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Reduction of radon in xenon-based experiments to search for rare events

Low Radioactivity Techniques (LRT2024), Kraków, Poland, Oct 1-4, 2024

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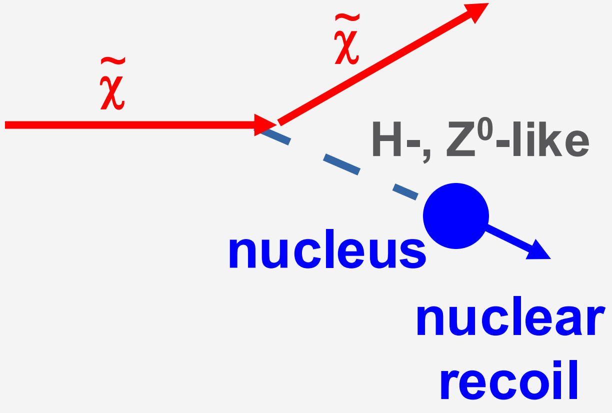
erc

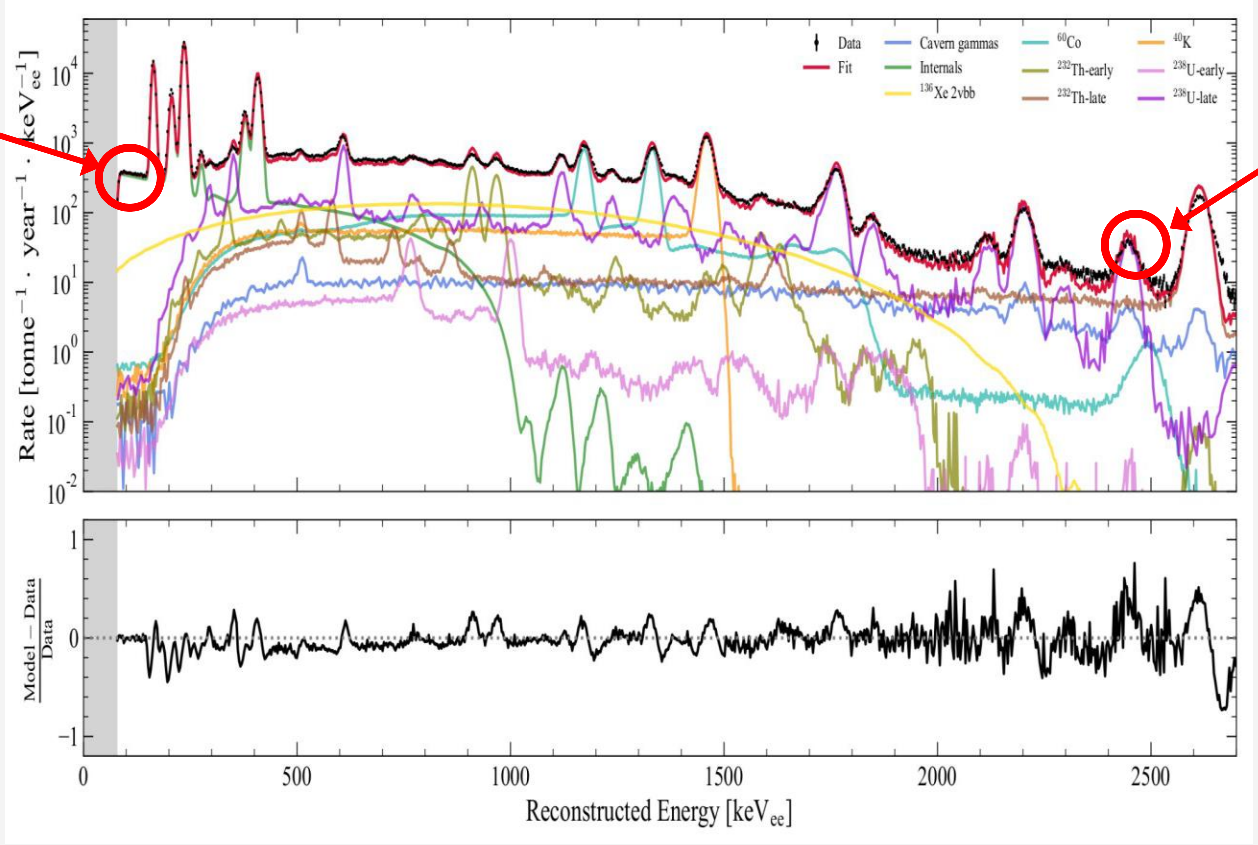
Outline:

