



# Improving nEXO Sensitivity with Radon Distillation

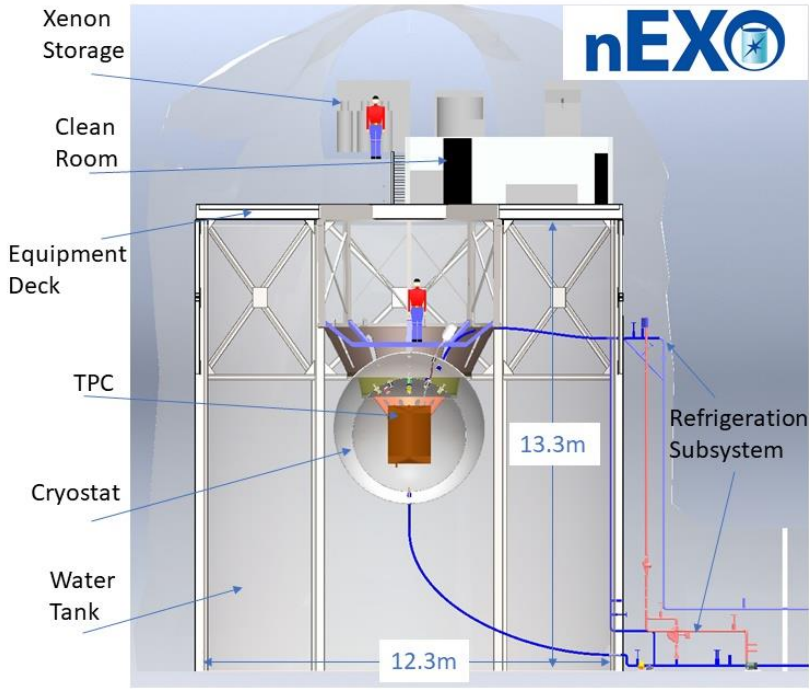
Brian Mong

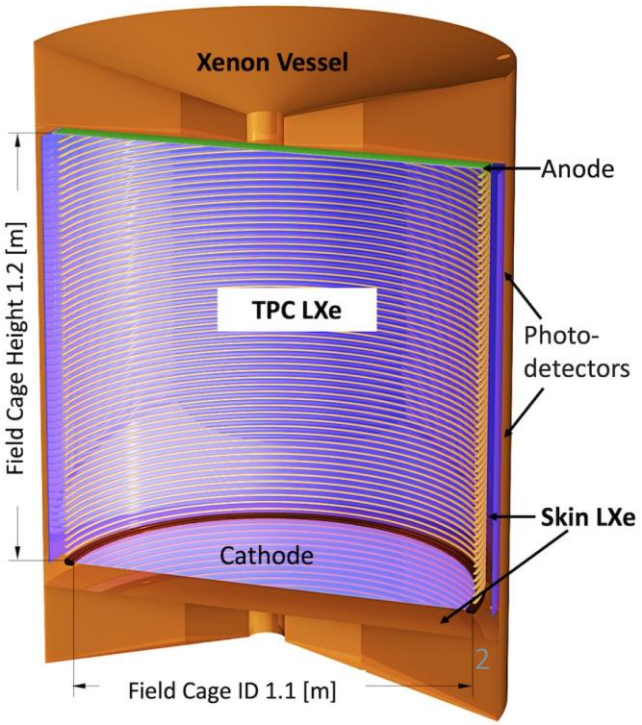
SLAC National Lab

This work supported by SLAC LDRD

# nEXO Physics

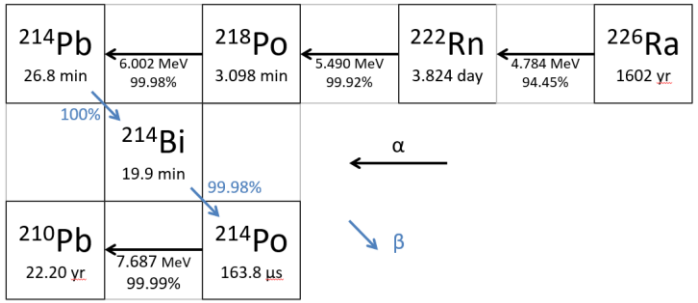
- Next generation 0νββ decay experiment in $^{136}$Xe (5000 kg)
  - Are neutrinos Majorana or Dirac like?
  - Discovery of lepton # violation
  - $\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} g_A^4 |M^{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$
- Estimated sensitivity $T_{1/2}$=1.35x10$^{28}$ years at 90% C.L.
  - $^{136}$Xe $Q_{\beta\beta}$ = 2458 keV point like event
  - Backgrounds controls are essential to measure such a rare process

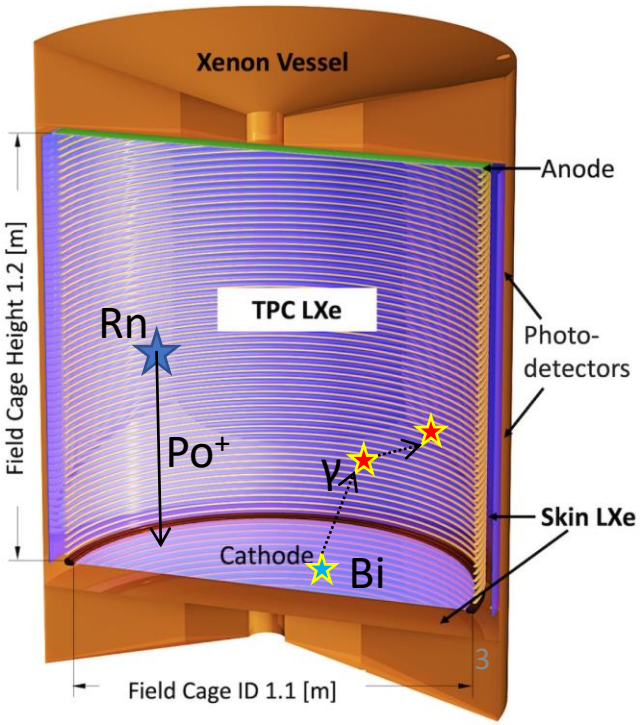


# nEXO Radon Background

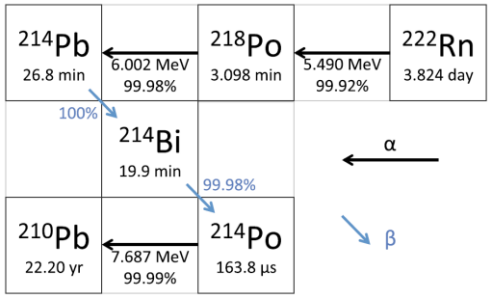
- $^{222}$Rn in LXe is supported by $^{226}$Ra ($^{238}$U) decays in Xe wetted materials that escape (recoil and outgassing)
- The behavior of Rn daughters in LXe TPCs has been studied in EXO-200 [1]
  - Alpha (beta) daughter create ions 50% (76%) of the time and drift to biased components of TPC, mostly on the cathode
  - Ions drift O(1mm/s) in EXO-200 E-Field
- The $^{214}$Bi is the background source with a gamma at $Q_{\beta\beta}$ (2447keV) with a 1.5% B.R.
  - Gammas can occasionally produce identical signals via photoelectric process
  - Usually they create multi-site events via Compton scattering that are easily rejected



