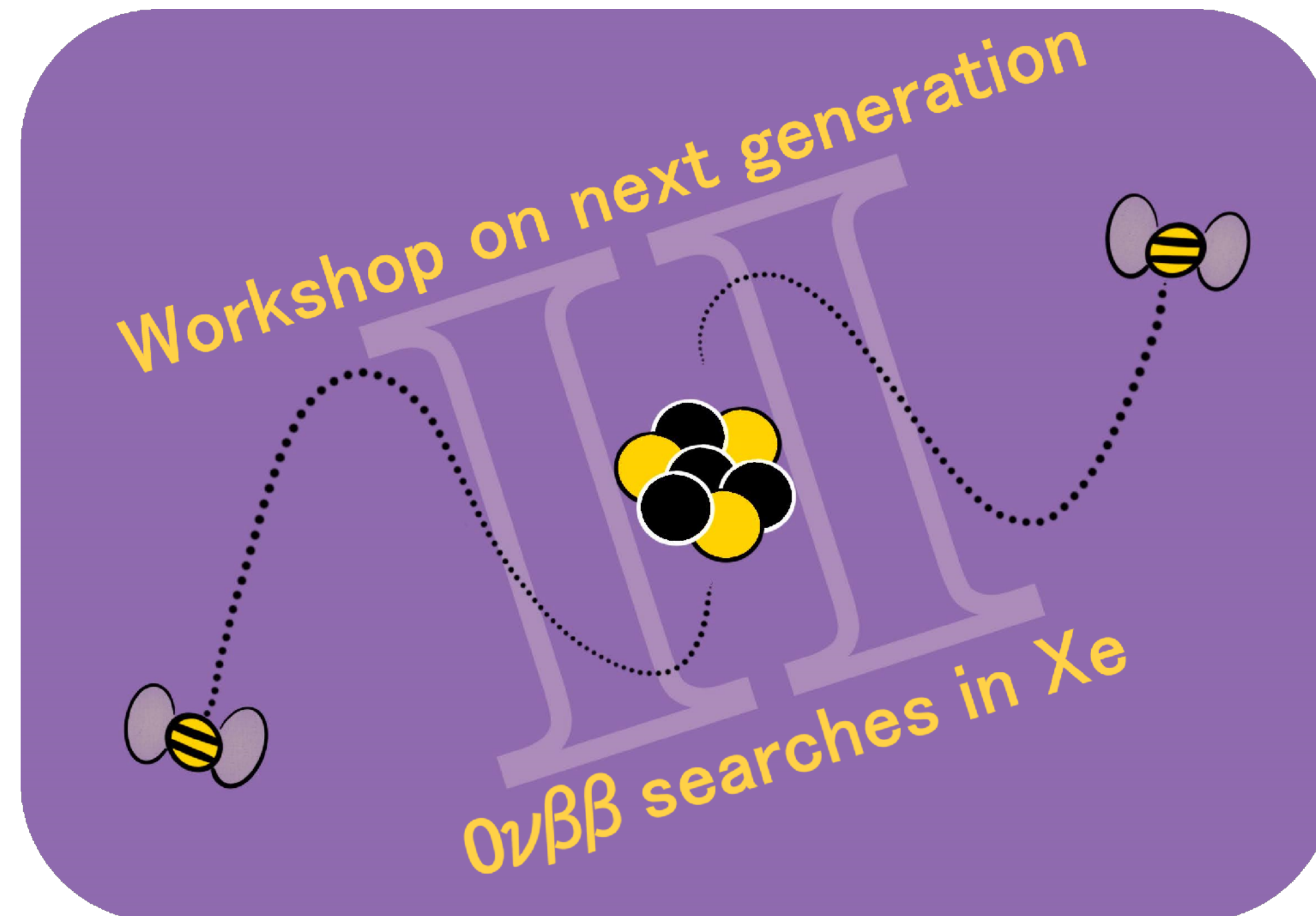


Second Workshop on Neutrinoless Double Beta Decay Search in Xe — Next-Generation Experiment —



The technical
legacy of nEXO

Andrea Pocar
UMass Amherst

Old Trafford, Manchester
September 15-17, 2026



University of
Massachusetts
Amherst

Outline of topics covered

The nEXO experiment as a technically viable multi tonne-scale $0\nu\beta\beta$ decay experiment

- Overview and target sensitivity
- Design drivers and technology solutions (novel and established)
 - EXO-200 roots
 - Inner detector and calibration
 - Cryogenic design and infrastructure
- Lessons learned and outlook

Outline of topics covered

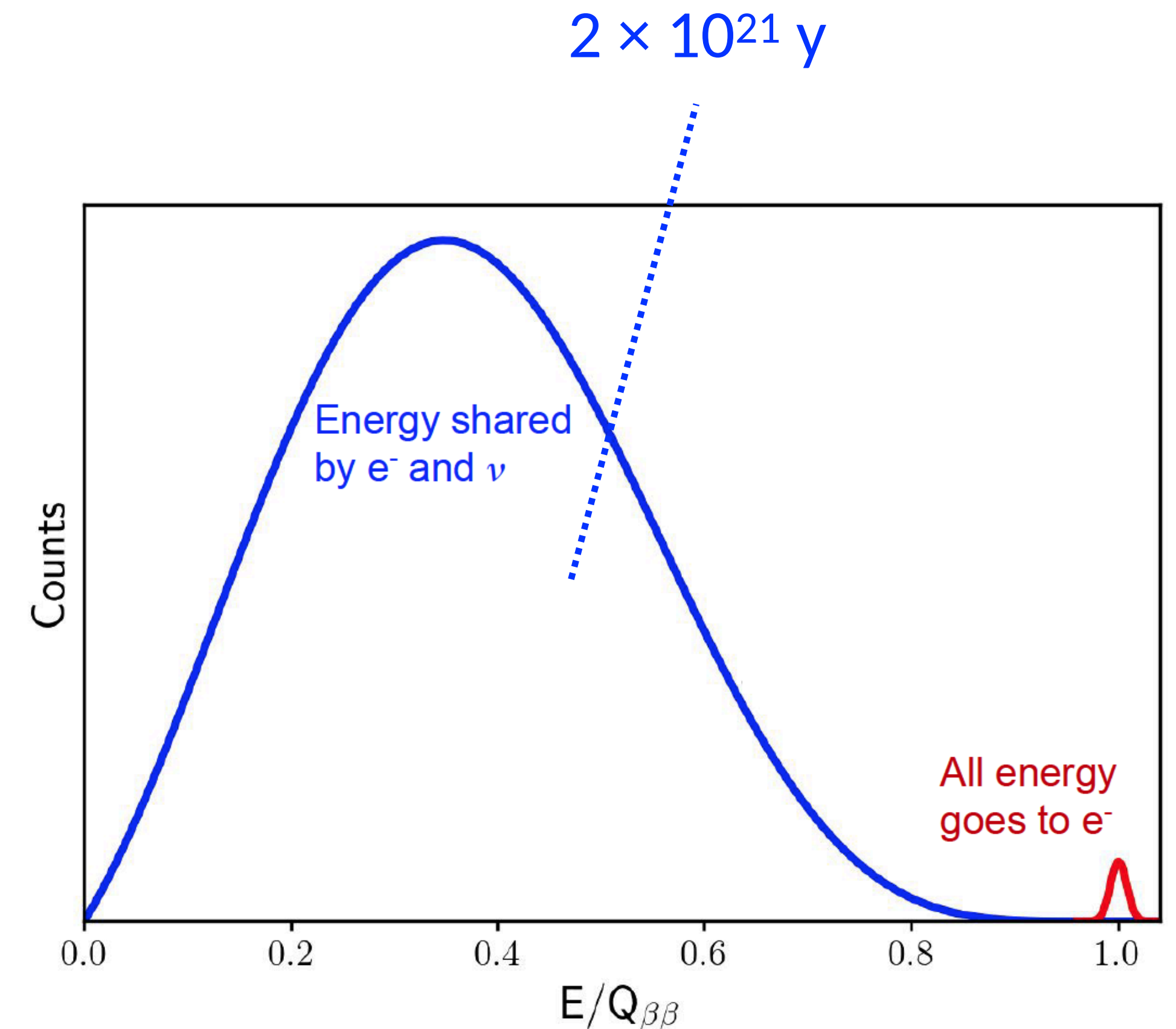
The nEXO experiment as a technically viable multi tonne-scale $0\nu\beta\beta$ decay experiment

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Rationale of choices made
What worked and not
What can help future experiments?

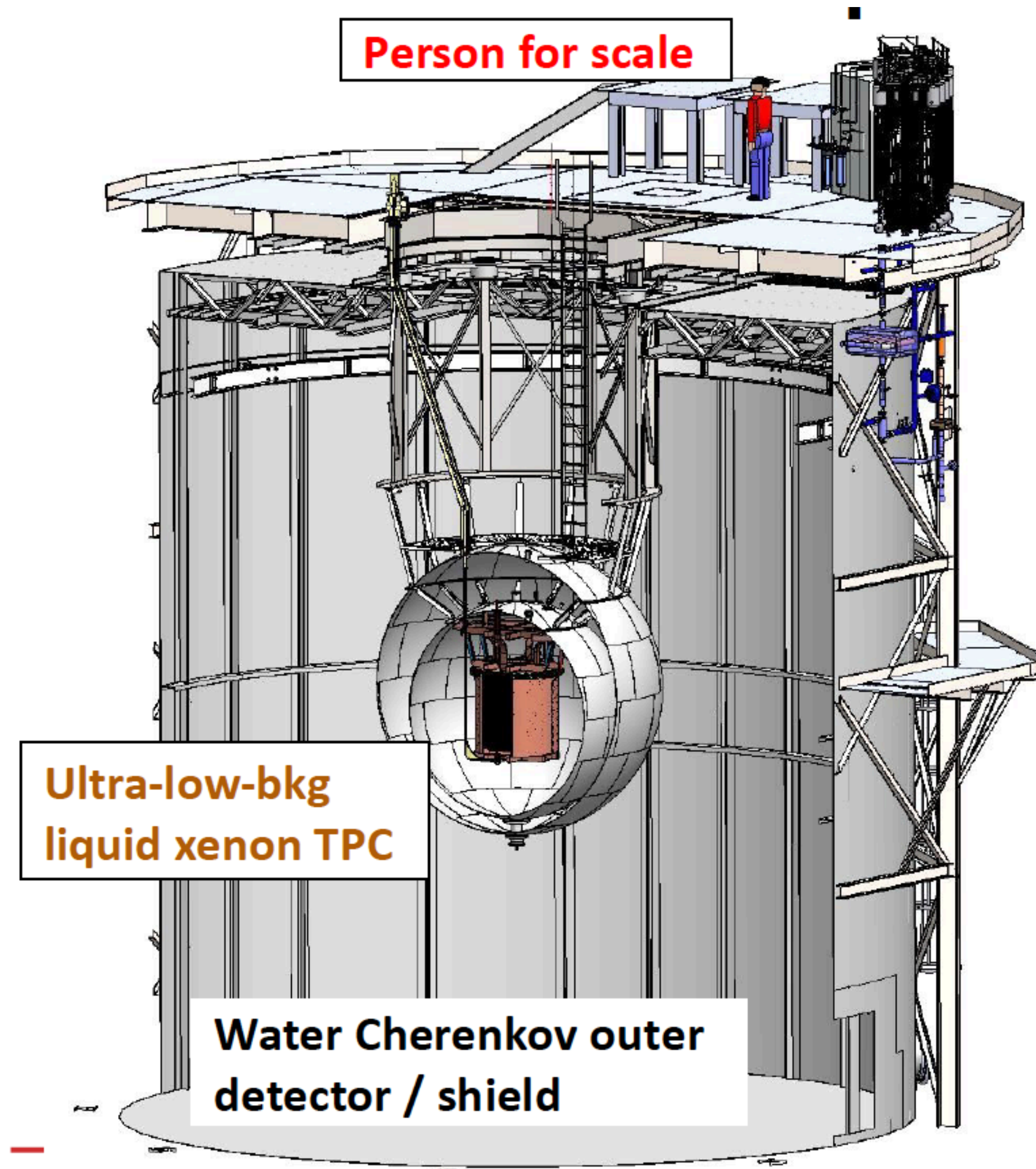
Low background liquid xenon (LXe) TPCs

- LXe TPCs hold technological promise in rare event searches
- Over the past 20 years, demonstrated scalable technology
- Today, several tonne-scale LXe TPCs are operational (XENONnT, LZ, PandaX-4T)
 - Dark Matter (WIMP-like) searches
 - Opportunistic searches: 2ν , 0ν DBD, 2EC , 0ν QBD
- Larger ones are in the construction/design/proposal stage
 - Dark matter searches (PandaX-20T/40T, XLZD)
 - nEXO: optimized for the search of $0\nu\beta\beta$ decay of ^{136}Xe can inform (should?) inform the design on next-gen experiments
- Lots of signal, low intrinsic background, signal/bg ID

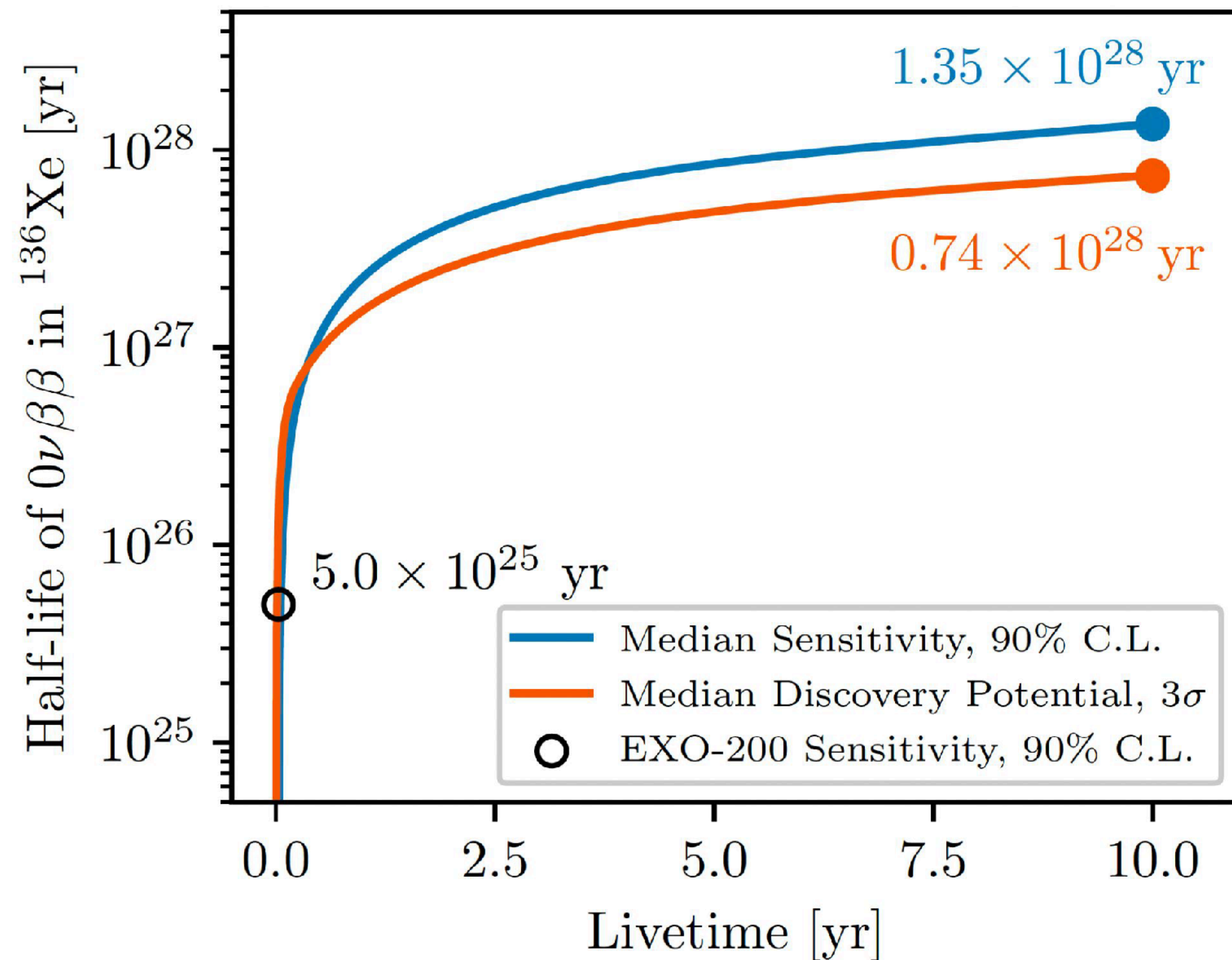


$$Q(^{136}\text{Xe}) = 2.458 \text{ MeV}$$

The nEXO detector design



- Single-phase liquid xenon TPC
- 5 tonne capacity
- 90% enriched in ^{136}Xe ($Q_{\beta\beta} = 2.457 \text{ MeV}$)
- 2000 m overburden (@SNOLAB in Sudbury, ON)
- Designed for sensitivity to $T_{1/2}(0\nu\beta\beta) > 10^{28} \text{ years}$

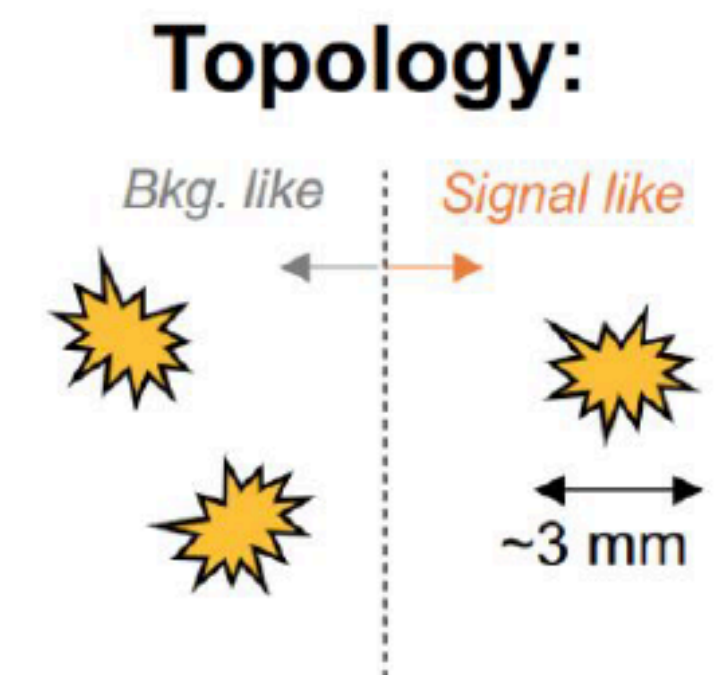
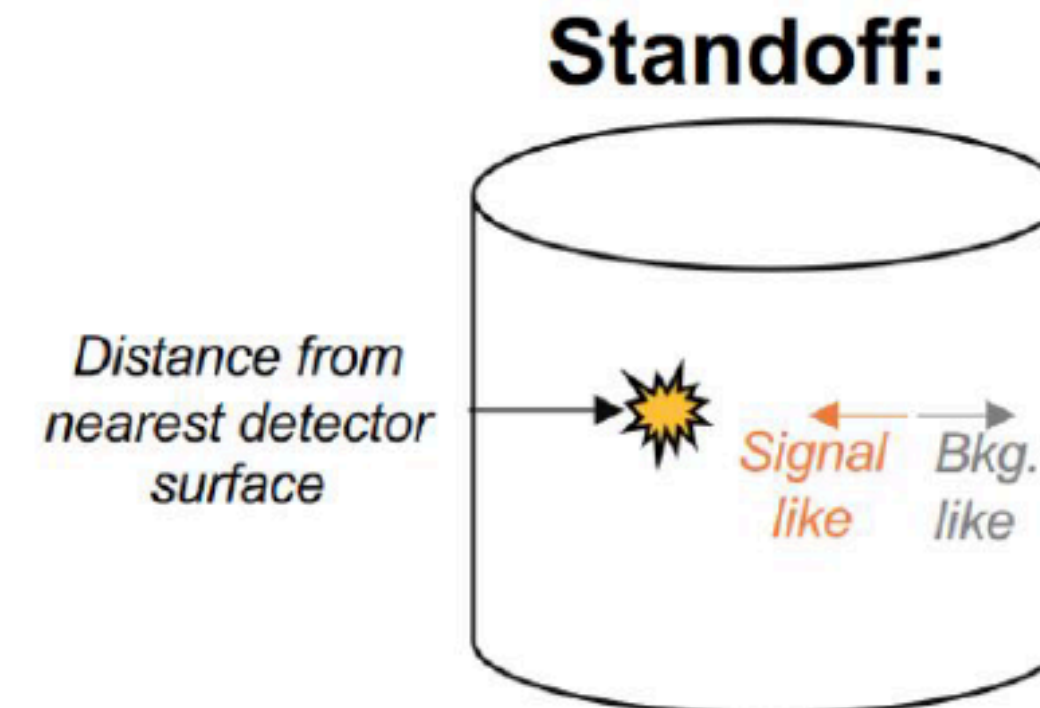
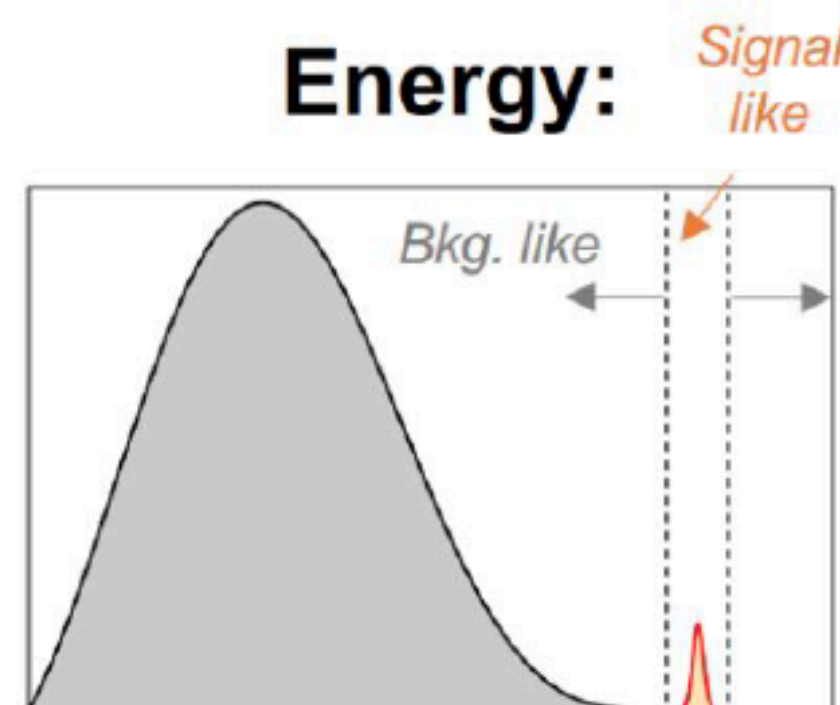
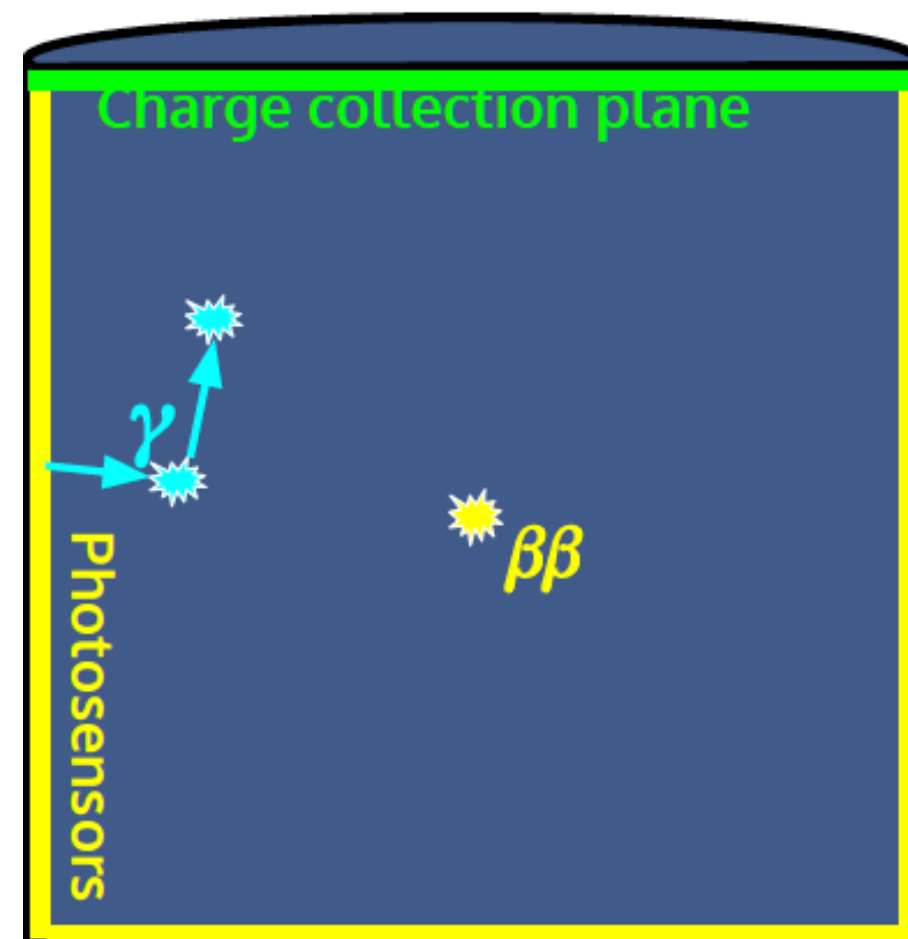


- Designed (and optimized) for sensitivity to $T_{1/2} > 10^{28}$ years
- Goalpost: complete coverage of inverted neutrino mass ordering (with assumptions on NMEs)
- There is nothing particularly special about 5 tonnes

nEXO design drivers

Detector highly optimized for $0\nu\beta\beta$ decay

- Meticulous care on mitigating detector radioactivity
- Particular focus on suppressing γ -ray background
- Such an optimization forces specific choices and compromises
- Environmental selection (depth, activation)