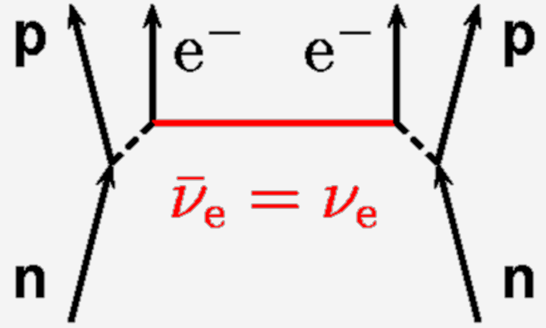
- **Motivation**
- **Different radon mitigation strategies**
- **Cryogenic online distillation**
- **Goals of ERC Advanced Grant „LowRad“**
- **Conclusions**

DM & 0νββ searches with liquid noble gas detectors

rather different energy scales, but similar background enemies to fight

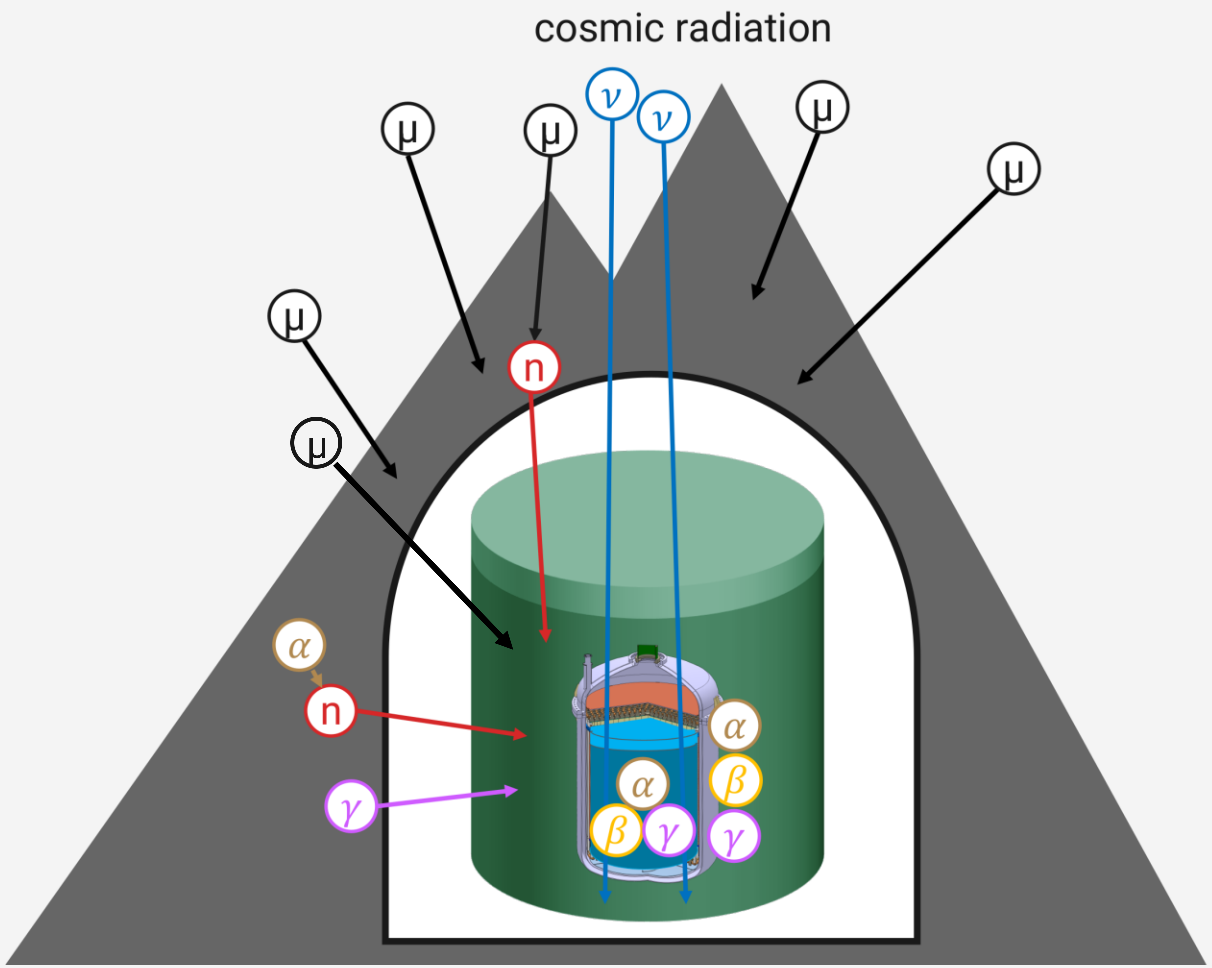






from LZ, see talk by P. Brás at XeSAT2023

Limiting backgrounds in rare event detectors