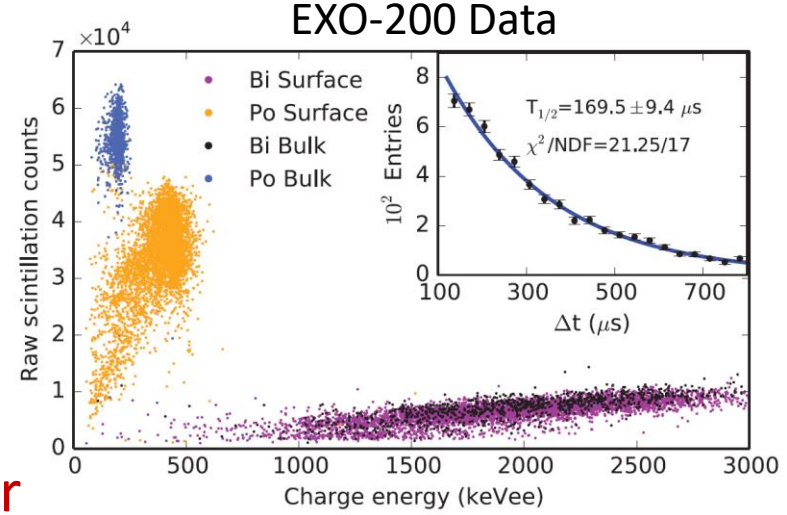

**[1]** J. B. Albert et al. "Measurements of the ion fraction and mobility of $\alpha$- and $\beta$-decay products in liquid xenon using the EXO-200 detector". In: *Phys. Rev. C* 92.4 (2015), p. 045504. doi:10.1103/PhysRevC.92.045504. arXiv: 1506.00317 [nucl-ex].

# nEXO Rn Background pt2

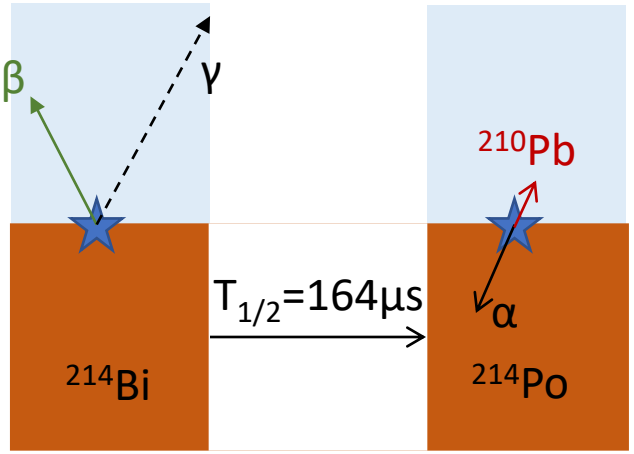



- $^{214}$Bi events are quickly followed by a $^{214}$Po α-decay
  - nEXO can detect the α-decay with 100% efficiency in LXe and ~50% on a surface (2π).

EXO-200 Data

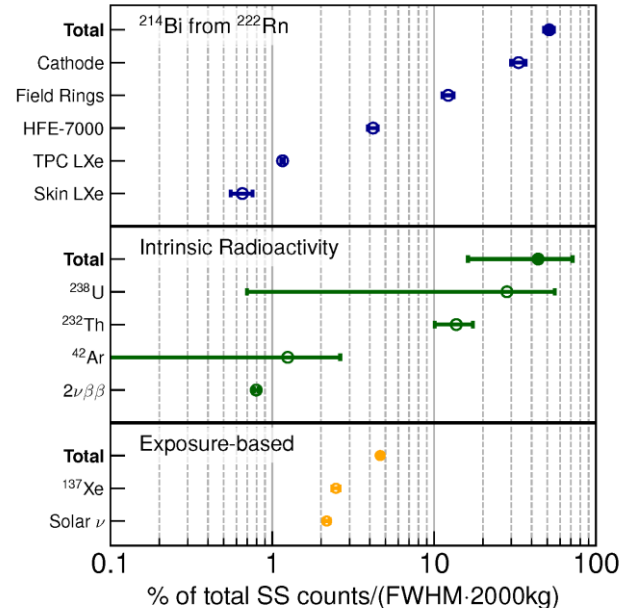



- On a surface we may also be able to detect the $^{214}$Bi β particle or the nuclear recoil of the $^{214}$Po α-decay
  - These would improve nEXO BG rejection further and is under investigation

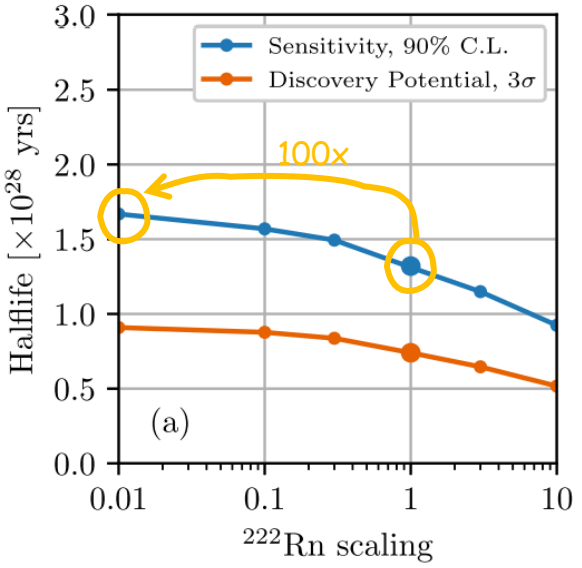


# Sensitivity vs Rn background

- nEXO has a goal of 600 atoms steady state of $^{222}$Rn in 5000kg of LXe
  - 600 atoms = 1.26 mBq, $\lambda = 2.1 \times 10^{-6}$ s$^{-1}$
  - Assumed in the B.G. model & sensitivity estimate
  - Amounts to ½ of all nEXO B.G. events [2]



