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Development of a cryogenic radon distillation column for next generation liquid xenon experiments

Herbstschule HEP 2026
Bad Hoennef

Robert Braun, Lutz Althüser, Volker Hannen, Christian Huhmann, David Koke, Ying-Ting Lin, Sakuntha Pratapage, Philipp Schulte, Patrick Unkhoff, Daniel Wenz and Christian Weinheimer

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This work is supported by the ERC AdG project „LowRad“ of C. Weinheimer (No. 101055063)

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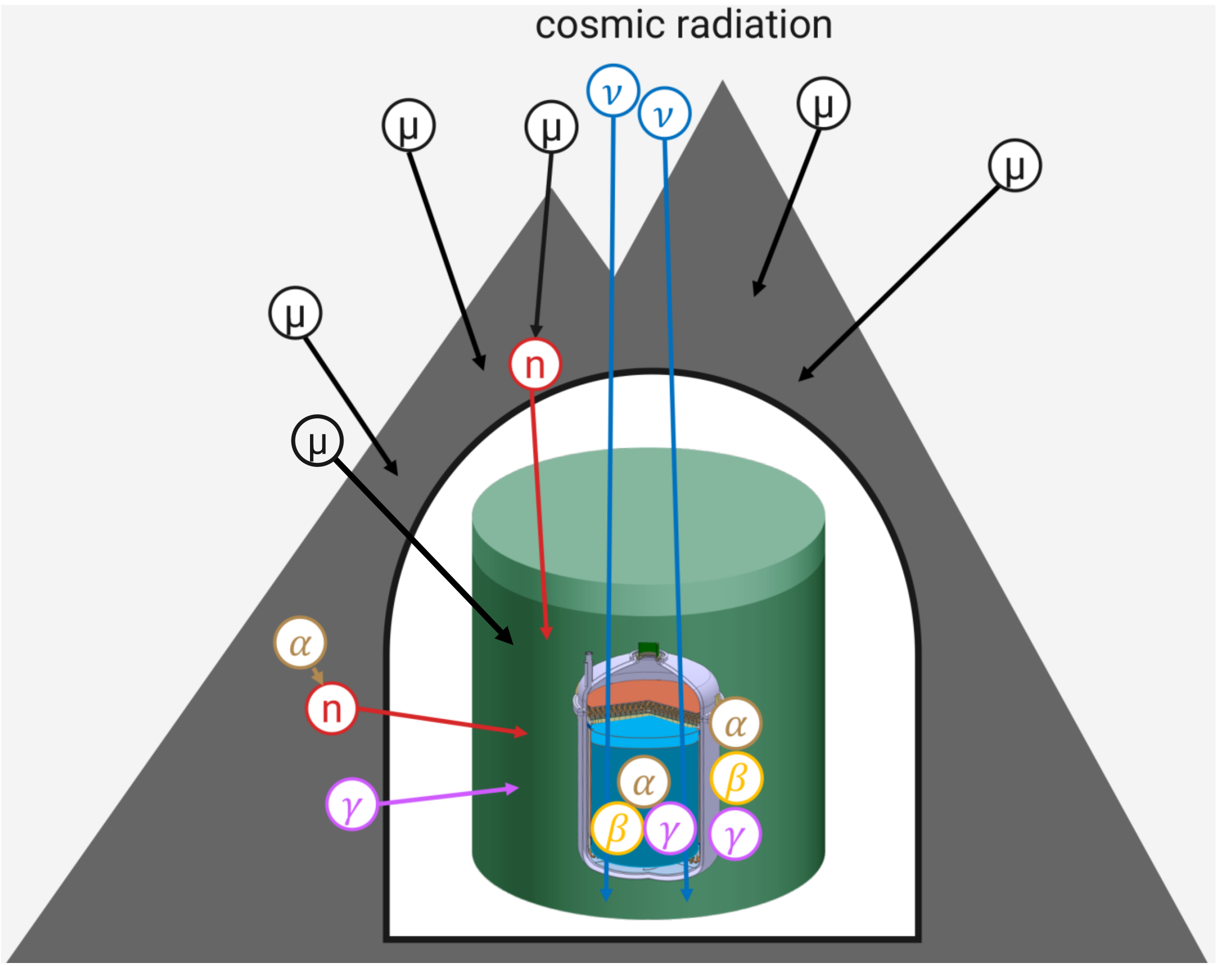
Limiting Backgrounds in xenon DM detectors

- Expected dark matter (DM) scattering rate:
  - O(0.1) events per tonne and year
- External background reduction:
  - Underground laboratory
  - Material screening of detector components
  - Shielding and vetoes
- Remaining backgrounds:
  - Solar neutrinos
  - Intrinsic noble gases: **^{85}Kr, ^{222}Rn**



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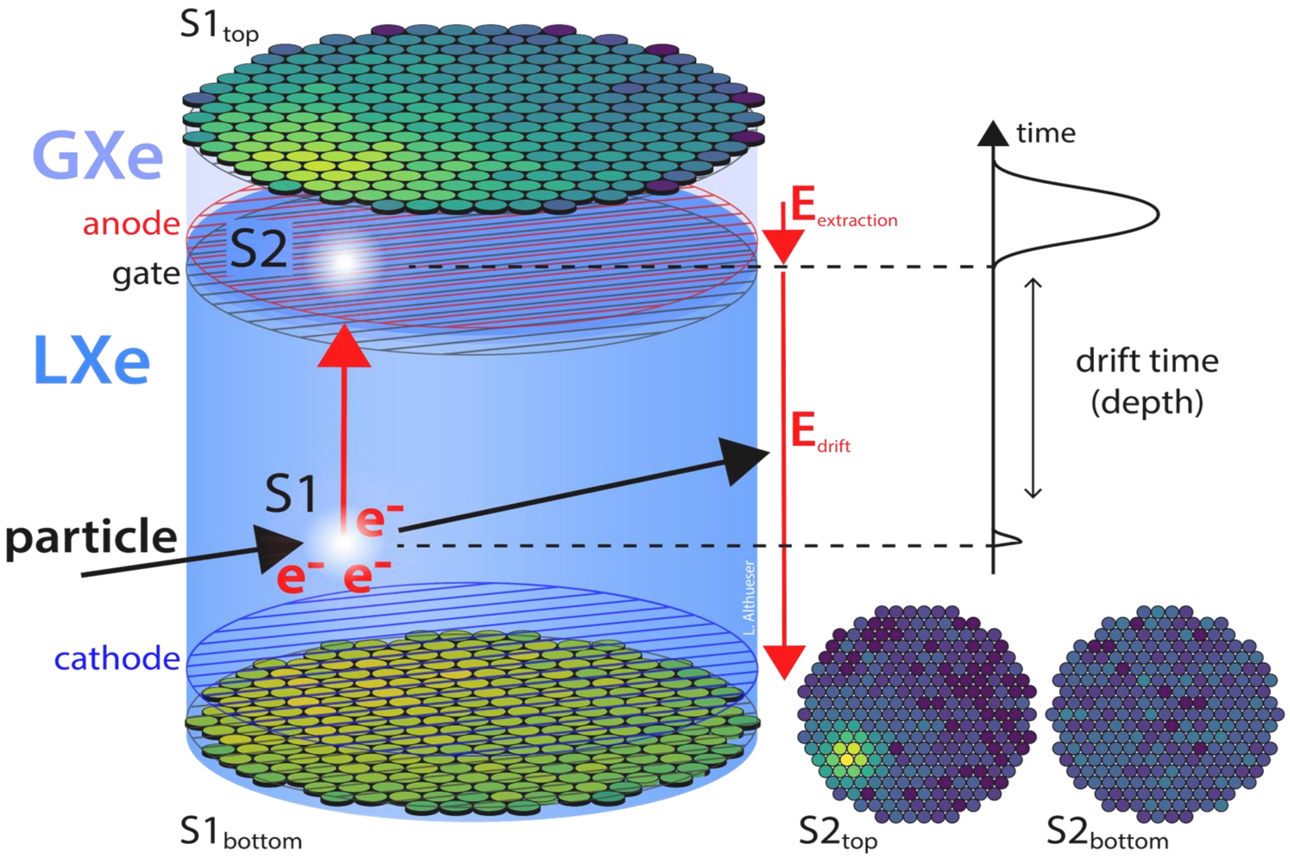
The XENONnT detector