Expected dark matter scattering or 0νββ rate:

1 - 10 events per 10t and year

⇒ Profit only from larger experiments if the experiment remains background-free

Most background problems solved by
- going underground
- careful material screening & selection
- extra shieldings & vetos

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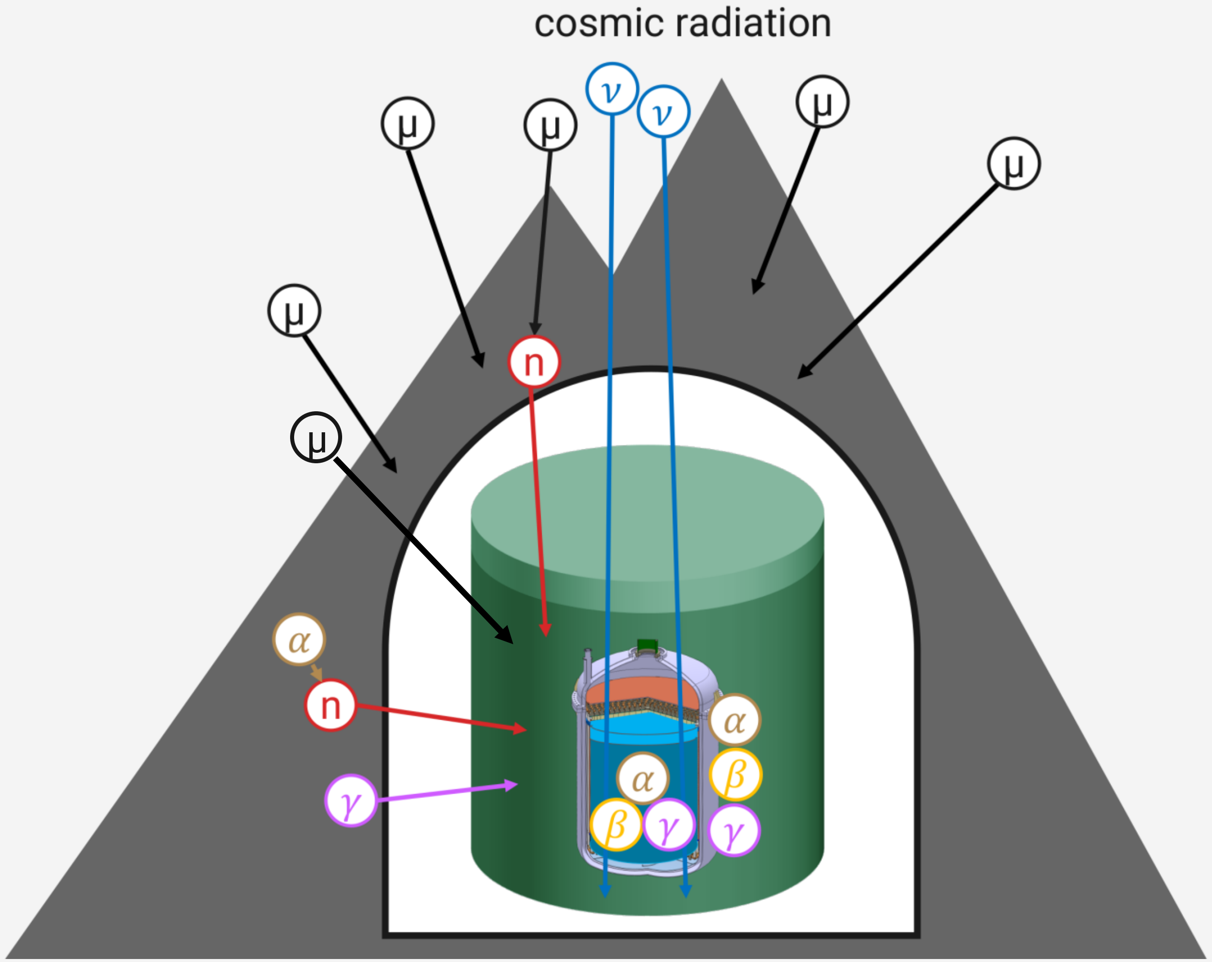
Limiting backgrounds in noble gas DM detectors