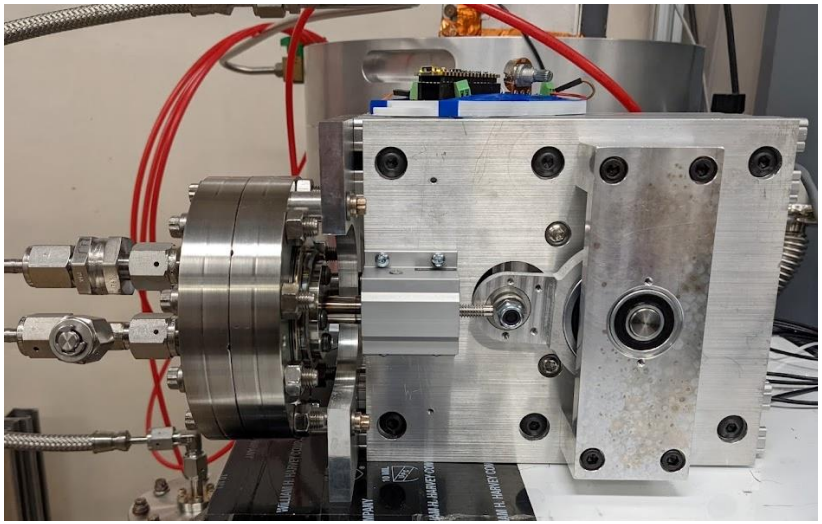

- Reduction of $^{222}$Rn below 600 atoms has the benefit of increasing nEXOs sensitivity
  - Baseline is $1.35 \times 10^{28}$ years at 90% C.L.
  - 100x reduction results in $1.7 \times 10^{28}$ years half-life sensitivity, a 27% increase




[2] G Adhikari et al. "nEXO: neutrinoless double beta decay search beyond 1028 year half-life sensitivity". In: Journal of Physics G: Nuclear and Particle Physics 49.1 (Dec. 2021), doi: 10.1088/1361-6471/ac3631

# Rn Mitigation

- The first opportunity to reduce Rn is to select the cleanest materials in the first place
- nEXO will screen all materials with sensitive emanation assays
  - Primary method using electrostatic counters (ESC) with Si diodes to collect and measure the Rn daughters
- ESCs primarily operated at SNOLAB surface lab w/ 7 counters (J. Farine)
- SLAC is developing new assay capabilities with all UHV parts
  - Electropolished 10L & 24L drift chambers with high drift efficiency
  - All metal pumps for recirculation
    - Bellows pump (shown)
    - Minatare EXO magnetic pump in R&D for critical measurements (100k$ getter)



# ESC Assay – Recirculation Mode

- Sample in B, carrier gas (Ar/N2/..) fills system 25mBar-1Bar (depends on assay)
- Rn (222/220/219) emanation from sample into gas
- Pump (C) mixes gas in system, Rn pushing it into the ESC chamber (A)
- $^{222}$Rn decays in ESC form charged $^{218}$Po ~88% of the time in dry air at 1 Bar [6]
- ESC field drifts ions in A to SiDiode (D) where further alpha decays create counts 50% of the time.
- Con - Efficiency loss of volume sharing (Rn decaying in B/C) + needs recirculation pump
- Pro – Rn emanation grows to steady state providing more statistics + sensitive to $^{220}$Rn and $^{219}$Rn

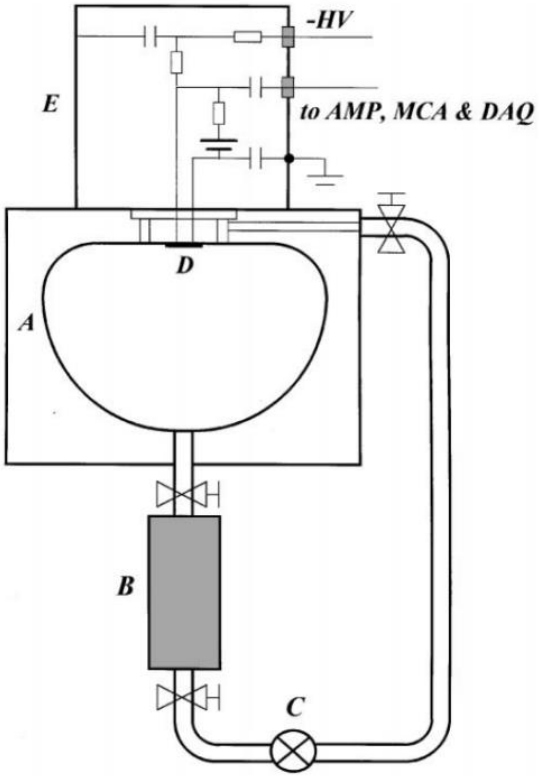
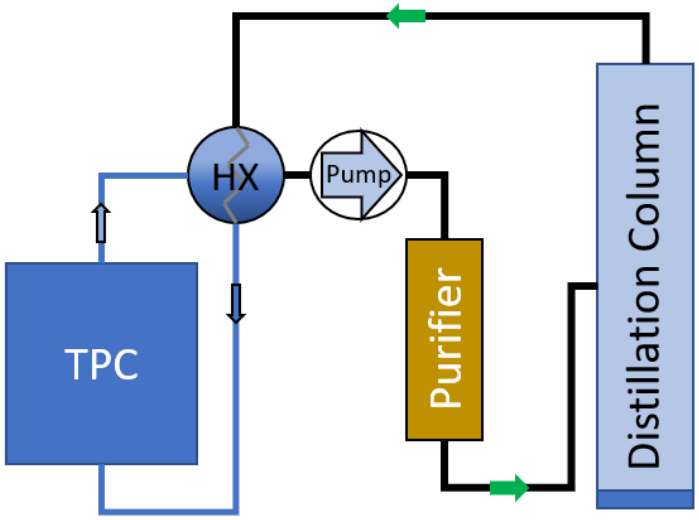



Image from: Jian-Xiong Wang, Tom C Andersen, and John J Simpson. “An electrostatic radon detector designed for water radioactivity measurements”. In: NIM-A, (1999)

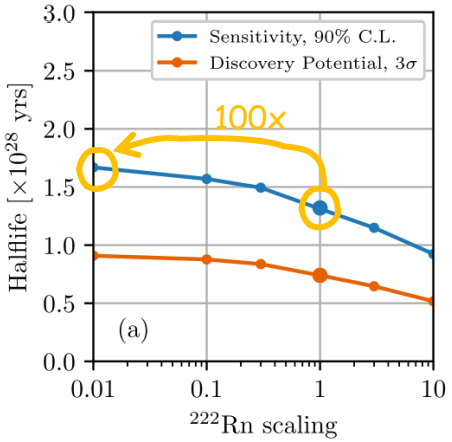
[6] Scott D. Goldstein and Philip K. Hopke. “Environmental neutralization of polonium-218”. In: Environmental Science & Technology 19.2 (Feb. 1985), pp. 146–150. doi: 10.1021/es00132a006. url:https://doi.org/10.1021/es00132a006.

