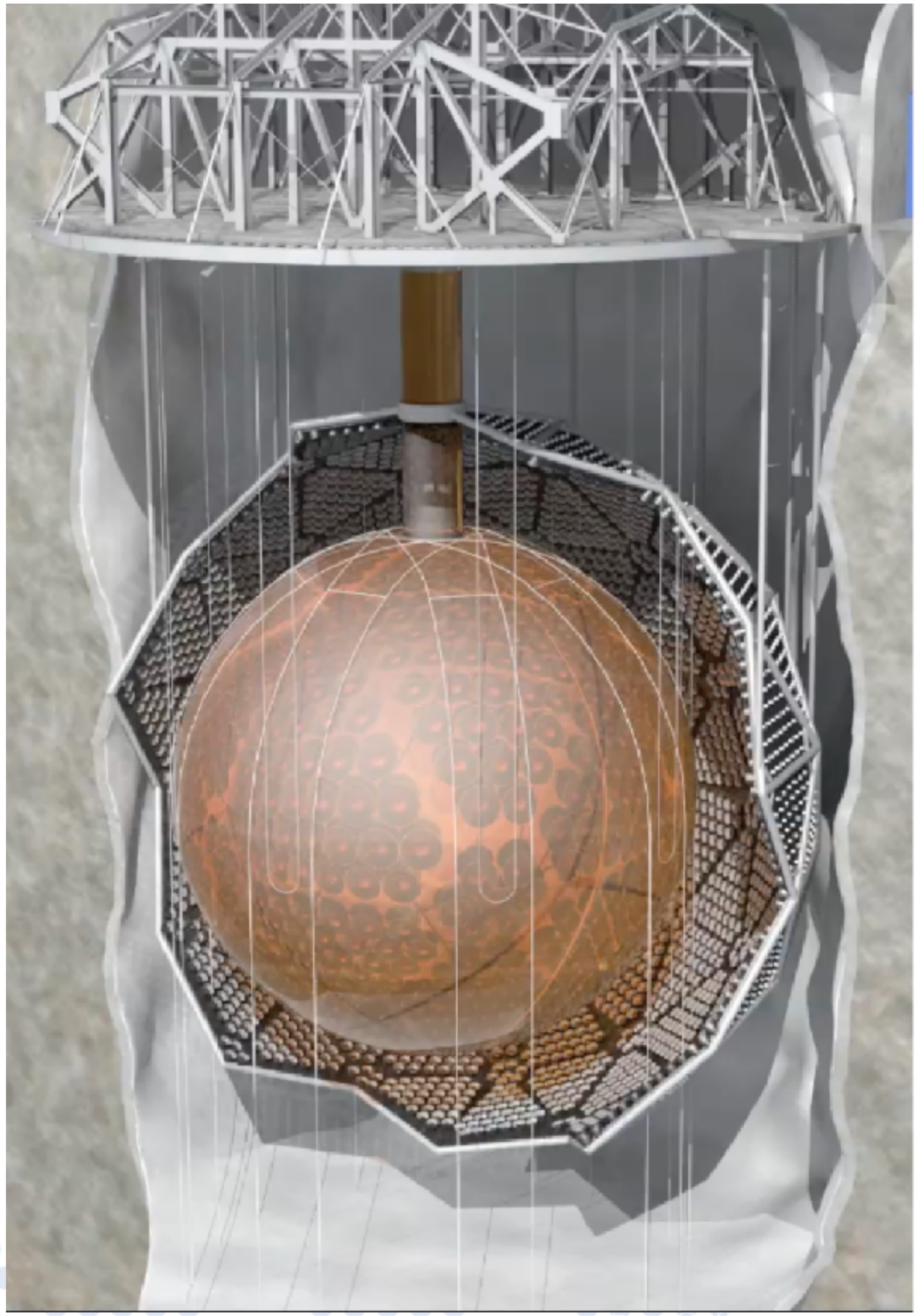


- 5000 m^2 of class 2000 cleanroom
- <2000 particles >0.5 μm in diameter per ft^3

SNO+

SNO+

- Floating Deck
- Urylon liner: Rn seal
- Acrylic Vessel
  - Φ 12 m,5 cm thick
- Water shielding
  - 1.7 kt inner, 5.3 kt outer
- ~9300 PMTs, 50% coverage

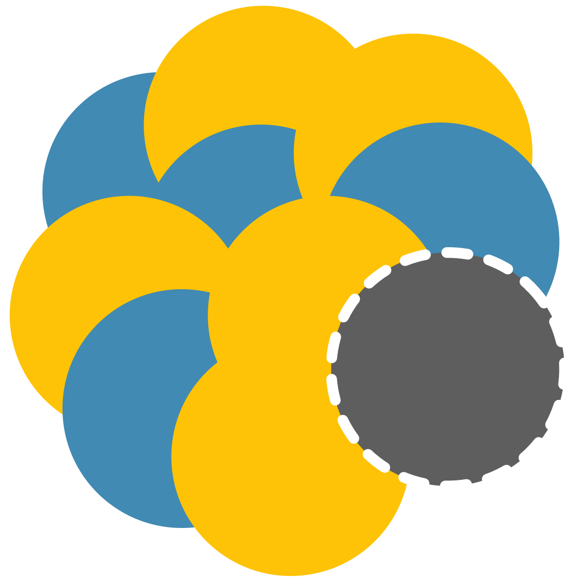


- Upgraded DAQ
- New Calibration Systems
- Replaced Hold Up Ropes
- Optical Monitoring System
- Hold Down Rope Net
- 780 t Liquid Scintillator
- 3.9 t Tellurium