Expected dark matter scattering or $0\nu\beta\beta$ rate:

1 - 10 events per 10t and year

⇒ Profit only from larger experiments
if the experiment remains background-free

Most background problems solved by

- going underground
- careful material screening & selection
- extra shieldings & vetos

Two remaining backgrounds:

- solar neutrinos, non-shieldable
- **intrinsic radioactive noble gases:**
  ^{85}Kr, ^{222}Rn and progenies, (^{37}Ar, ^{39}Ar, ^{136}Xe)

β-decays matter for nuclear recoil search, even for dual phase Xe TPCs

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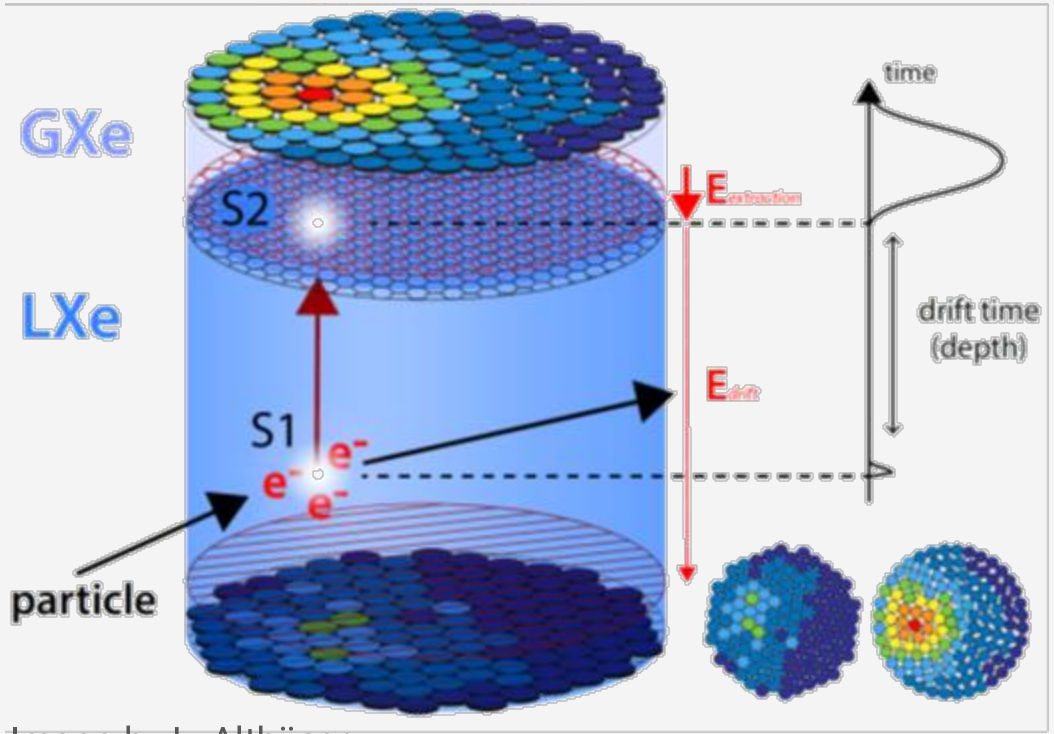
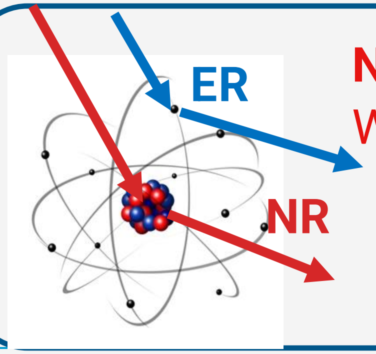