# Rn removal can improve sensitivity

- Achieving 600 atoms is possible without removal based on assays in literature:
  - GXe Pump (EXO/XENONnT) = 150 atoms [3]
  - GXe Purifier (SAES PS4-MT50) = 114 atoms [4]
  - 8m2 of SS tubing at 10uBq/m2 [4,5] = 38 atoms
  - 8m2 of SS in HX at 10uBq/m2 [4,5] = 38 atoms
  - Total = 340 atoms + instruments/valves/etc
- There is R&D ongoing to reduce these components further
  - Investigating sources in Xe Pump
  - Novel purifiers using ultra pure Zr and Cu
- A removal system with a factor of 100x reduction increases sensitivity to 0νββ by 27% ($1.7 \times 10^{28}$ years at 90% C.L.)
  - Also mitigates risks of exceeding 600 atoms



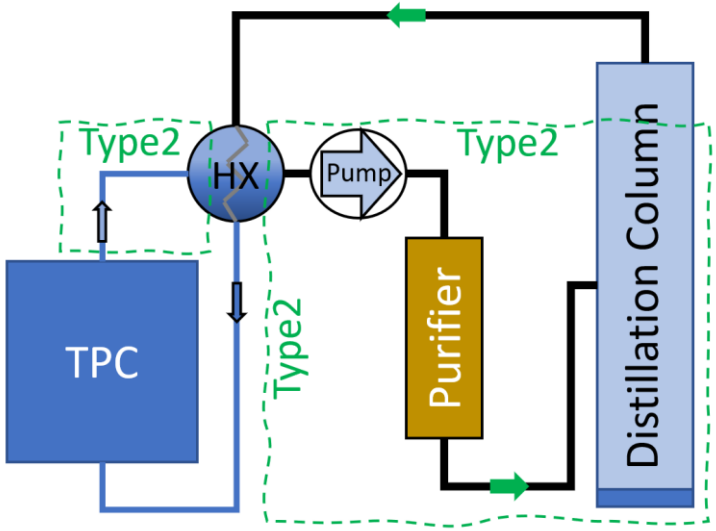

nEXO Xe recirculation system



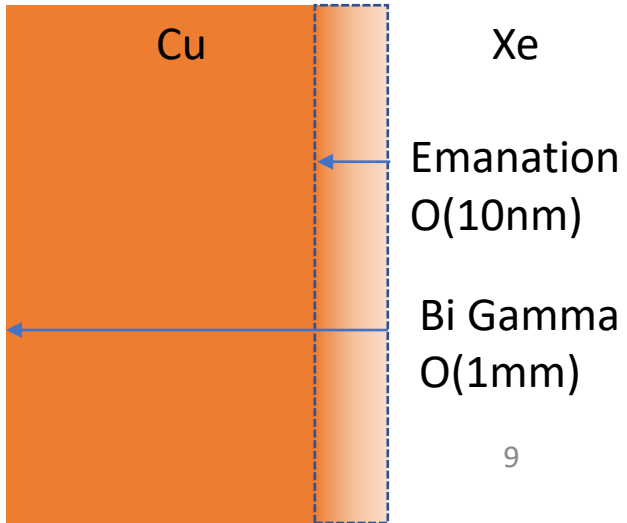

[3] D. Schulte et al. "Ultra-clean radon-free four cylinder magnetically-coupled piston pump". Journal of Instrumentation 16.09 (Sept. 2021), P09011. doi: 10.1088/1748-0221/16/09/p09011
[4] E. Aprile et al. "222Rn emanation measurements for the XENON1T experiment". Eur. Phys. J. C 81.4 (2021), p. 337. doi: 10.1140/epjc/s10052-020-08777-z
[5] G. Zuzel and H. Simgen. "High sensitivity radon emanation measurements". Applied Radiation and Isotopes 67.5 (2009). doi: https://doi.org/101016/j.apradiso.2009.01.052

# Not all emanation is the same

- Classified by where in the system it originates w.r.t. column and TPC
  - Type1 mixes in TPC before removal
  - Type2 goes through the removal system before the TPC
- Because nEXO has strict limits on $^{214}$Bi in the bulk material the TPC must have negligible emanation
  - Contributed by the near-surface O(10 nm) only
- Majority of $^{222}$Rn will be type2 in nEXO
  - Removal system will provide full reduction on $^{222}$Rn concentration