- Dual-phase Time projection chamber (TPC)
- Filled with 8.4 t of LXe
- Light (S1) and charge (S2) signal
- Position reconstruction allows for fiducial volume (xenon self shielding)
- Two signals carry information about the type of interaction



Source: Lutz Althueser

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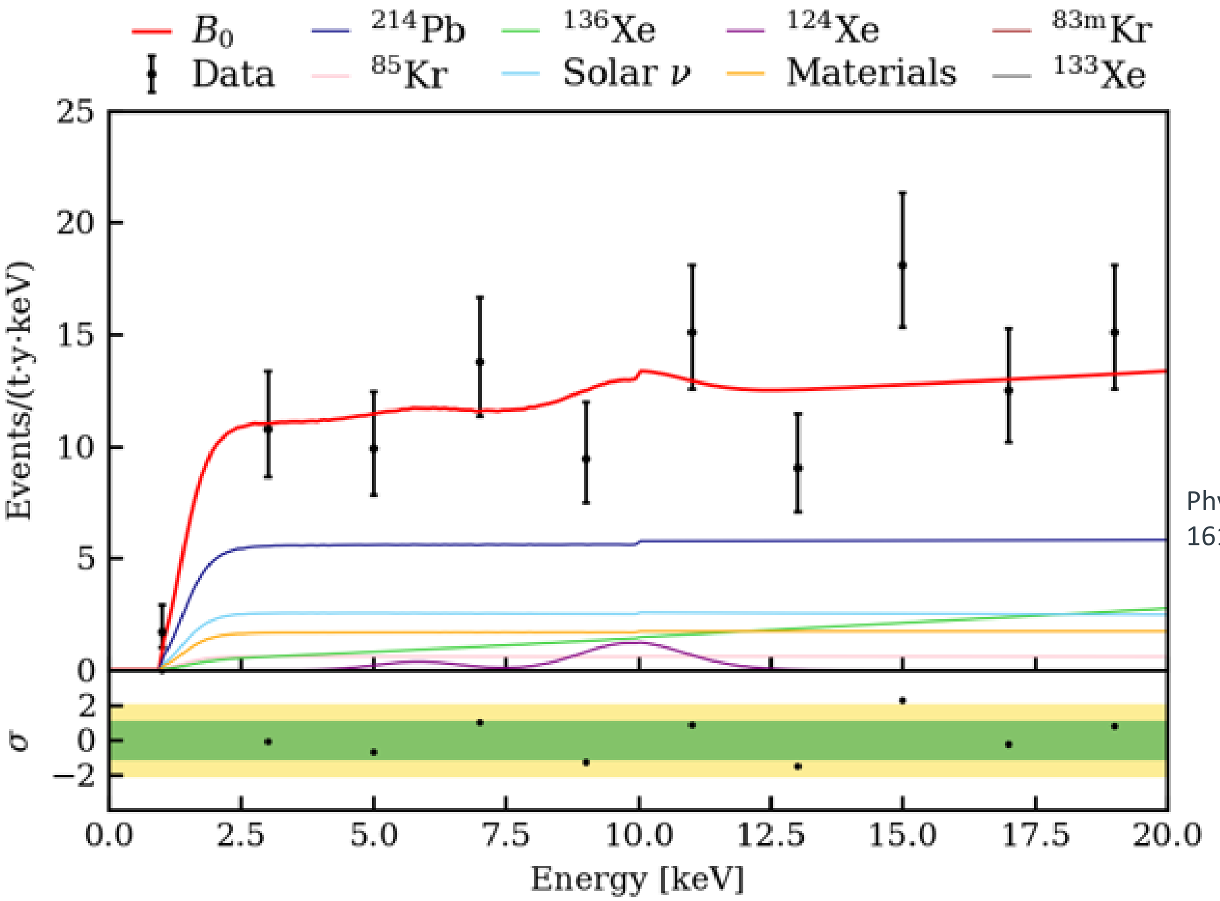
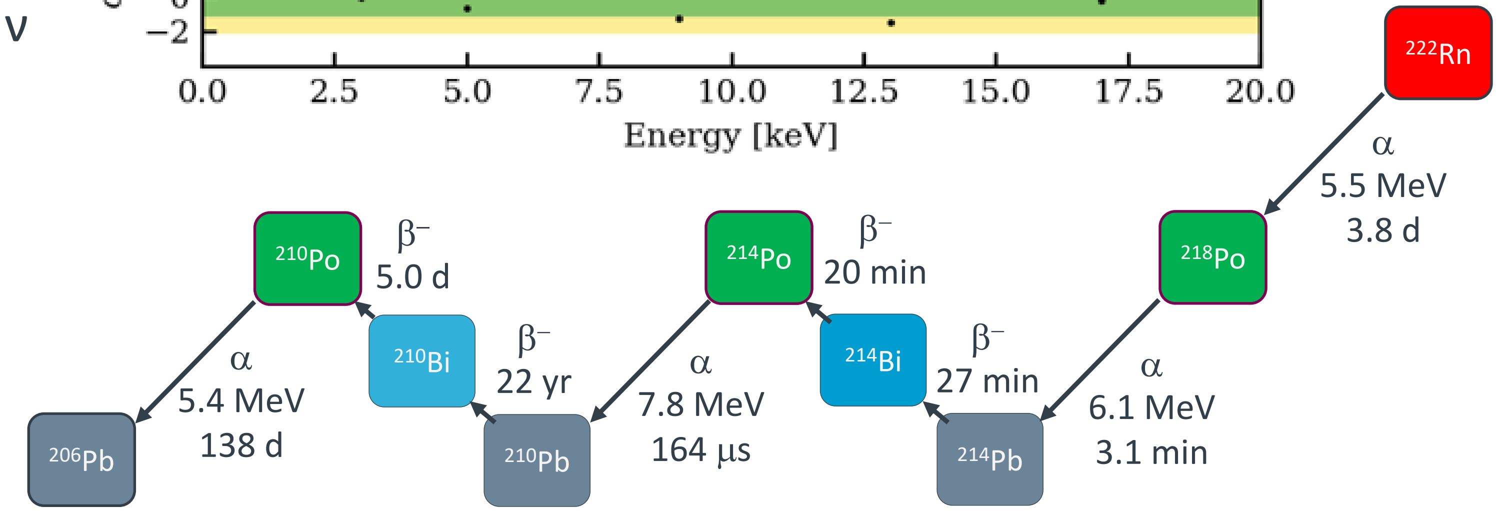
Radon background

- Rn is continuously emanated from detector material
- α–decays give large, monoenergetic signals
- Decay chain contains multiple β- decays
- Low energy background for DM and ν searches