SNO+ Physics Program

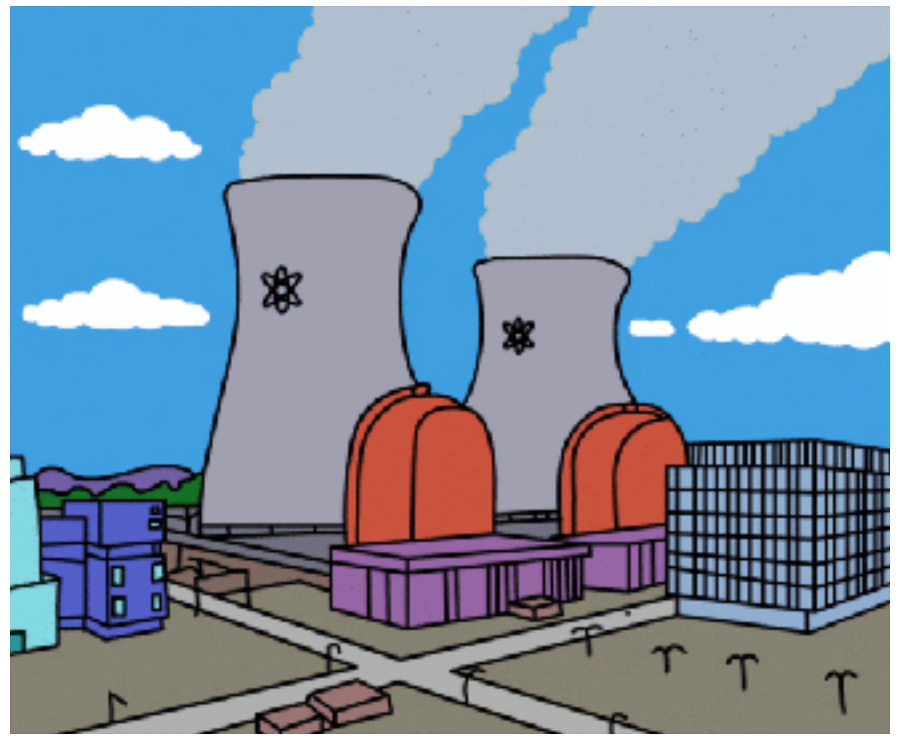
Solar Neutrinos

Supernovae

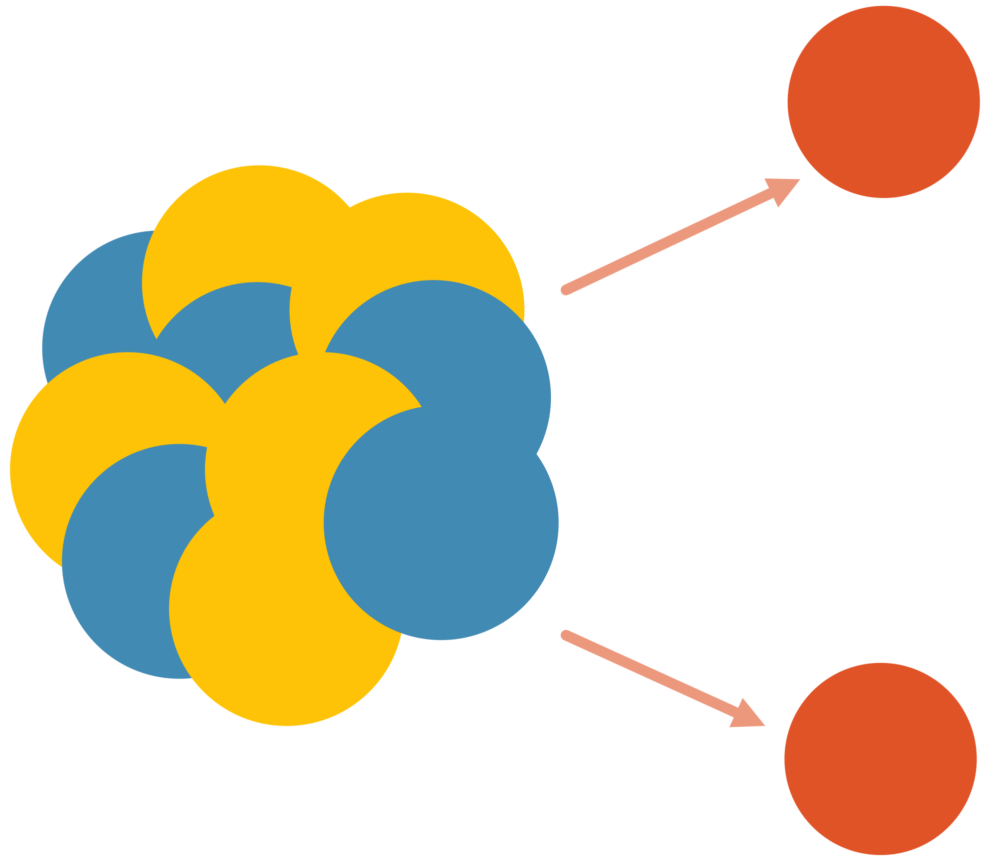


Nucleon Decay

Geo Antineutrinos



Reactor Antineutrinos

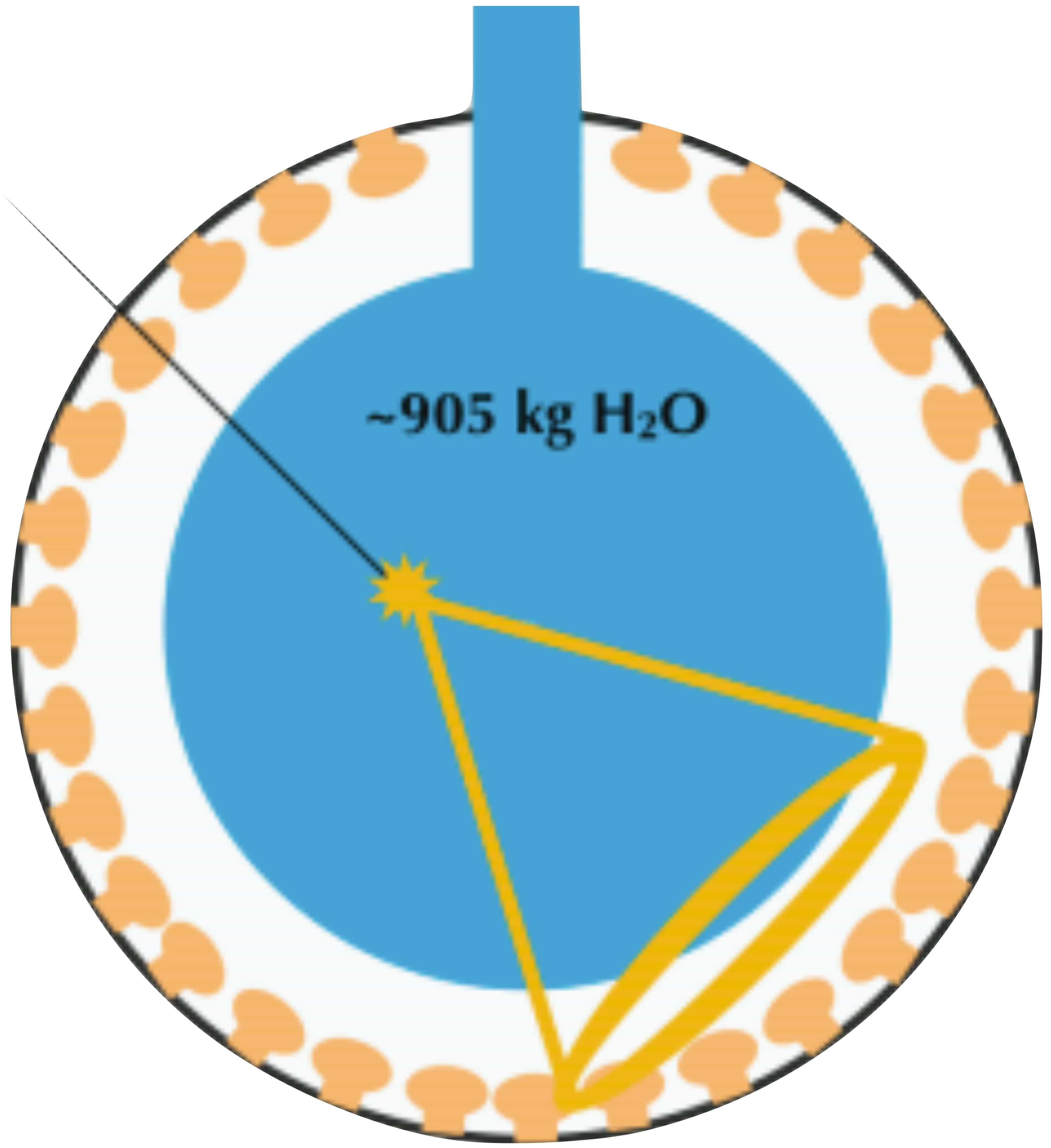


Double Beta Decay

SNO+ Timeline

SNO+ Timeline

1. Water Phase (May 2017-July 2019)
   - Detector Calibration [Phys.Rev.C102,014002(2020)]
   - Backgrounds Measurement
   - Solar ^{8}B Flux [Phys.Rev.D**99** (2019) 012012]
   - Invisible Nucleon Decay [Phys.Rev.D**99** (2019) 032008]



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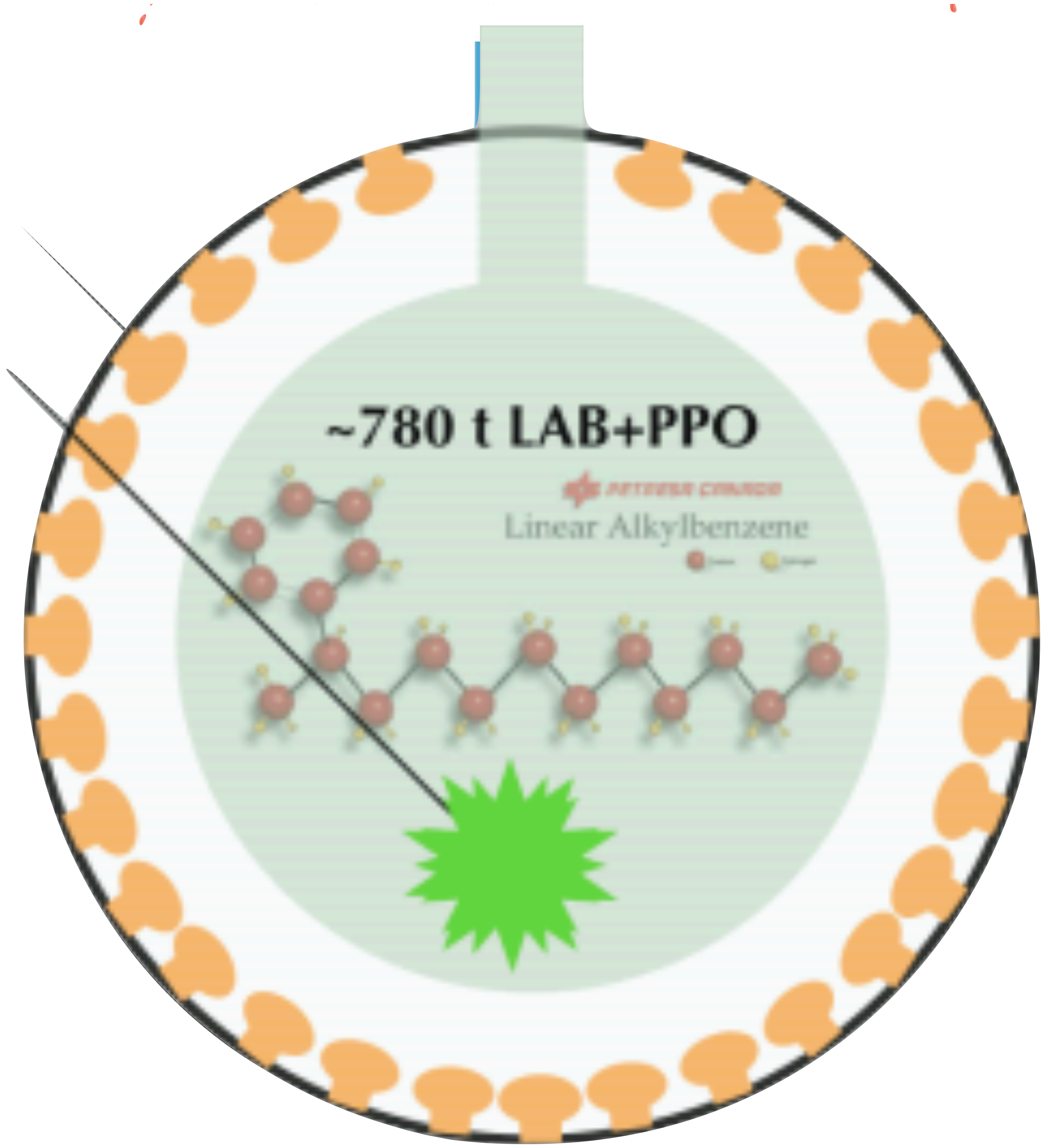
2. Scintillator Phase (Currently)
   - Detector Calibration
   - Background Measurements
   - Antineutrino Measurements
   - Supernova Neutrinos



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2. Scintillator Phase (Currently)
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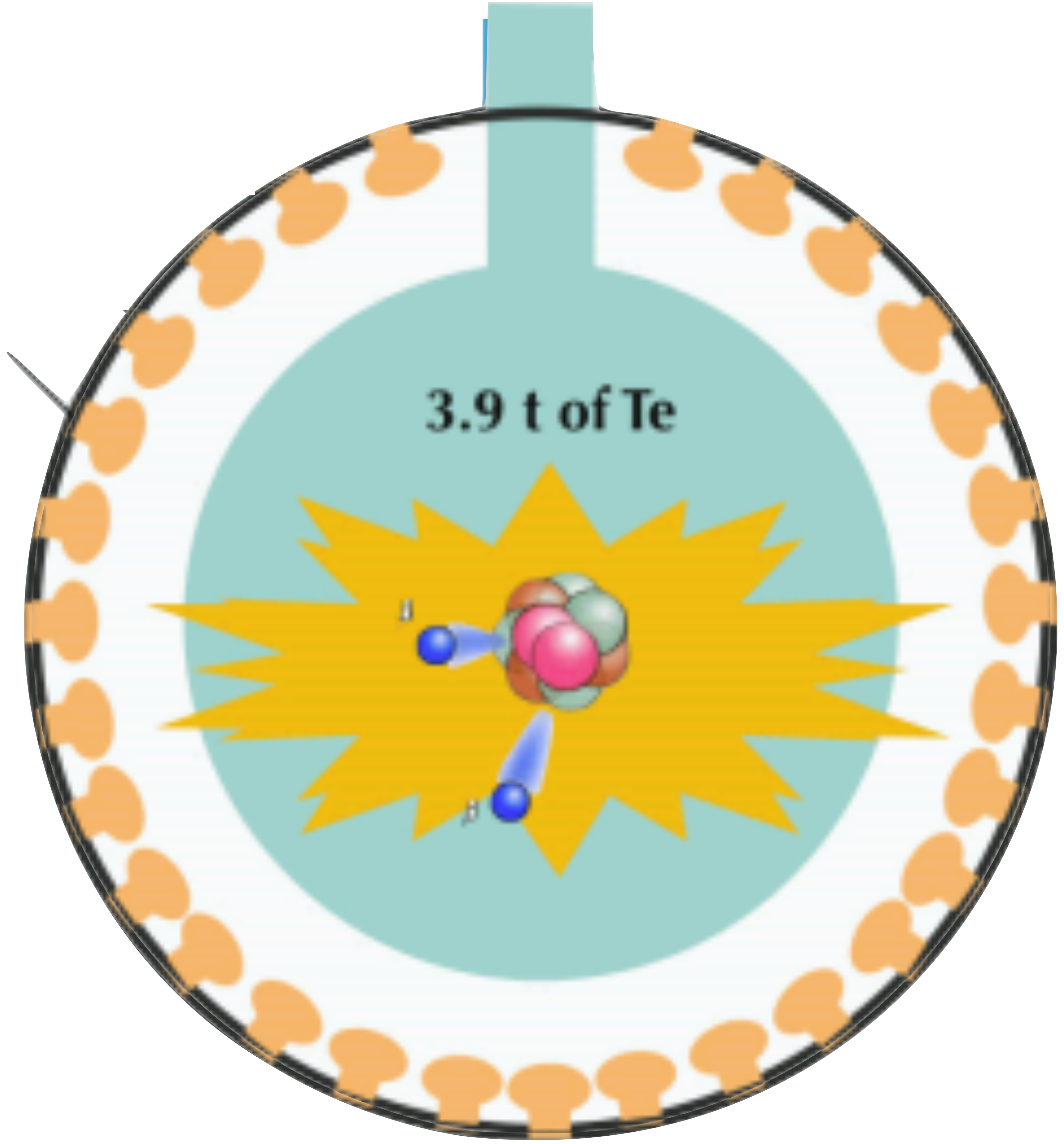
   - Antineutrino Measurements
   - Supernova Neutrinos
3. Te-loaded Phase (Late 2021)
   - Neutrinoless Double Beta Decay
   - ^{130}Te (34% nat. ab.)
   - 0.5% loading by mass (1.3t of ^{130}Te)