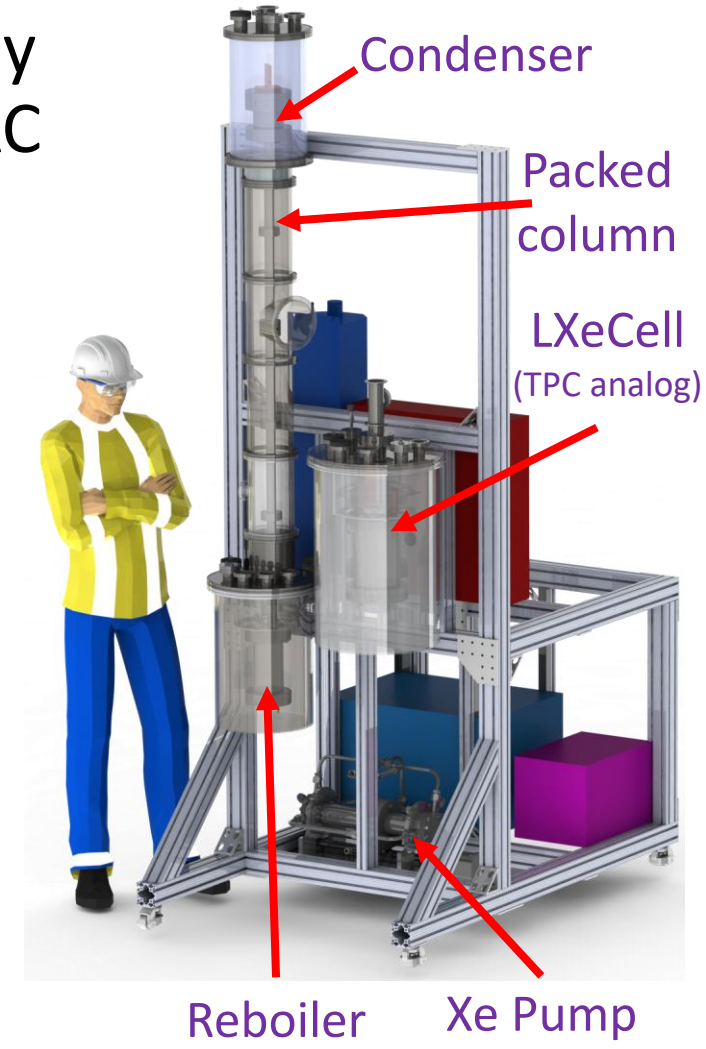



nEXO Xe recirculation system



# Distillation R&D at SLAC

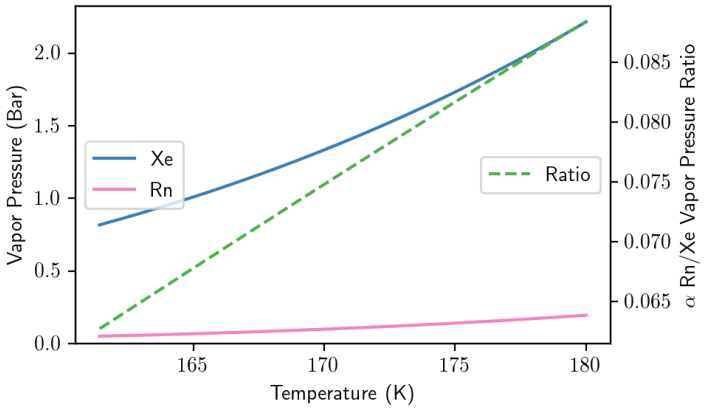
- We have designed and are currently constructing an R&D system at SLAC
  - First LXe *hopefully* this summer
- Goals:
  - Demonstrate 100x reduction
  - Investigate packing materials
  - Understand control systems within nEXOs constraints
    - Single phase TPC w/ tight ΔP requirements
  - Minimize $^{136}$Xe use in column

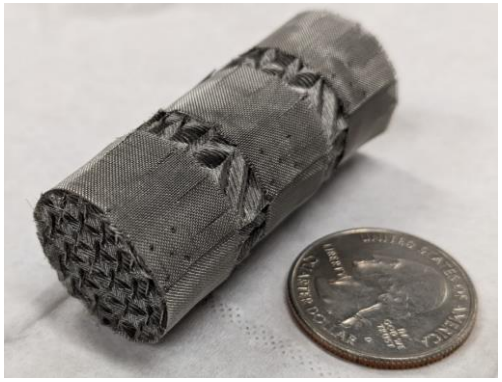


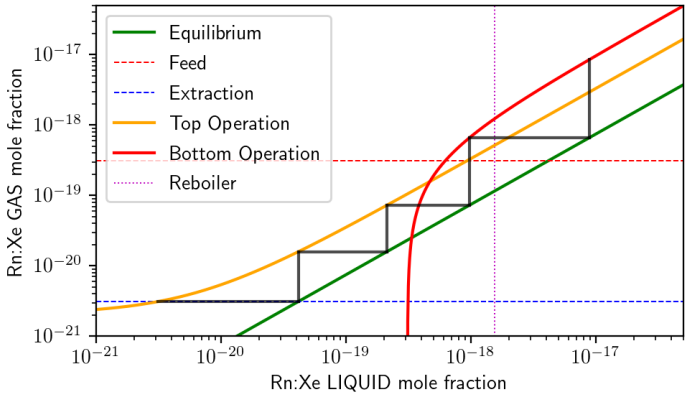

Credit where credit is due:
E Aprile et al. "Application and modeling of an online distillation method to reduce krypton and argon in XENON1T".
In: Progress of Theoretical and Experimental Physics (Apr. 2022). url:https://doi.org/10.1093/ptep/ptac074.

# Radon Distillation

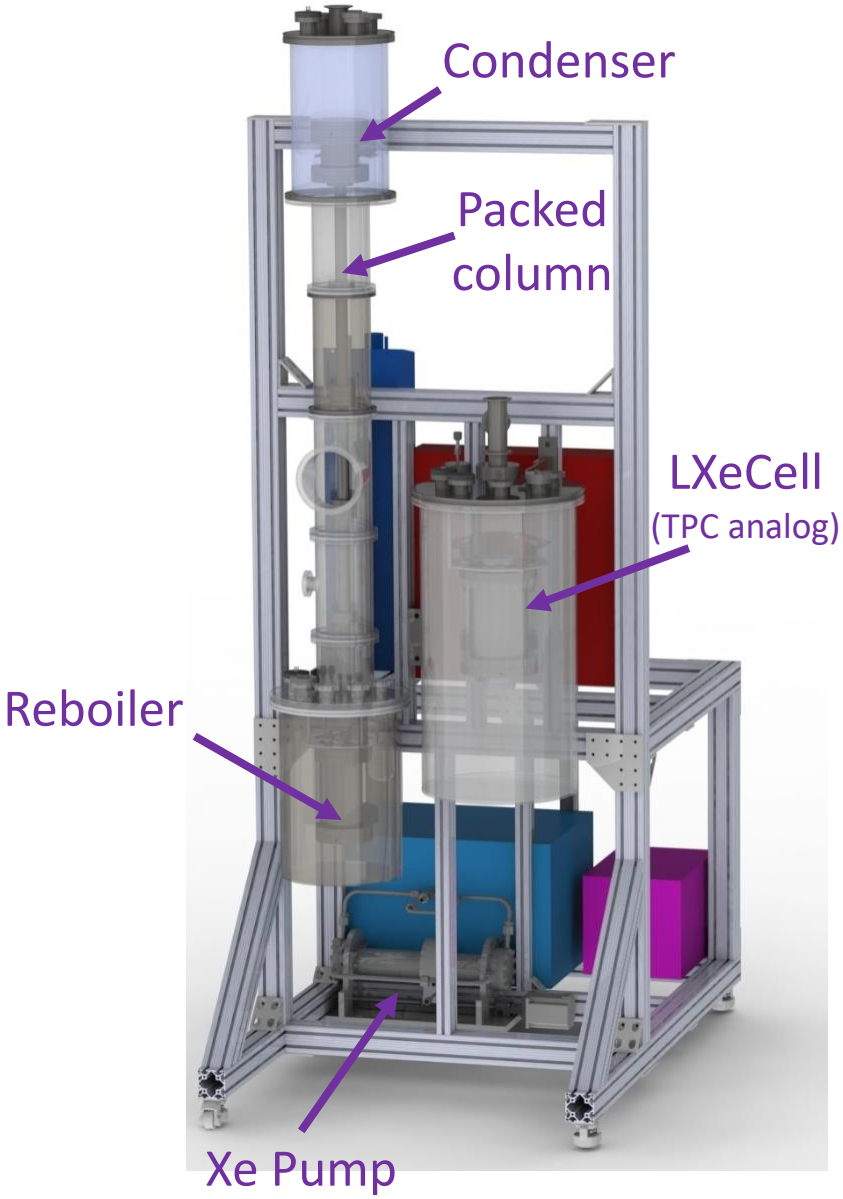
- Distillation is the process of separating species by their relative vapor pressures
  - Raoult's Law: the concentration (Rn) in the liquid (Xe) equals the vapor pressure times its mole fraction.
- Packing material in the column is loaded with liquid xenon through reflux established with the condenser and reboiler.
  - Radon is concentrated at the bottom by dissolving in the liquid xenon and falling downward.
- The Rn:Xe gas is input at the midpoint of the column, and Xe extracted from the top. The Rn:Xe concentration is modeled in the column with the McCabe-Thiele method





# Present Status




COVID supply chain issues have delayed commercial lead times

Still waiting on MKS mass flow controller for 1 year since PO.