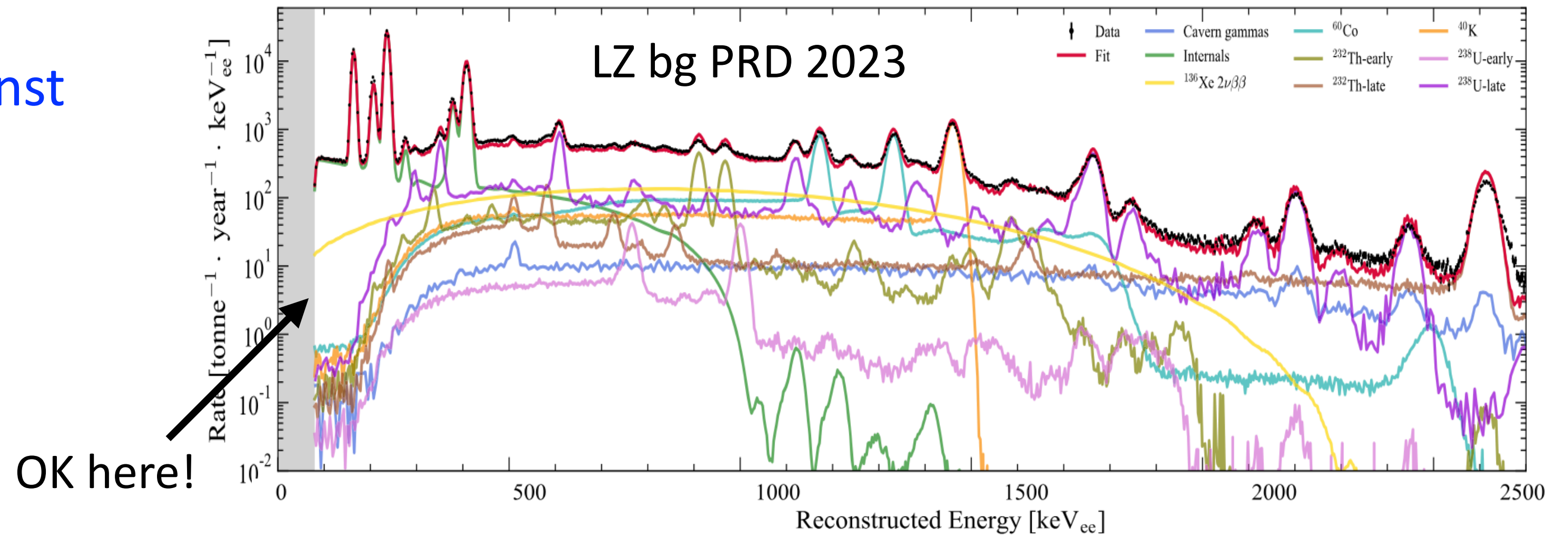


Simultaneous $0\nu\beta\beta$ /WIMP optimization in non-trivial

WIMP-like DM searches optimize against

- Neutrons
- Low-energy X-rays, some β s

Higher energy searches come with deep fiducial selection

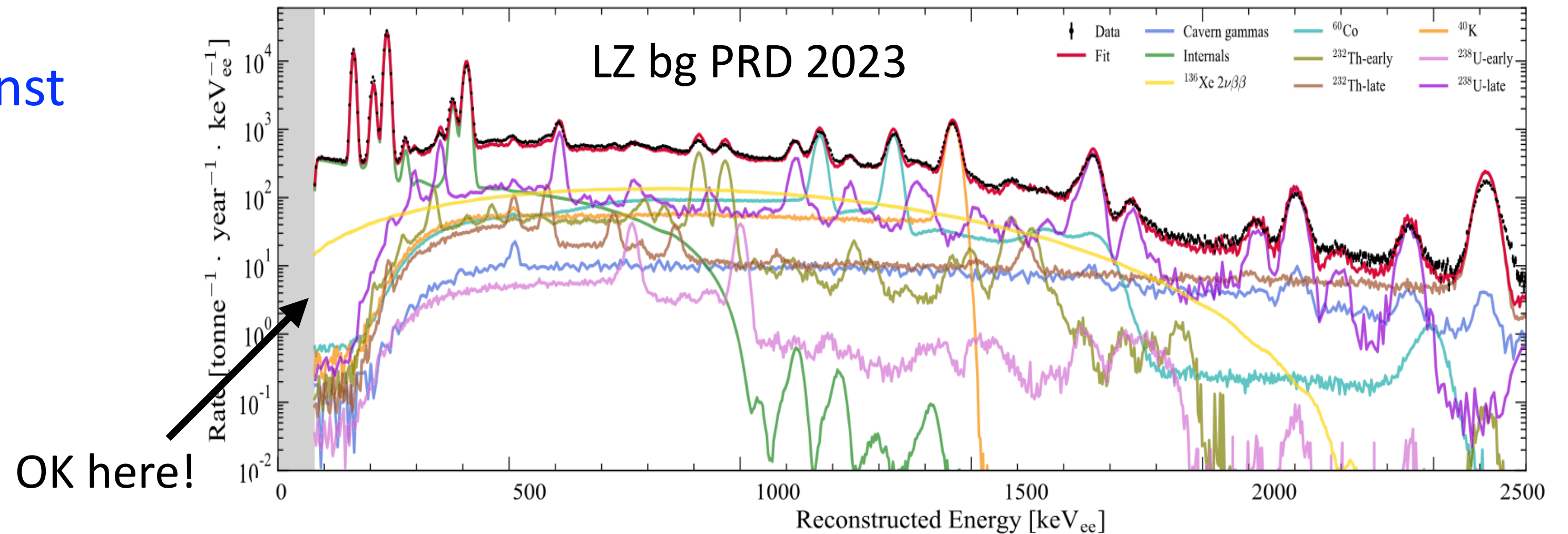


Simultaneous $0\nu\beta\beta$ /WIMP optimization in non-trivial

WIMP-like DM searches optimize against

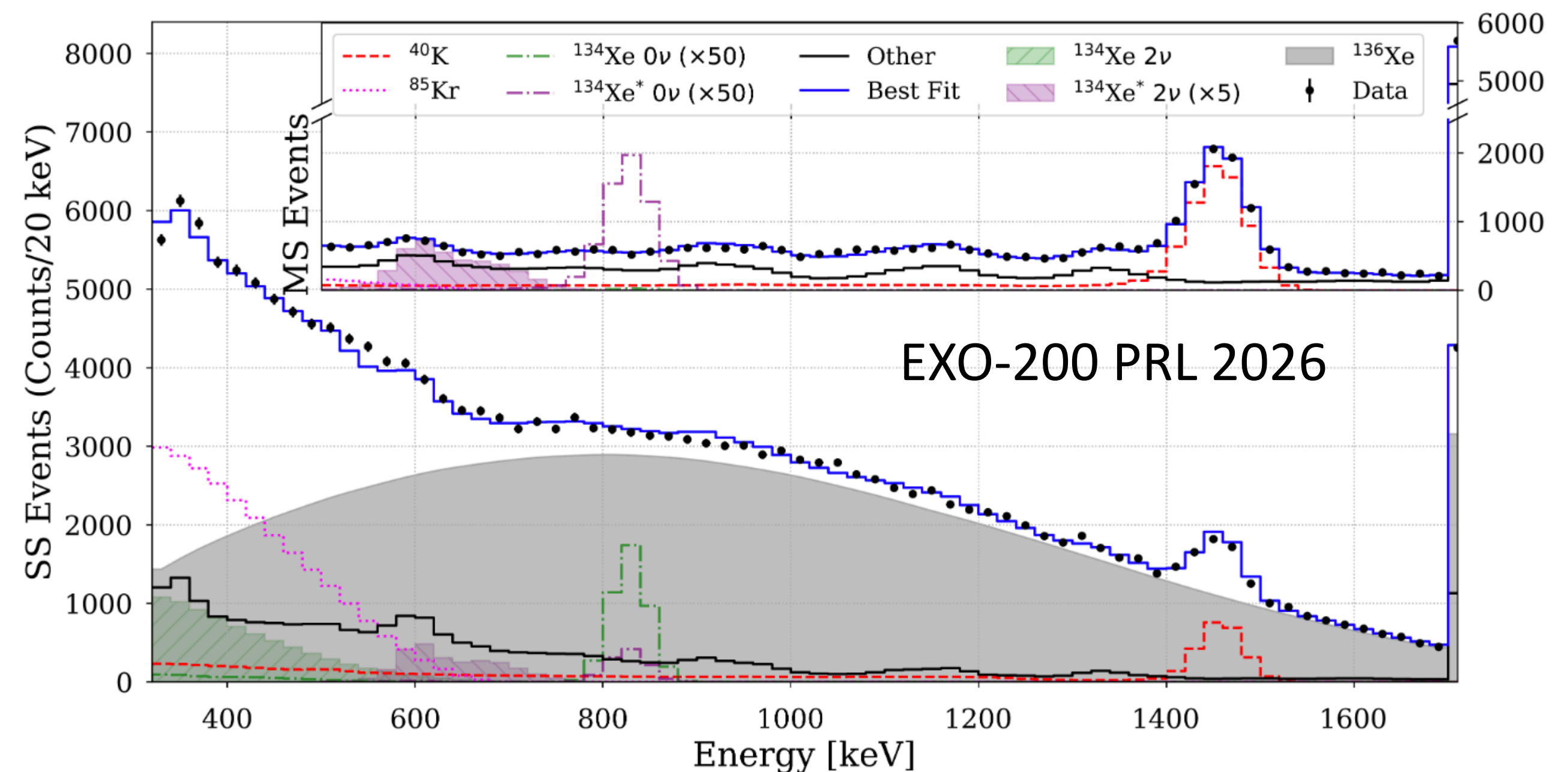
- Neutrons
- Low-energy X-rays, some β s

Higher energy searches come with deep fiducial selection



$0\nu\beta\beta$ decay searches optimize against MeV gamma-rays (and betas)

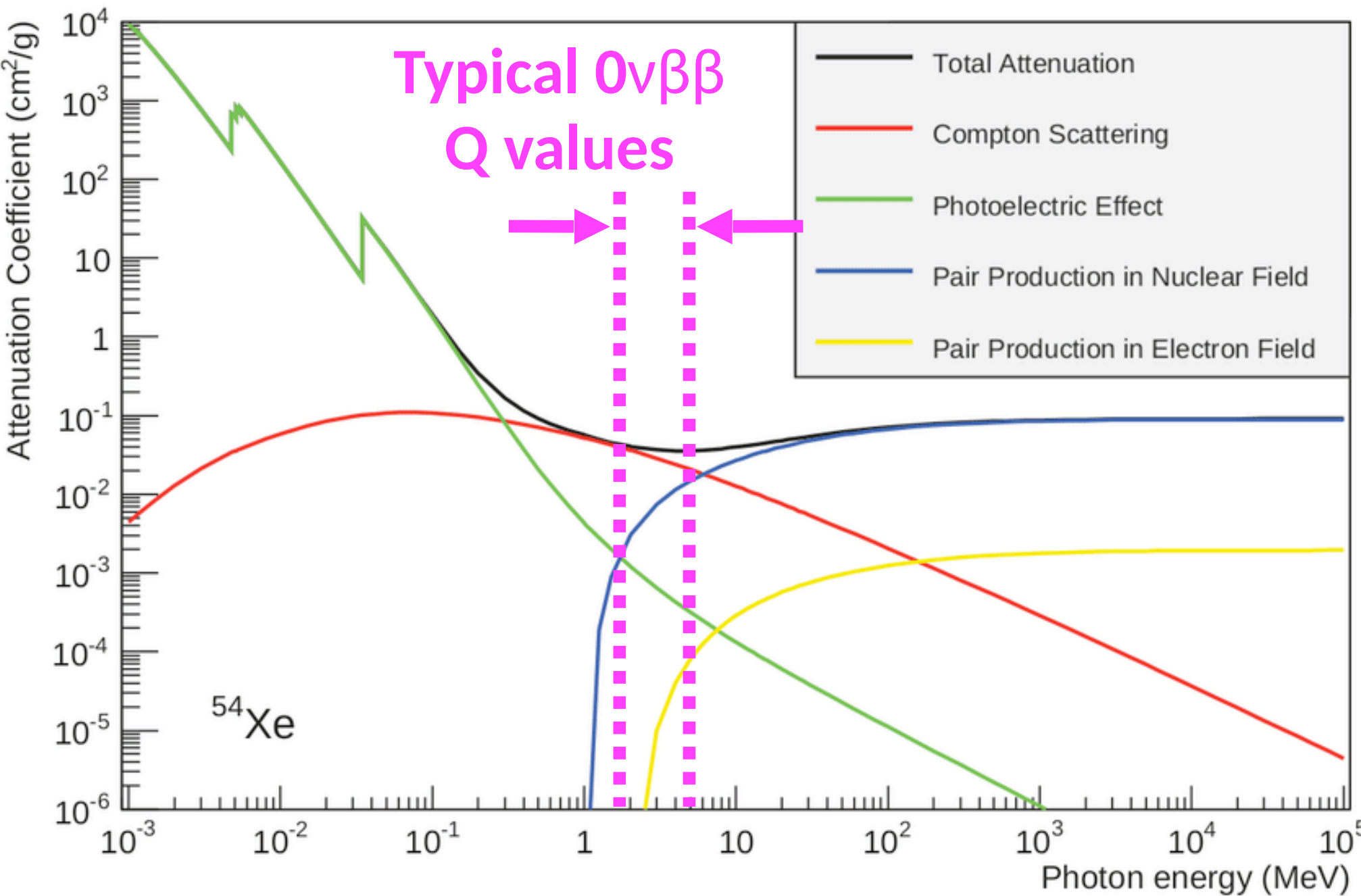
- long-lived decay chains, neutron capture, activation products
- Tl-208, Bi-214, Co-60, (K-40)
- (n,γ) on Cu, F, Xe;



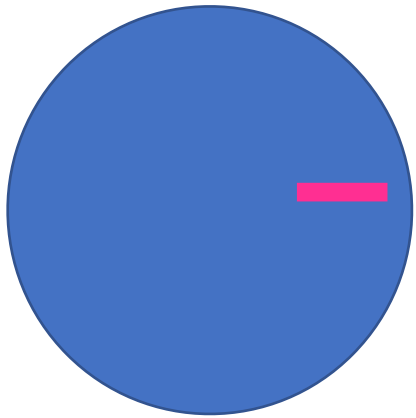
Suppressing MeV-scale gamma rays

LXe mass (kg)	Linear size (cm)
5	13
150	40
5000	130

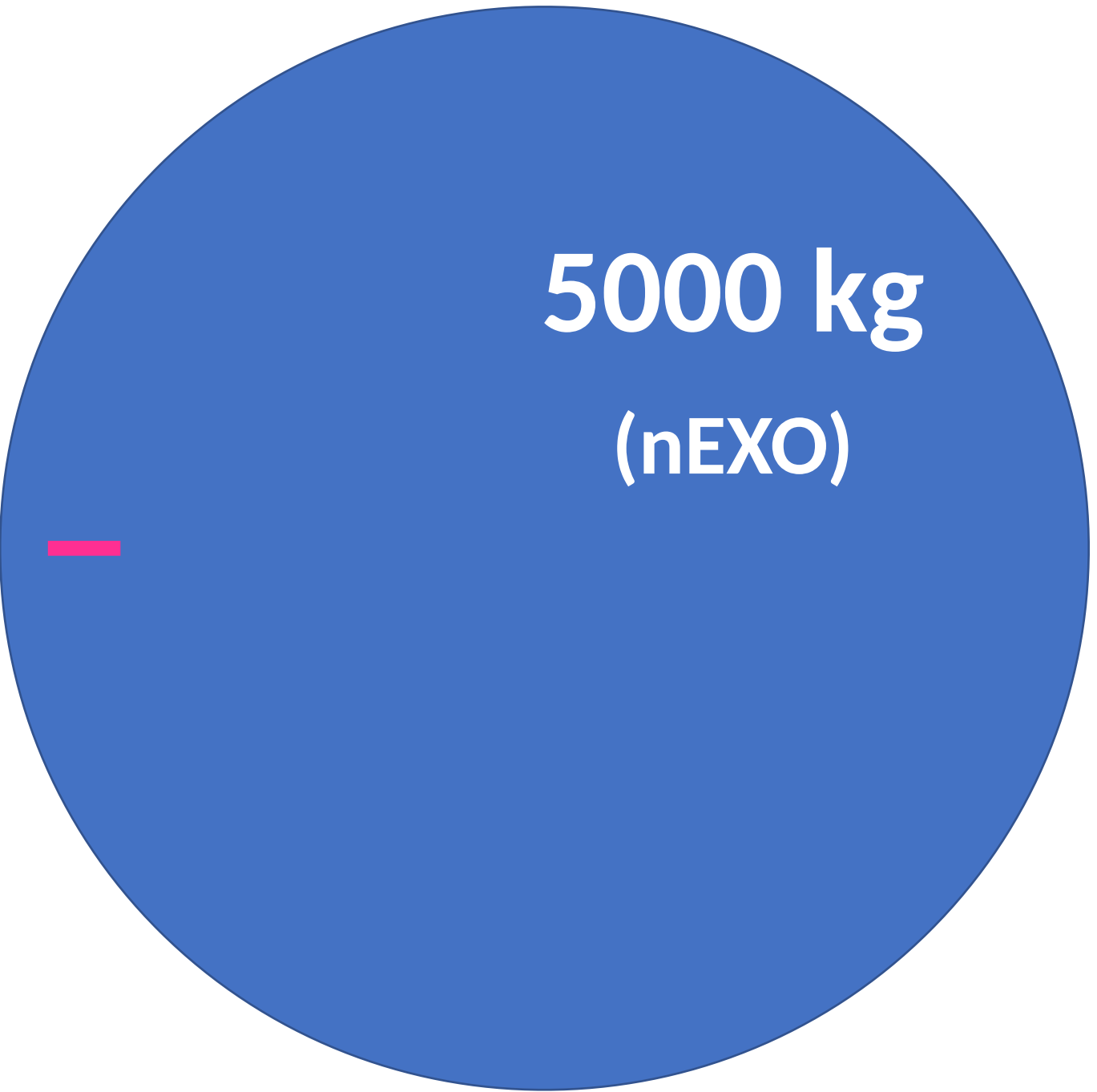
2.5 MeV γ attenuation length: 8.7 cm



150 kg
(~EXO-200)

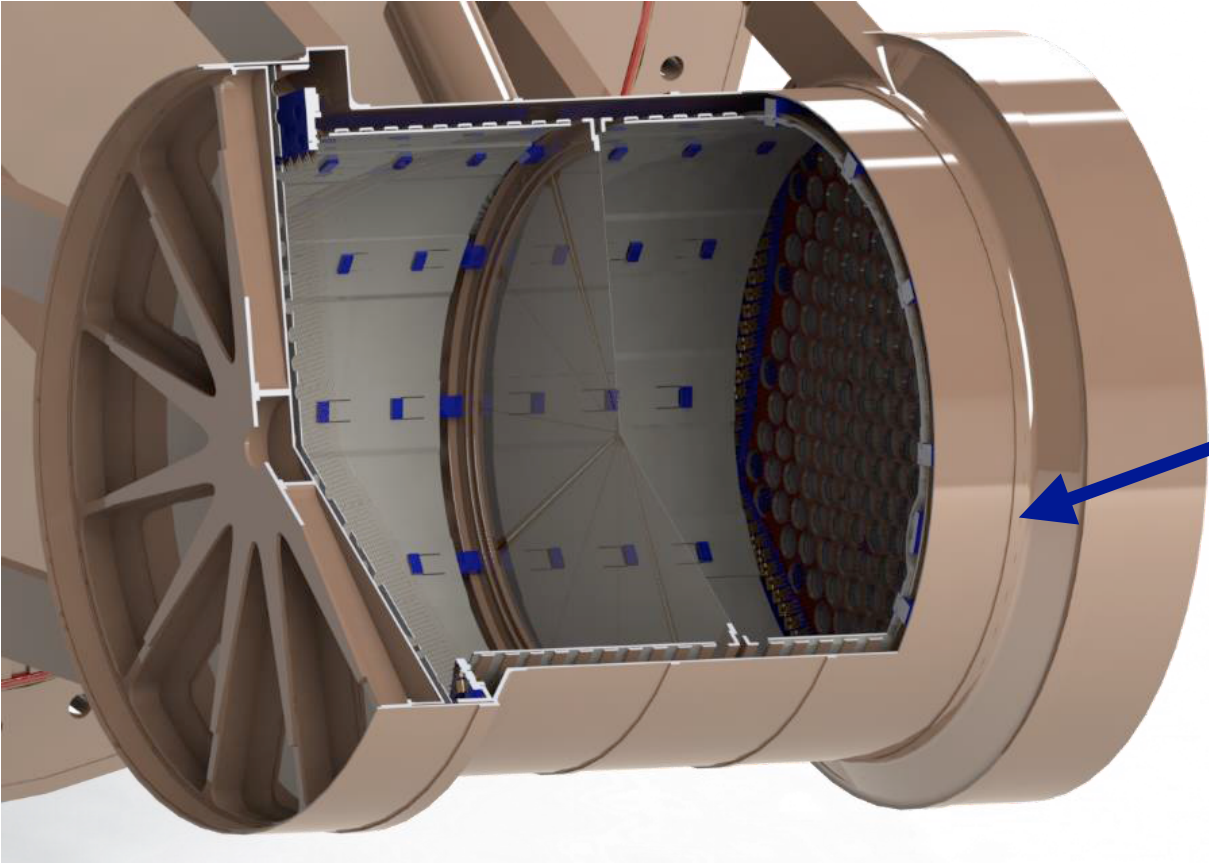


5000 kg
(nEXO)

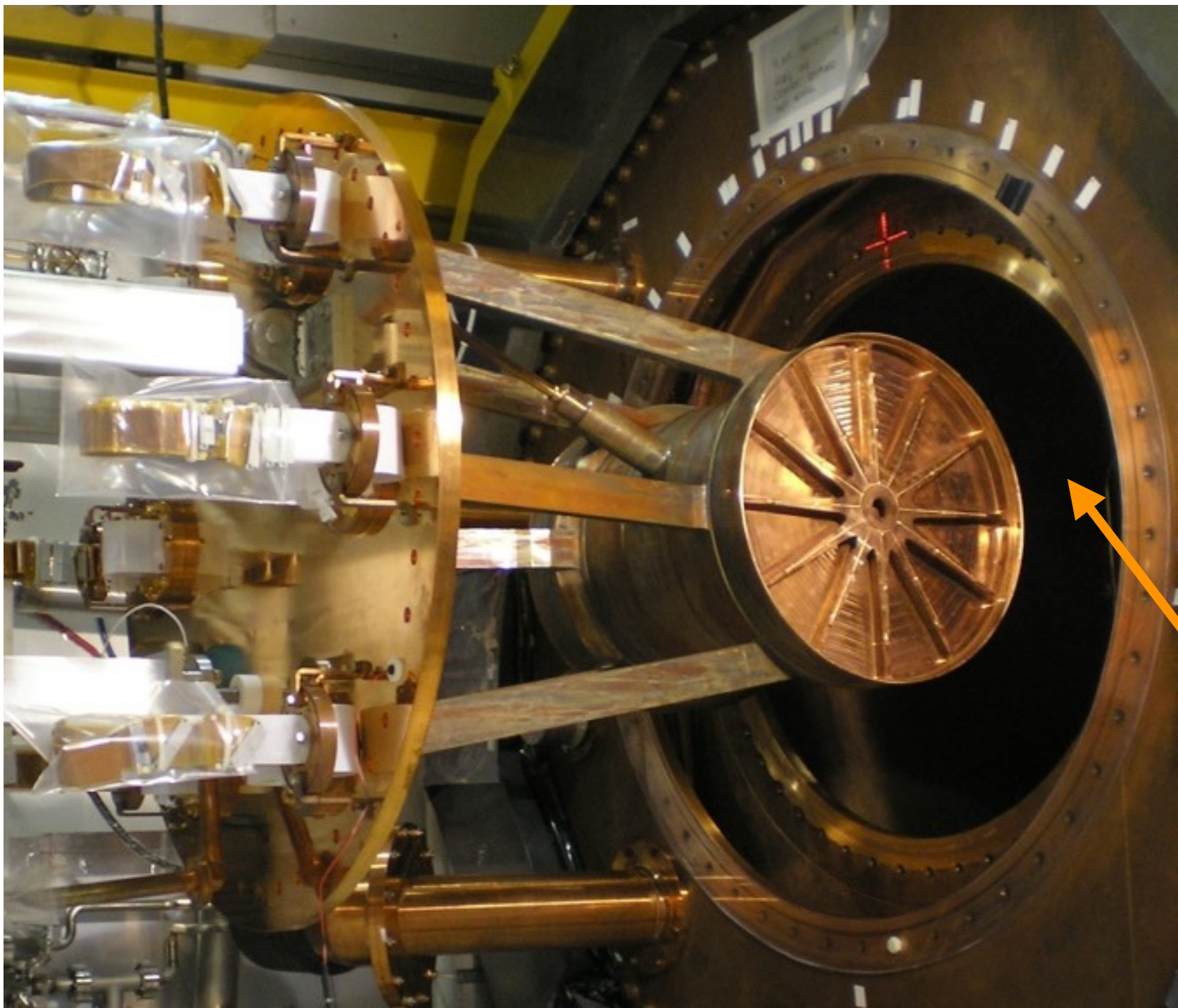


- Shielding from external ~MeV E&M background is harder(?) than what needed for dark matter detectors
- Detector sizes now greatly exceed gamma-ray interaction lengths