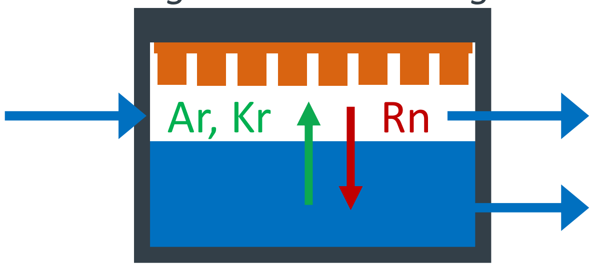


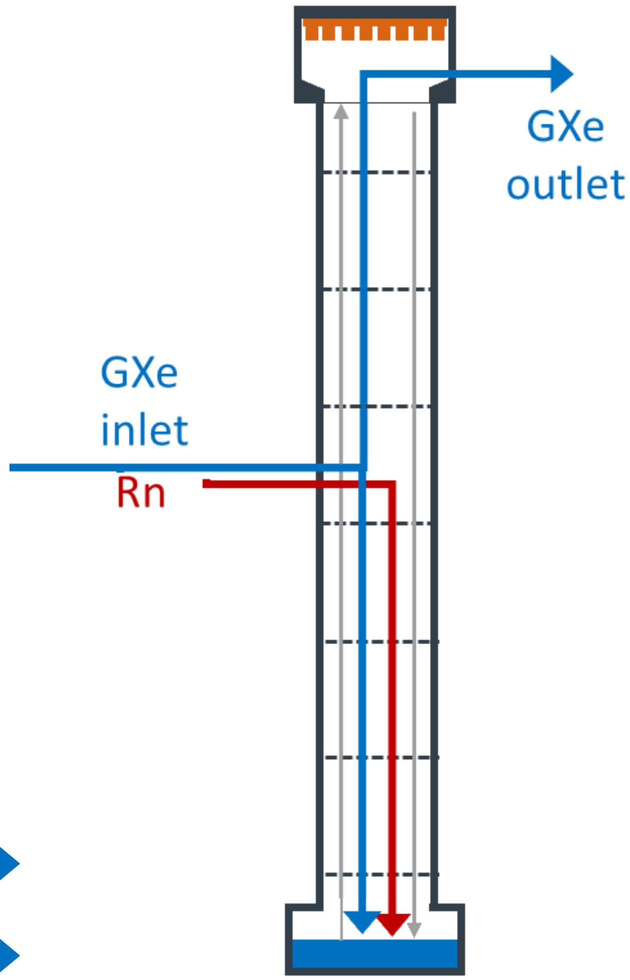
Phys. Rev. Lett. **129**, 161805 (2022)



Cryogenic radon distillation

- Based on difference in vapor pressure $\boldsymbol{P}$ of noble gas elements
- Relative volatility: $\boldsymbol{\alpha = P_{Rn}/P_{\mathrm{Xe}}}$
- **^{222}Rn:**
    - $\boldsymbol{\alpha = 0.1}$ (at -100 °C)
    - Less volatile Rn is collected at the bottom
    - Trap Rn until decay ($t_{1/2} = 3.8\ \mathrm{d}$)
    - Extract Rn-depleted Xe from top
- Rn is continuously emanated from radioactive impurities inside detector material





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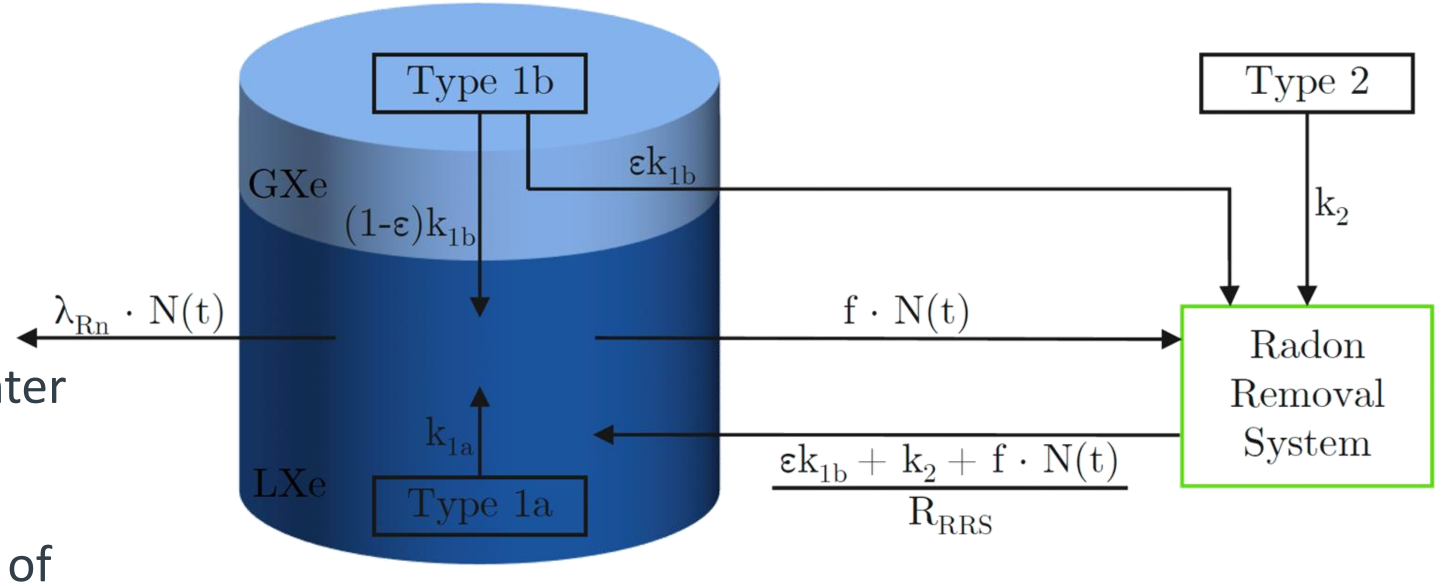
Continuous radon removal

- Source types:
  - **1b:** Enters GXe phase
  - **1a:** Enters LXe phase
  - **2:** Enters Rn Column directly
- Removal from GXe phase before it can enter the LXe (reduction factor of 2)
- Reduction factor of 2 requires circulation of detector mass within Rn half life $t_{1/2} = 3.8\ \mathrm{d}$
- For 8.4 t in XENONnT: ≈ 200 slpm (72 kg/h)



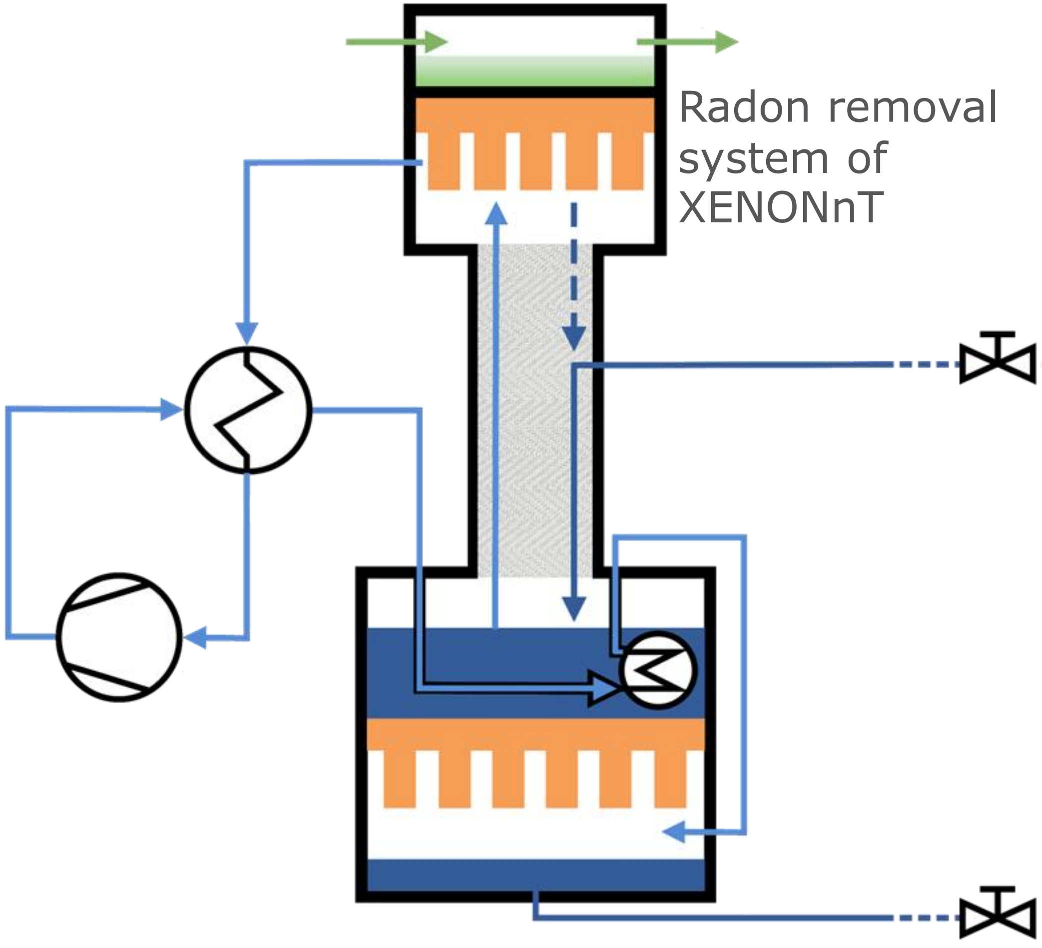
$$r(R_{\mathrm{RRS}} \to \infty, f, \epsilon) = \frac{\lambda_{\mathrm{Rn}} + f}{\lambda_{\mathrm{Rn}}} \cdot \frac{k_{\mathrm{tot}}}{k_{1\mathrm{a}} + (1-\epsilon)k_{1\mathrm{b}}} \approx 2 \cdot 2 = 4$$