Next step is Xe recirculation plumbing and instrumentation

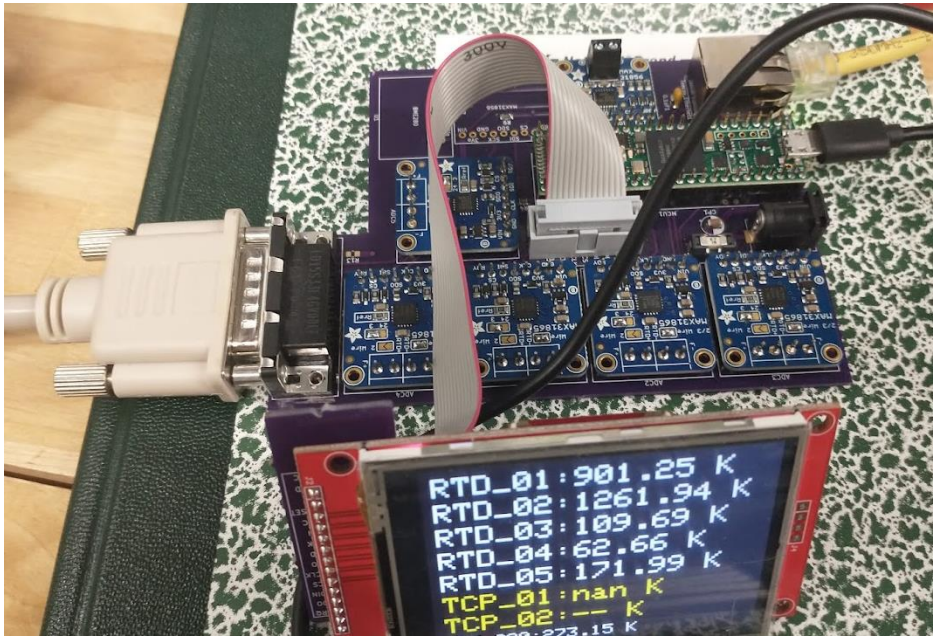
Hopefully LXe this summer!

# Questions?


Laurentian University
Université Laurentienne
Carleton University
McGill
Université de Sherbrooke
UMass Amherst
Yale University
Brookhaven National Laboratory
WWU Münster
Rensselaer
The University of British Columbia
FAU Friedrich-Alexander Universität Erlangen-Nürnberg
ИТЭФ
TRIUMF
Pacific Northwest National Laboratory
Technical University of Munich
Institute for Basic Science
Skyline College
Lawrence Livermore National Laboratory
IHEP
SLAC National Accelerator Laboratory
IMECAS
Stanford University
Caltech
UC San Diego
Colorado School of Mines
Colorado State University
The University of Alabama
Oak Ridge National Laboratory
University of Kentucky
University of the Western Cape
UNCW University of North Carolina Wilmington
Drexel University
Universität Bern
Subatech

# Opensource Temp Sensors

- Eric Cheng (SLAC 2021 CCI intern) developed a 5 channel PT100 2channel TC sensor for our instrumentation based on Arduino platform. All files available:
  - https://github.com/bungernut/nEXO_Thermometry
- O(160$) per instrument, not perfect but will be used and debugged
- Data read out via ModBusTCP
- High Accuracy PT100 and TC readout modules from Adafruit



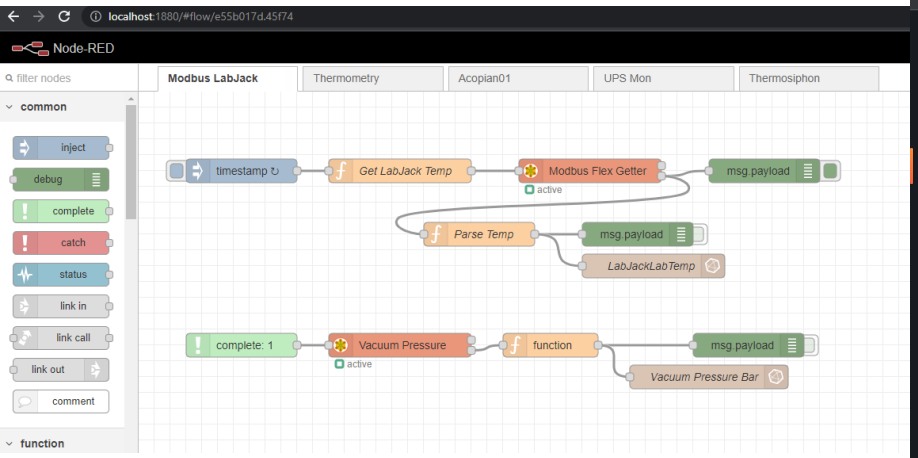

# Opensource Alternative for LabView

Docker stack of NodeRED, InfluxDB, Portainer, Grafana

Works very well (better than L.V.) and is fully web based

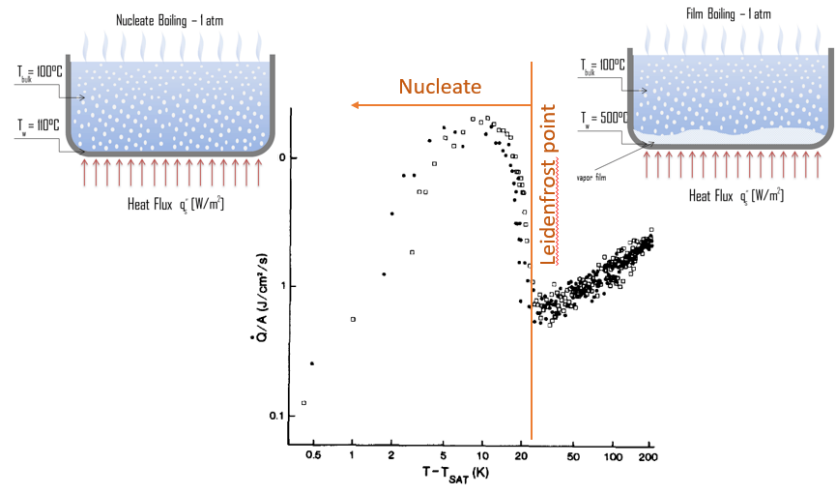
Plan will be to release a public version of the stack, scrubbed for passwords and documented this summer.