Image by L. Althüser

S1 light signal:
- prompt scintillation photons

S2 charge signal:
- secondary scintillation photons from electroluminescence in GXe due to drifted electrons

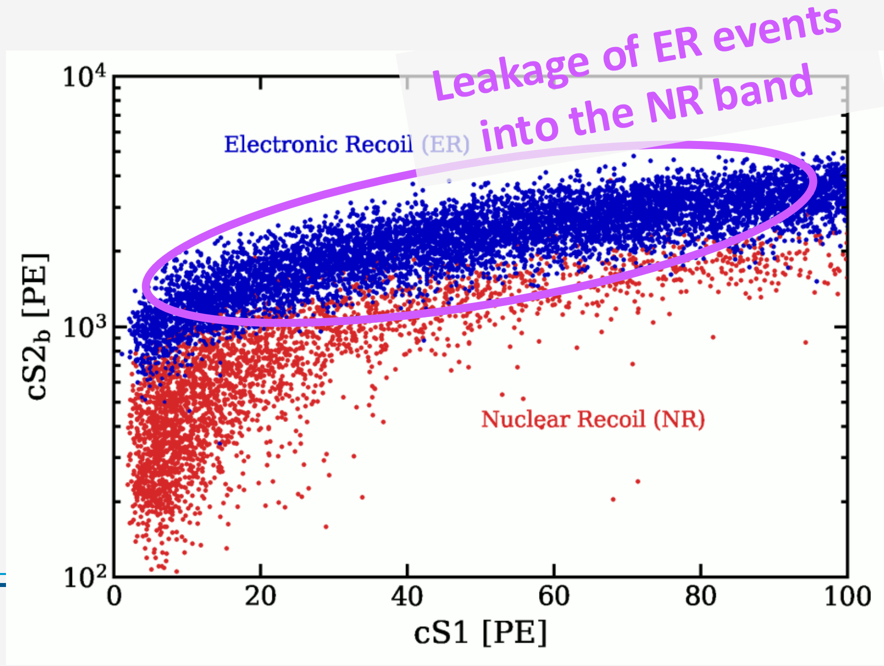
3D vertex reconstruction (-> fiducialisation):
- X,Y: S2 hit pattern
- Z: drift time S2-S1