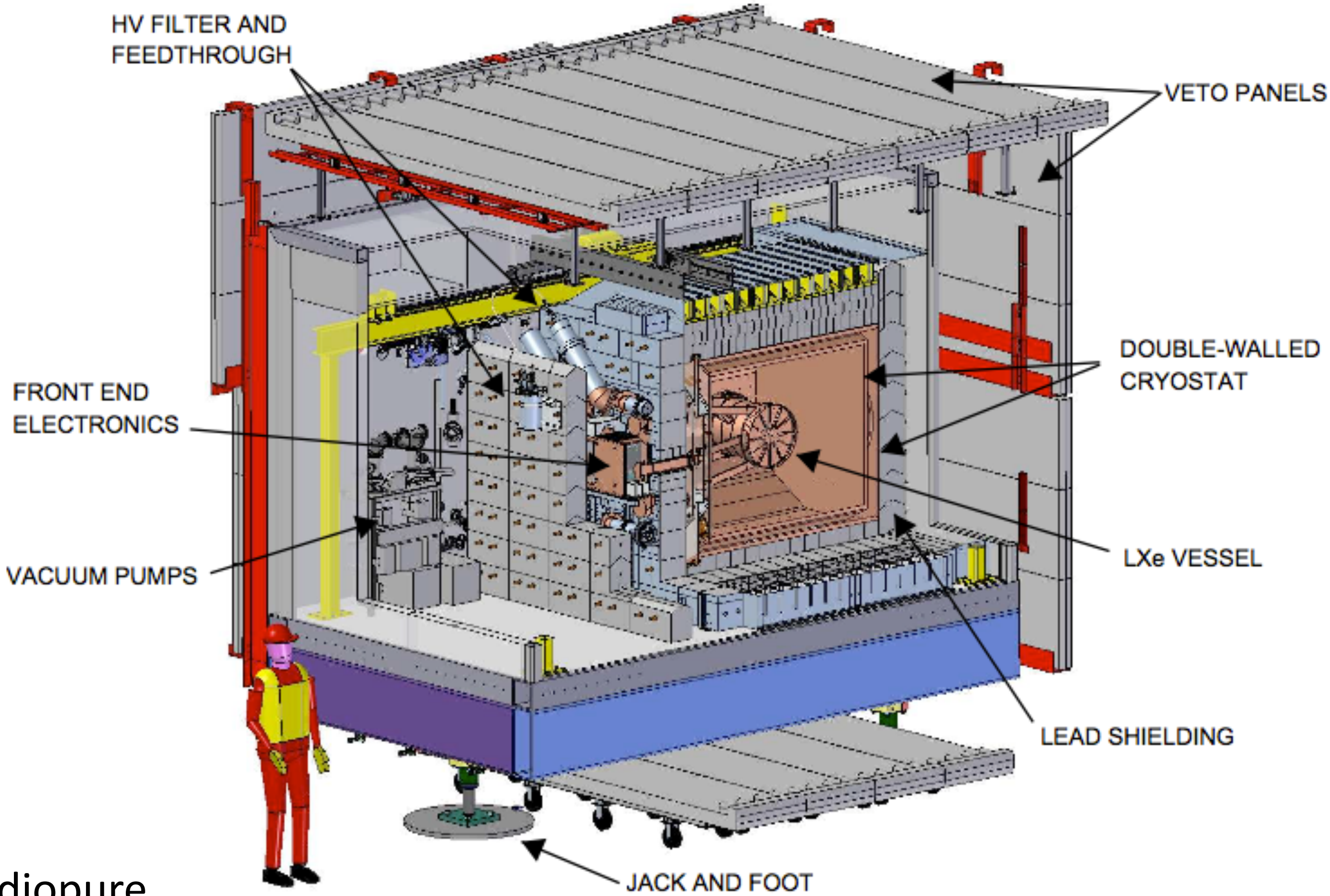
The nEXO roots: EXO-200



Thin, radiopure LXe vessel

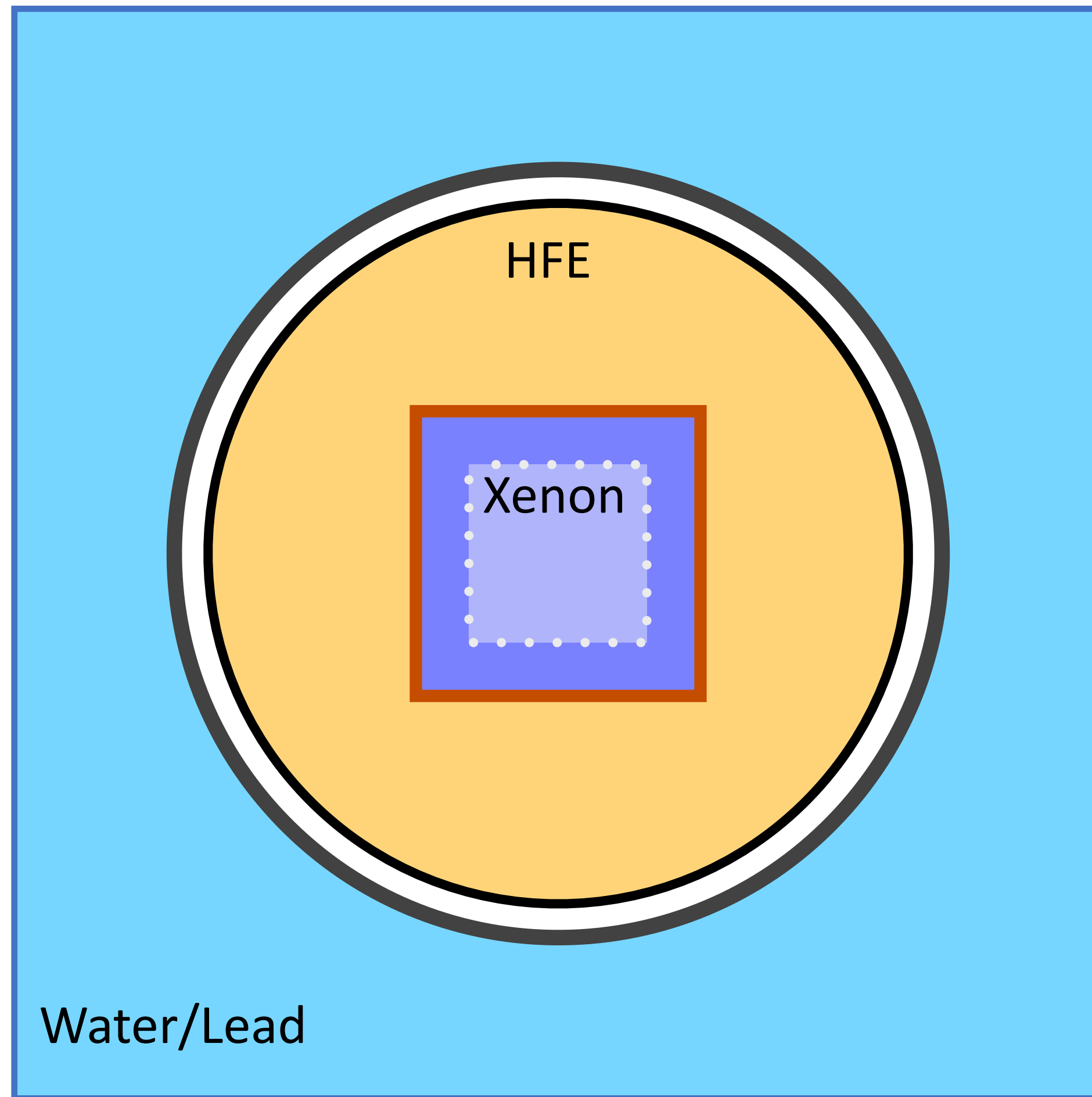


Dense, radiopure cold liquid buffer (HFE 7000, few tons)



EXO-200 low background cryogenic design

(Use xenon wisely — inspired by large neutrino detectors)



i) Largest Xe volume with the lowest background

- ▶ Thin single vessel, low-radioactivity copper
- ▶ Bulky double-vessel cryostat pushed far away, shielded by low-background, high density fluid

ii) HFE fluid is cleaner than any structural solid material

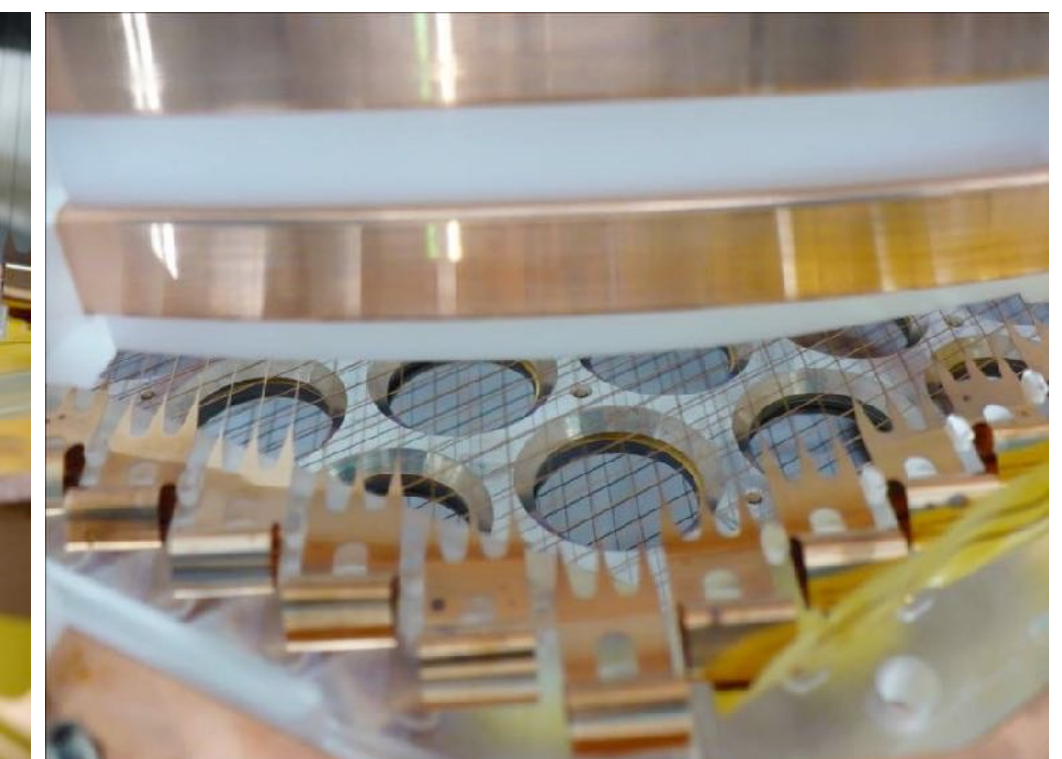
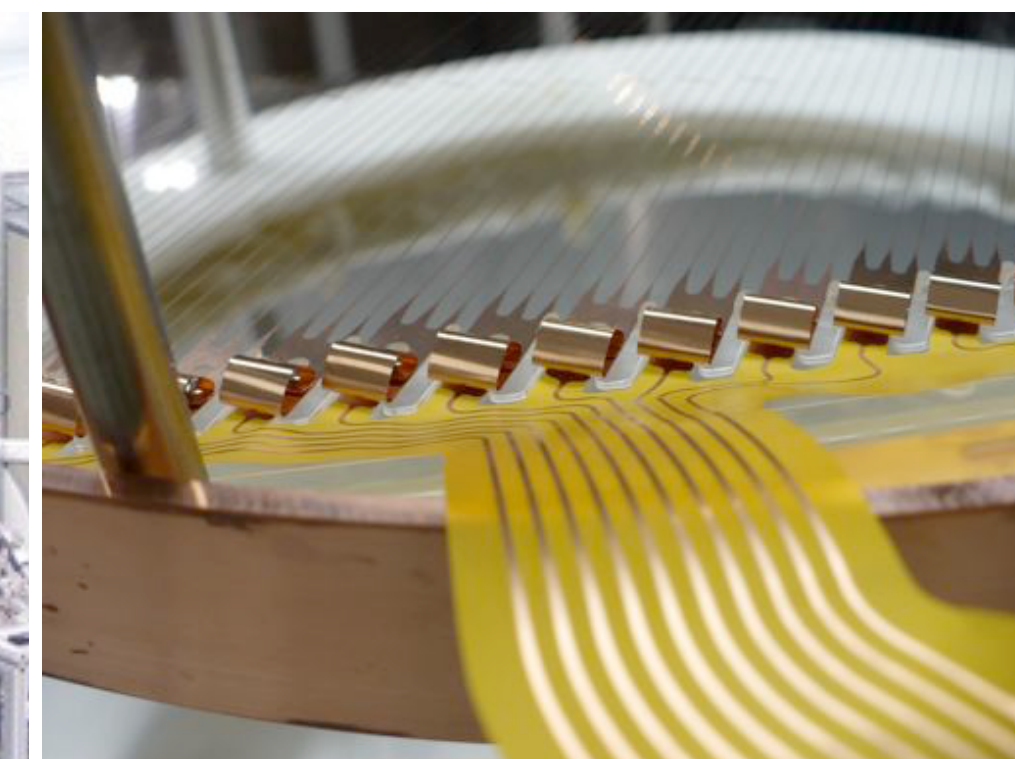
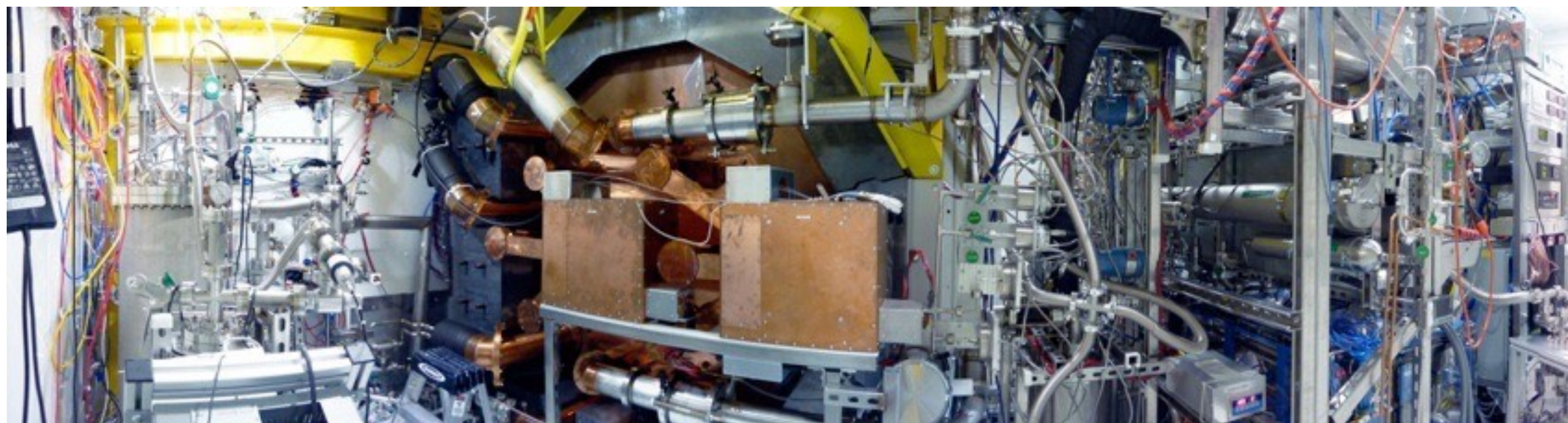
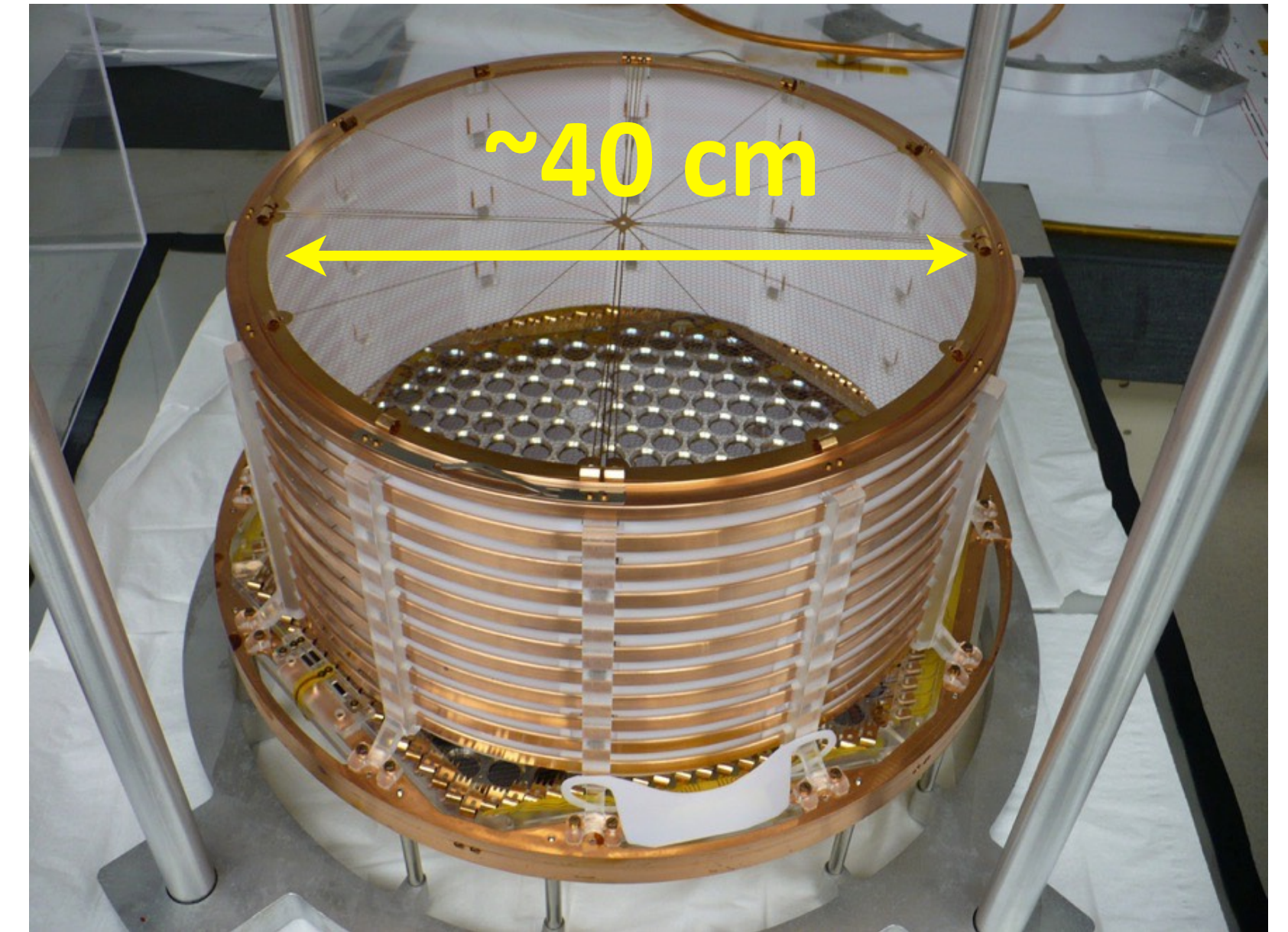
- ▶ Balance background contributions from cryostat, HFE
- ▶ Cryostat mass/background/cost/feasibility vs. size
- ▶ Cost, handling/storage of HFE

iii) HFE provides desirable thermal stability and inertia

- ▶ Efficient cooling relies on convection

A surprisingly sensitive experiment for its size

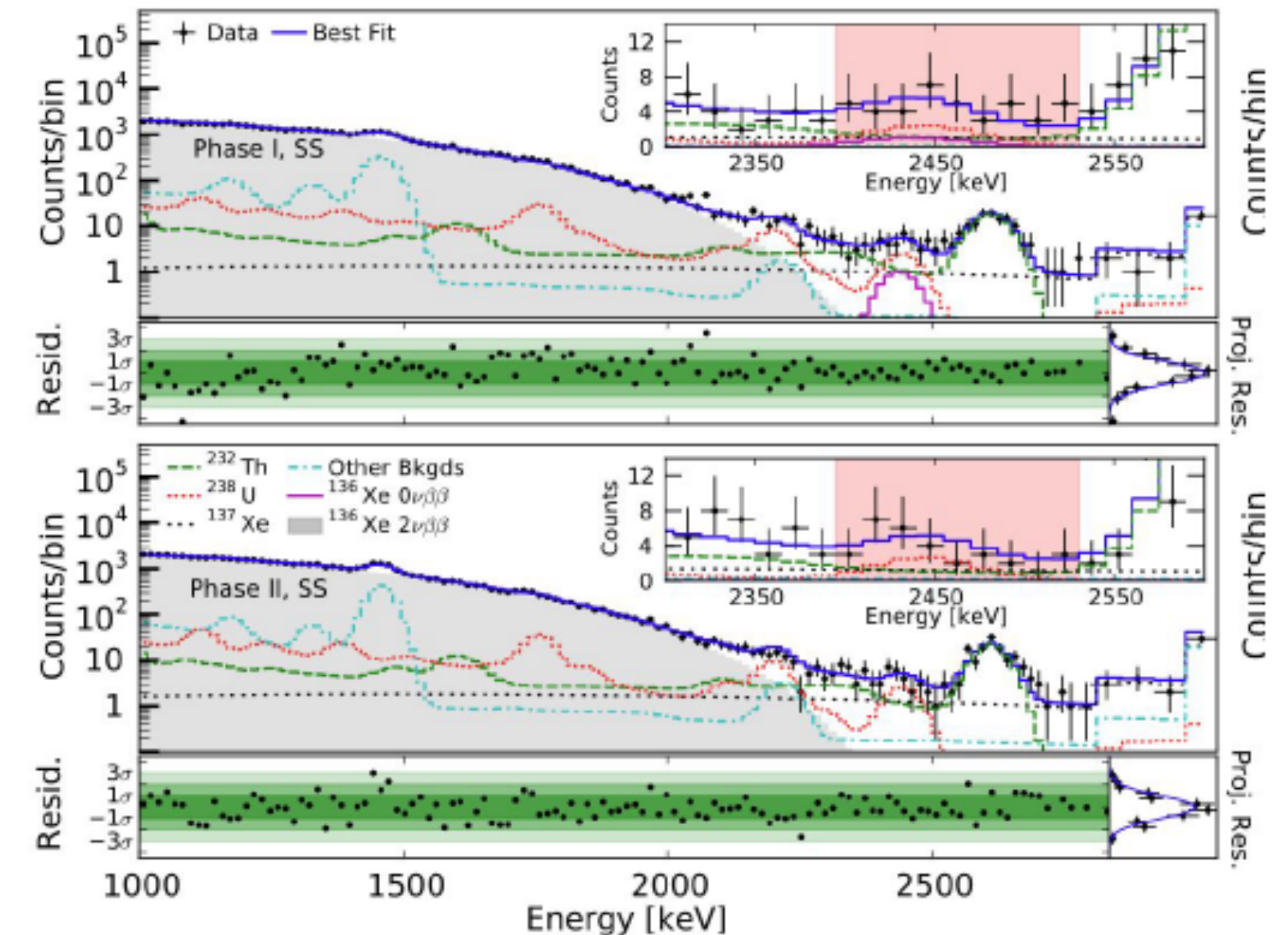
- 200 kg enriched LXe (80% ^{136}Xe) TPC
- Single phase
- Light readout with VUV-sensitive silicon LAAPDs
- Flat kapton cables
- Ultra-low bg design with HFE heat transfer fluid



- **First measurement of ^{136}Xe $2\nu\beta\beta$ decay (2011)**
(signal dominates)
- Best bound on ^{136}Xe $0\nu\beta\beta$ decay (2012)
- **First sub-3% measurement of any $2\nu\beta\beta$ decay (2015)**
- Very strong $0\nu\beta\beta$ decay measurement (2019)
(matched design sensitivity)
- Best bound on ^{134}Xe $0\nu\beta\beta$ decay (2026)
- Lowest ^{222}Rn concentration in LXe (for a while)
- Measurement of $W_{\text{tot}} = 11.5 \text{ eV}$ @MeV energy

Trades:

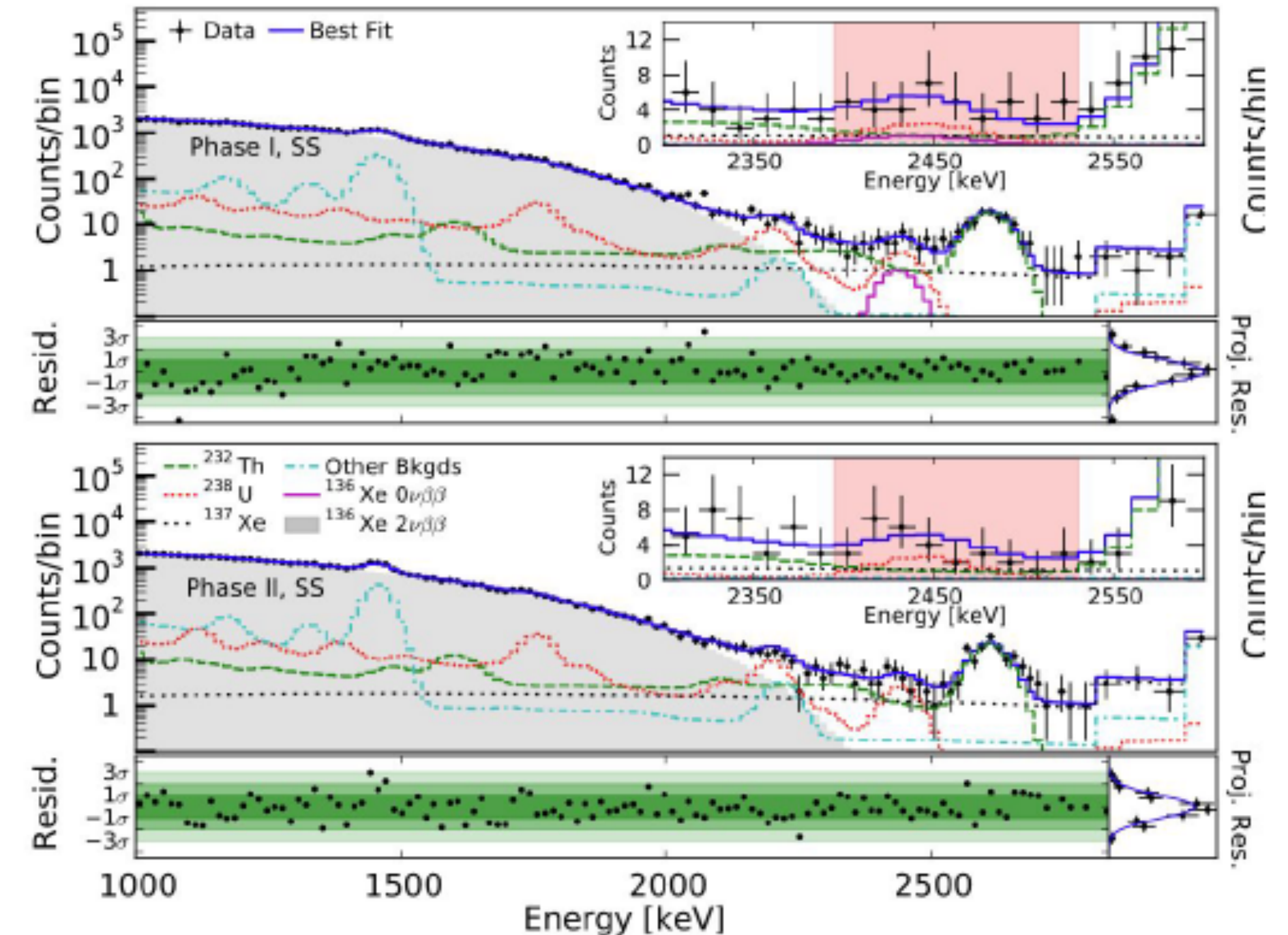
- Not a single photon/electron detector
- ~100 keV threshold



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Trades:

- Not a single photon/electron detector
- ~100 keV threshold



Take-homes:

- E&M background precisely predicted and controlled from radio assay + modeling (PRC 92, 015503, 2015)
- Precise measurement of background