bung@slac.stanford.edu if interested

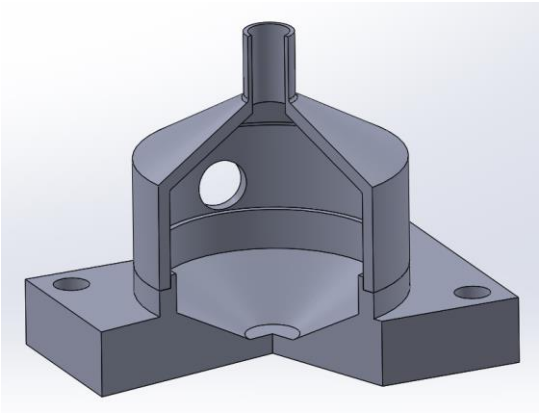


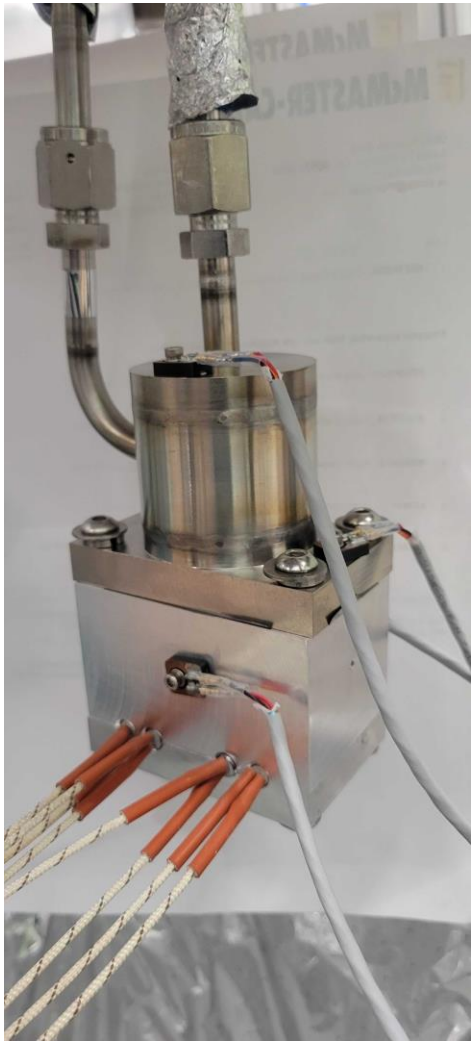

# Developing/Testing/Learning Thermosiphons

- Novel design hopefully to increase power by extending operations in nucleate boiling regime.