Eur. Phys. J. C 82, 1104 (2022)

Rn removal system of XENONnT

- Radon concentration of 0.9 µBq/kg[1] (≈1 Rn atom per 10 mol Xe) was achieved in XENONnT
- Cleaned GXe must be liquified before returning to the detector
- Heat pump principle using MagPump compressors to reduce required external cooling power from **3 kW to 1 kW**
- For next generation LXe detectors (e.g. XLZD) with O(80 t) LXe and a goal of 0.1 µBq/kg :
  - O(60 kW) cooling and heating power[2]

→ **Low radon and low internal radioactivity – LowRad**



European Physical Journal C (2022) 82:104

[1] Physical Review X 15(3), 031079 (2025)

[2] Schulte, P., Wenz, D., Althüser, L. *et al.* Proof-of-concept of a xenon-based cryogenic heat pump demonstrator for future liquid xenon observatories. *Eur. Phys. J. C* **86**, 488 (2026)

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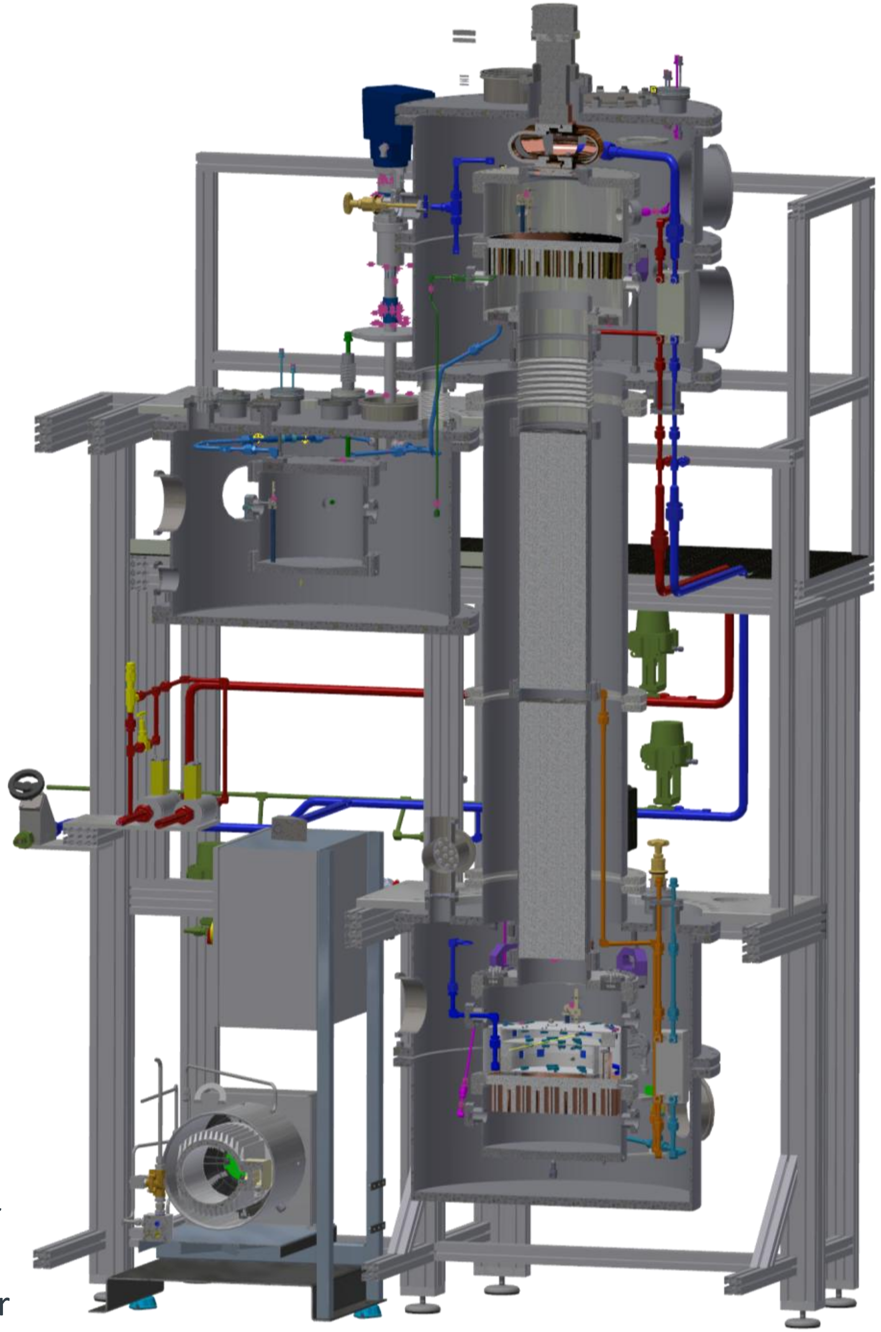
The LowRad radon distillation column

- Hermetically separated xenon heat pump to meet increased cooling power demand
- XENONnT sized demonstrator (72 kg/h) currently under construction
- Heat pump design based on test setup
    - Using phase change of xenon for heat transfer
    - 120 W heating and cooling power [1]
- Demonstrate scaling of heat pump and operation of distillation column



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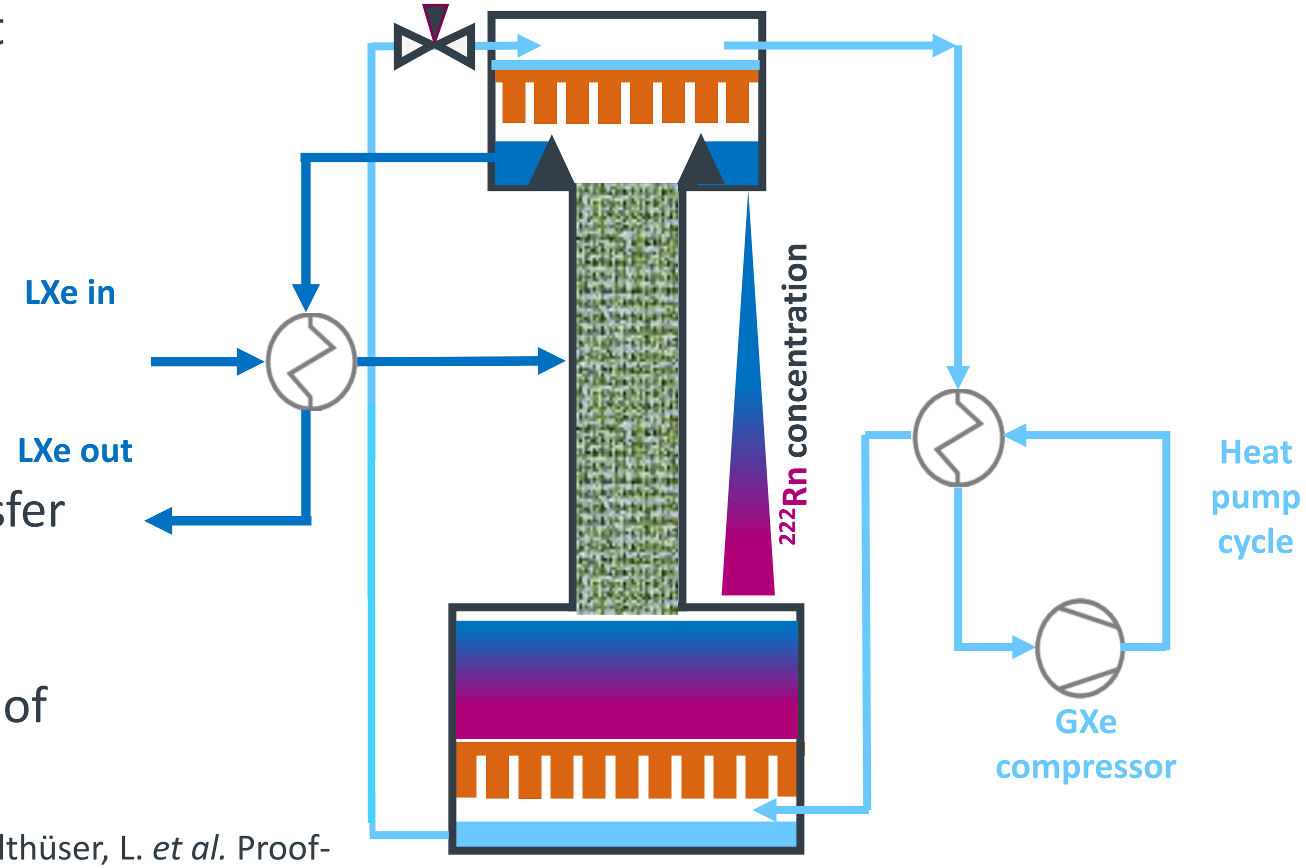