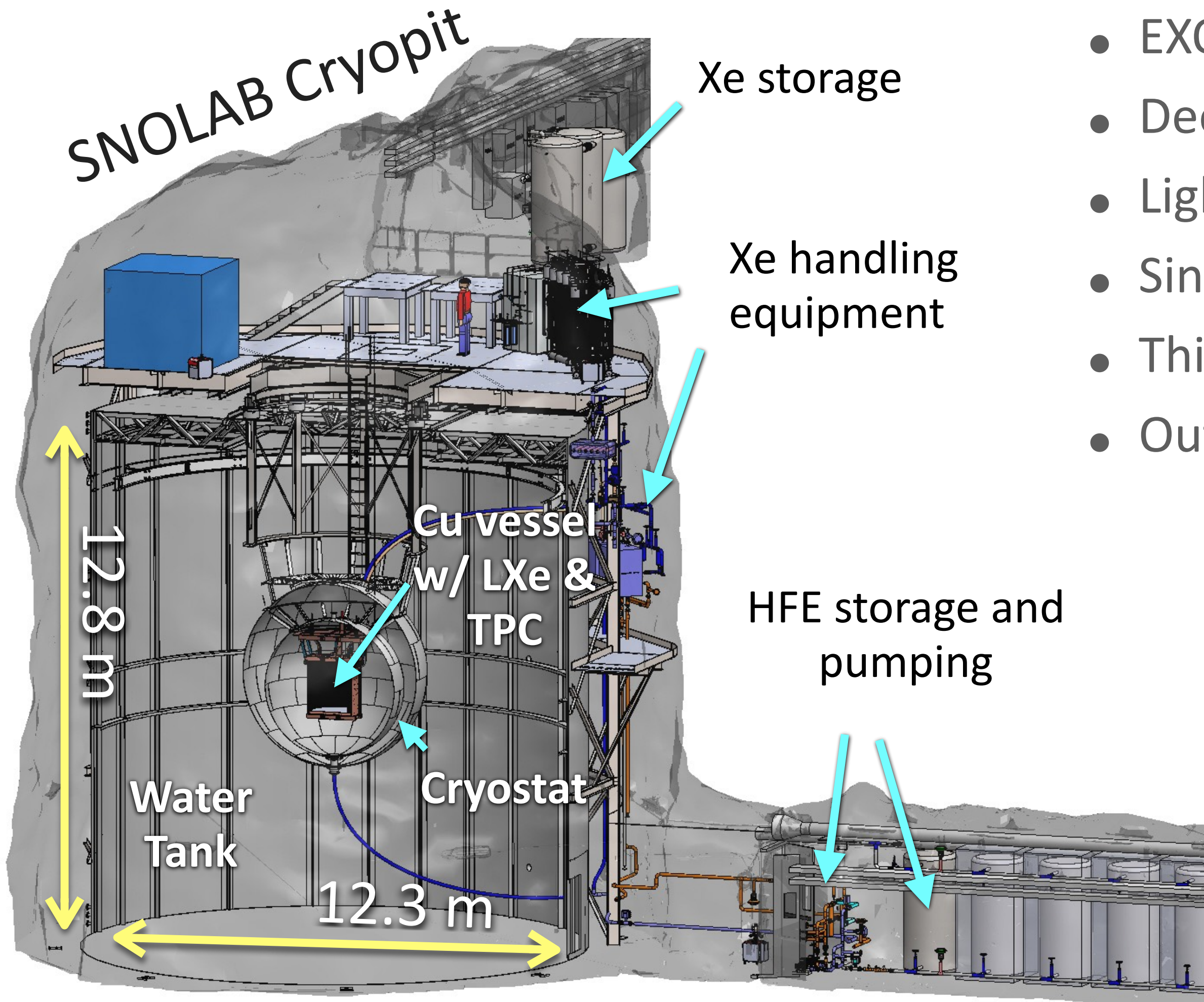
The nEXO design

nEXO designed to explore $T_{1/2}$ beyond 10^{28} years

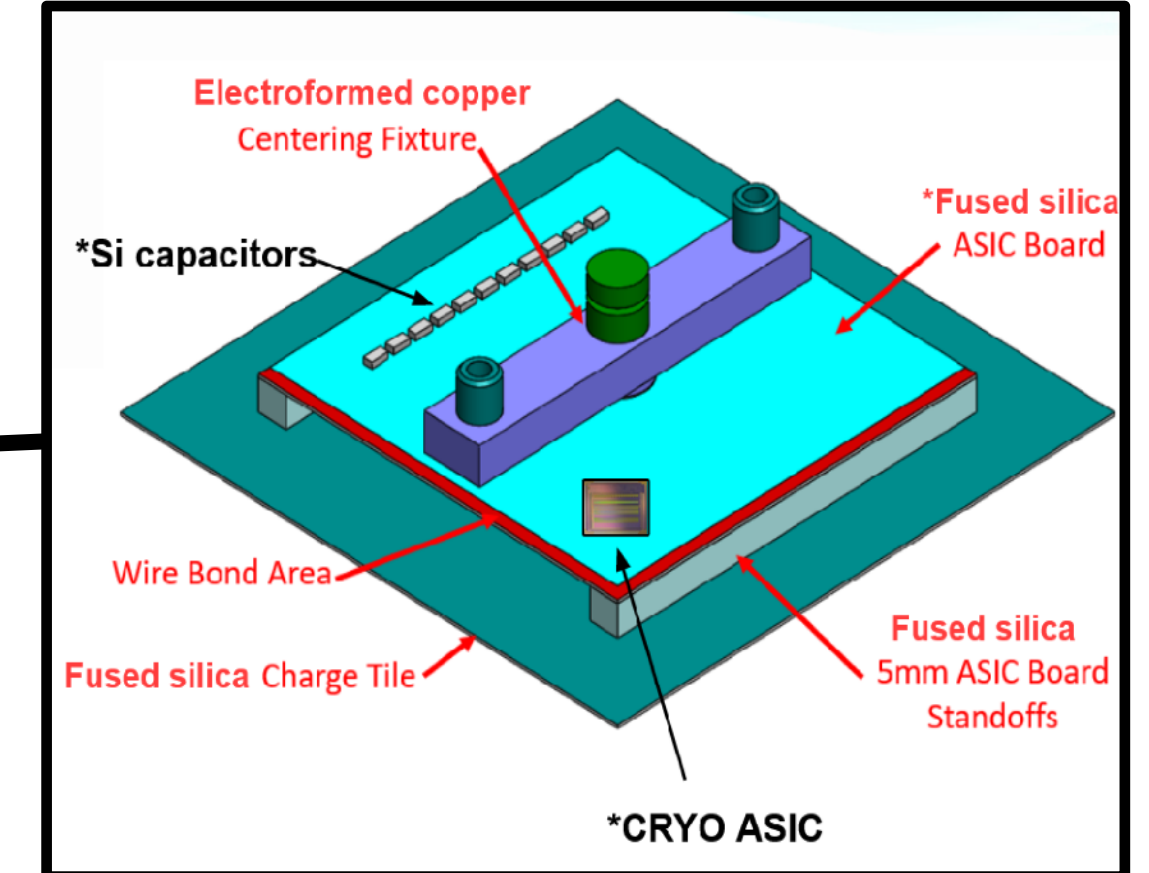
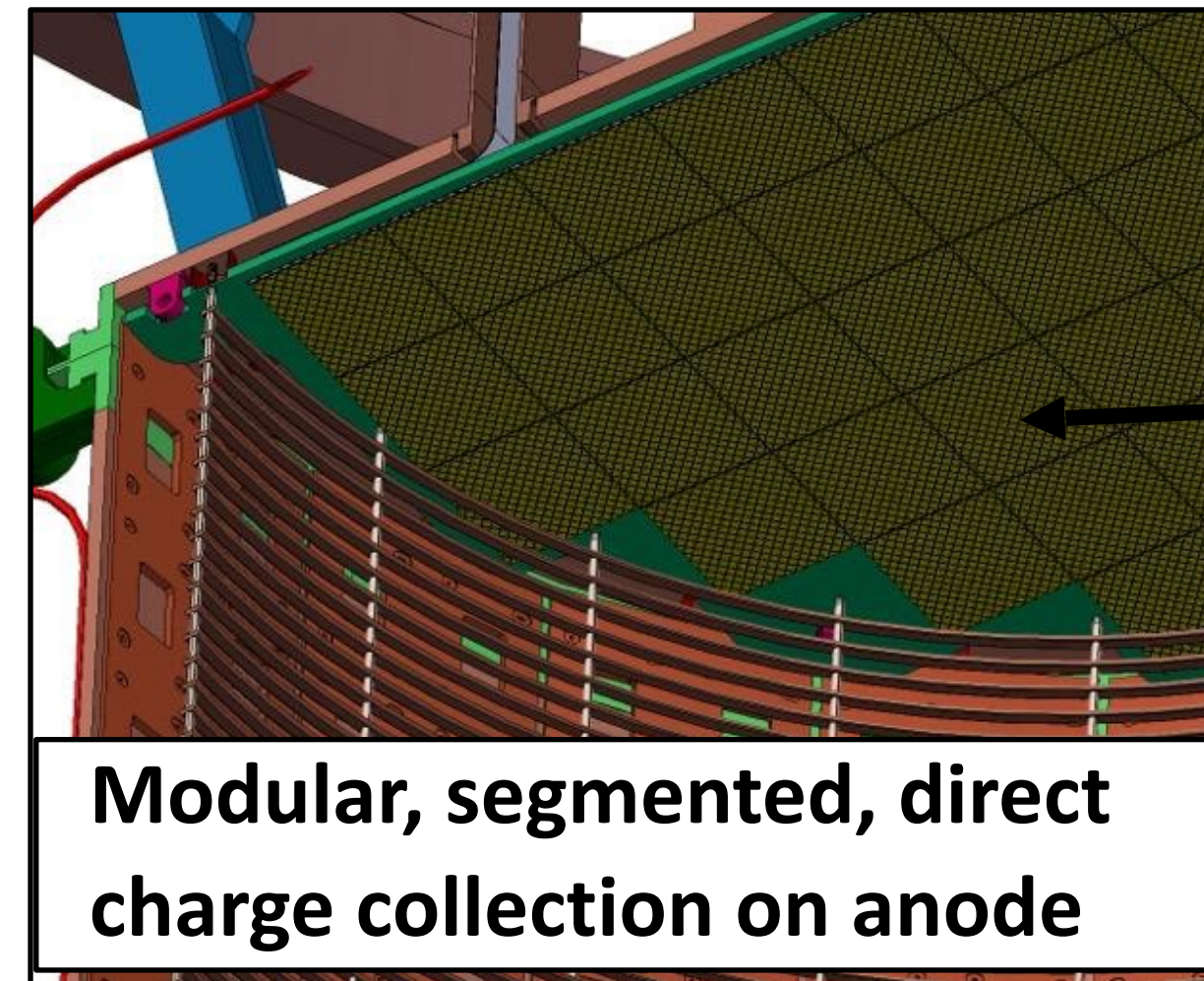
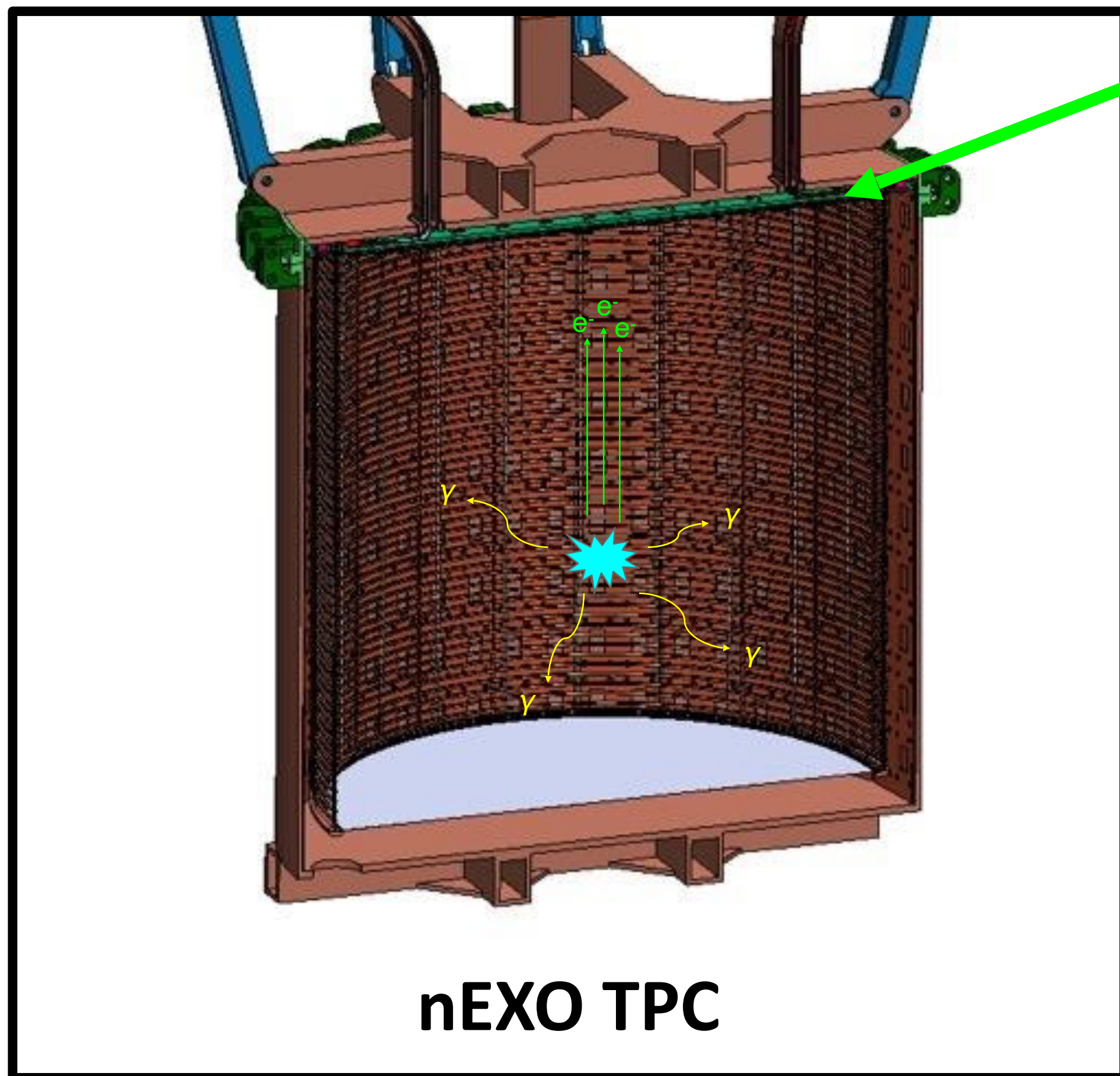
- 5000 kg enriched LXe (90% ^{136}Xe) TPC + light readout
- EXO-200 design, with novel solutions
- Deeper underground: WIPP $\rightarrow$ SNOLAB
- Light readout with VUV-sensitive silicon SiPMs
- Single drift TPC (no central cathode)
- Thin electro-formed Cu vessel of the LXe
- Outer shielding: Pb $\rightarrow$ water

Scaled up shielding and cryogenic concept

- 32 tons of HFE (7200 or 7000)
 - 75 cm minimum thickness
- Ability to recirculate HFE through external HEX (enhanced cooling power and fewer bg worries)
- Low radioactivity Nickel cryostat

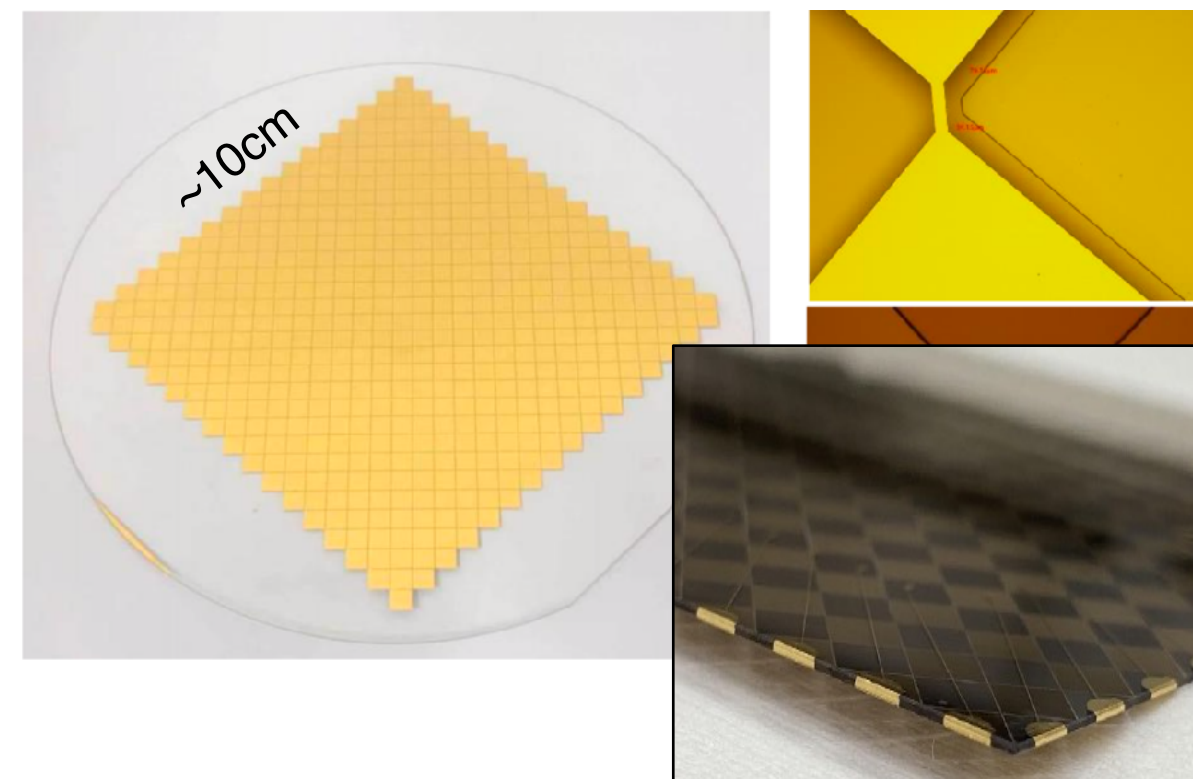


Dual scintillation and ionization detector systems with cryogenic ASIC readout

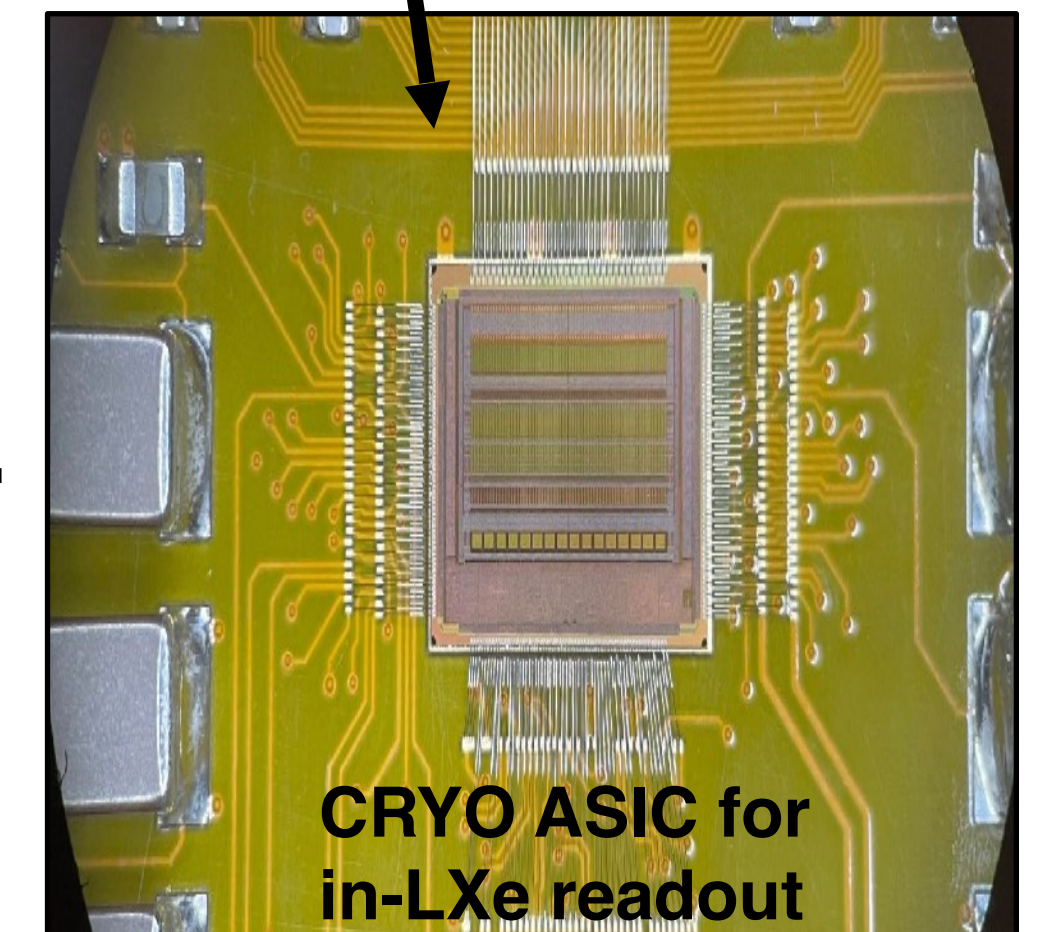


32-channel readout per module with 6mm pitch/ch

Ultra-low-bkg fused silica sensor tiles



+



Dual scintillation and ionization detector systems with cryogenic ASIC readout

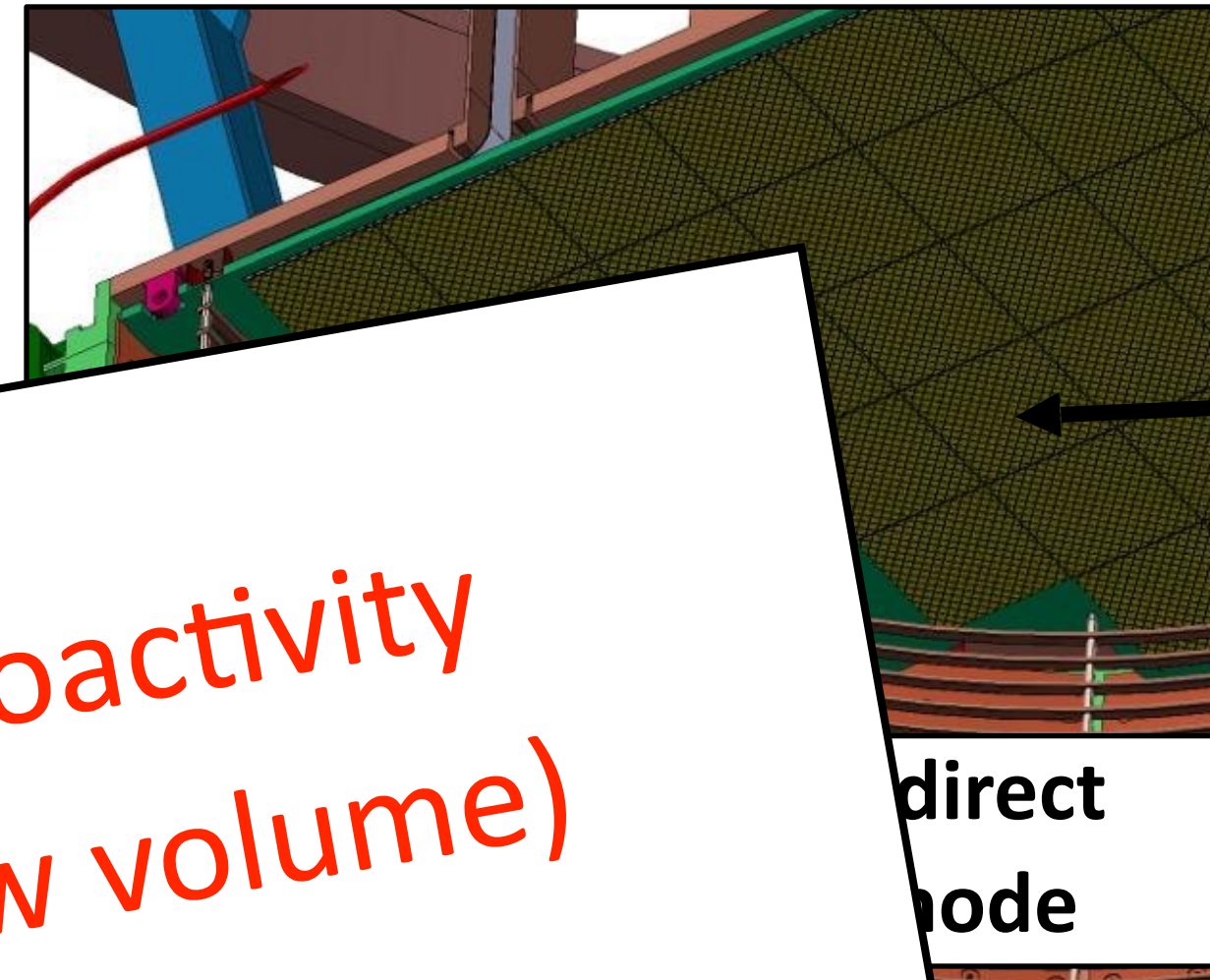
Pros:

- Very low radioactivity
- Compact (low volume)
- Low noise

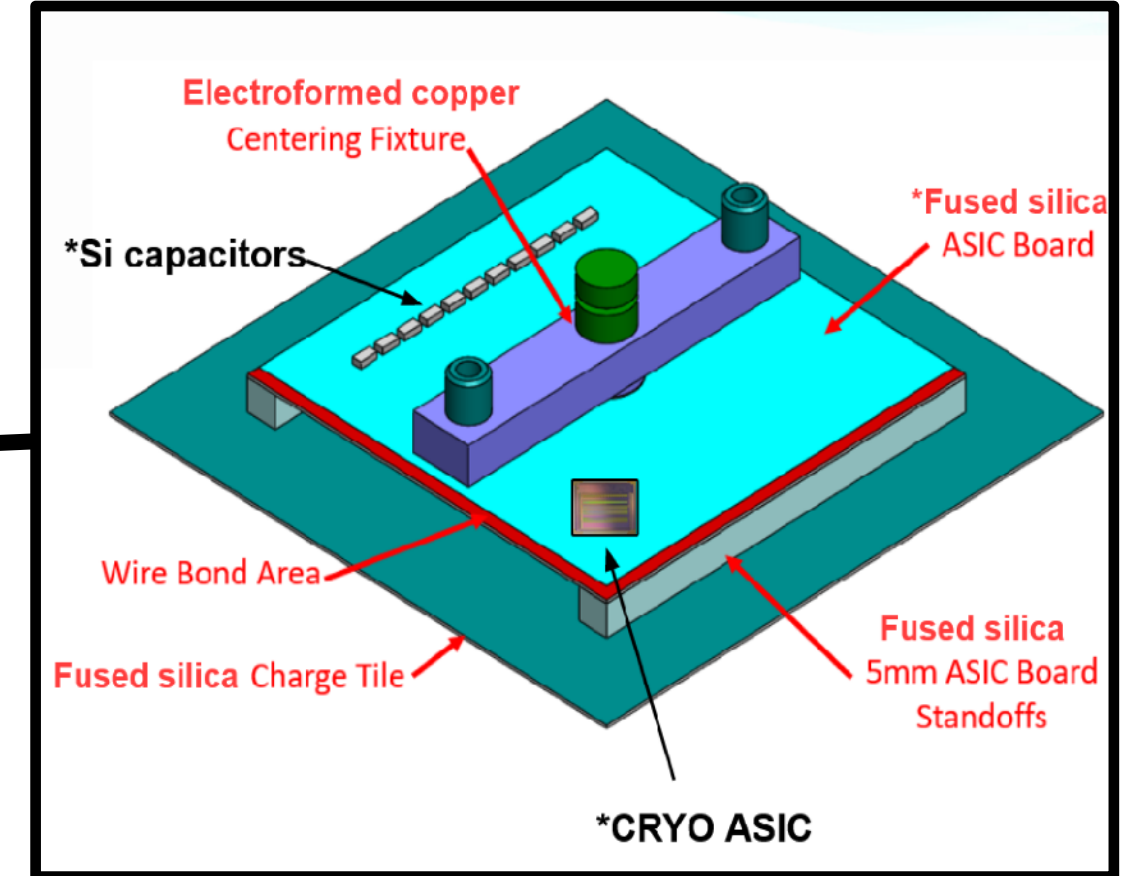
Cons:

- No gain (LXe single phase)

nEXO TPC

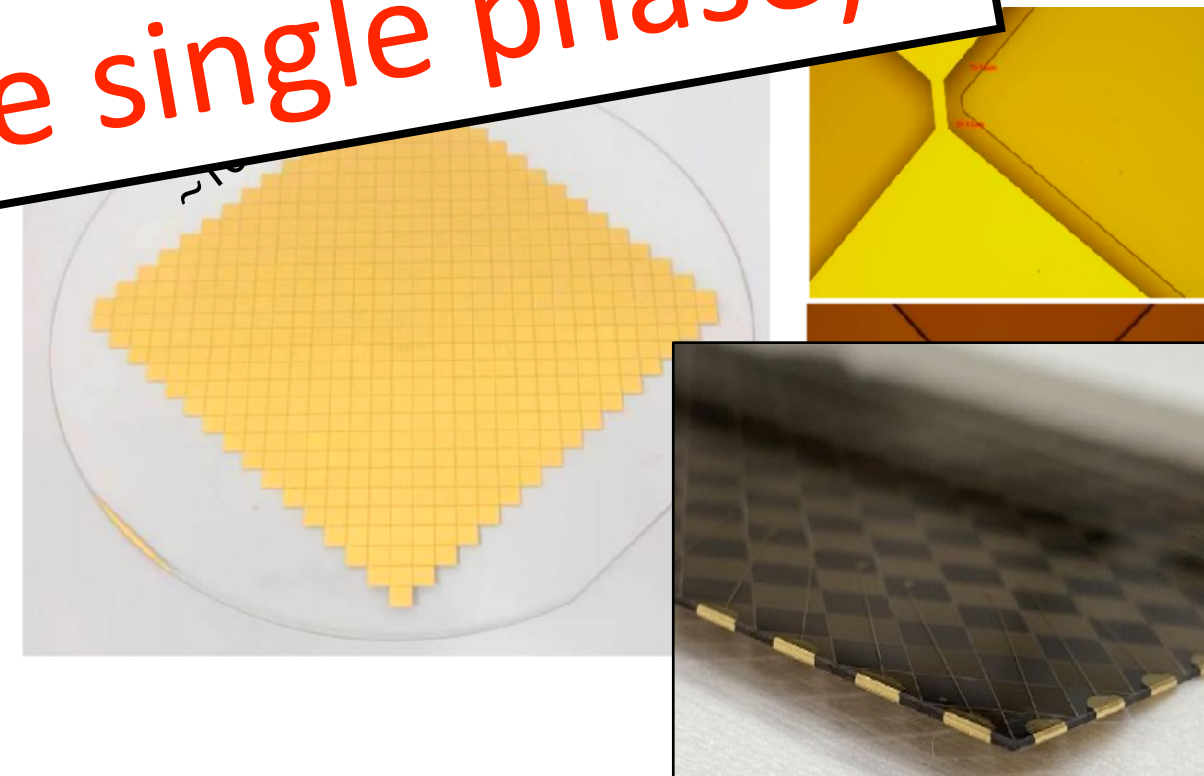


direct mode

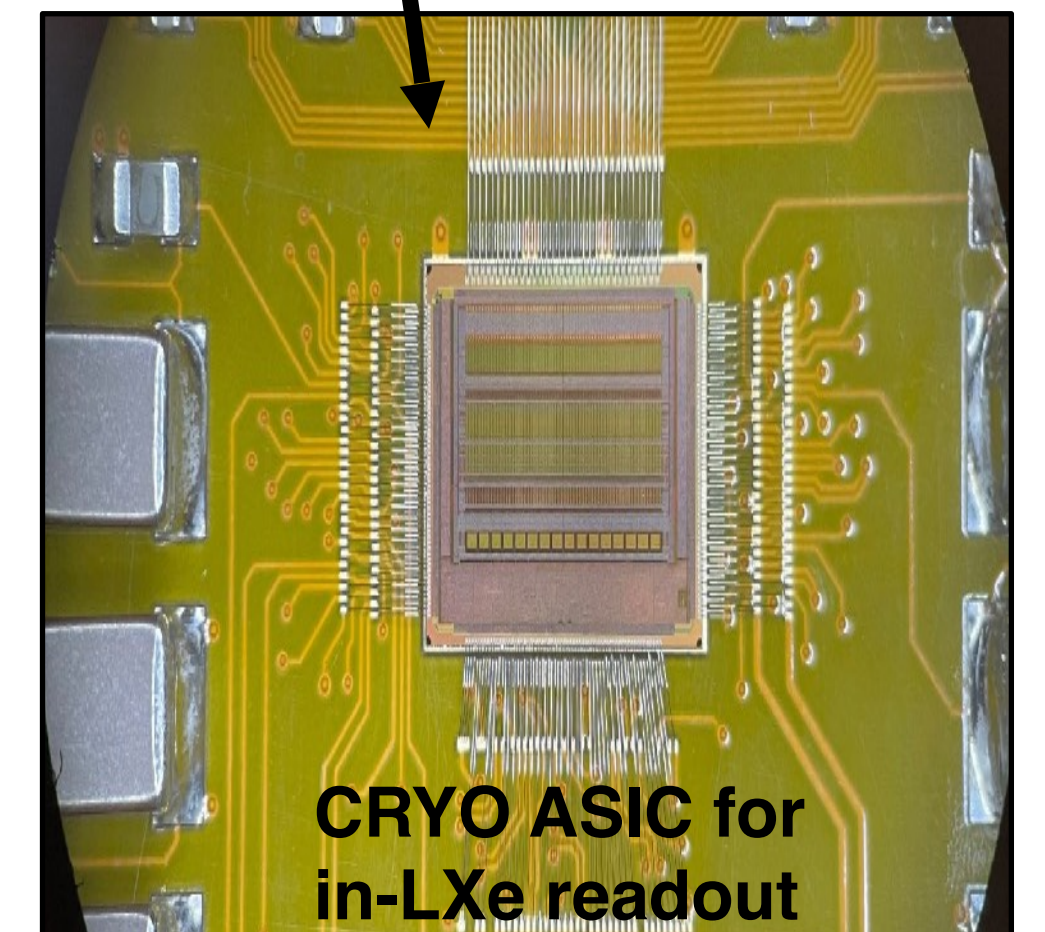


32-channel readout per module with 6mm pitch/ch

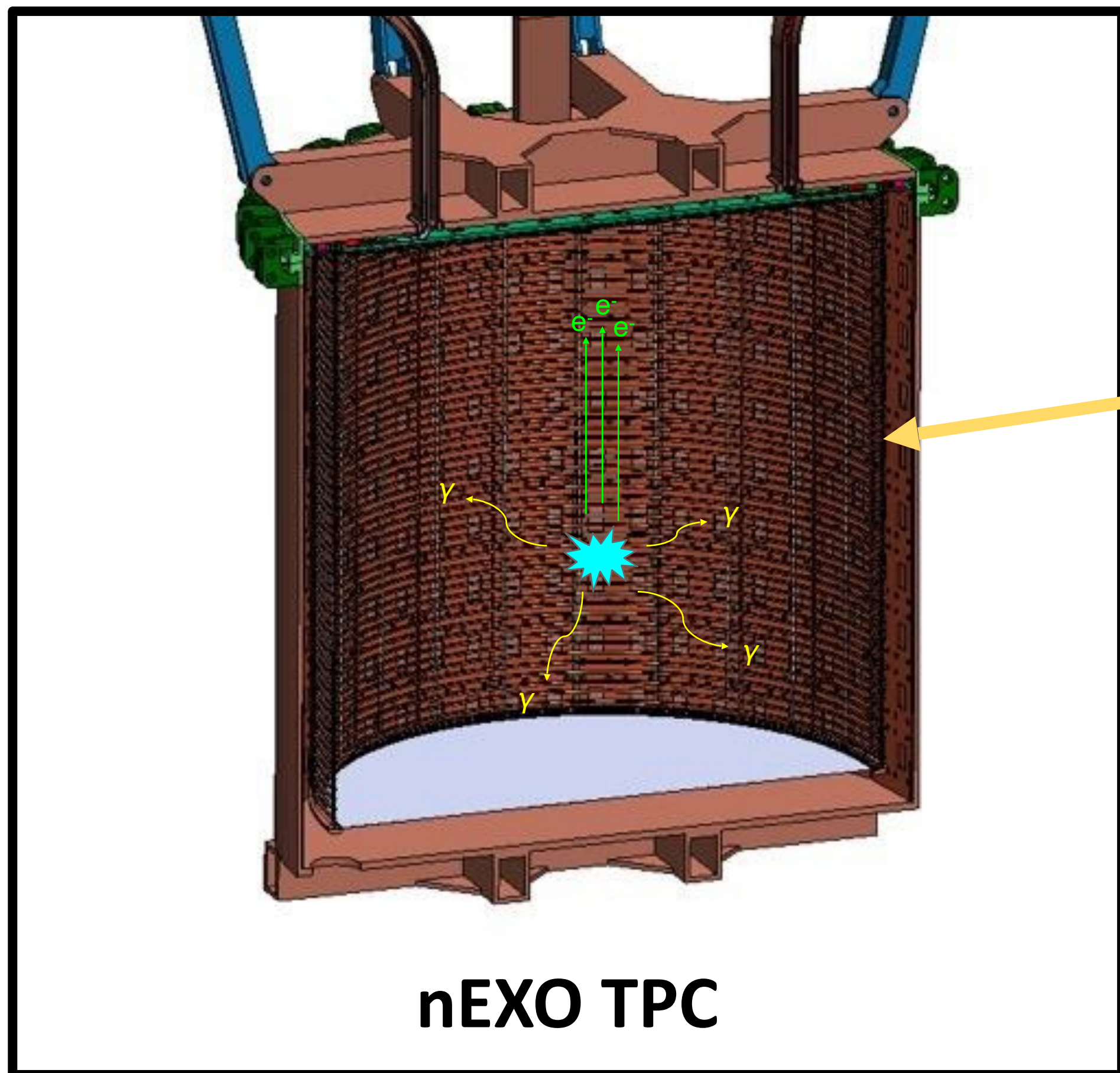
sensor tiles



+

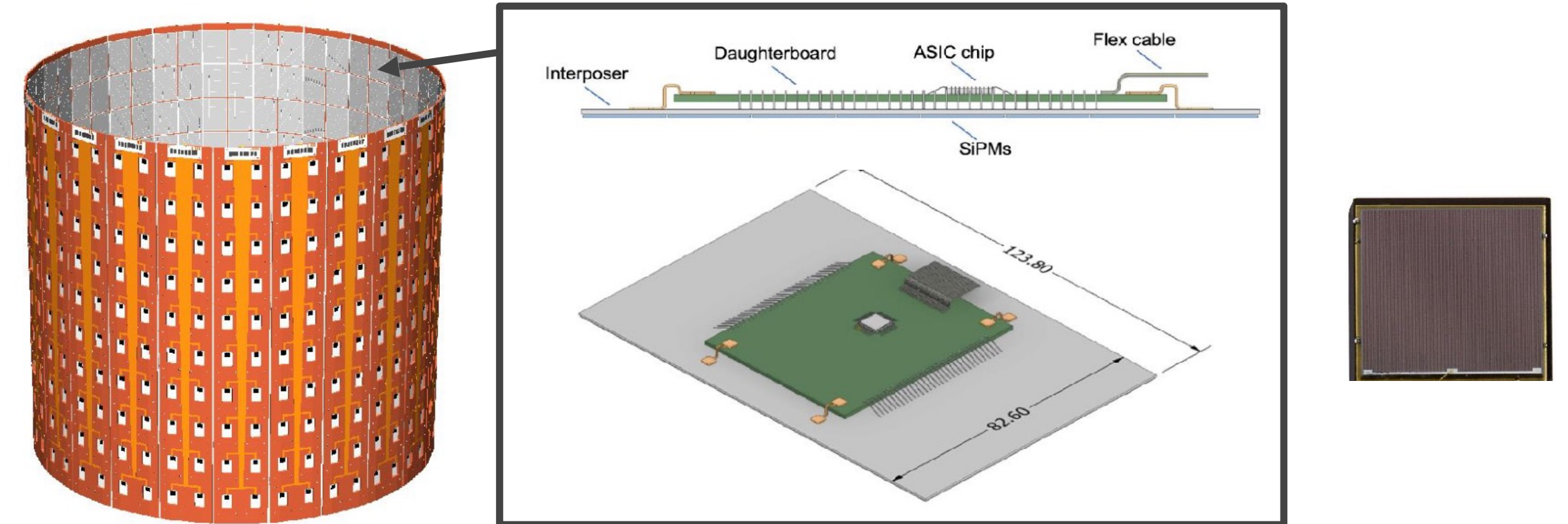


Dual scintillation and ionization detector systems with cryogenic ASIC readout

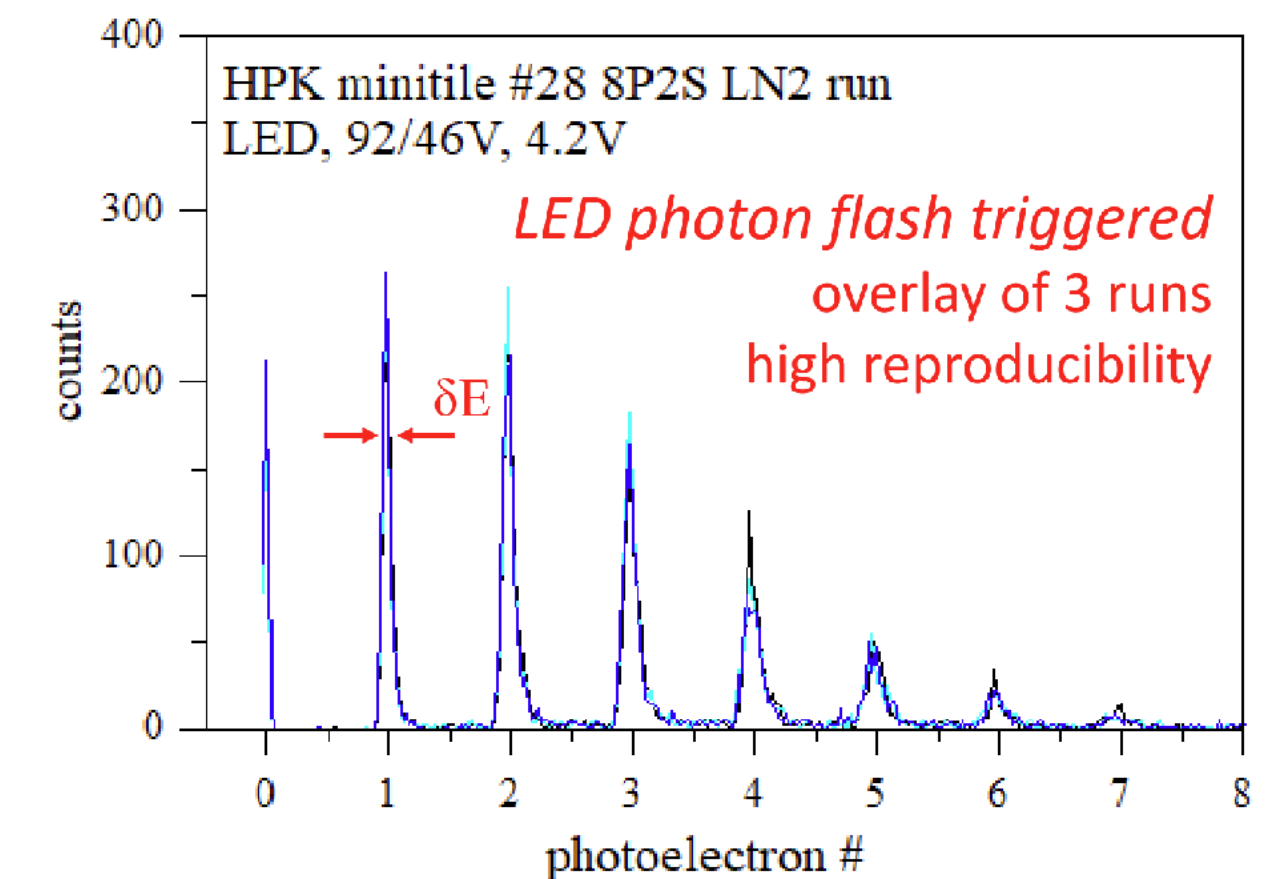
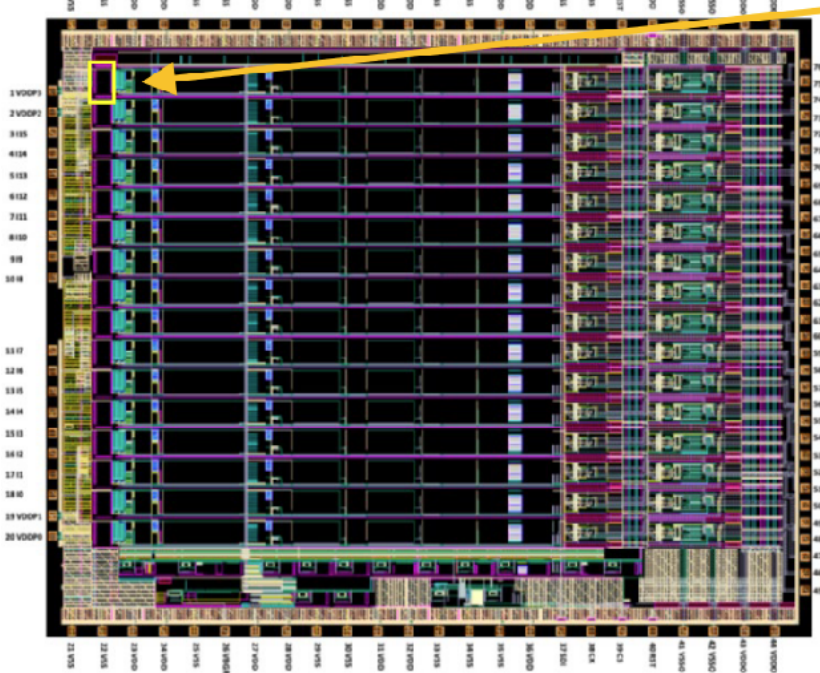


Tiled SiPM scintillation readout around barrel

>4 m², high-density coverage with VUV-sensitive, 1cm x 1cm SiPMs



In-LXe readout with LArASIC



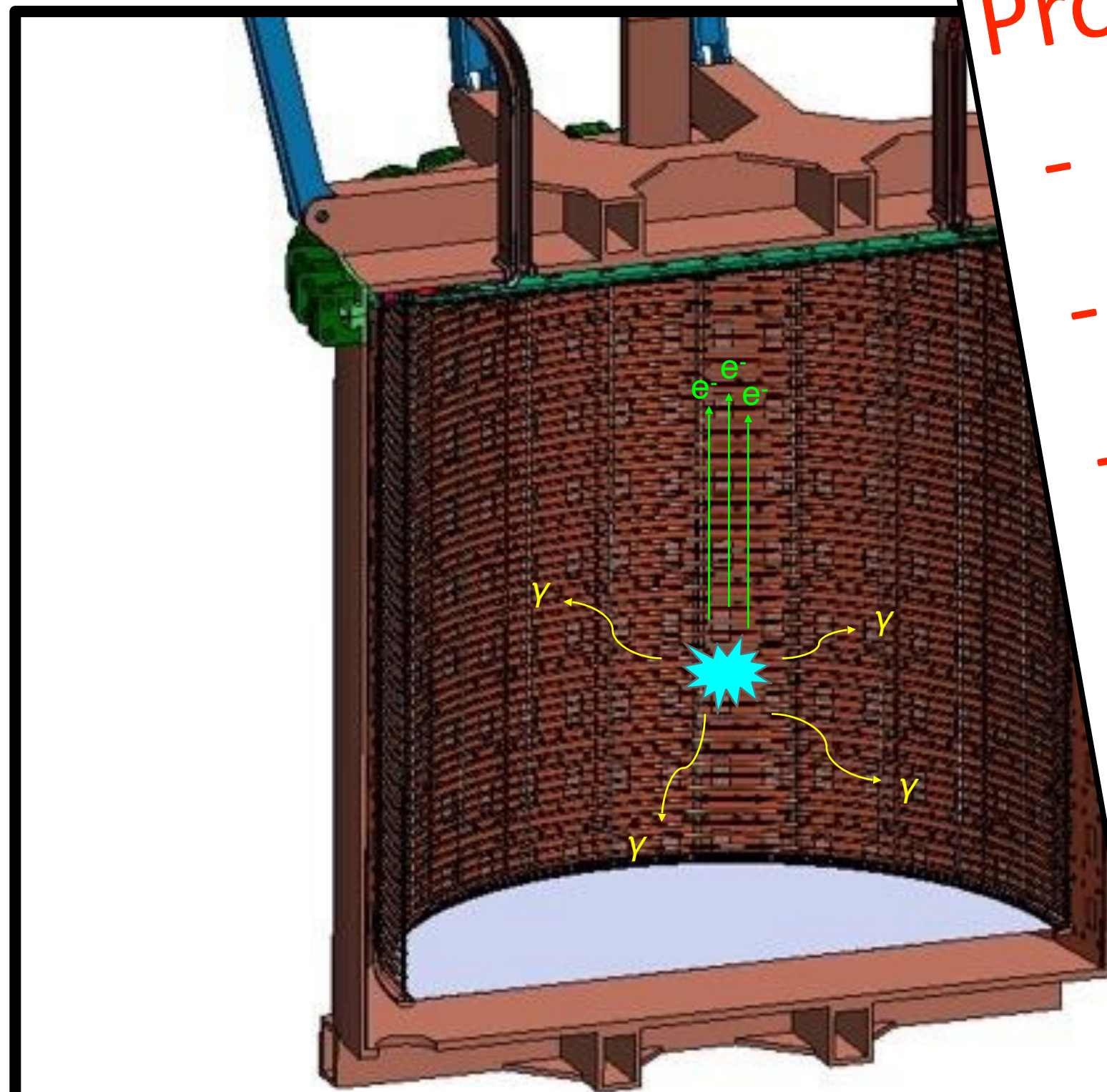
Dual scintillation and ionization detector systems with cryogenic ASIC readout

Pros:

- Very low radioactivity
- Compact (low volume)
- Low voltage
- Optically open TPC $\rightarrow$ bg rejection

Risk:

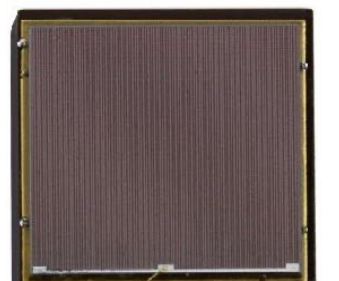
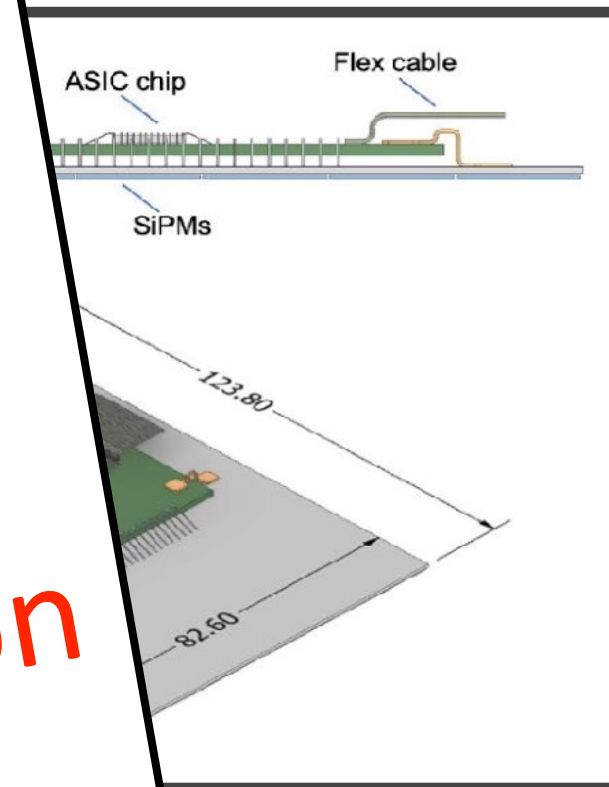
- Novel technology wrt to PMTs



nEXO TPC

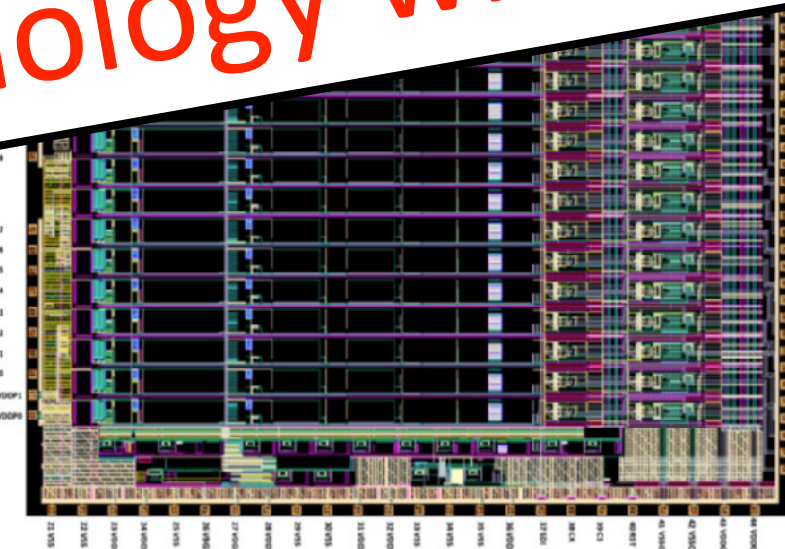
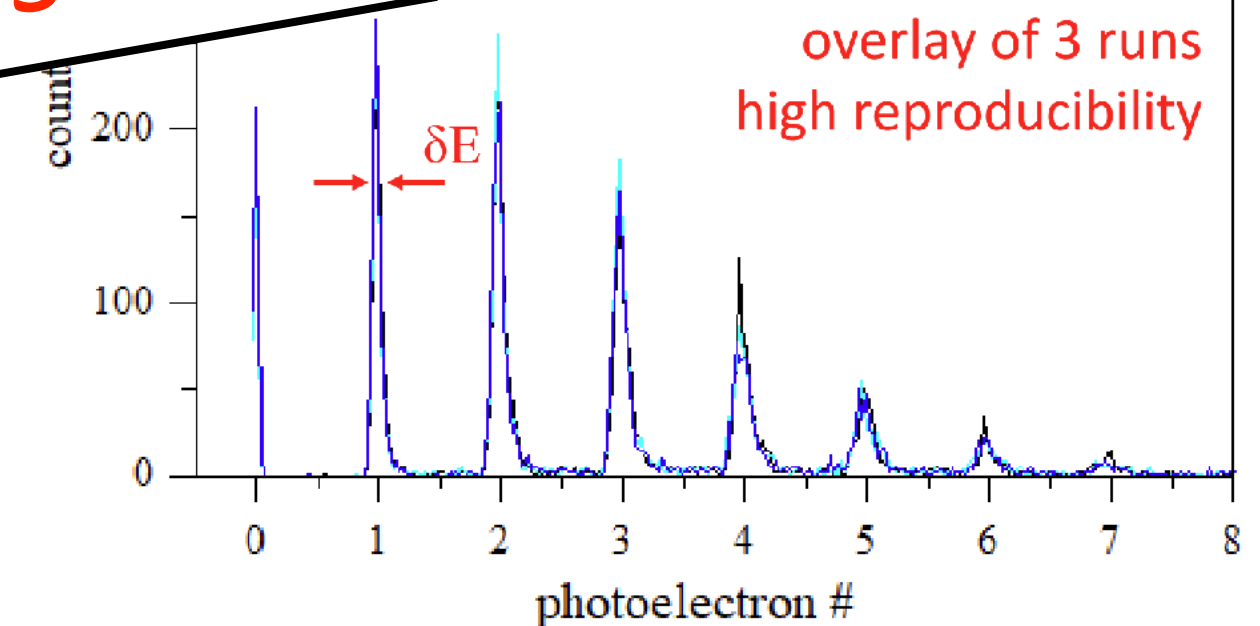
Tiled SiPM scintillation readout