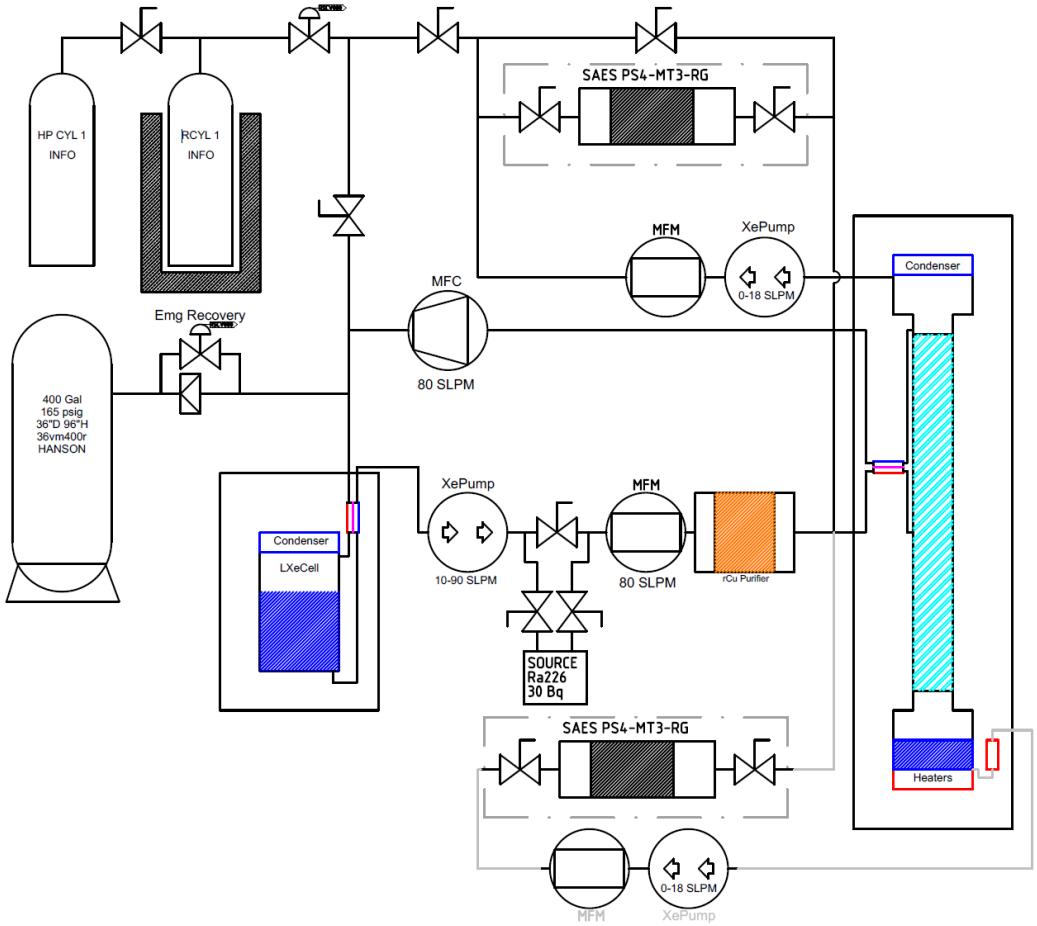

Plot From https://doi.org/10.1119/1.14563



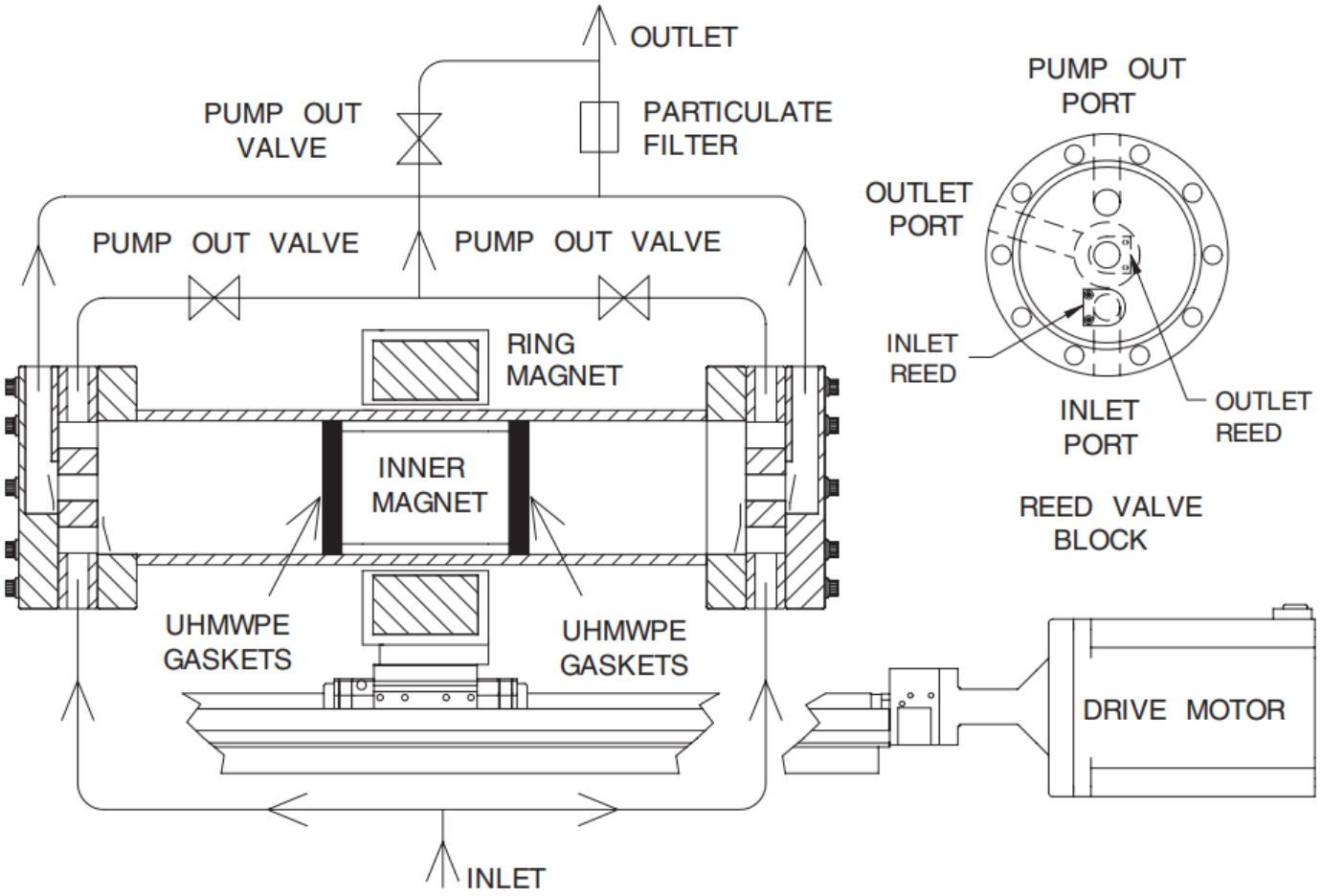


# Concept for distillation concentrated purification

- Distillation separates species from Xe
- Impurities concentrate at top and bottom of still
- Small purifiers can be used on small fraction of recirculation flow

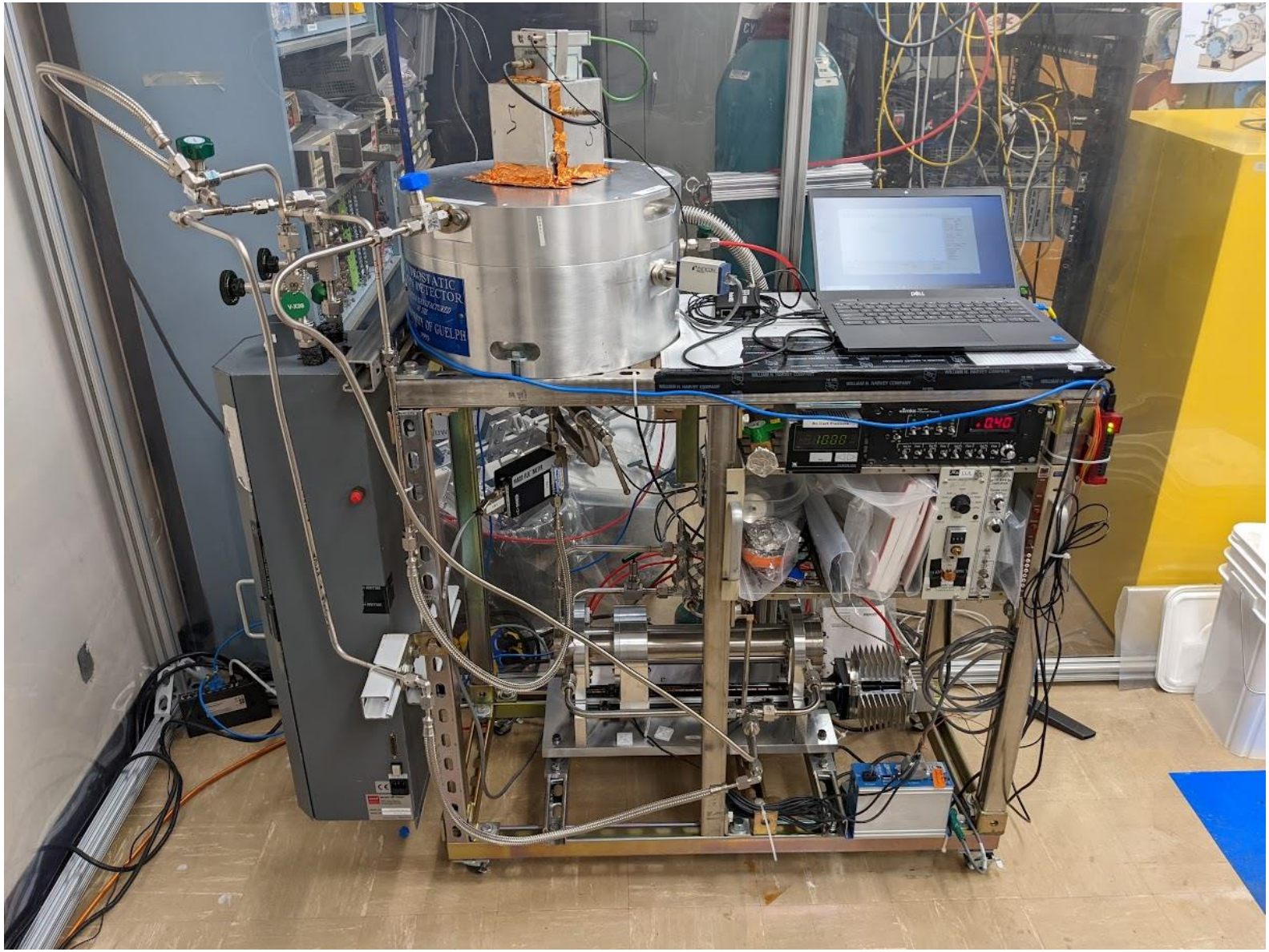


# EXO200 Magnetically Coupled Pump




F LePort et al. “A magnetically driven piston pump for ultra-clean applications”. In: Review of Scientific Instruments 82.10 (2011), p. 105114.

# Assay of SAES PS4-MT3 purifier



# Geometry of SLAC ESC V1