3 February 2021

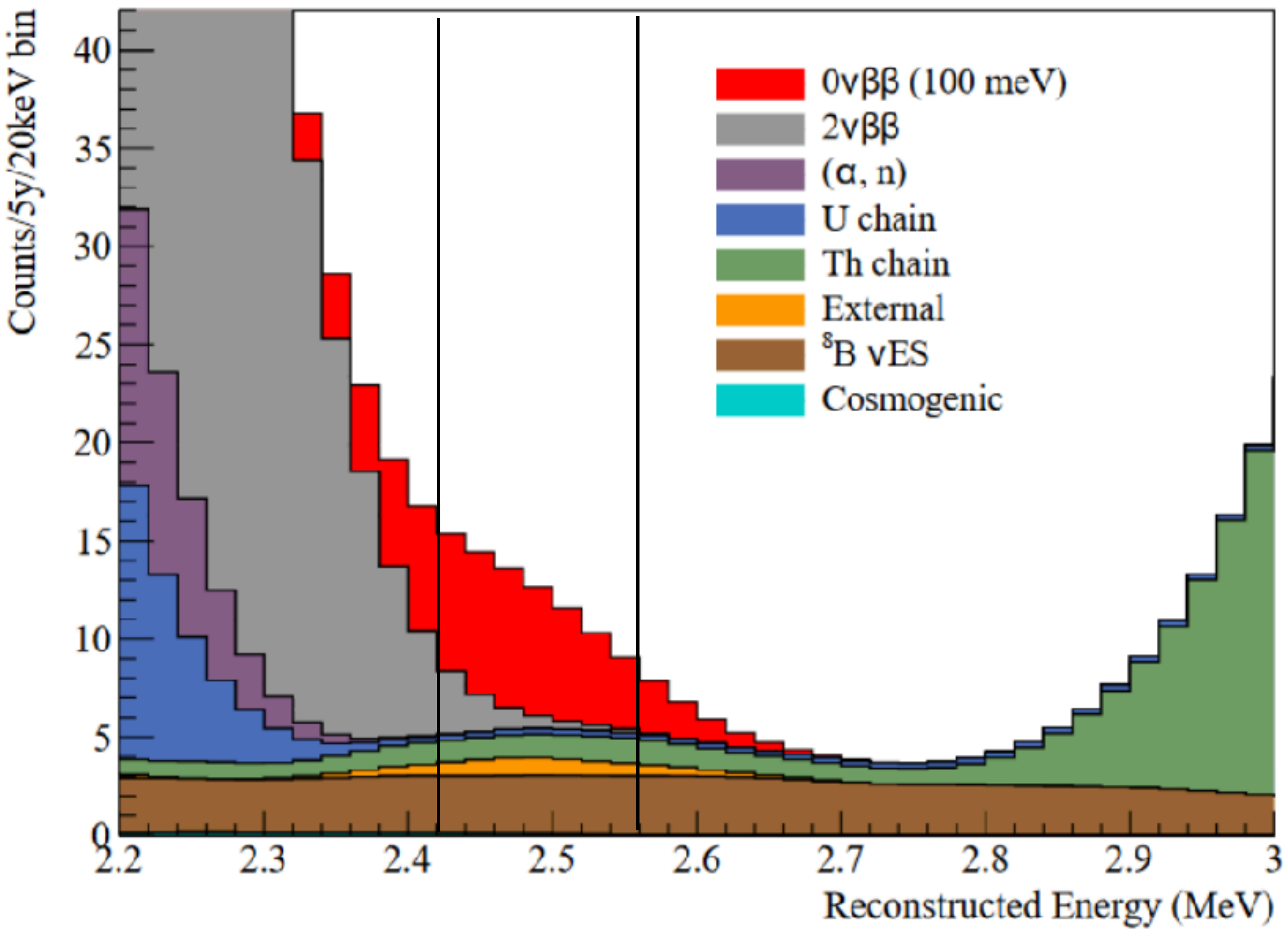
Telluric Acid Purification Plant Commissioning

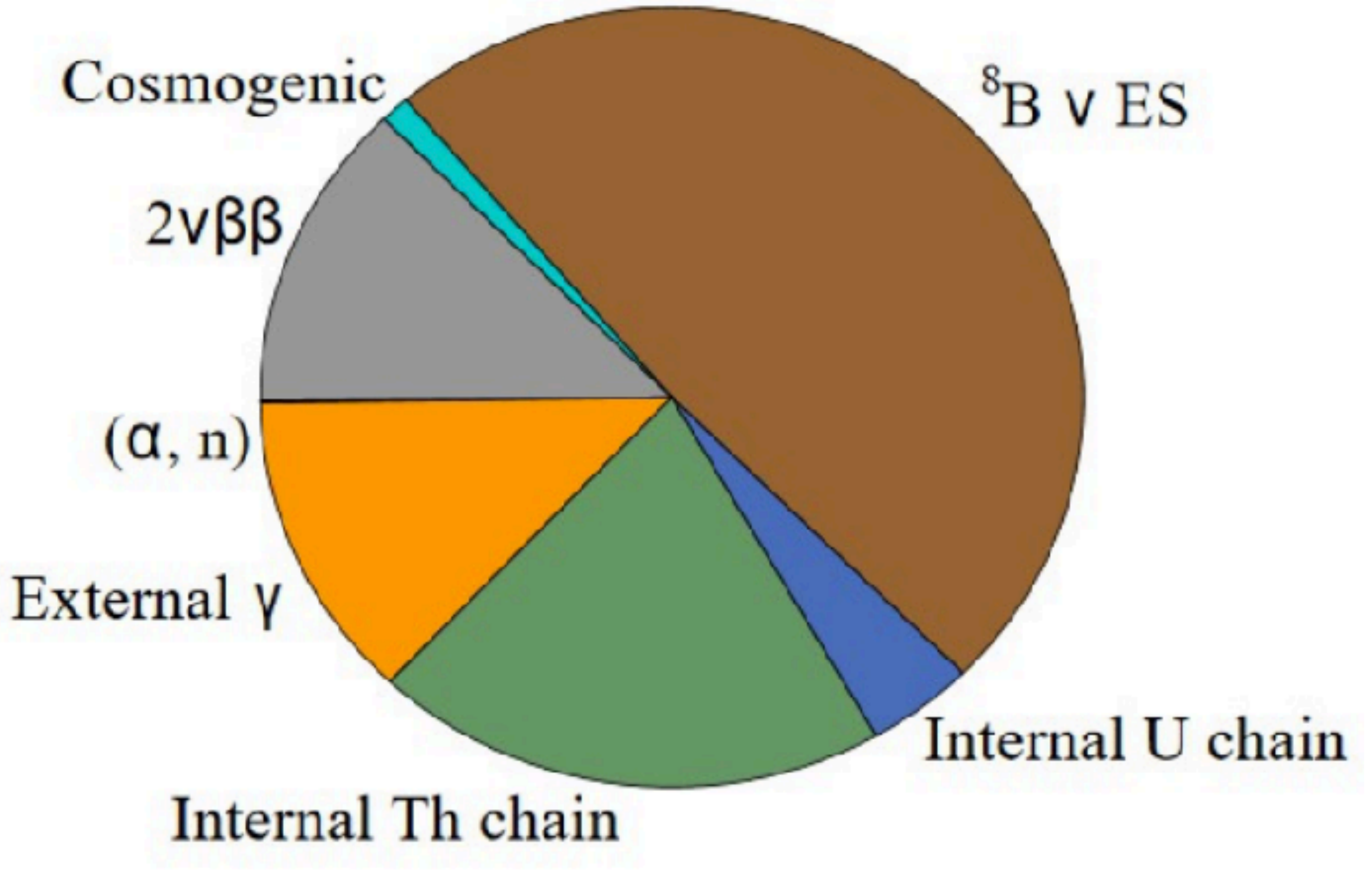
Purify Telluric Acid in pH and temperature based reaction.

Tellurium Diol Plant Commissioning

Synthesize Butanediol to combine purified Telluric Acid in scintillator.