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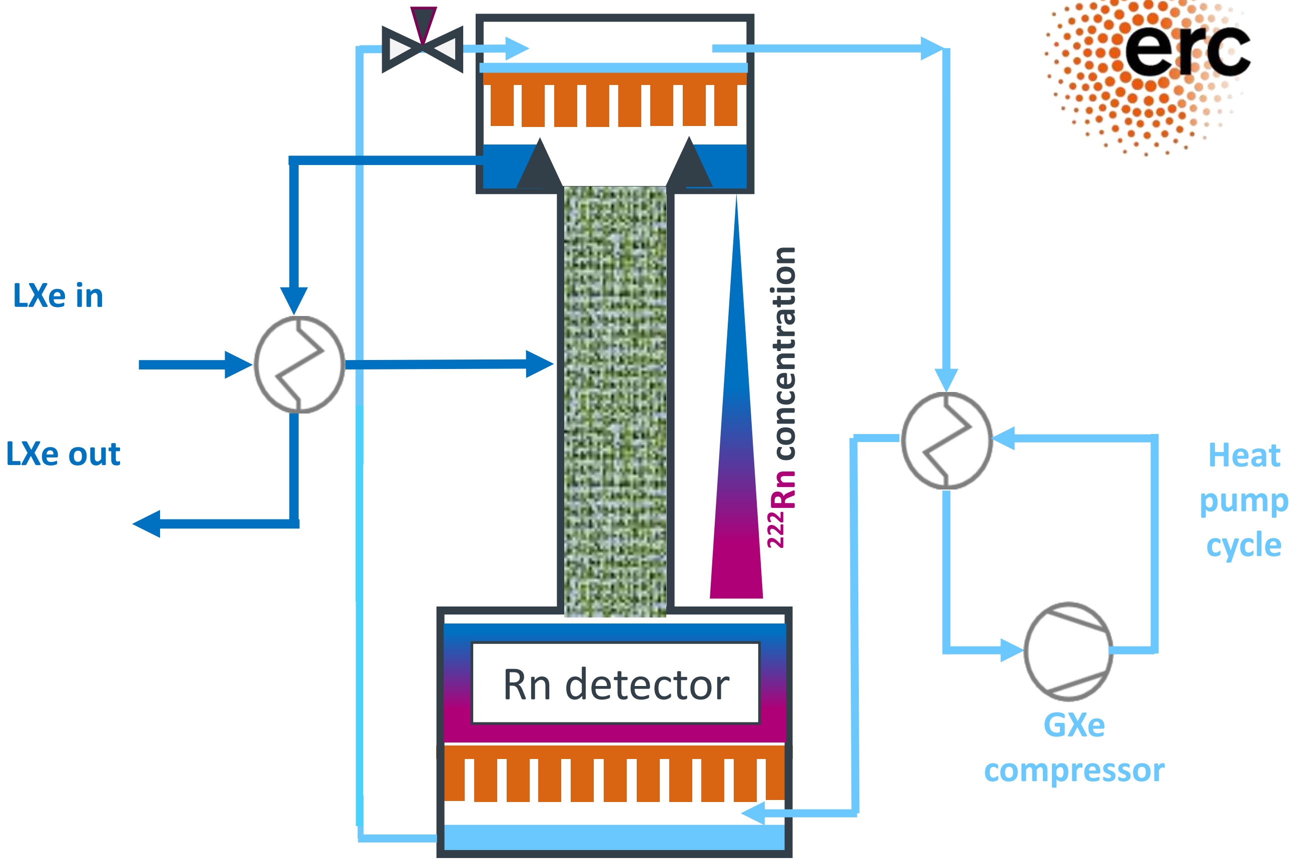
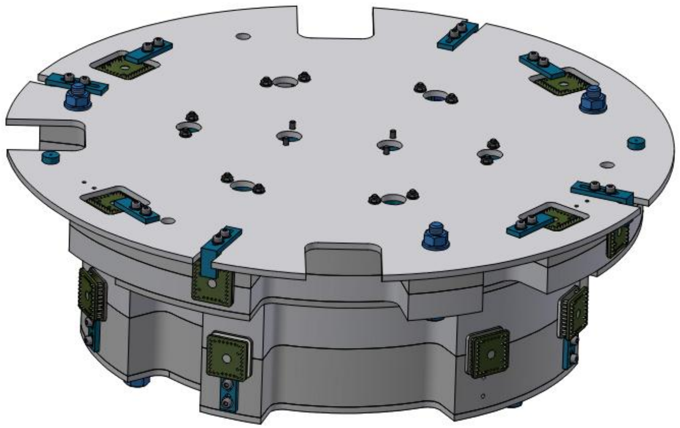
Radon decay monitor

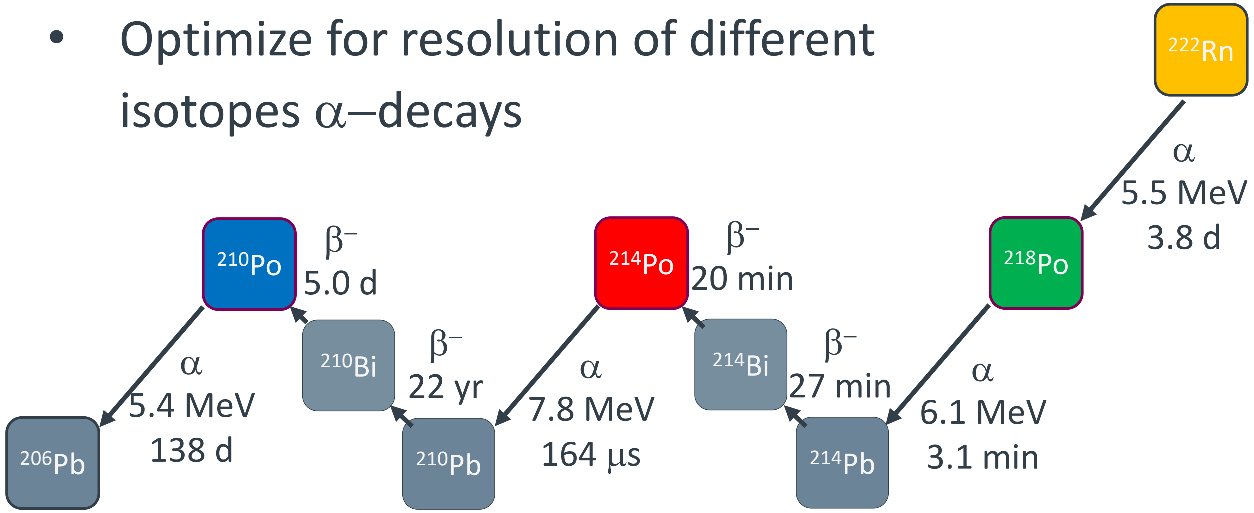
- Detect scintillation light from Rn decays inside Reboiler
- Constructed from 16x 1” PMTs and PTFE walls to improve light collection
- Two separated volumes:
    - Lower volume for Rn detection
    - Upper volume and sides for muon veto
- Setup on surface level → muon veto
- Light-tight holes for fluid exchange