high-density coverage with sensitive, 1cm x 1cm SiPMs

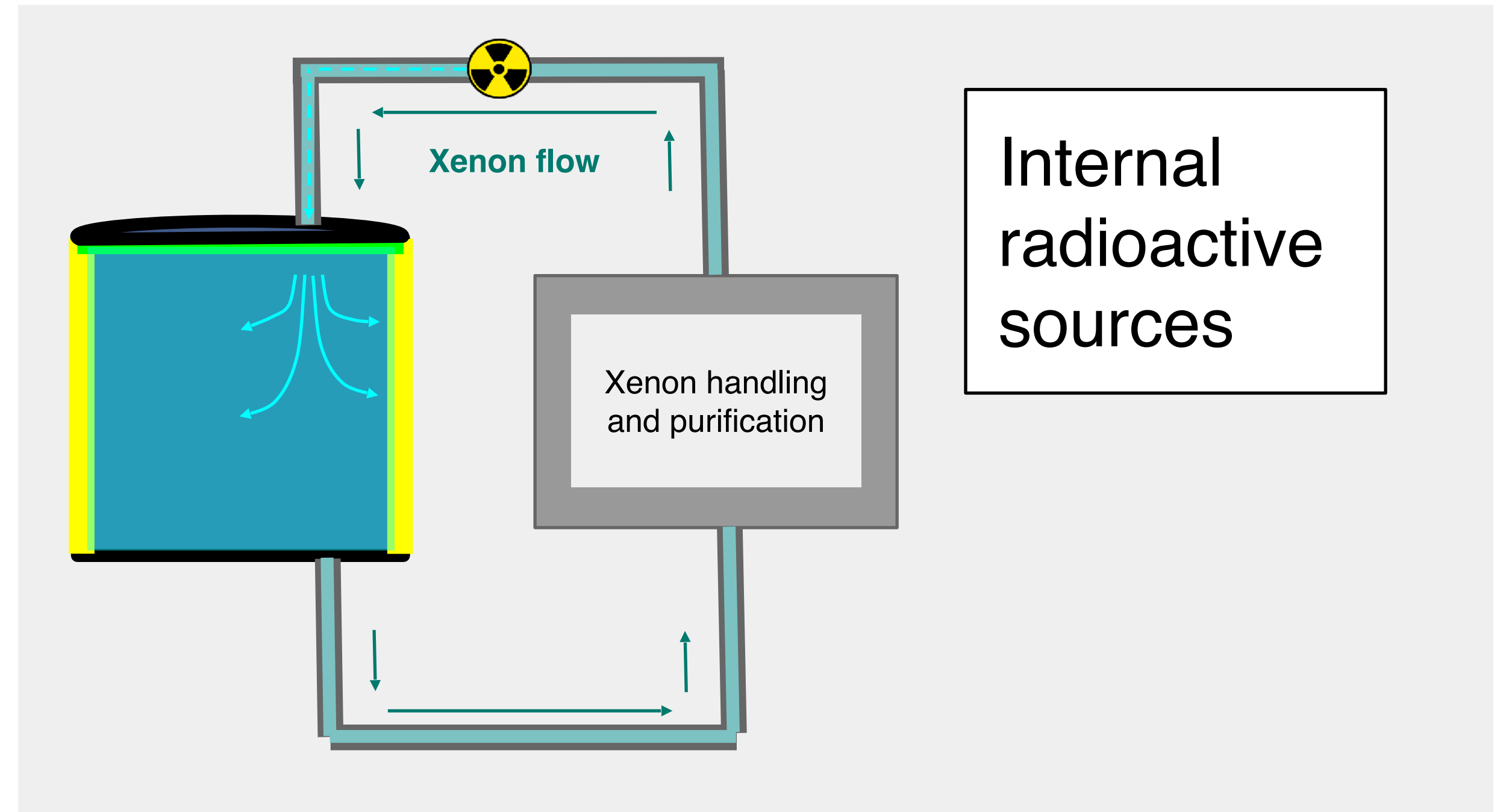
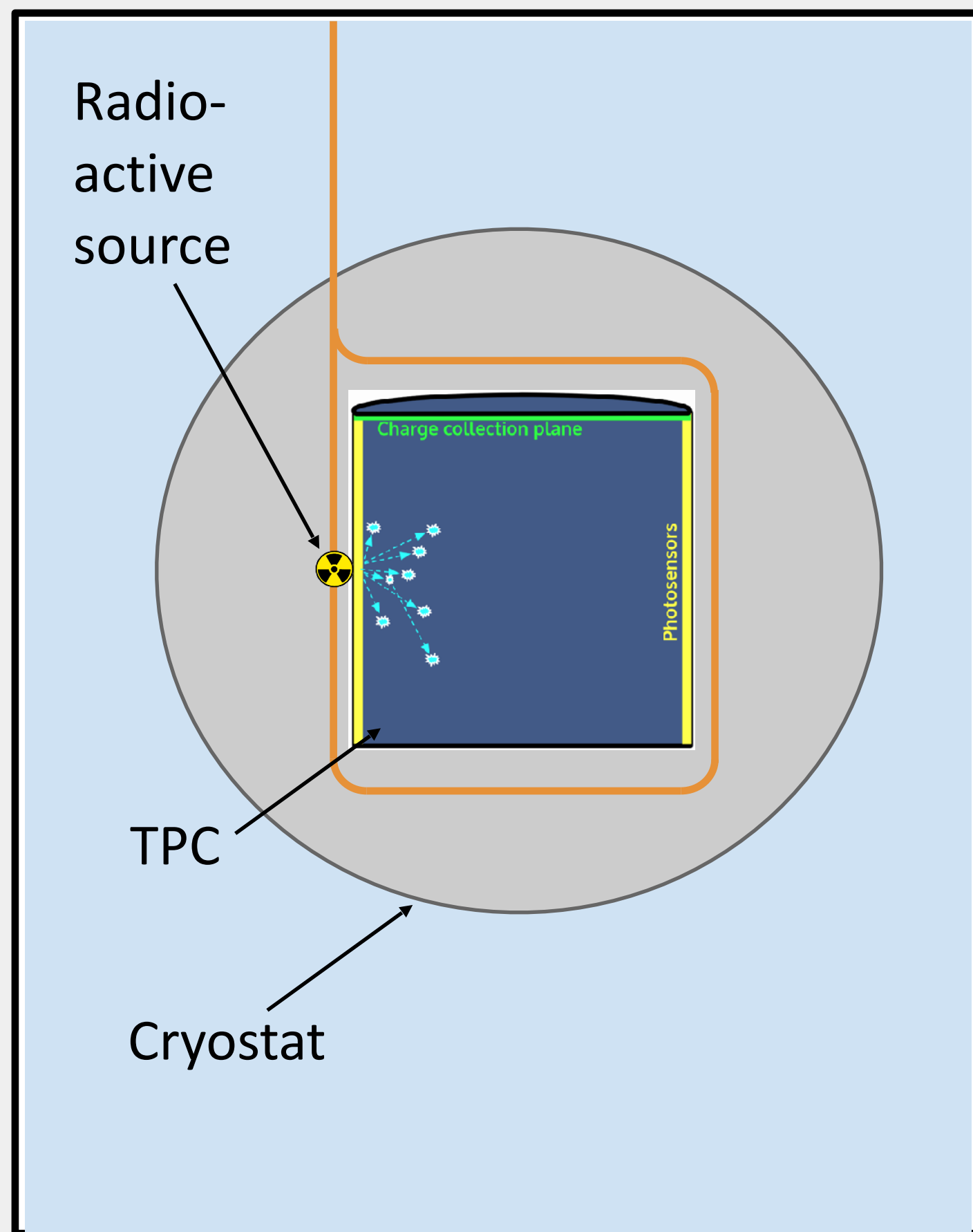


Tile #28 8P2S LN2 run
46V, 4.2V

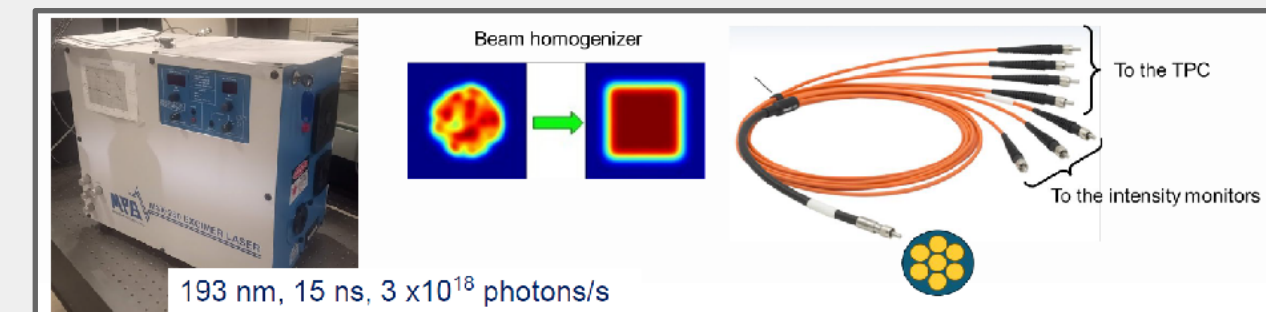
LED photon flash triggered
overlay of 3 runs
high reproducibility



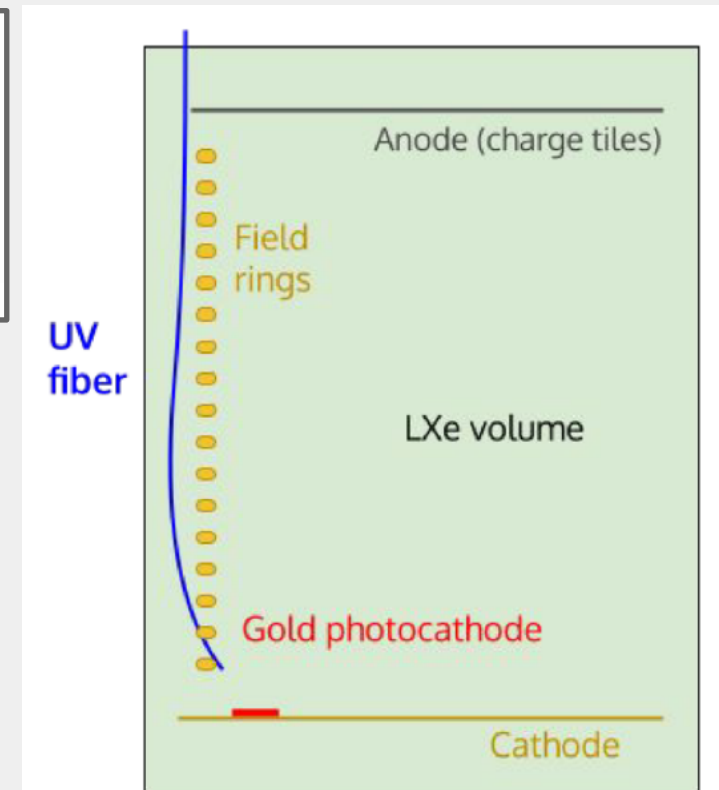
External radioactive sources



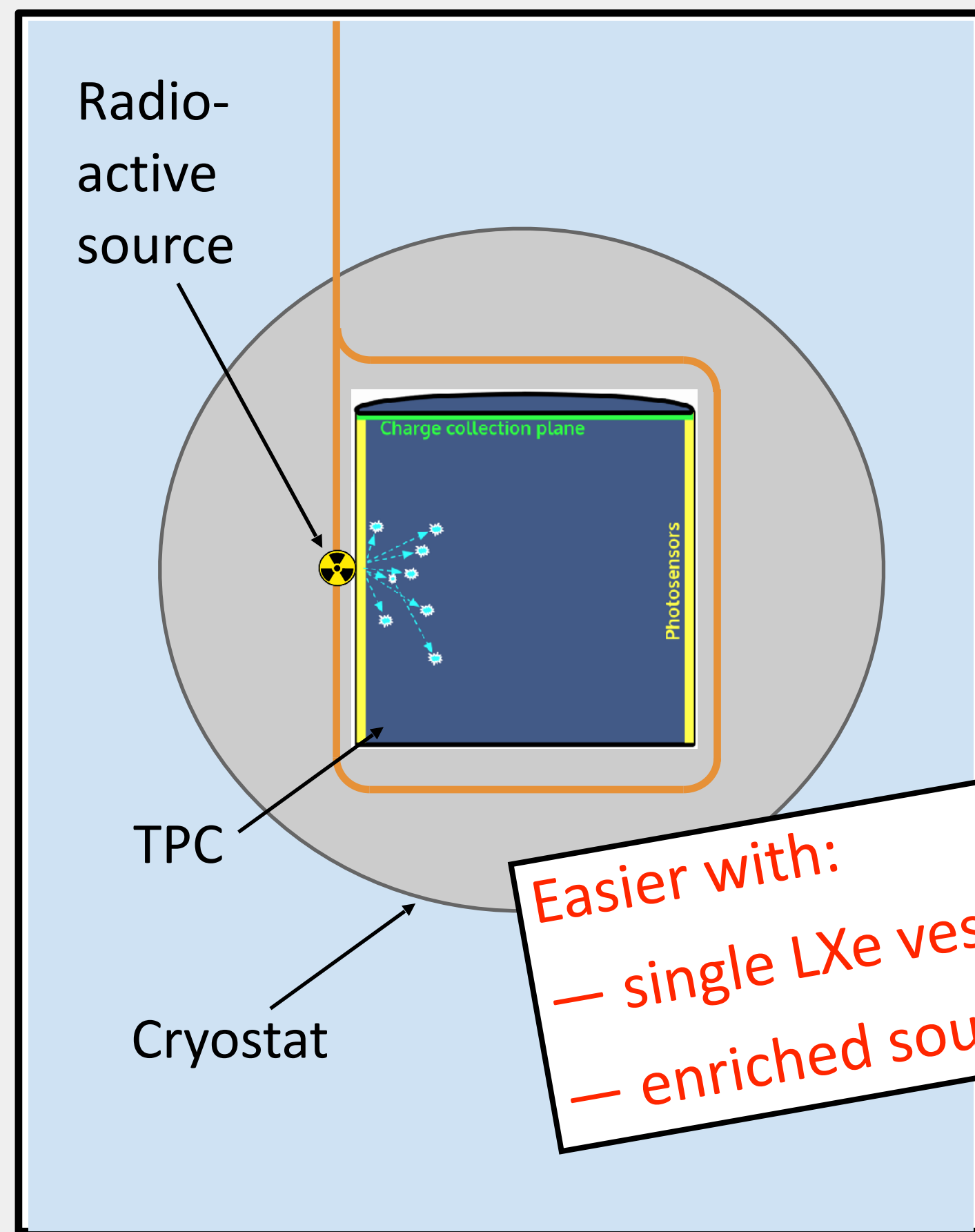
Internal radioactive sources



Non-radioactive-source calibrations

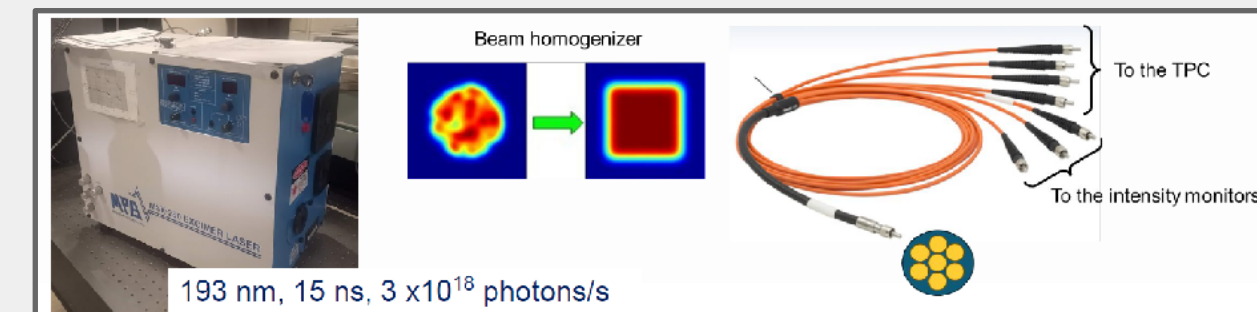
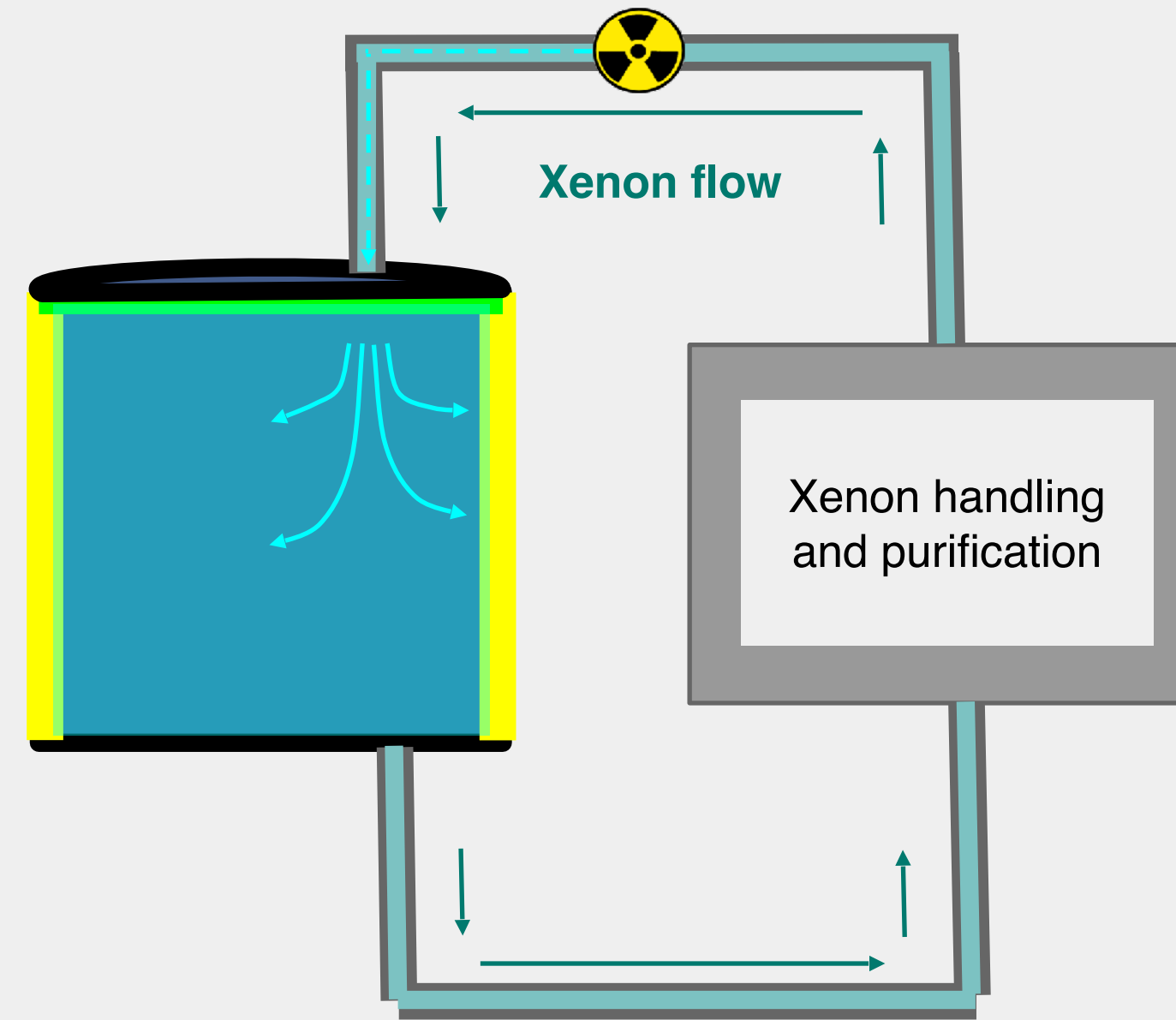


External radioactive sources

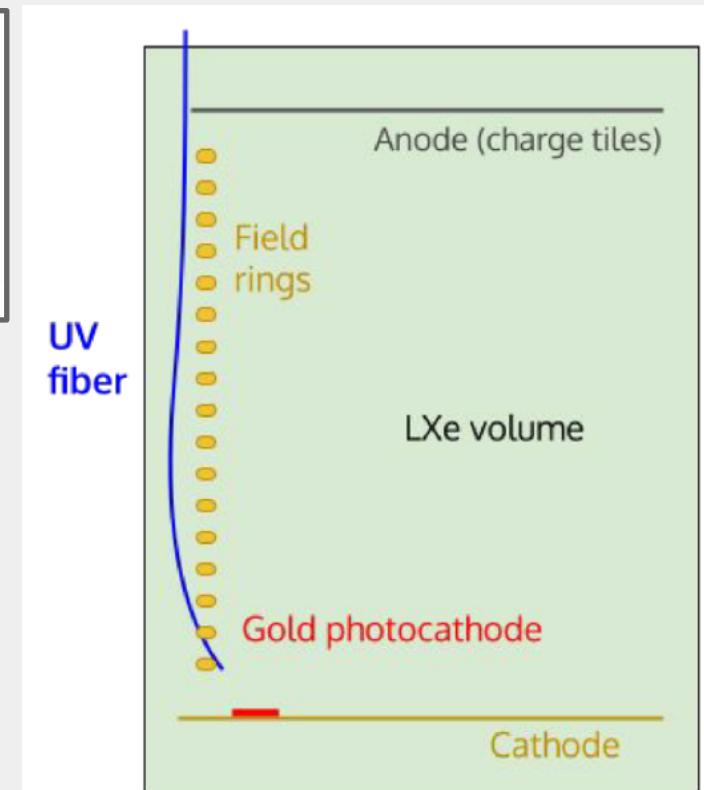


Easier with:
— single LXe vessel
— enriched source

Internal radioactive sources



Non-radioactive-source calibrations

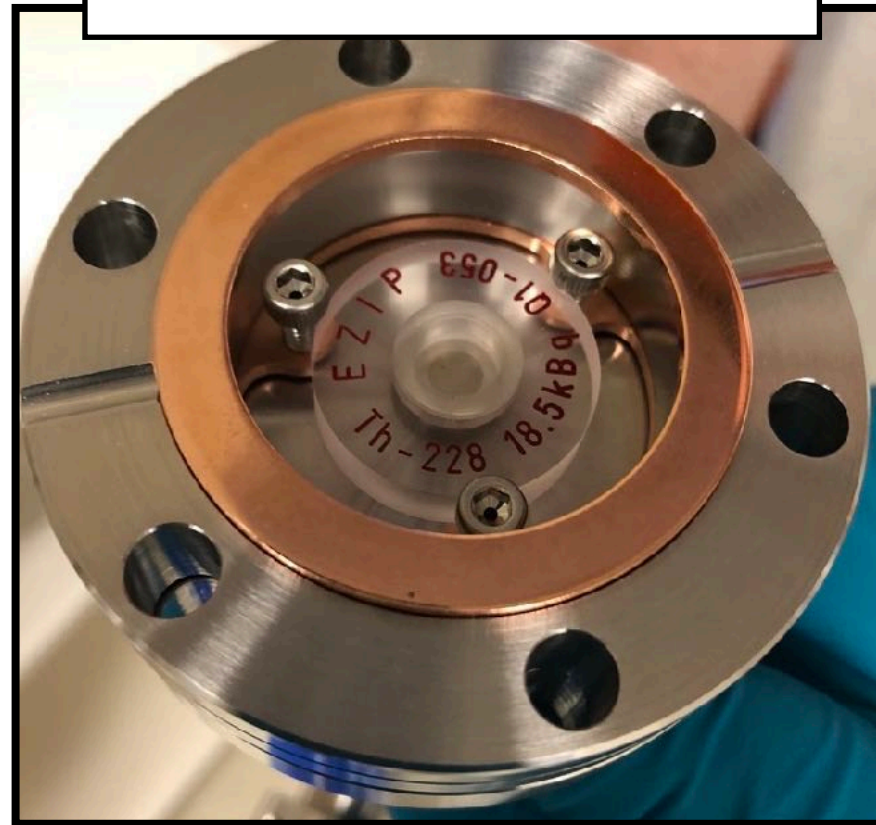


Internal radioactive sources: ^{220}Rn and ^{127}Xe

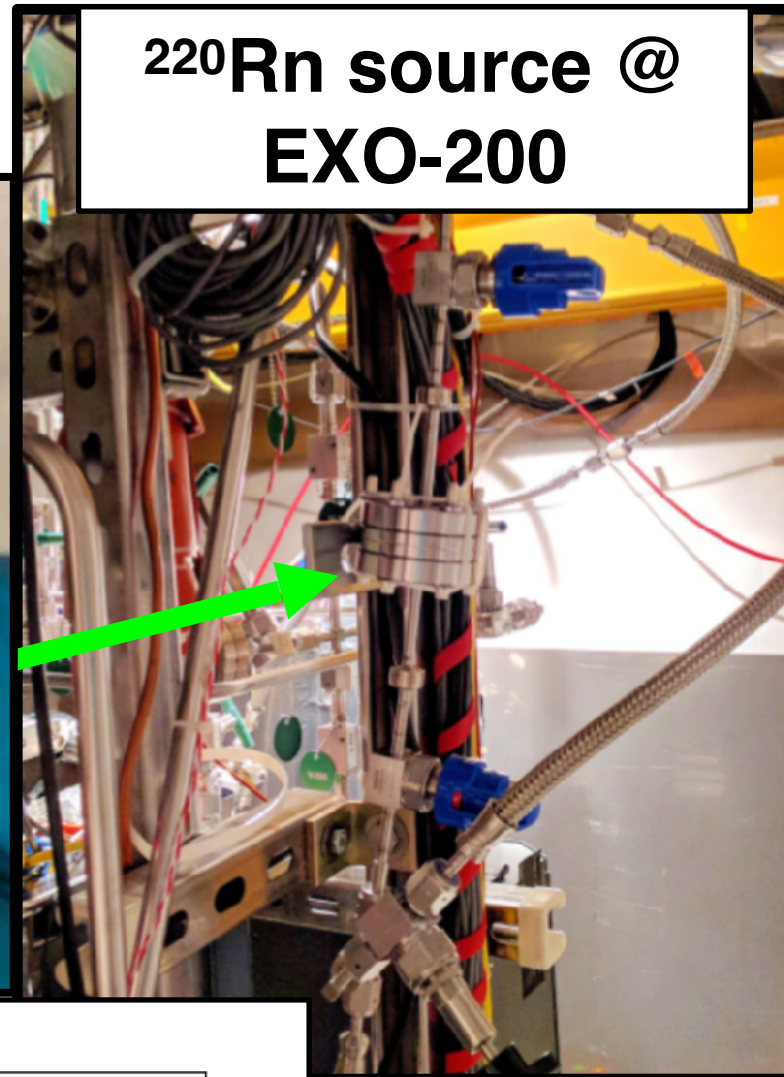
[Adapted from Brian Lenardo XeSat 2026]



Commercial ^{228}Th source (LZ design)