0νββ decay of ^{130}Te in SNO+





ROI: 2.42 - 2.56 MeV [-0.5σ - 1.5σ]
Counts/Year: 9.47

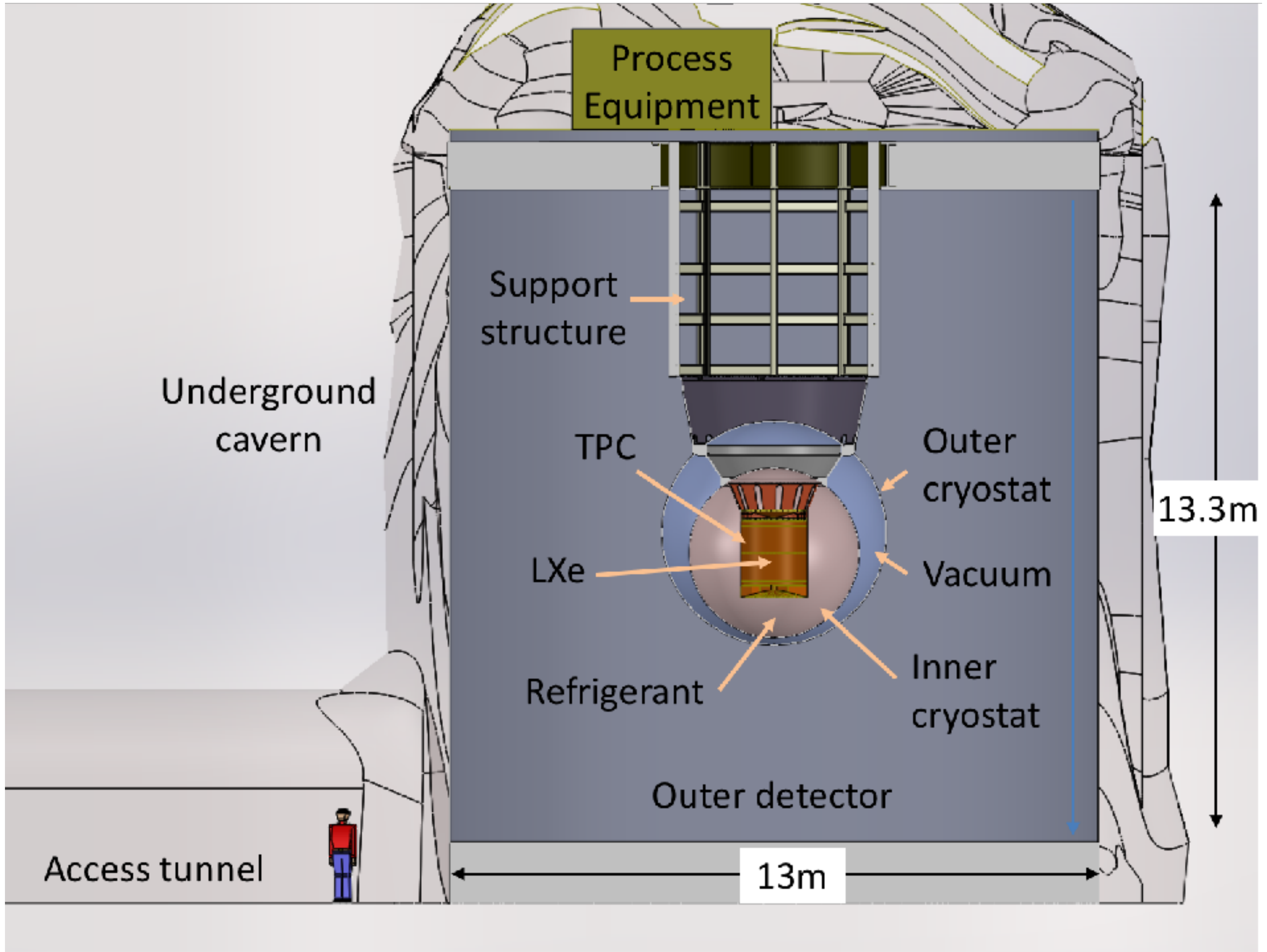
- 5 years of initial loading
- Fiducial Radius: 3.3m
- 0νββ decay half-life sensitivity:

$$T_{1/2}^{0\nu} > 2.1 \times 10^{26} \text{yr (90\%C.L.)}$$

nEXO

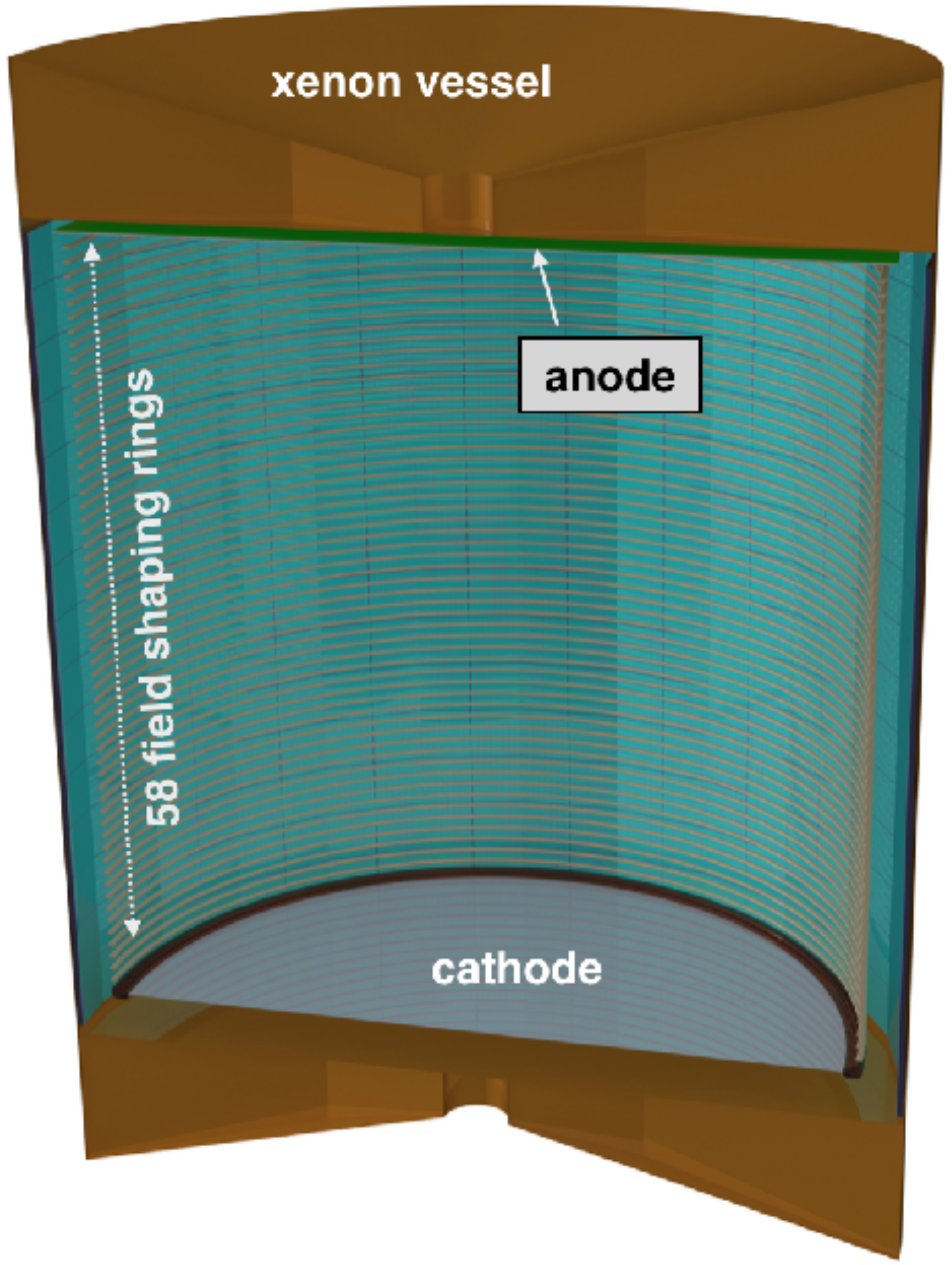
nEXO

- 5 tonnes liquid Xenon, enriched in ^{136}Xe to 90% isotopic purity
- Pending selection but US DOE of 0νββ detector technology and site
- SNOLAB's Cryopit is nEXO's preferred site