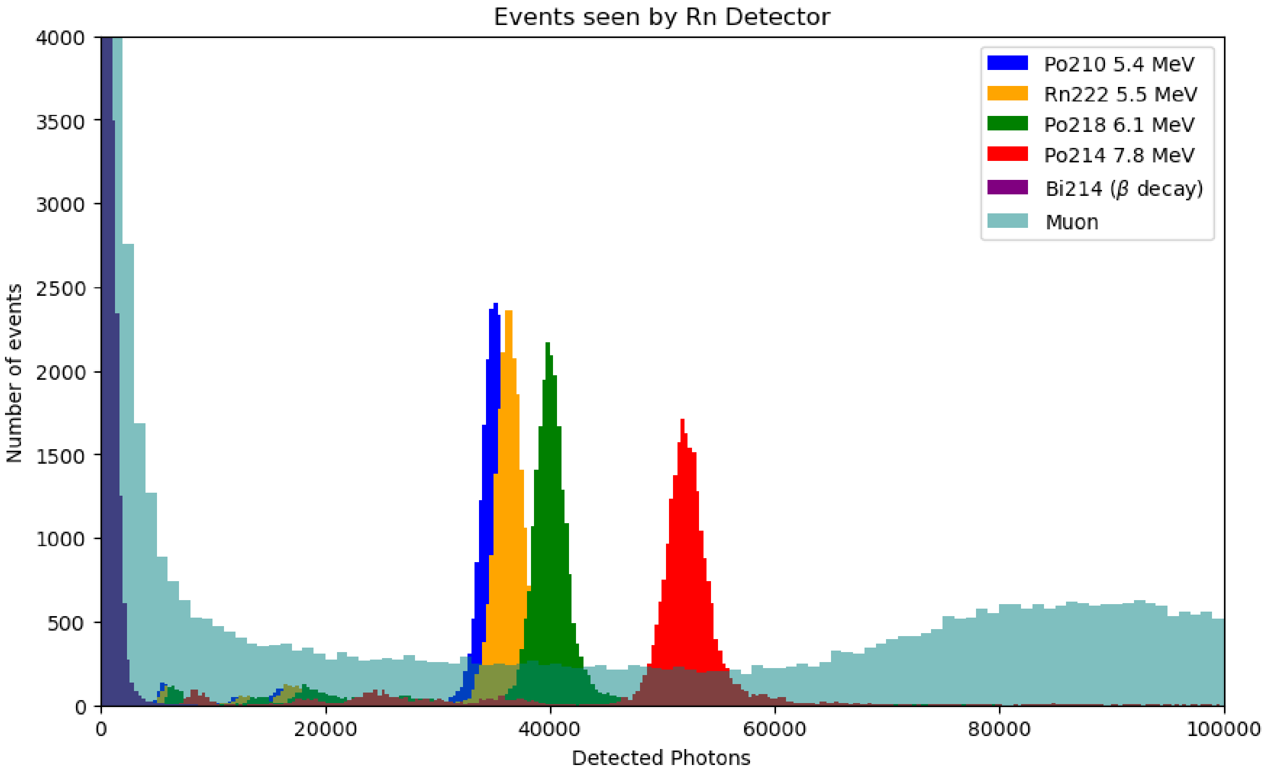




Radon decay monitor simulation

- Simulation of Rn monitor for detector design
- Geant4 optical simulation
- Accumulation of ^{210}Pb in the detector
- Optimize for resolution of different isotopes α–decays





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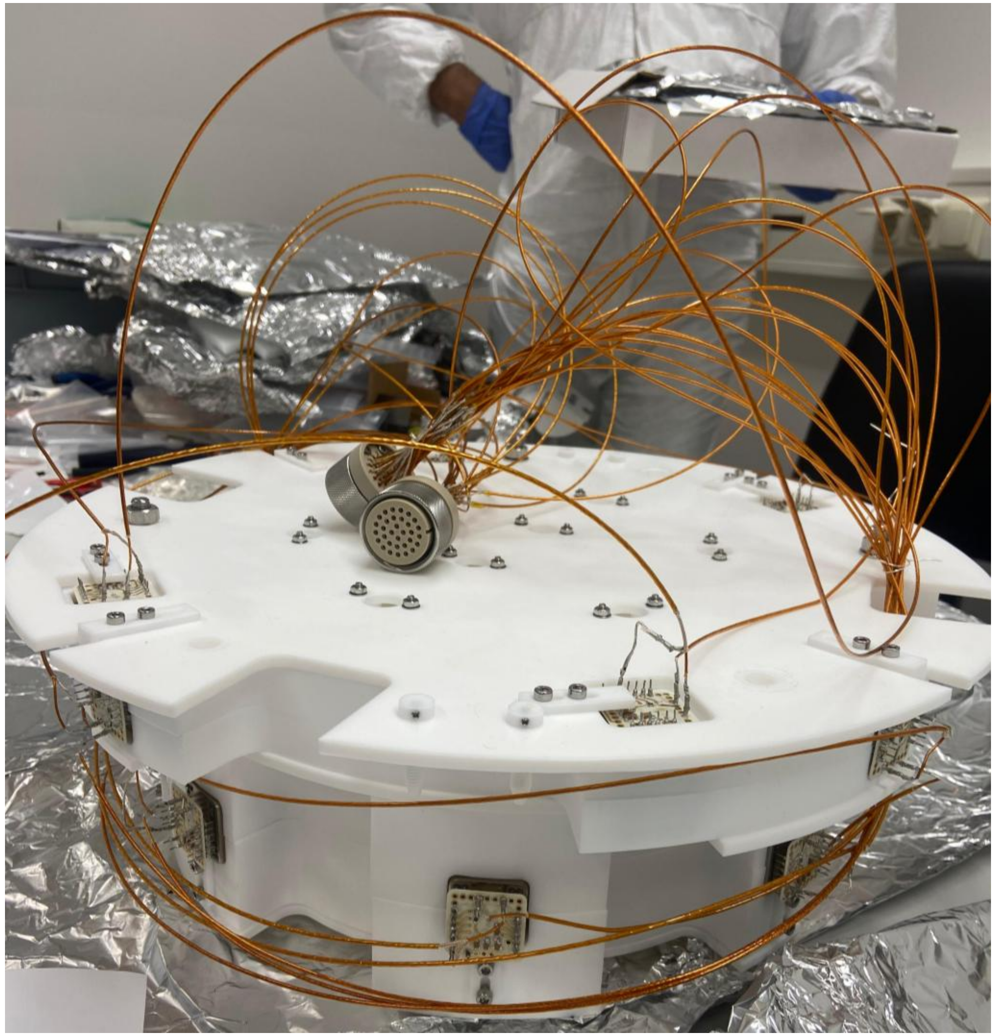
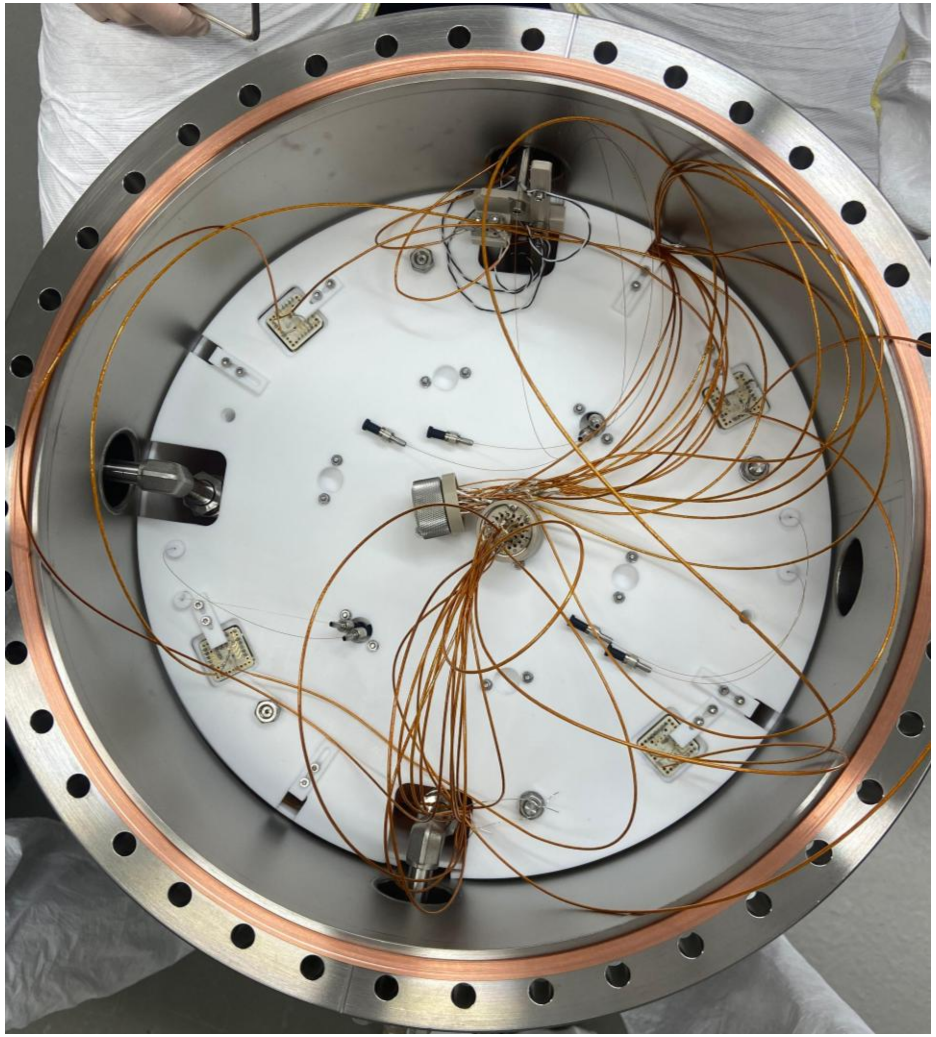
Pictures of Rn Column construction