^{220}Rn source @ EXO-200

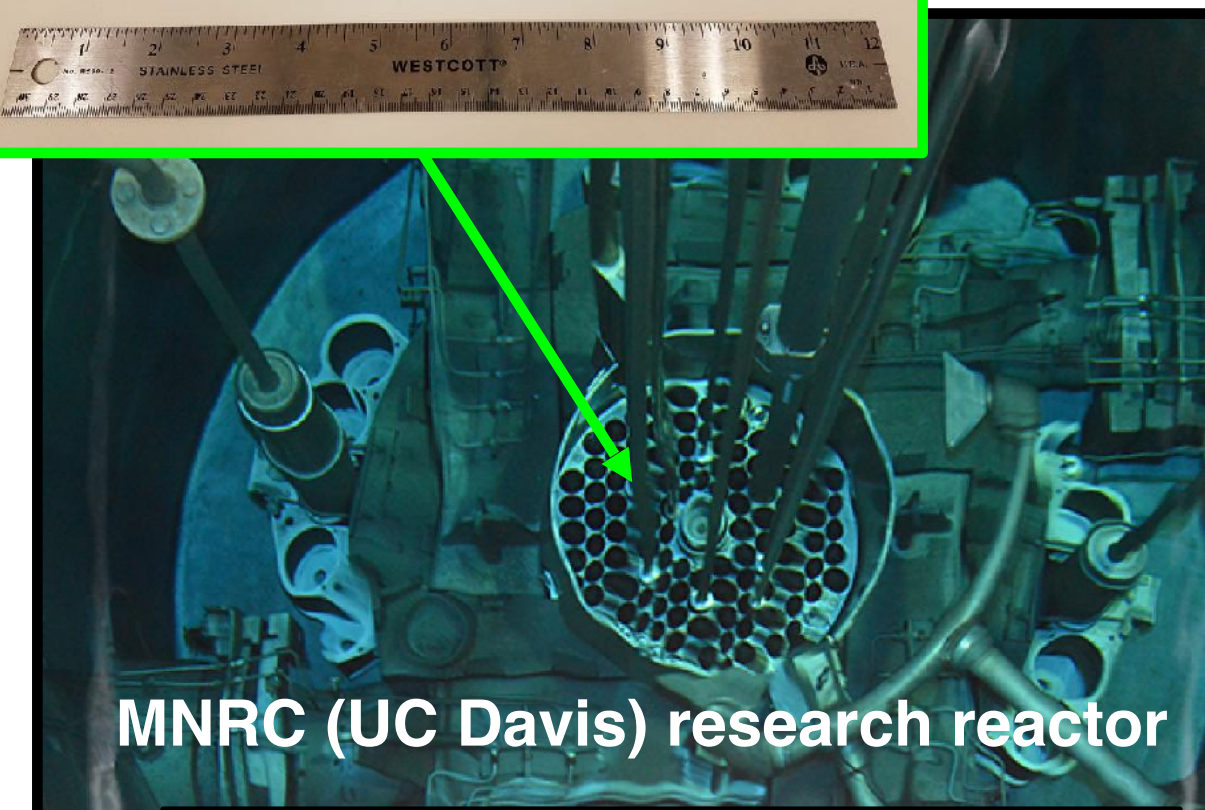


Sample cylinder with natXe gas



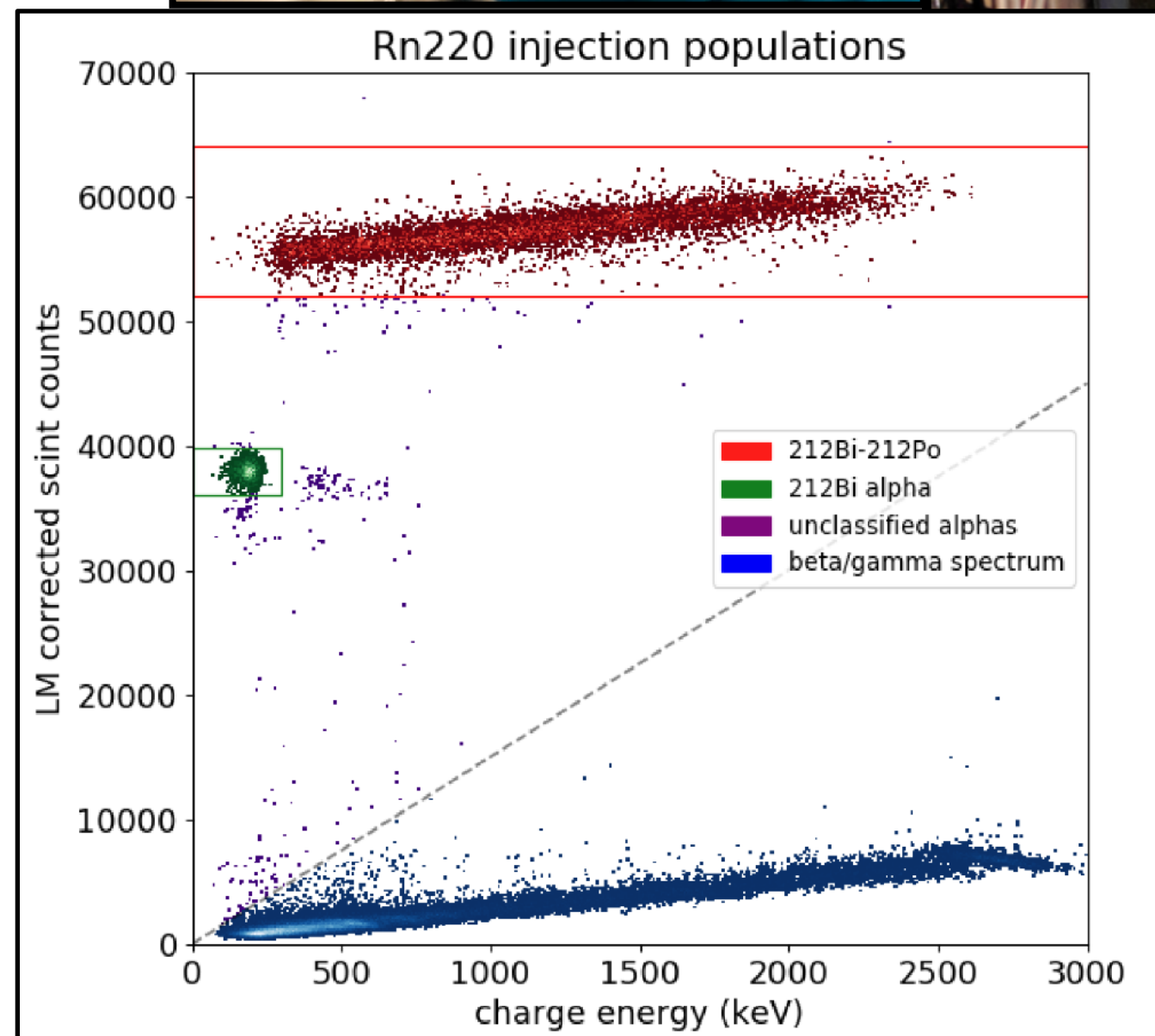
^{127}Xe EC source provides gamma lines at 236 keV and 408 keV with 36-day half-life

Regular injections for uniformly distributed, continuous source for detector response mapping



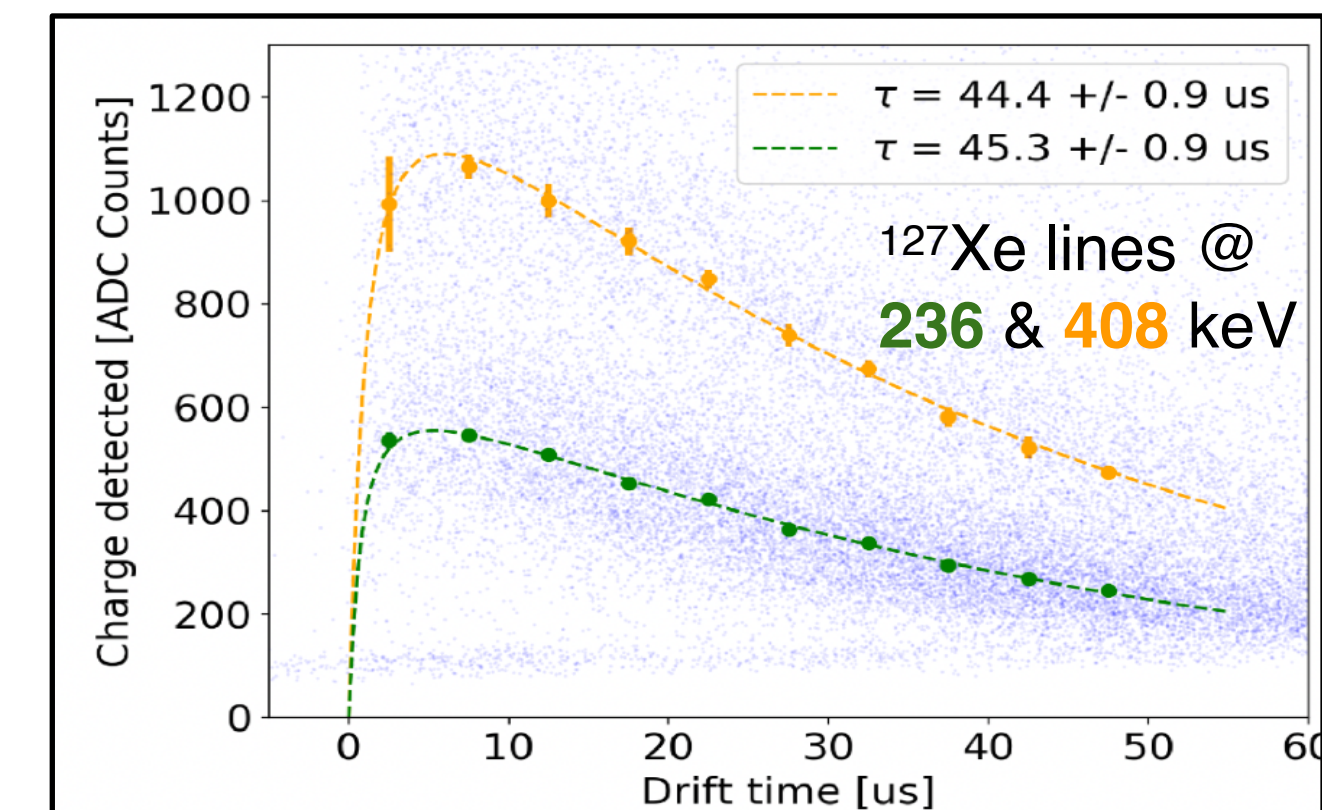
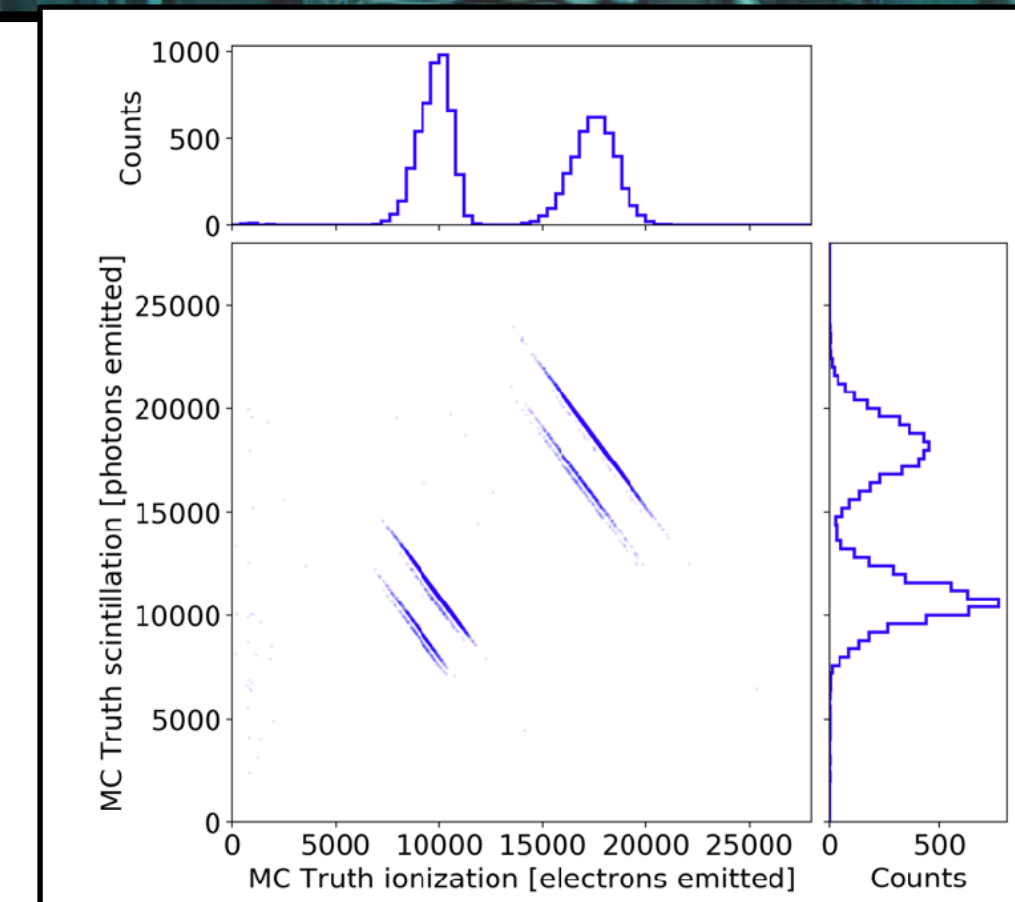
MNRC (UC Davis) research reactor

Measurement of electron lifetime in impurity-doped LXe TPC @ Stanford



^{220}Rn emanation source deployed in EXO-200, inspired by Xe dark matter expts

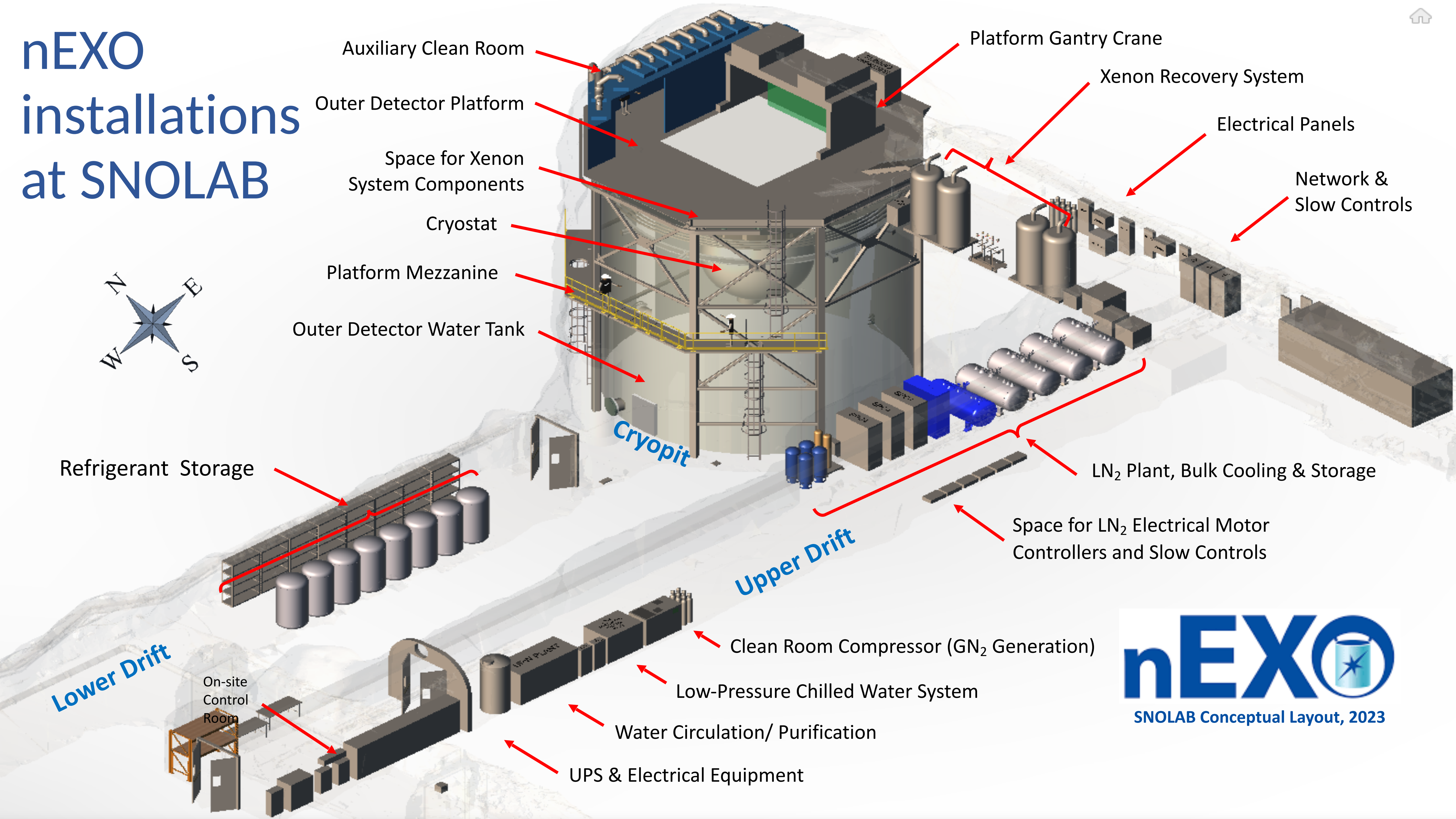
Provides mono-energetic alphas, broad-energy betas



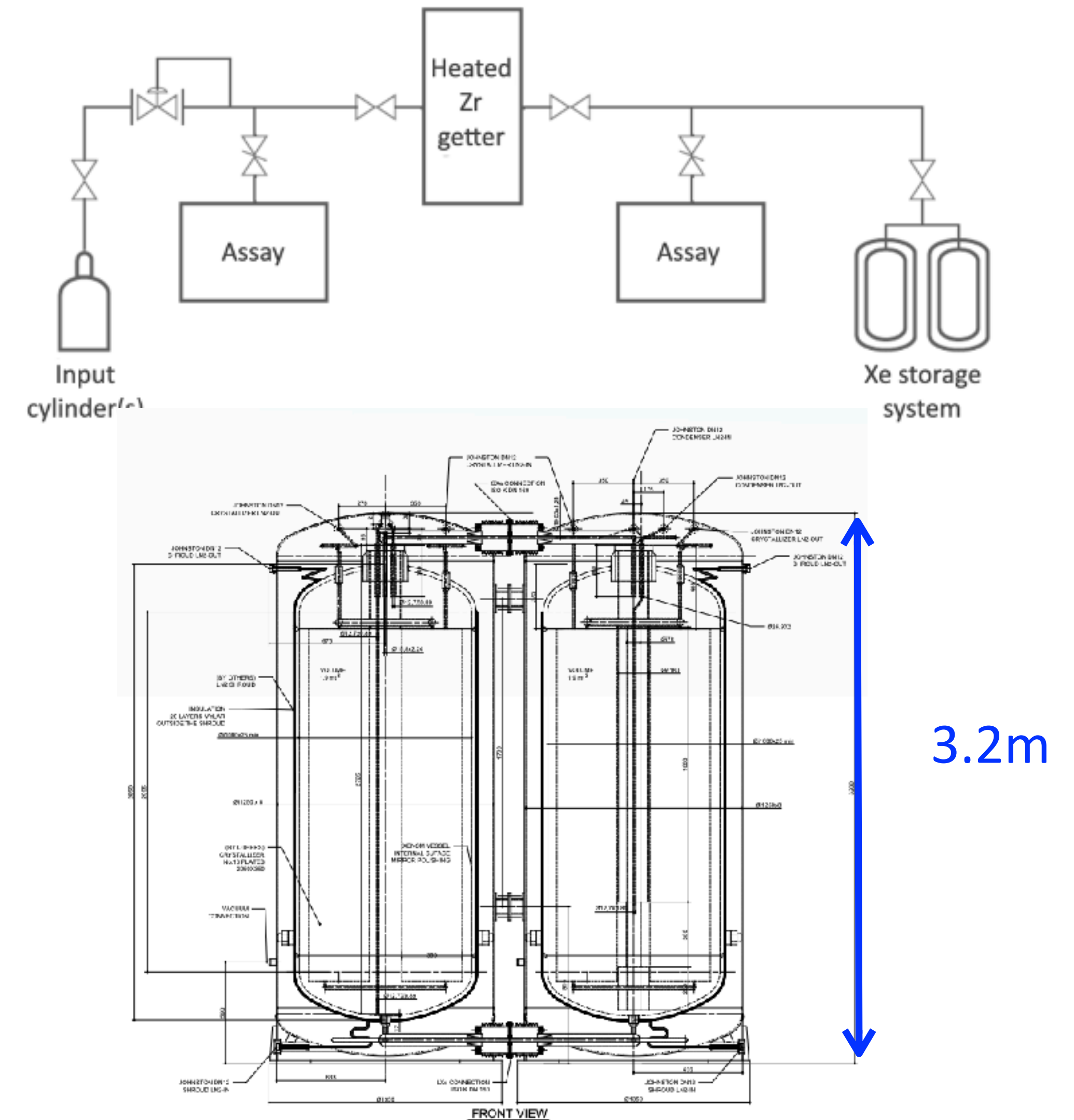
E. Hansen, PhD thesis, Drexel University (2019)

B.G. Lenardo et al., *JINST* (2022)

nEXO installations at SNOLAB



- Enriched xenon will be pre-purified with heated Zr getters and transferred in underground storage system
 - Process xenon stockpile in <1 year
- Xe high pressure storage system inspired by ReStoX infrastructure at LNGS (XENON collaboration)
- LN₂-driven LXe condenser and SXe crystallizer
- Two tank system gives operational flexibility and eases certification (units built on surface)



Sized for SNOLAB

EXO-200

- Transferred HFE 7000 using N₂
- Cooled inside the cryostat
- Refrigerators



nEXO

- Cryogenics envisioned with recirculating HFE 7200 through an external HEX (cut cooldown time)
- Volumetric (gear) pump
- LN₂ refrigeration



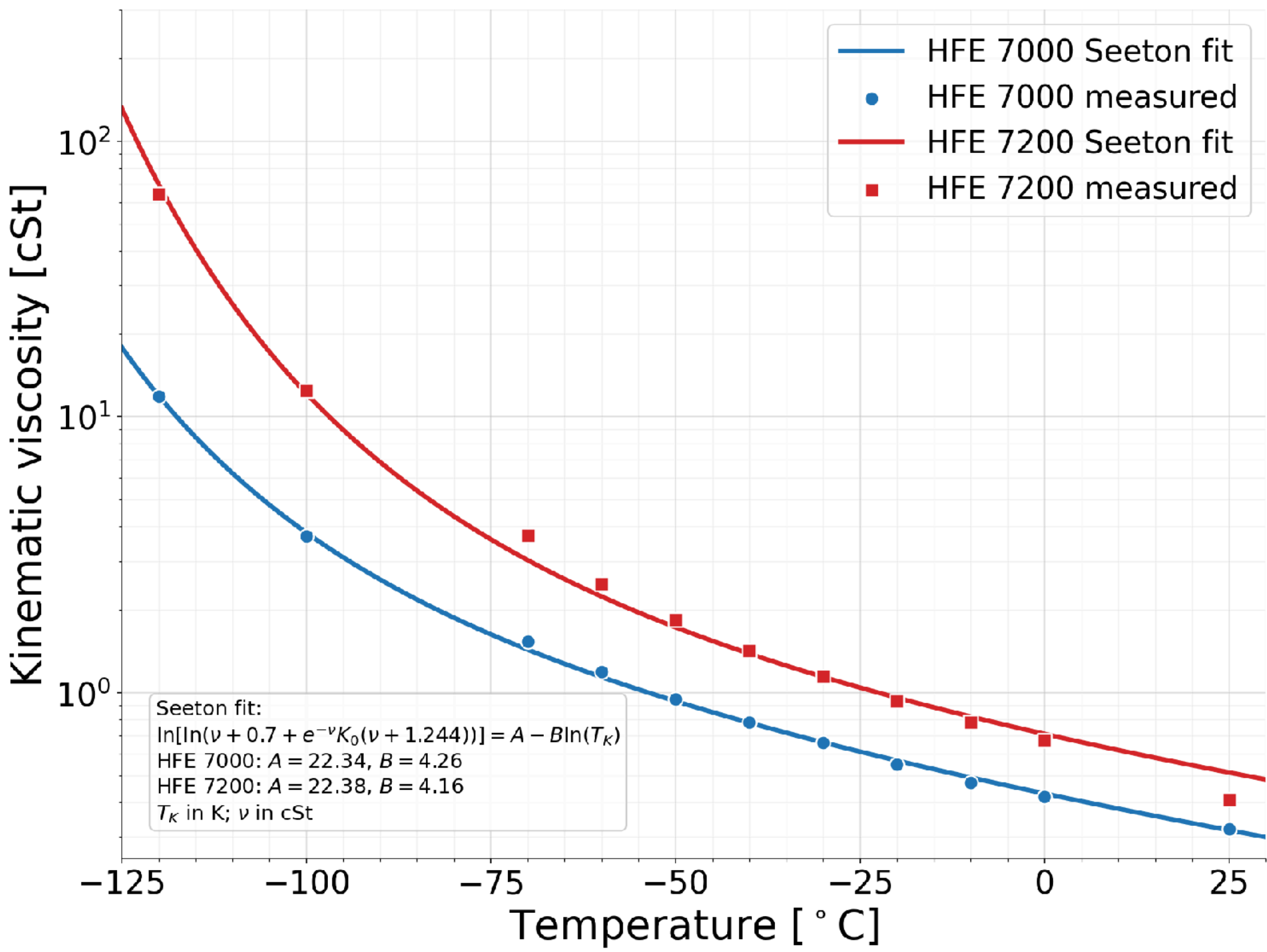
CRYOCONTROL PX20

Hydrofluoroethers (HFEs)

- HFEs are perfluorinated, engineered fluids (molecular masses in the 100s amu)
- HFE-7000 and -7200 are liquid at room temperature, all the way down to -100C
- Shown to be ultra-low radioactivity: ppq-level U, Th (see nEXO arXiv 2026)
(quite refractory to impurities, purifiable)
- High density: $1.4 \div 1.8 \text{ g/cm}^3$
—> excellent γ -ray shield
- Protonated —> neutron moderation