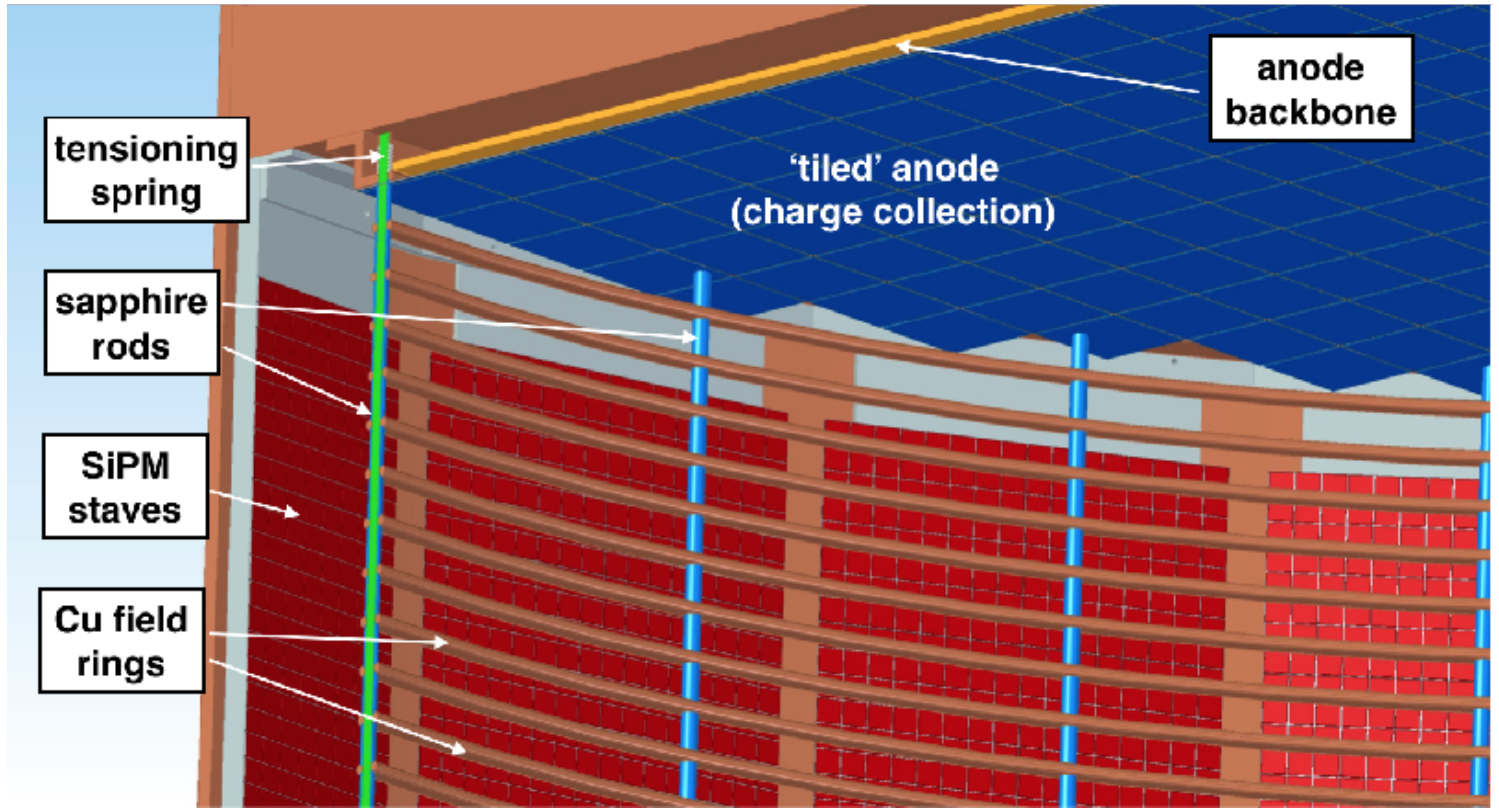


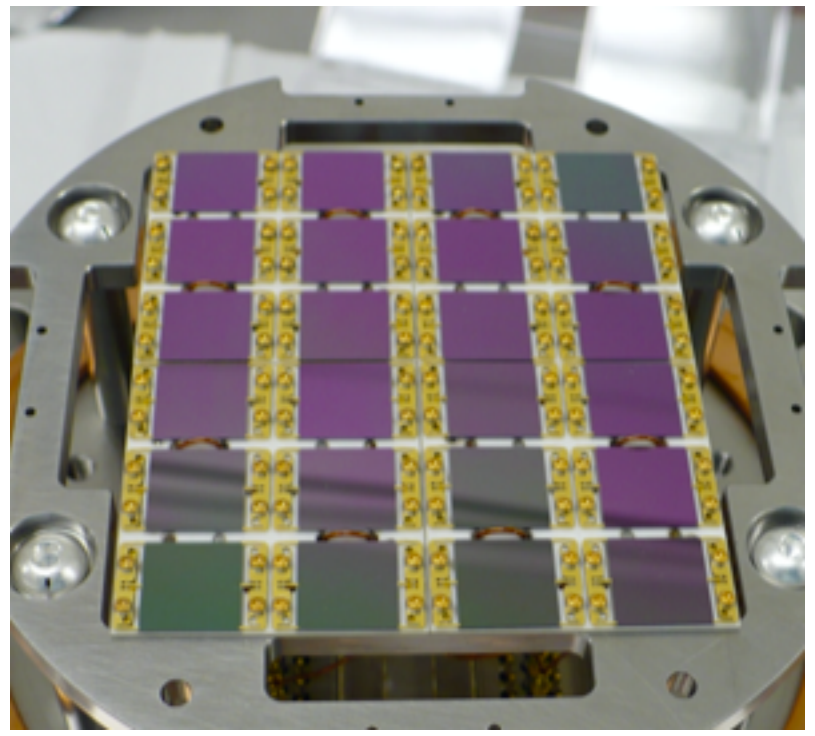
arXiv:1805.11142

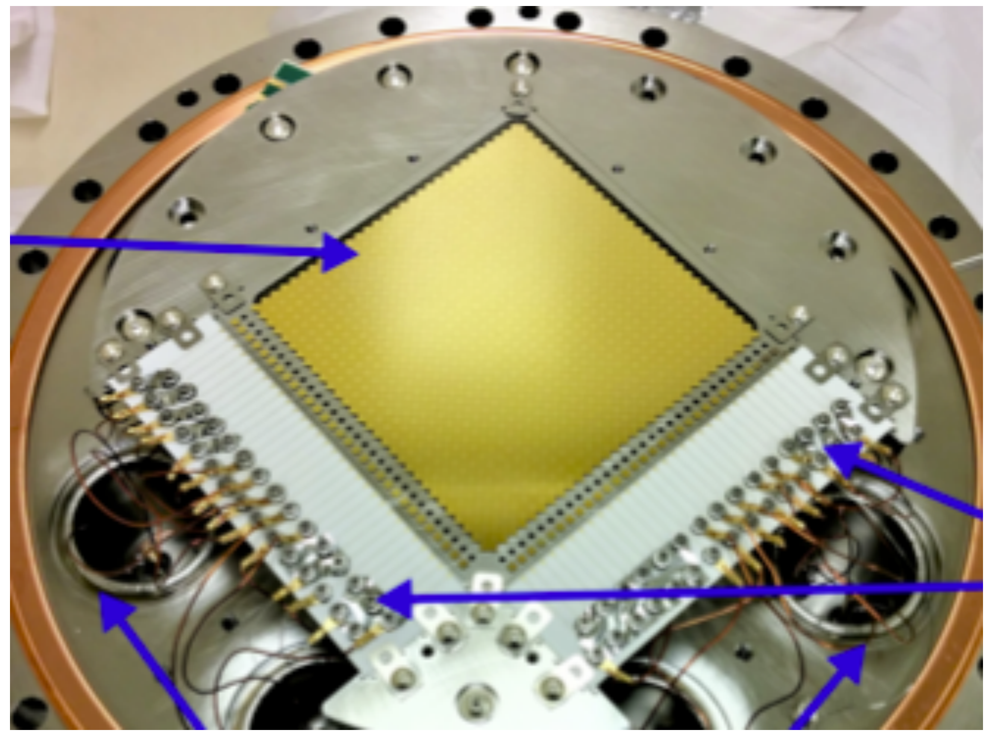
nEXO Detector



- Single Drift Volume
- ASIC Electronics in LXe
- Charge Collection Tiles on Anode
- VUV SiPMs on Staves
- Copper Field Shaping Rings







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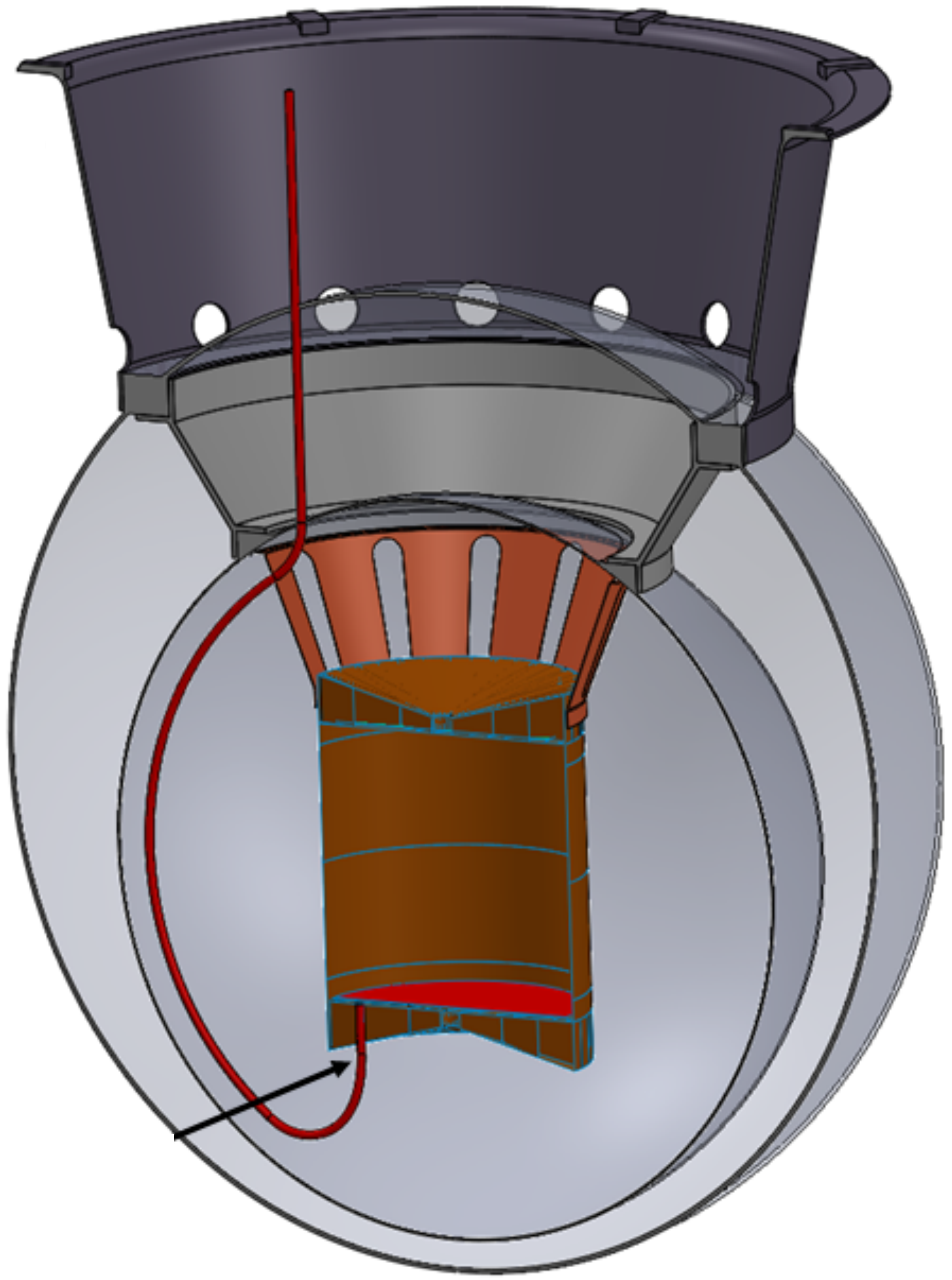
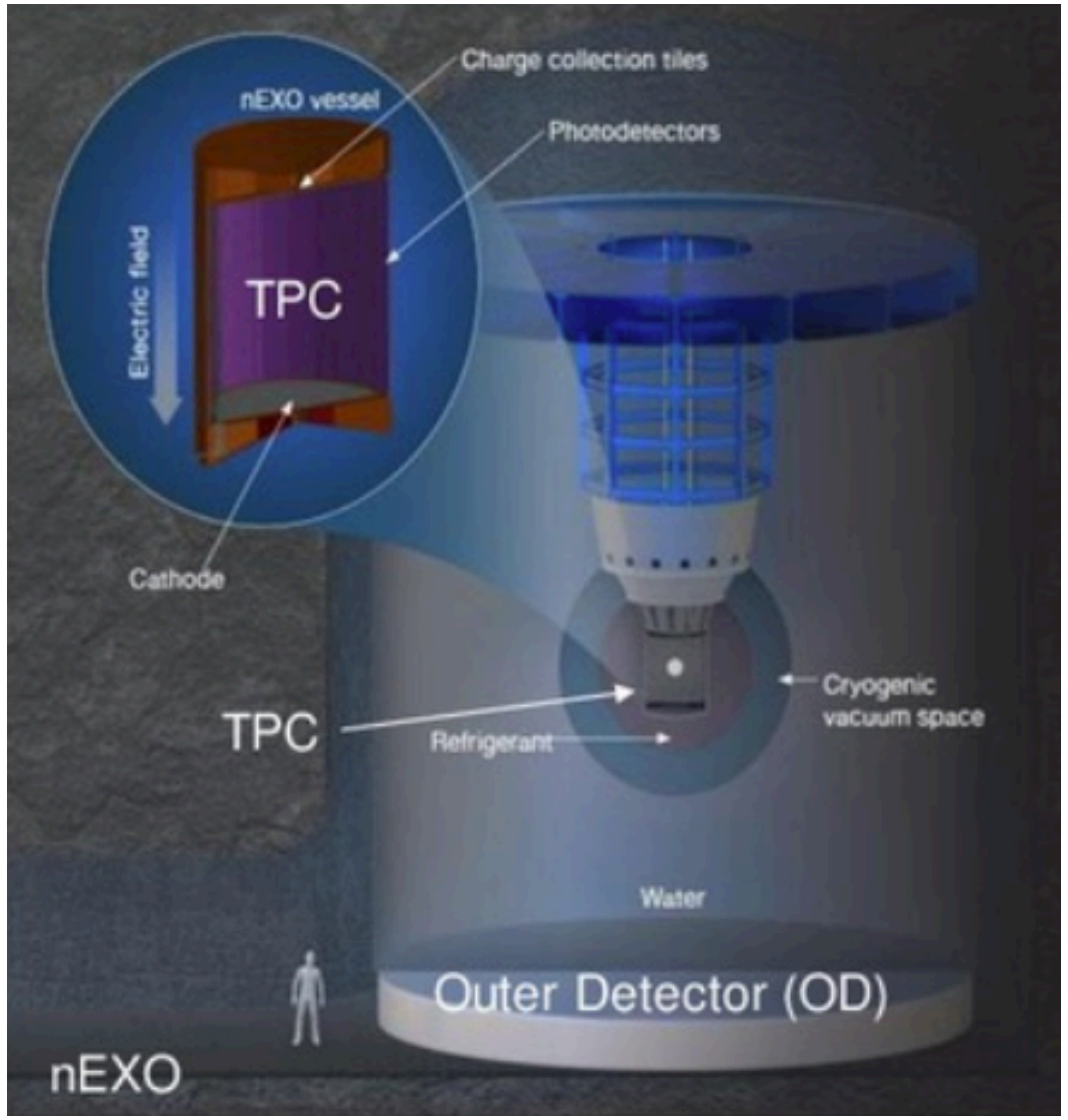
nEXO Detector