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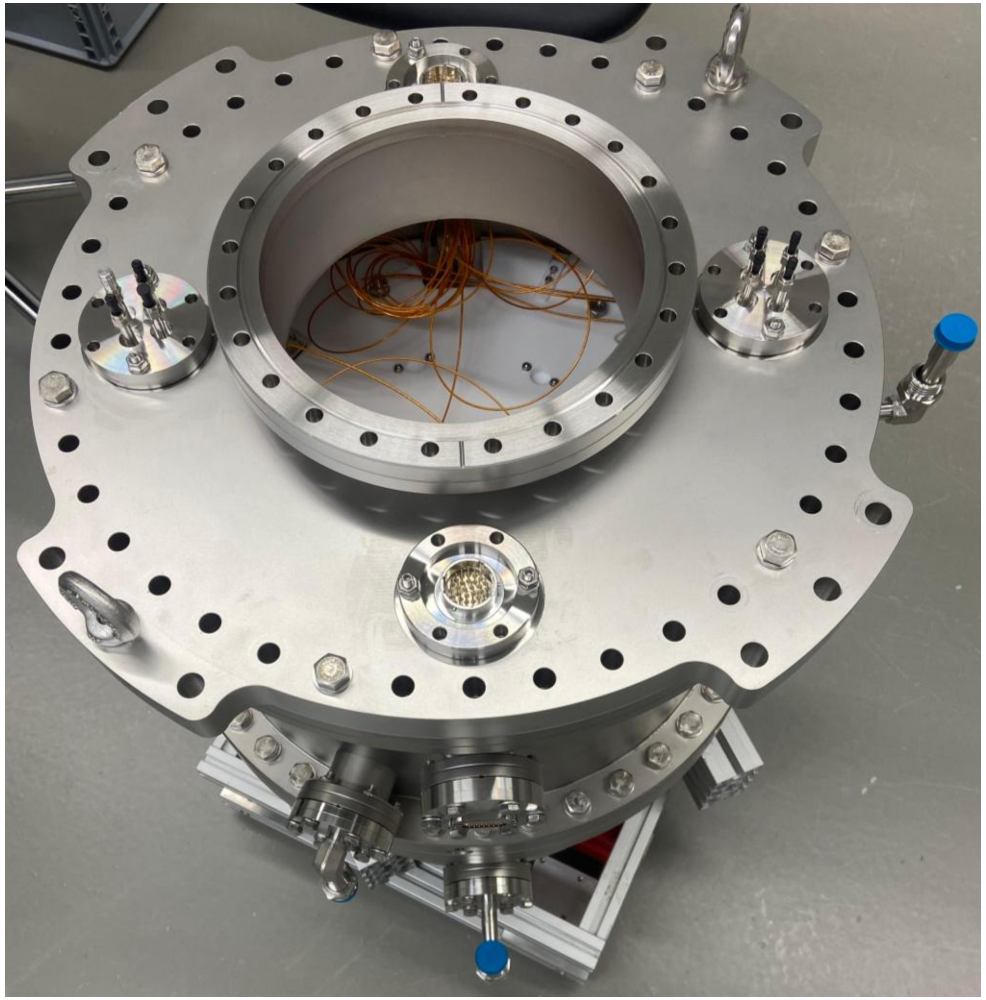
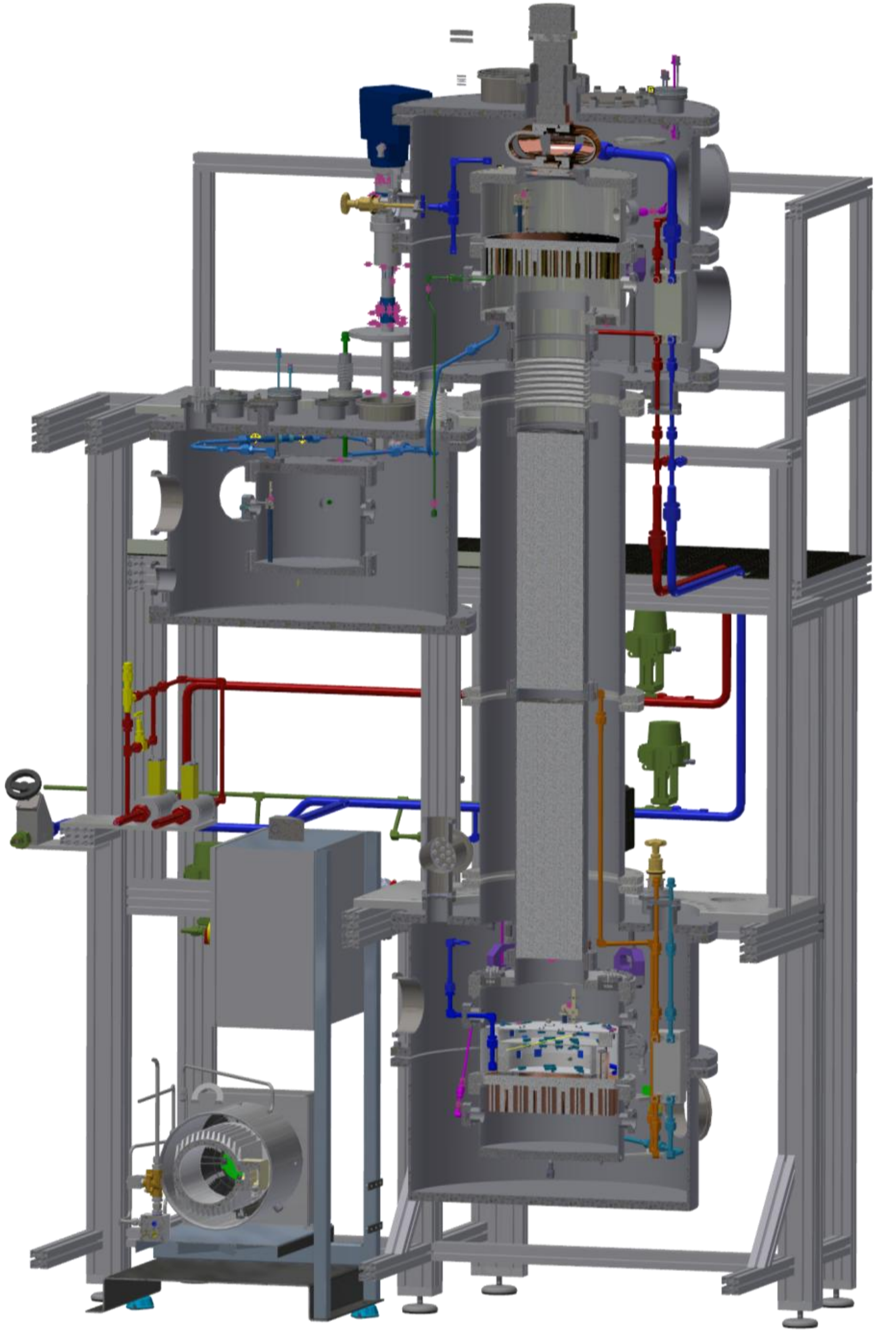