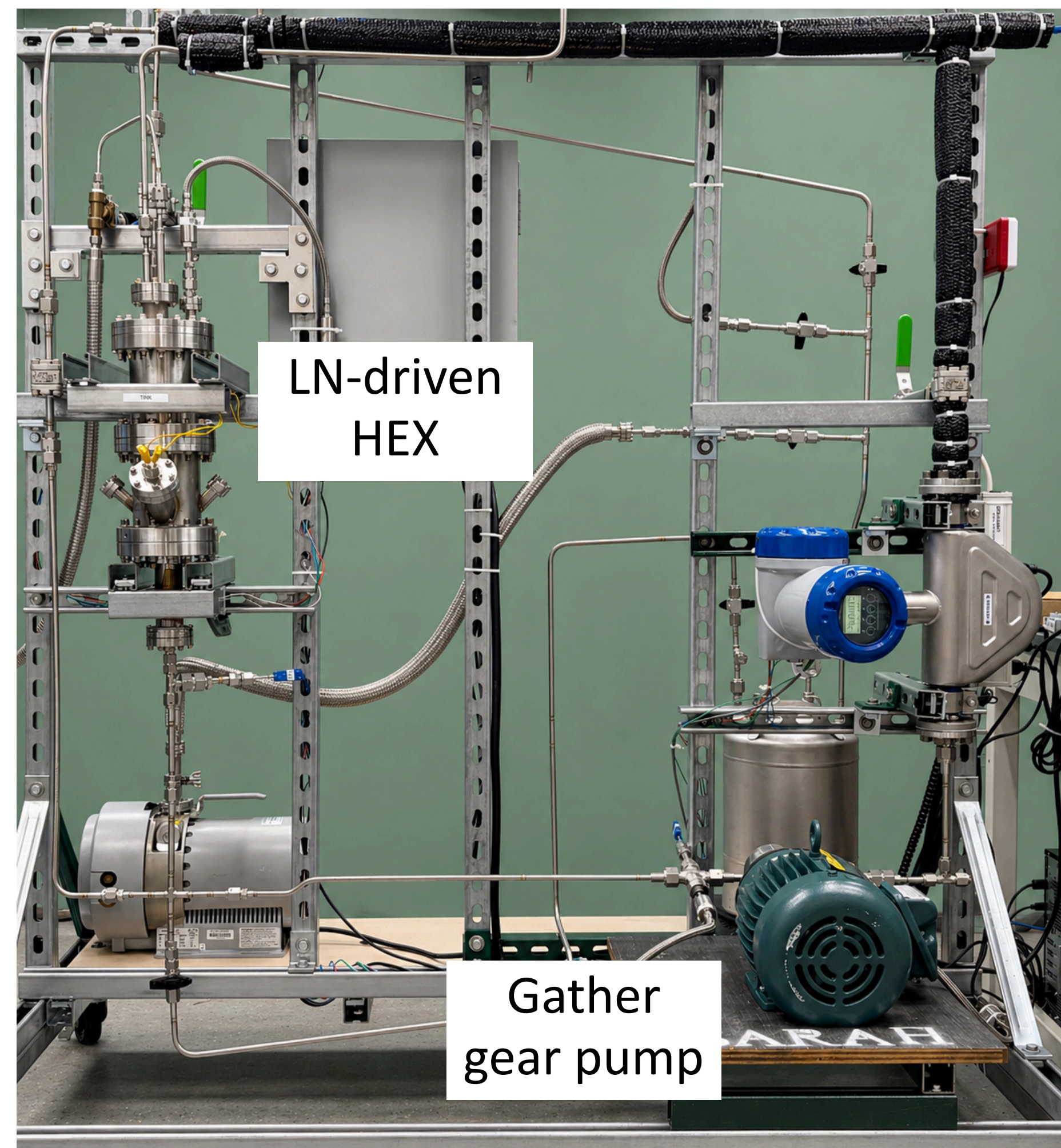
HFE 7000

Property	Value
Molecular Weight	200 g/mol
Freezing point	150.65 K
Boiling point @ 1 atm	307 K
Heat of Vaporization	142 J/g
Solubility of N ₂	55 vol %
Density vs T	$(2.26 - T/347.2) \text{ g/cm}^3$
Specific heat vs T	$(382 + 3.08 \cdot T) \text{ J/kg} \cdot \text{K}$
Thermal conductivity vs T	$(0.13 - T/5102) \text{ W/m} \cdot \text{K}$

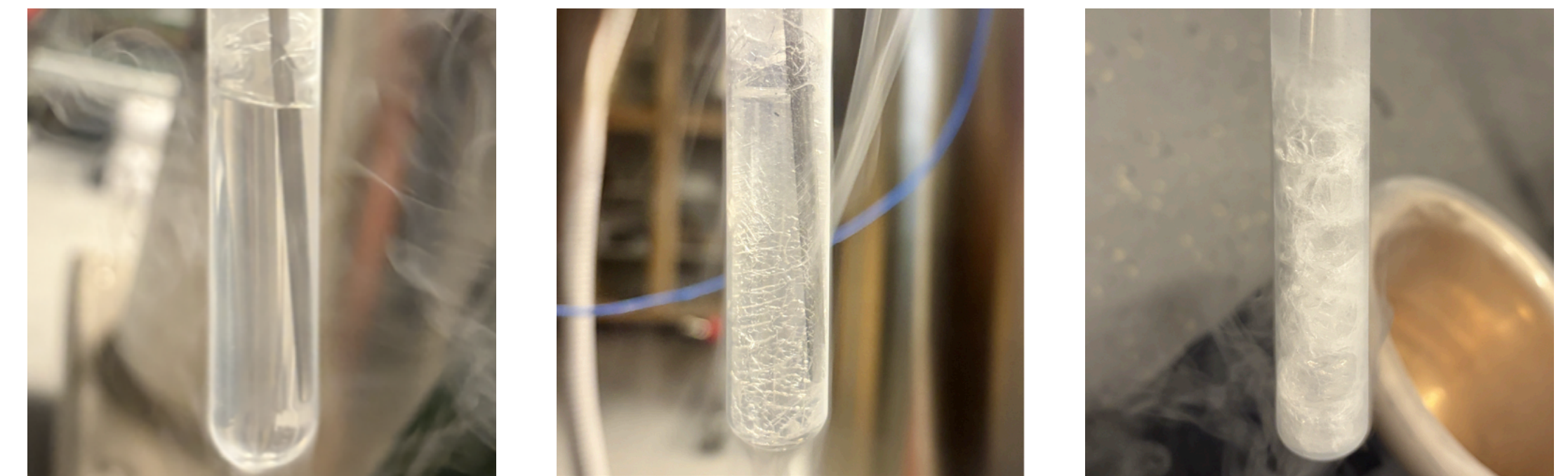


The HFE tests (at UMass)

(work by Graeme Sullivan and Antoine Amy,
continued by Sophia Ruggeri and Jonah Hebda)



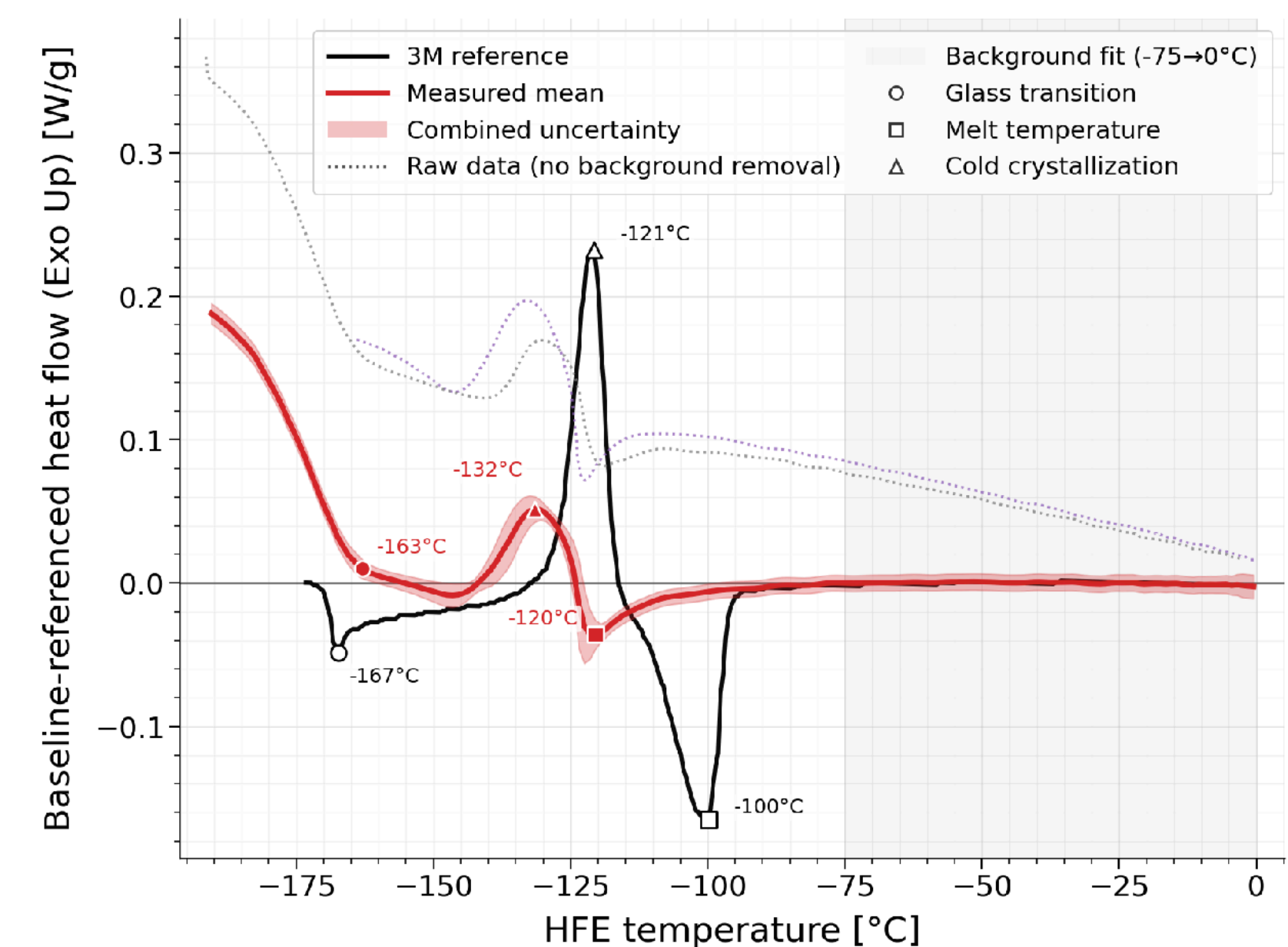
Circulated HFE-7200 down to -100 C



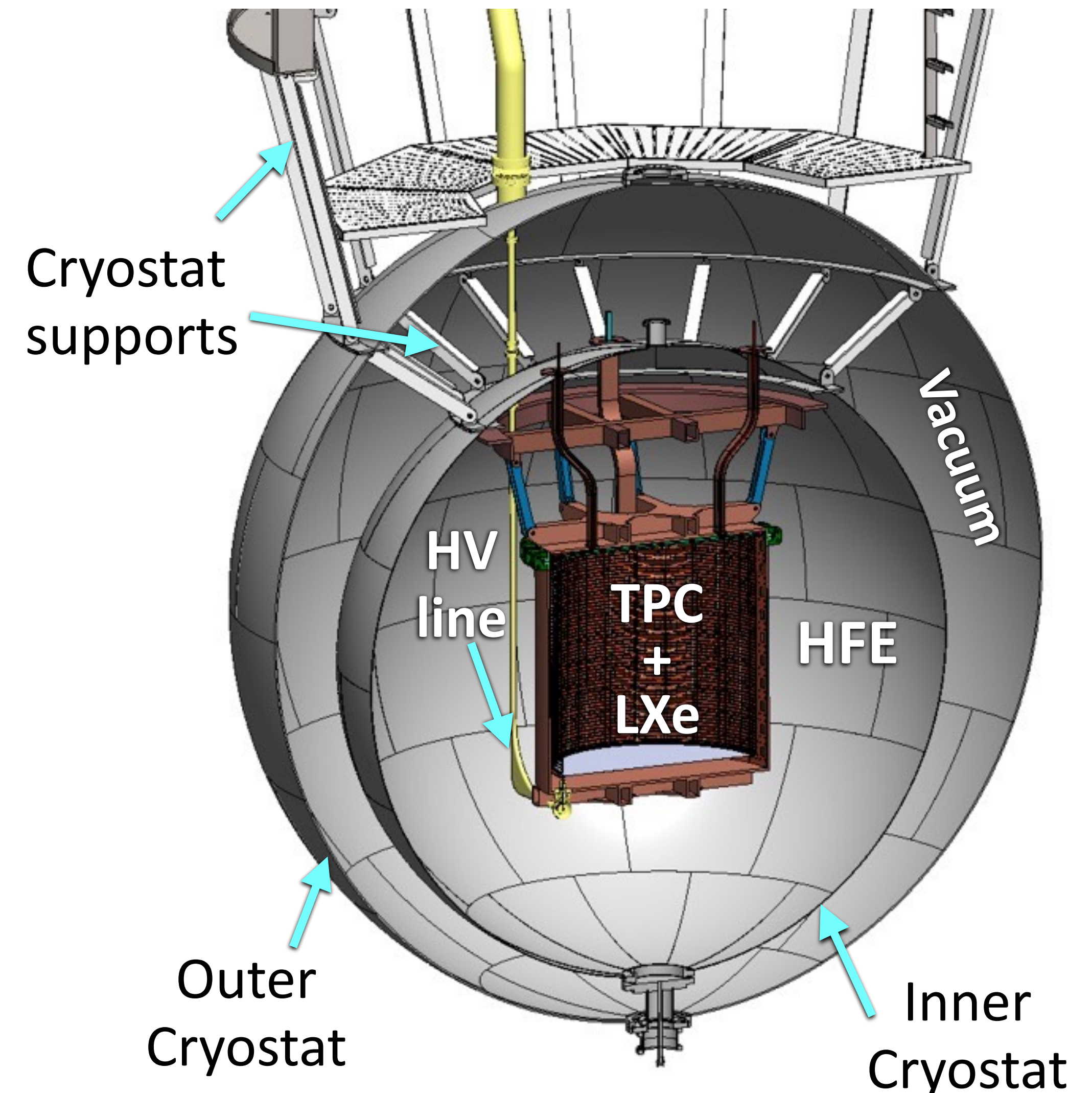
-128 °C

-161 °C

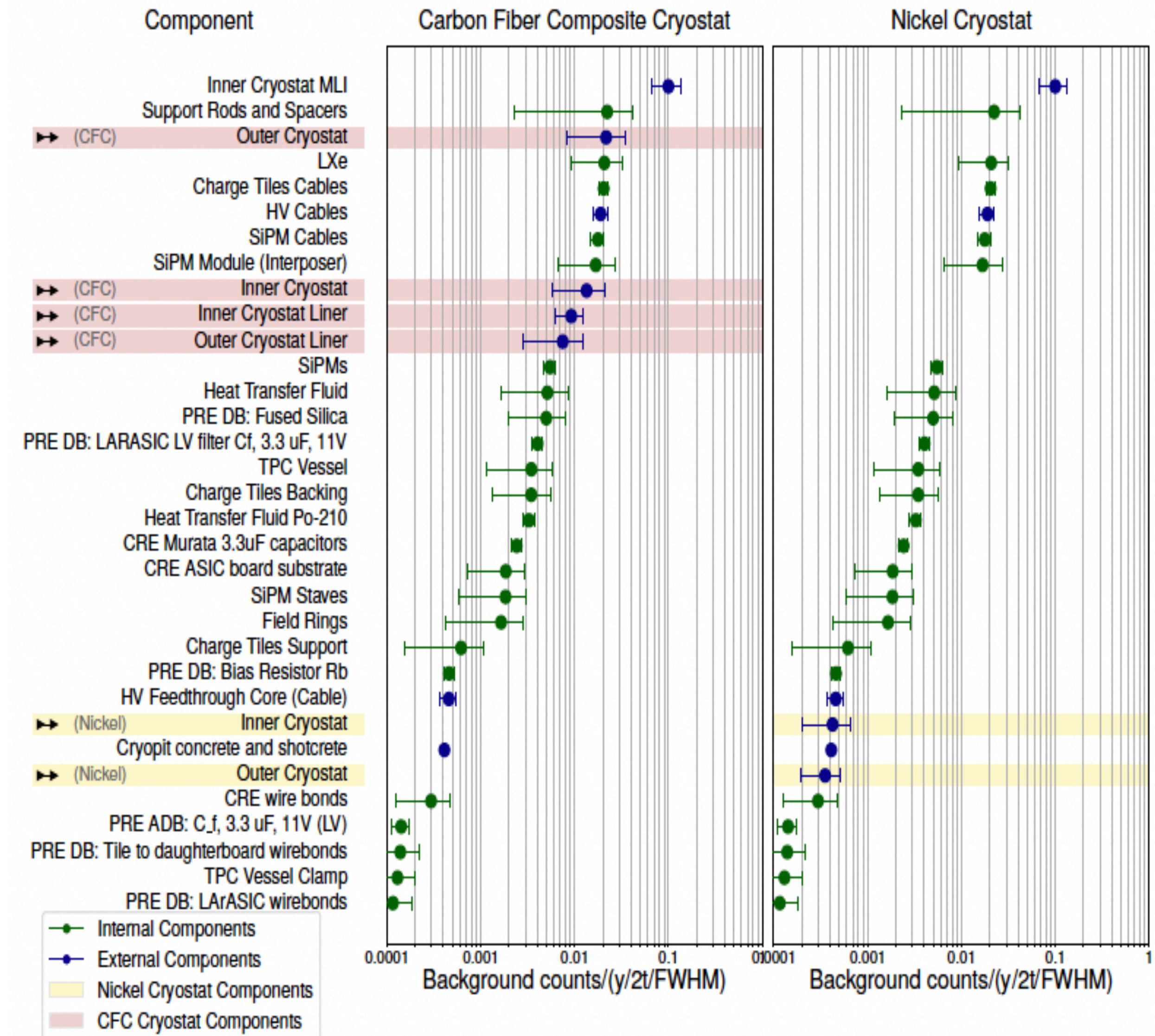
-188 °C



- The nEXO 2022 sensitivity calculation ($T_{1/2} > 1.35 \times 10^{28}$ y) assumed cryostats made with carbon fiber composite (with a thin Ti liner)
 - 75 cm HFE buffer required (32 t)
- The 2024 nEXO Conceptual Design Report (CDR) featured a **CVD Nickel cryostat**
 - still, 75 cm thick HFE buffer (overkill)



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- The Inner Cryostat multi-layer insulation assumes EXO-200 values (no nEXO R&D performed → room for improvement!)



Material	²³⁸ U [uBq/kg]	²³² Th [uBq/kg]	⁴⁰ K [uBq/kg]	Yield Strength [MPa]	*Bulk contamination determined by ICP-MS (top of the chain) ** Unwelded, Property Characterization of CVD Nickel, Masters Thesis, Patrice Bansa, University of Toronto
SS (XENONnT)	300 +/- 100	600 +/- 200	1600 +/- 600	200-240	
Titanium (LZ)	< 90	230 +/- 20	< 540	170-310	
CVD Nickel	< 1.2*	~0.3*	~30	~400**	



- CVD Nickel produced by CVMR was used for the SNO 3He proportional counter tubes
- Produced through the MOND process with nickel carbonyl (extremely hazardous)
- Recently explored by nEXO for cryostat vessel NIM A 1087, 171402 (2026) - arXiv:2508.08230
- Deposition rates can be as fast as 0.75 mm/hr, with achievable thickness over 5 cm

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nEXO work is continuing for XLZD led by Canadian scientists

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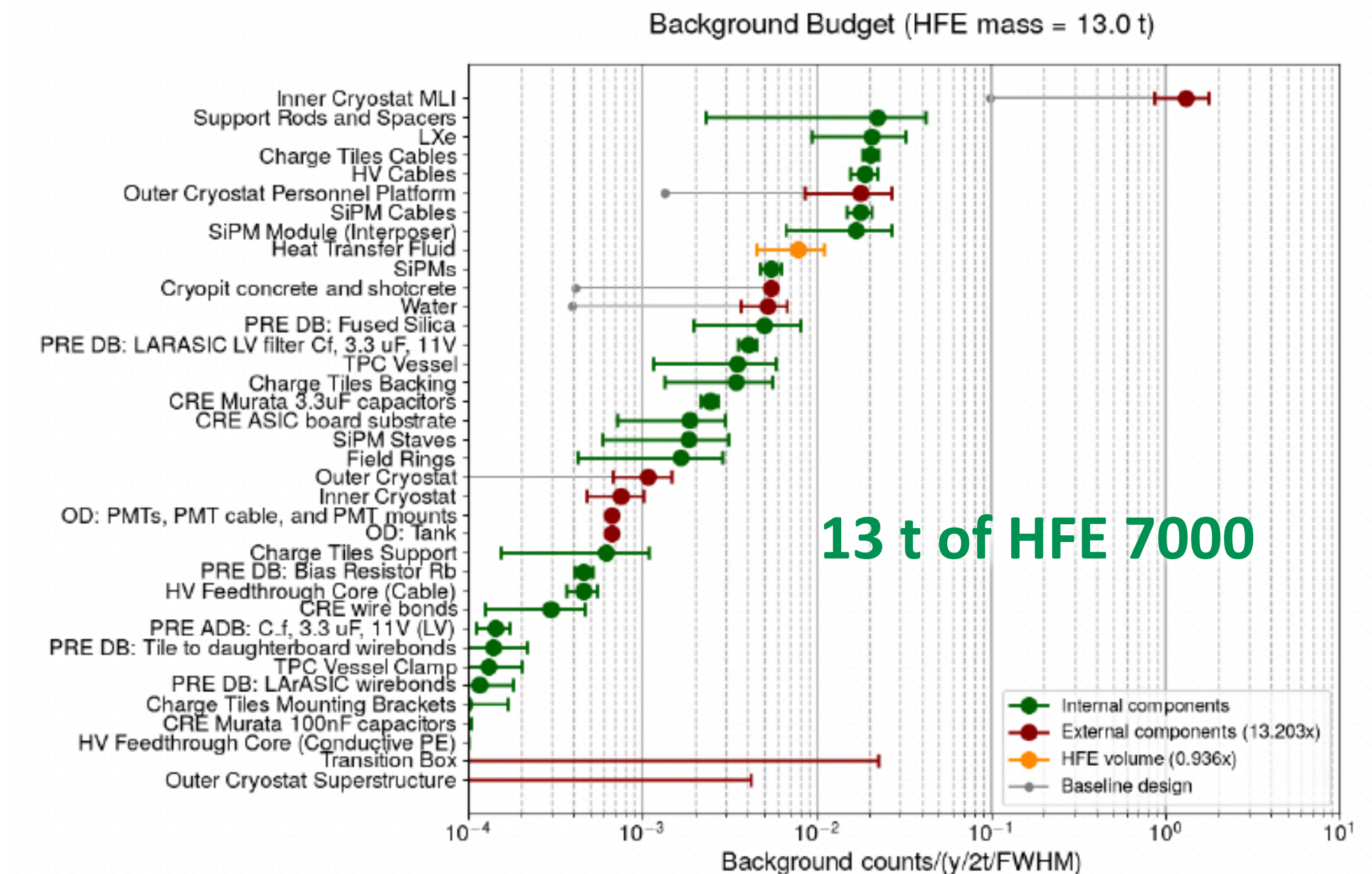
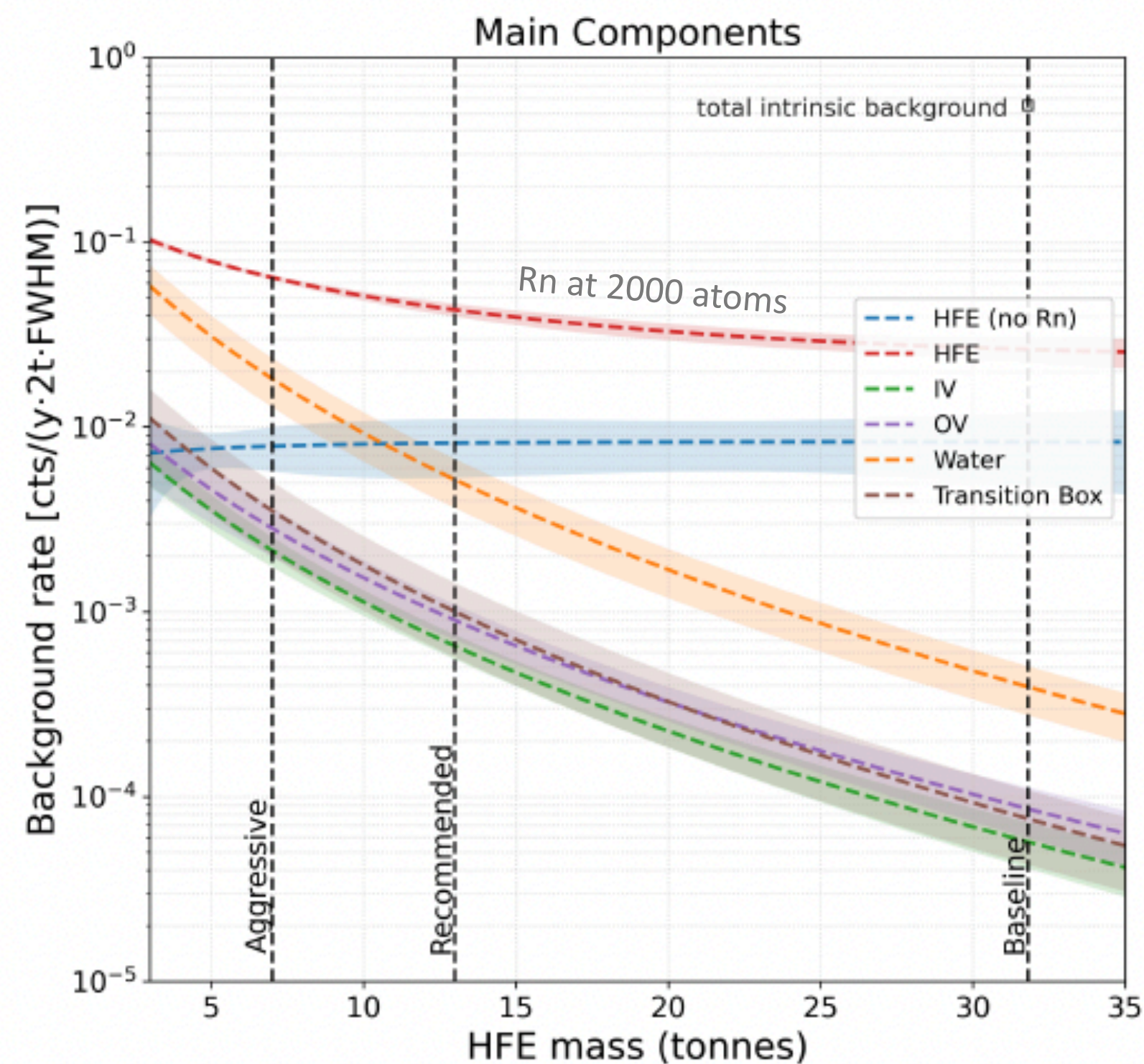
HFE can be more than halved with Ni cryostat

(work by Antoine Amy)



The ultra-pure CVD nickel offers the opportunity of reducing the required amount of HFE

- Cost savings, reduced safety concerns
- Less underground real estate for storage
- Thermal benefit only moderately affected



The keys of the nEXO design:

- Single phase, enrLXe TPC
- “Minimalistic”
- Material purity (low γ -ray, low Rn)
- Silicon-based light readout
- ASIC FE electronics
- HFE-based cryogenics and shielding
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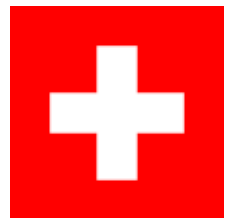
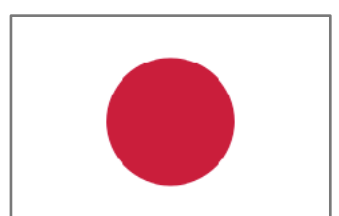
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Possible trades?

- enrXe
- Single $\longleftrightarrow$ dual phase
- Scintillating cryogenic buffer (à la PandaX)
- SiPM $\longleftrightarrow$ PMT
- More

Outlook

- nEXO was specifically designed to search for $0\nu\beta\beta$ decay at sensitivity set as a top priority (coverage of inverted ν mass ordering)
- The detector design was geared at suppressing the leading backgrounds for $0\nu\beta\beta$ decay (γ -rays, including from Rn)
- The slippage of schedule, cost range and paucity of funding for next-generation large LXe TPCs (in the US and elsewhere) suggests setting new ambitious targets for scale and sensitivity, beyond “tonne scale”.
- This, in turn, may offer the opportunity for an ambitious simultaneously leading instrument for $0\nu\beta\beta$ decay + dark matter
- Solutions developed for nEXO could greatly contribute to realize this goal



Thank you