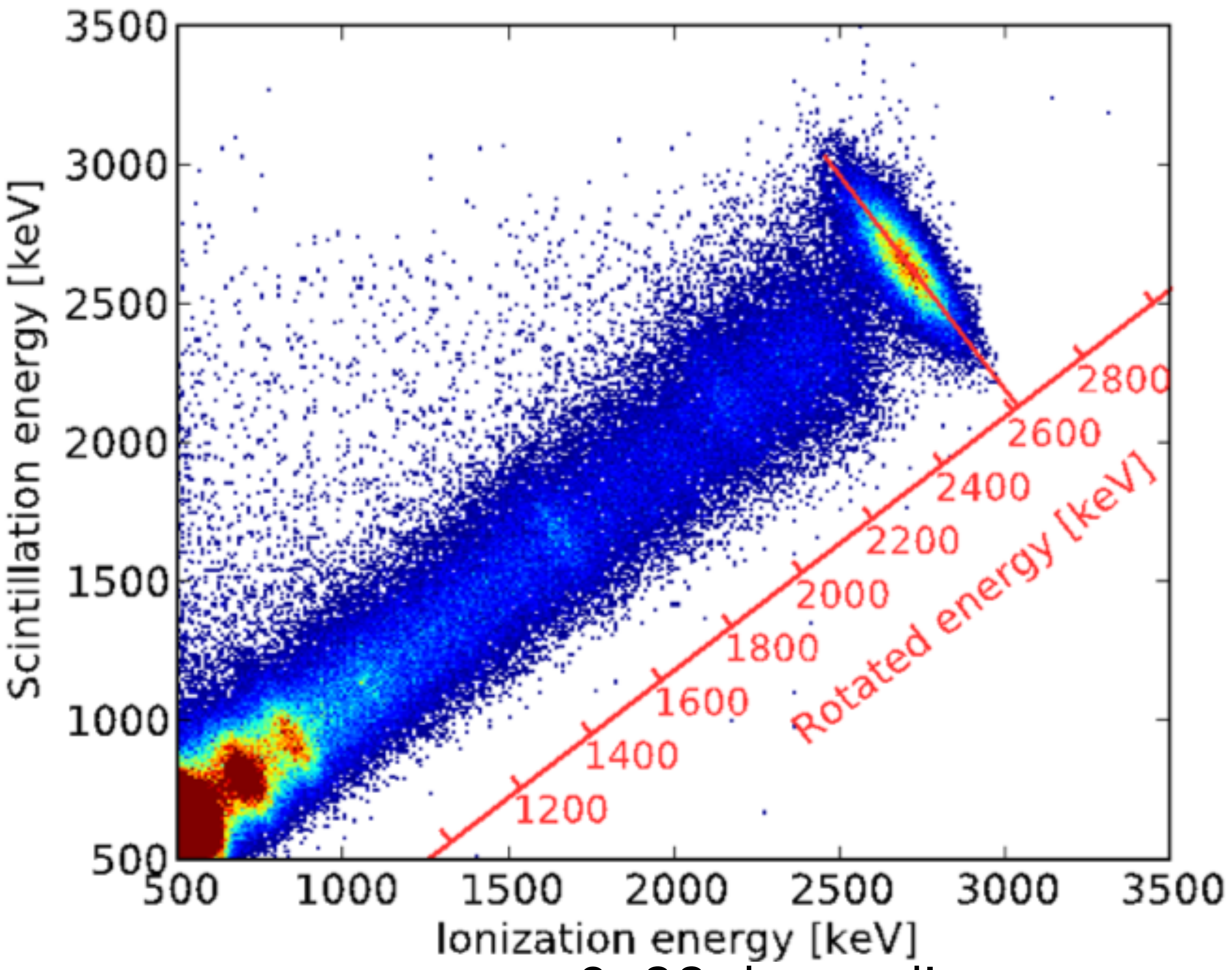


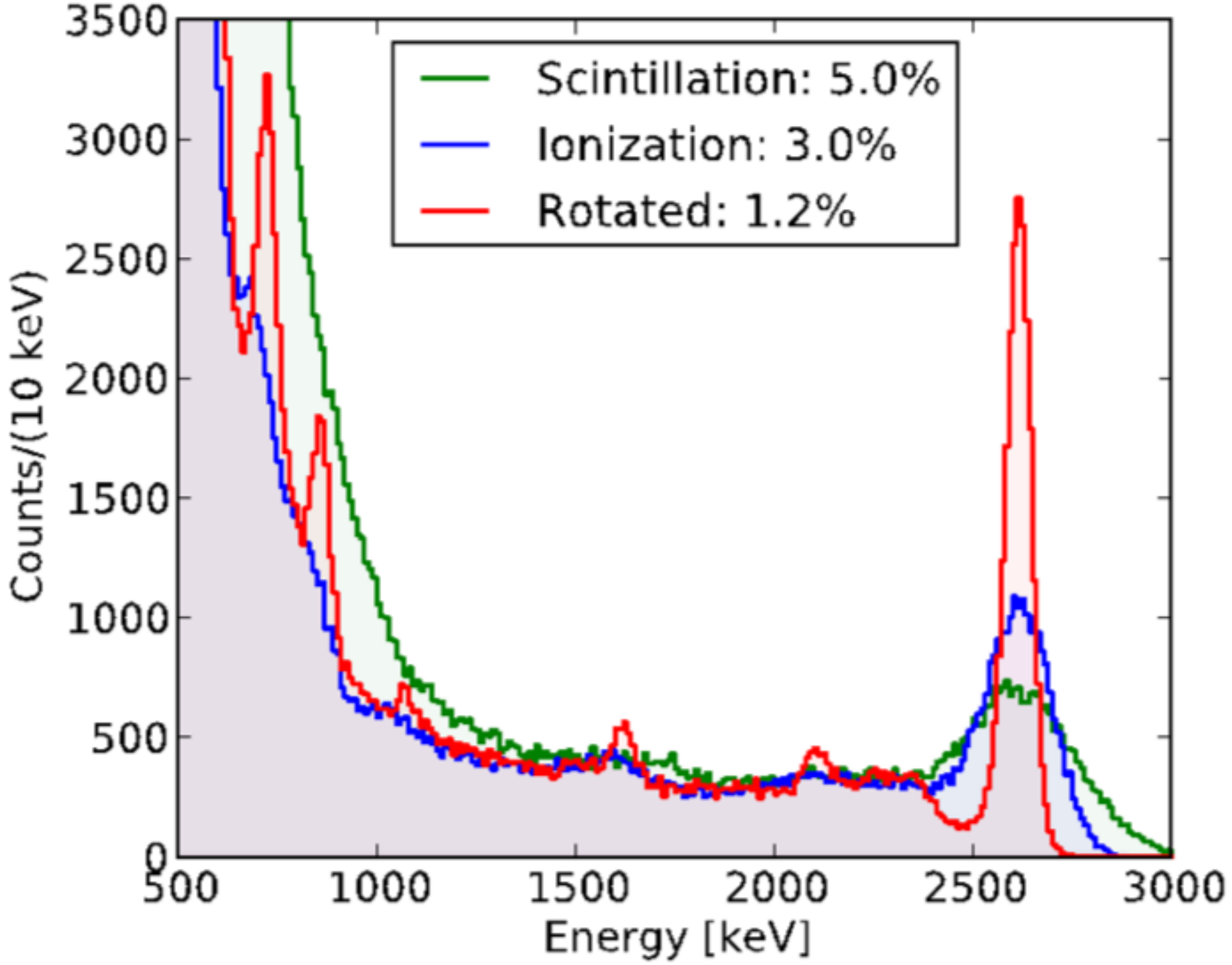
- TPC is housed inner cryostat filled with refrigerant
- Enclosed in outer vacuum cryostat
- Suspended in instrumented active veto Outer Detector