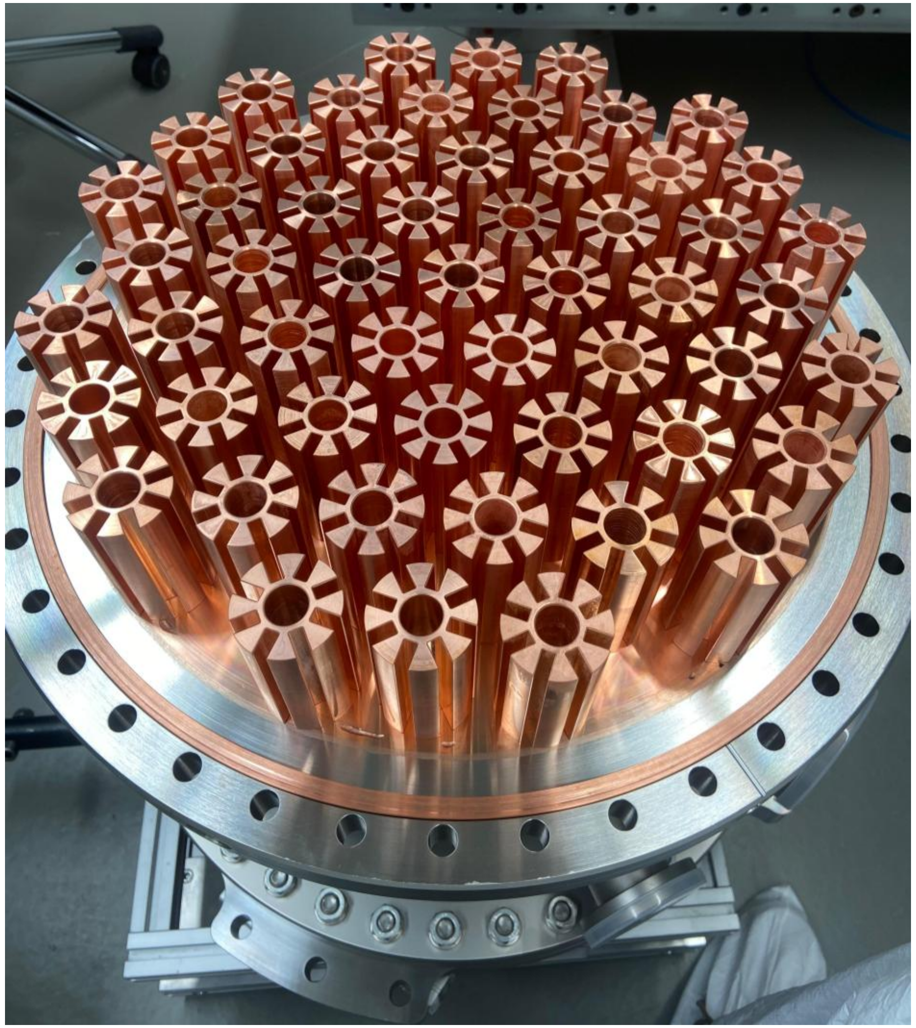
Pictures of Rn Column construction

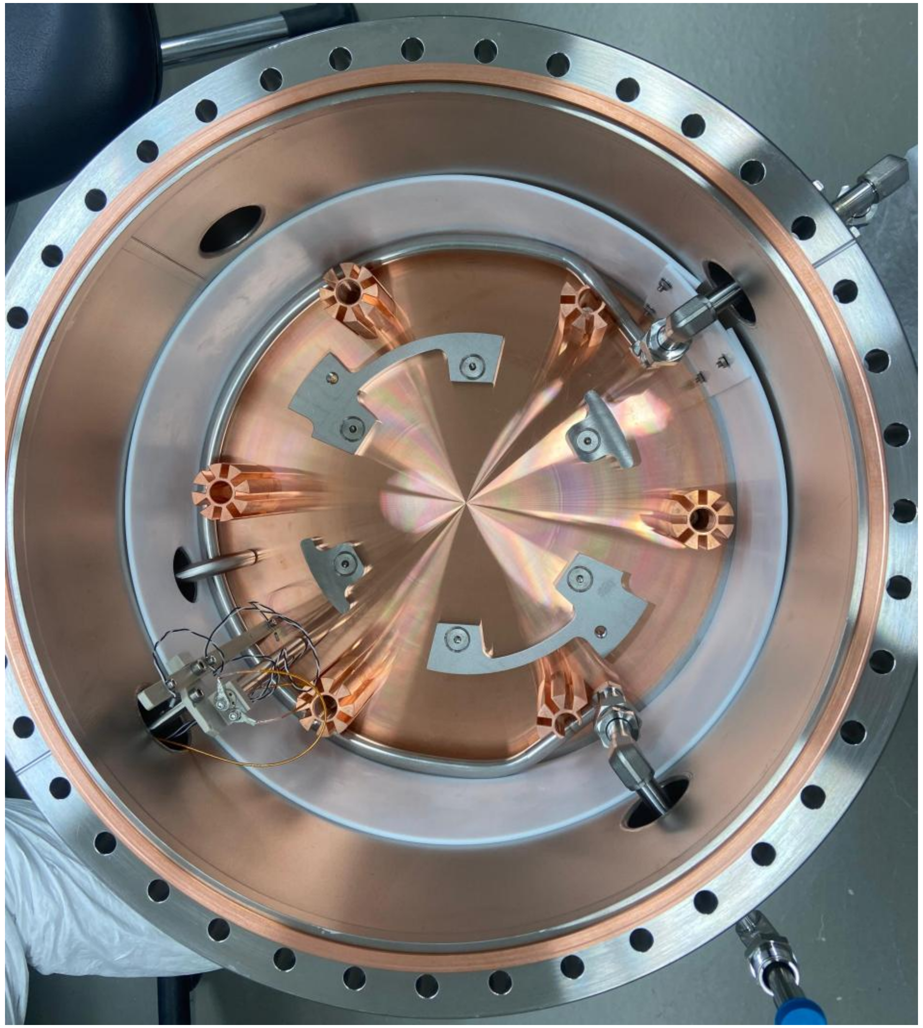
Summary



Backup Slides

Pictures of Rn Column construction





Liquid xenon experiment: XENONnT

- Dark matter experiment looking for weakly interacting massive particles (WIMPs)
- Underground laboratory in Italy
- Water tank with nested detector system
- Service building for liquid xenon handling