arXiv:1805.11142

Energy Resolution in nEXO

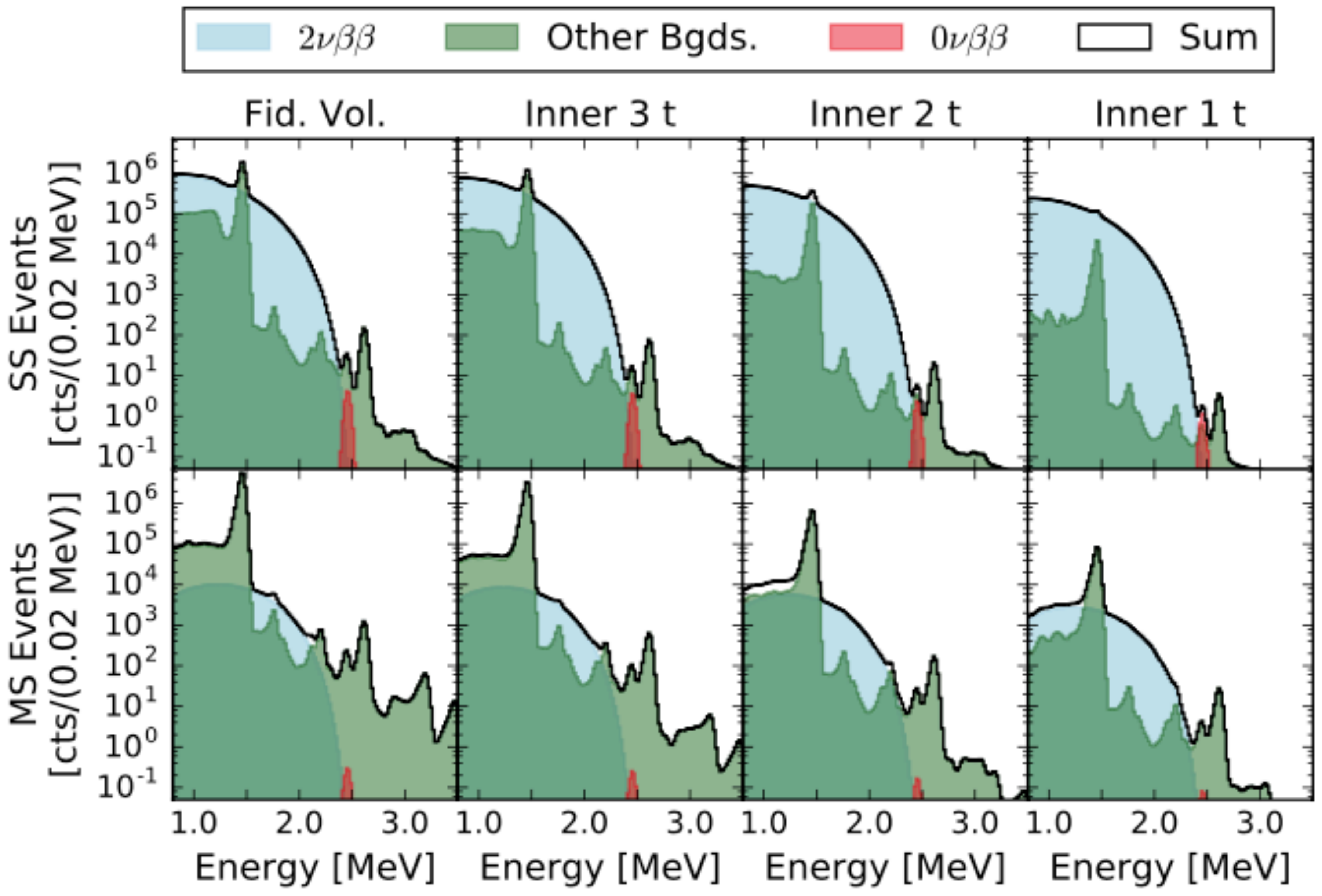


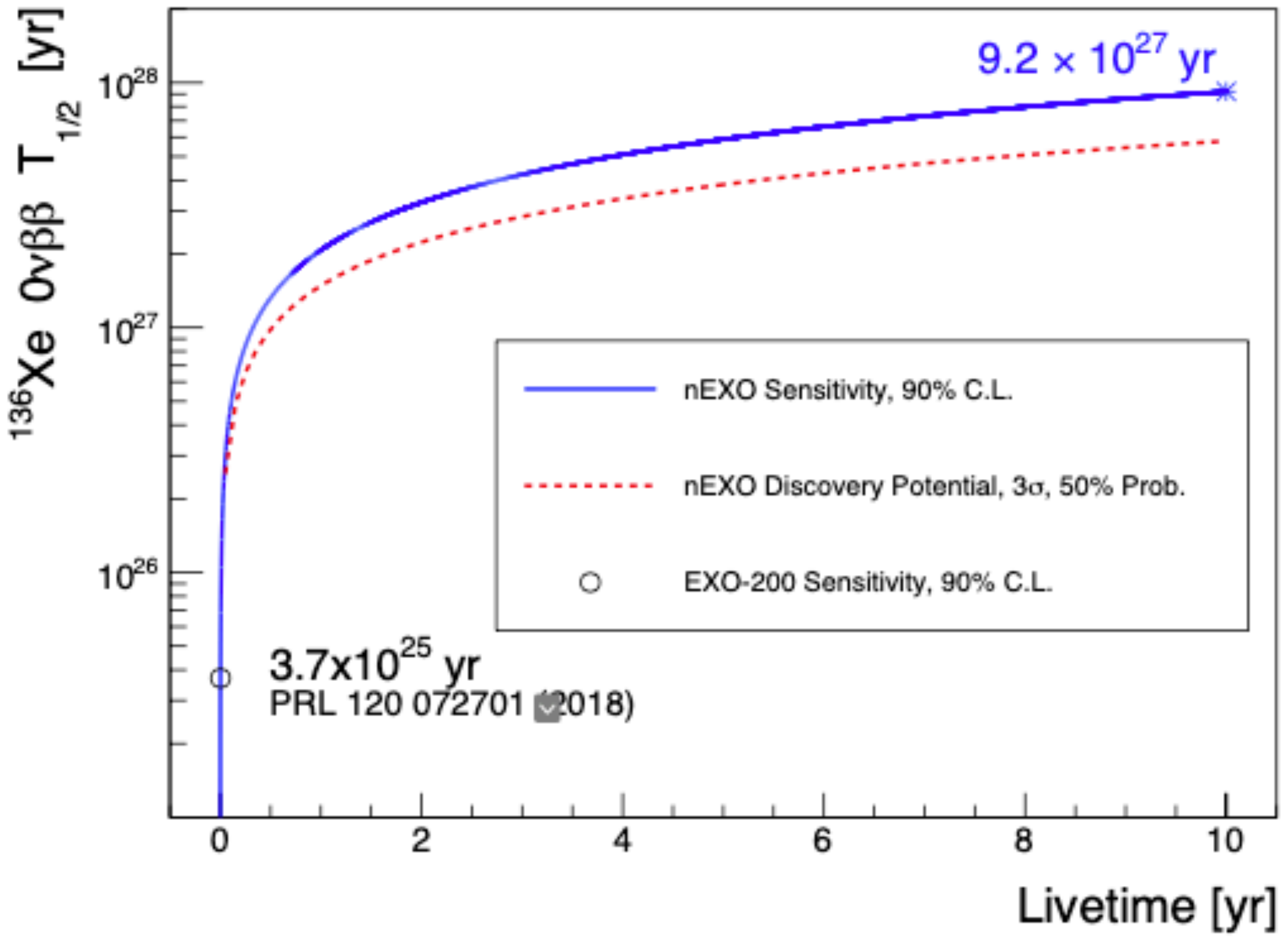


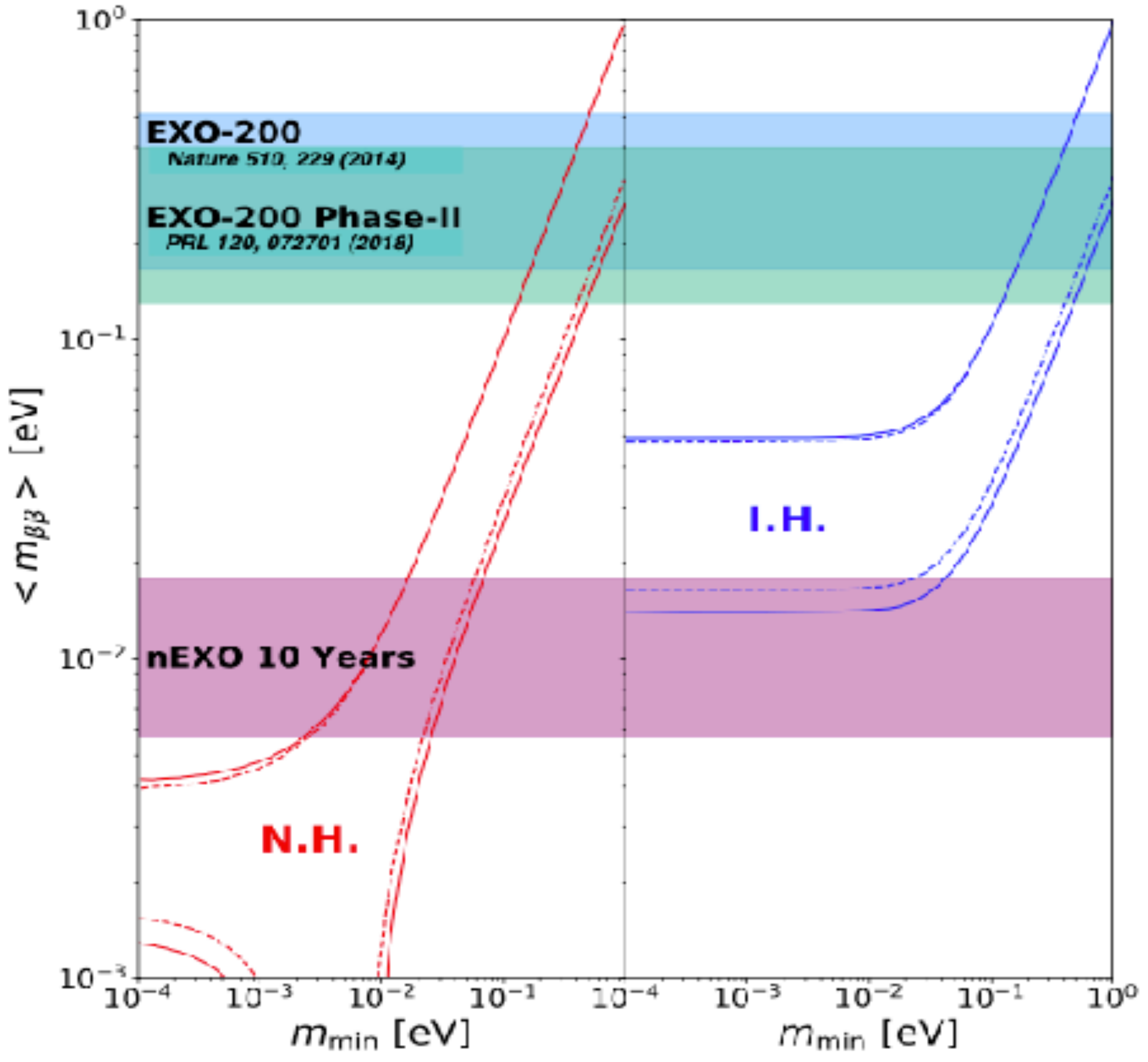
- $0\nu\beta\beta$ decay discovery requires excellent energy resolution
- Light + Charge collection in Single Phase LXe TPC
- Cancel fluctuations in ionization vs scintillation yield

arXiv:1805.11142

nEXO Sensitivity







- Energy spectra for SS and MS events as a function of the LXe mass. Spectra are evaluated for a detector live time of 10 years.
- The 0νββ signal corresponds to a half-life of 5.7×10^{27} years.

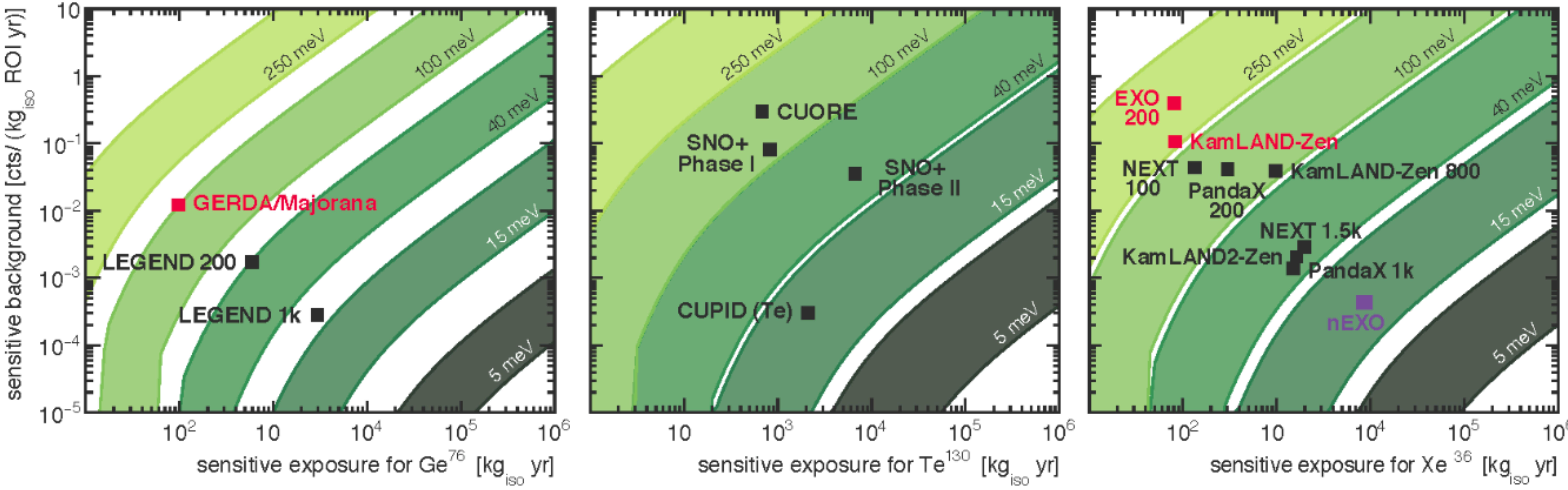
- nEXO Median sensitivity at 90% CL and 3σ discovery potential as a function of the experiment livetime

- 90% C.L. exclusion sensitivity reach to the effective Majorana neutrino mass $\langle m_{\beta\beta} \rangle$ as a function of the lightest neutrino mass for normal and inverted neutrino mass hierarchies.

arXiv:1805.11142

Summary

0νββ Decay Experiment Sensitivities



Agostini, Benato, Detwiler, PRD 96 (2017) 053001; and A. Caldwell et al., PRD 96 (2017) 073001

🇨🇦 U of Alberta, Laurentian U, Queen's U, SNOLAB, TRIUMF

🇩🇪 TU Dresden

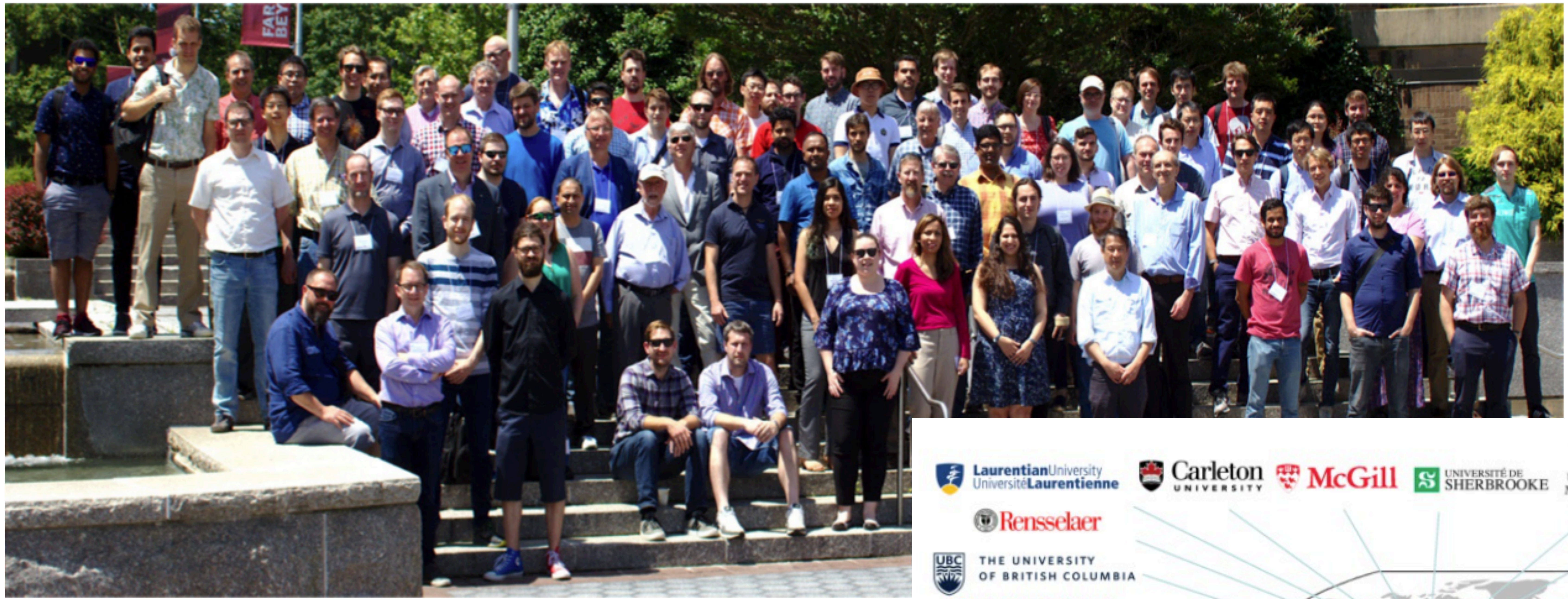
🇲🇽 U National Autonoma de Mexico

🇵🇹 LIP Lisbon & Coimbra

🇬🇧 Lancaster U, U of Liverpool, King's College London, U of Oxford, Queen Mary U of London, U of Sussex

🇺🇸 UCBerkeley/LBNL, Boston U, Brookhaven National Lab, UChicago, UCDavis, Norwich U, U of Pennsylvania nEXO

SNOLAB

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Mines
Colorado State
University of South Dakota
The University of Alabama
Oak Ridge National Laboratory
Duke University
UNCW
University of North Carolina Wilmington

https://en.wikipedia.org/wiki/SNOLAB

Mass Hierarchy

- The oscillation experiments can only measure Δm^2.

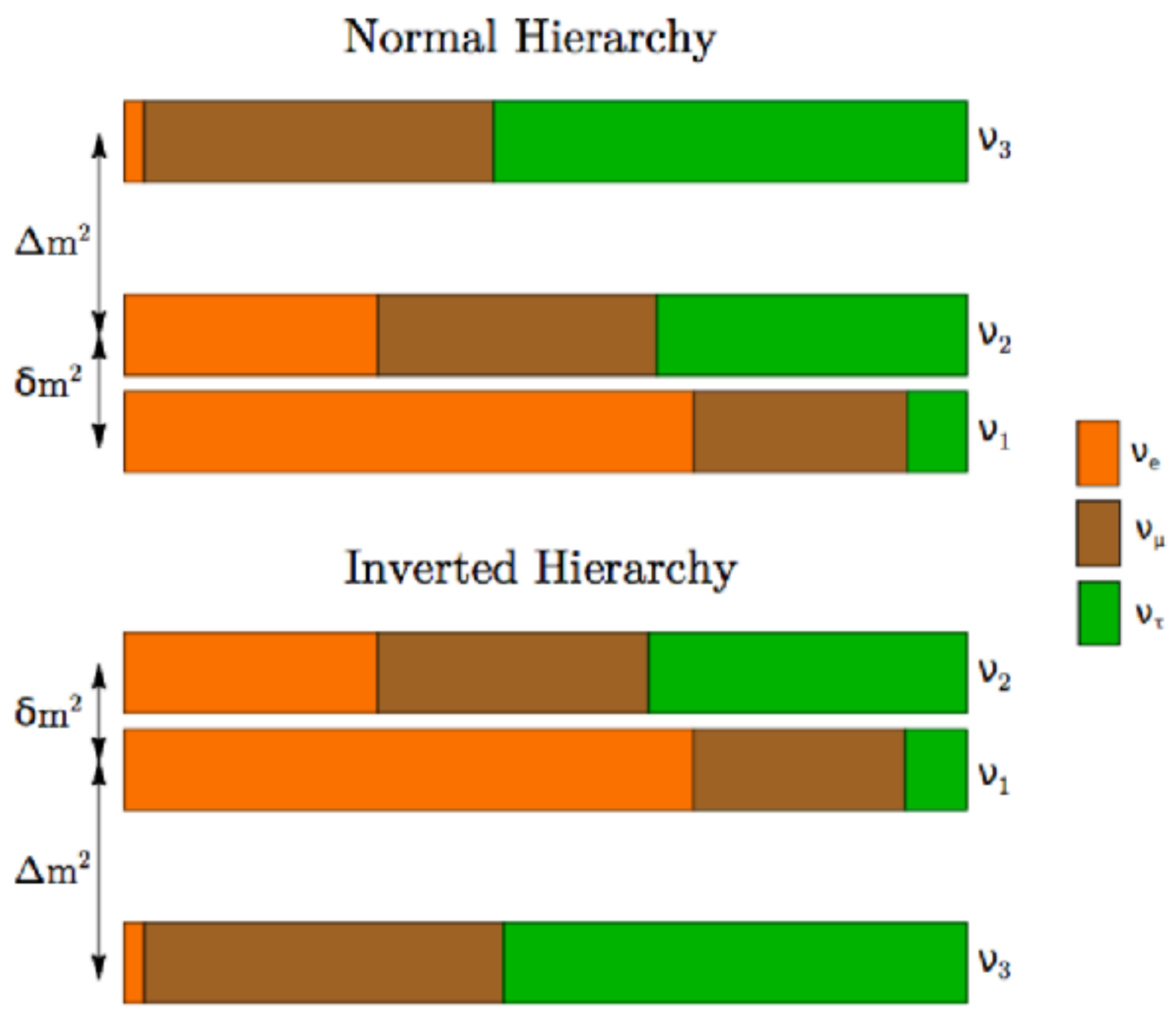
$$P_{\alpha\rightarrow\beta,\alpha\neq\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

Text

- Up to now, we have only determined the sign of $\delta m^2{}_{21}$. Thus, we don't know the ranking of m_3 relative to $m_{1,2}$

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

$$m_{\beta\beta} = \left| \sum_{i=1,2,3} \mathrm{e}^{i\xi_i} \, |U_{\mathrm{e}i}^2| \, m_i \right|$$



Oscillation

$|\nu_\alpha\rangle$ is a neutrino with definite flavor $\alpha = e, \mu, \tau$

$|\nu_i\rangle$ is a neutrino with definite mass m_i, $i = 1, 2, 3$

$$|\nu_i\rangle = \sum_\alpha U_{\alpha i} |\nu_\alpha\rangle$$

$$P_{\alpha\rightarrow\beta} = |\langle\nu_\beta(t)|\nu_\alpha\rangle|^2 = \left|\sum_i U^*_{\alpha i} U_{\beta i} e^{-im_i^2 L/2E}\right|^2$$

$$U_{\alpha i} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{bmatrix} \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} e^{i\alpha_1/2} & 0 & 0 \\ 0 & e^{i\alpha_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

Atmospheric, Accelerator $\theta \sim 45°$

Reactor, Accelerator $\theta \sim 9°$

Solar, Reactor $\theta \sim 32°$

$0\nu\beta\beta$

What we DO know about Neutrinos

- Fermion: spin 1/2, electrically neutral
- Only experience the weak force, rarely interacting with anything
- They come in three flavors associated with three other fundamental particles
  - electron, muon and tau
- They change, or oscillate, from one type to another
- Most abundant massive particles in the universe, 340/cm^3