NR (Nuclear Recoils)
WIMP signal, neutrons, CEvNs

ER (Electronic Recoils)
γ, β backgrounds

Discrimination from S2/S1
Larger for ER than NR



A closer look to ^{85}Kr and ^{222}Rn with its progenities

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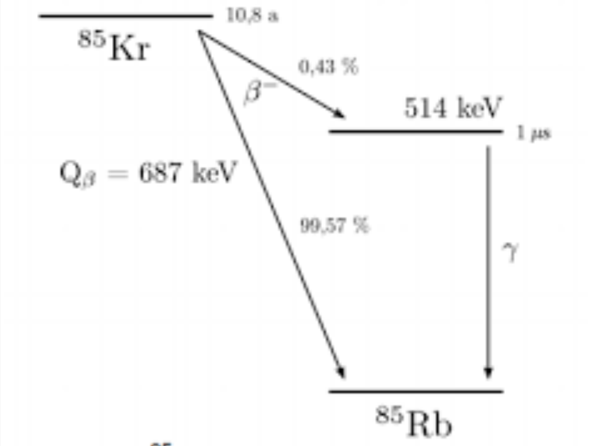
Why: intrinsic noble gas contaminants ^{85}Kr and ^{222}Rn (→ ^{214}Pb) (as well as calibrating isotopes, e.g. ^{37}Ar)

- leakage events from the low energy β-spectrum contaminate ROI for dark matter WIMP search
- searches for new physics inside the electronic recoil spectrum only possible with low levels of impurities

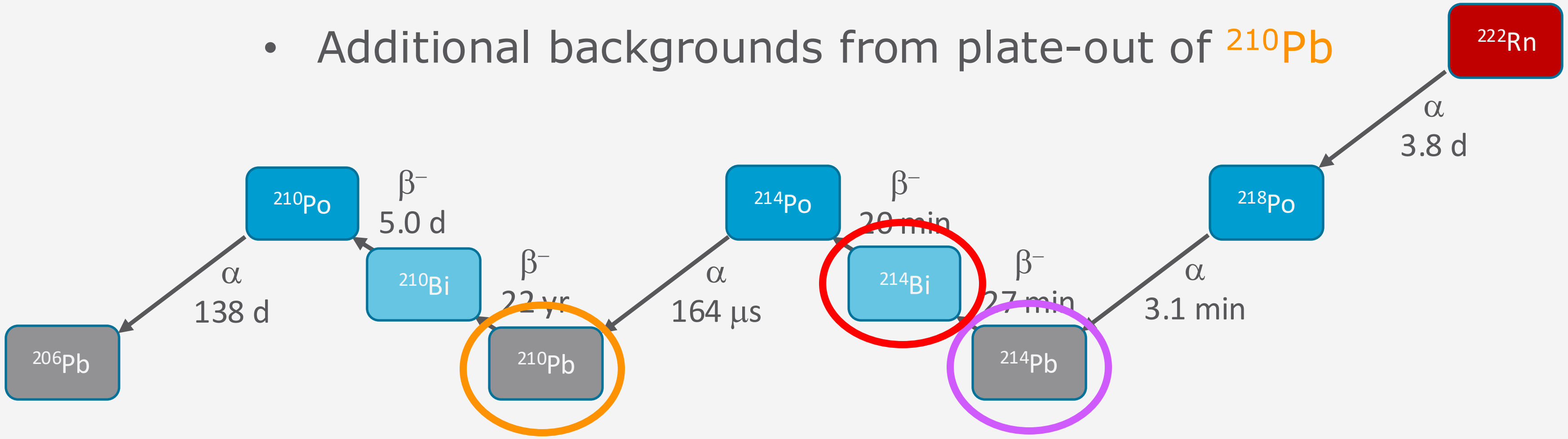
^{85}Kr: $1 - 2 \cdot 10^{-11}$ in ^{nat}Kr, man-made



^{85}Kr decay scheme

^{222}Rn: $t_{1/2} = 3.8$ d, continuously emanating from detector materials,

- Background from β-decay of ^{214}Pb which cannot be identified by accompanying α-decay
- Background from γ-decay of ^{214}Bi for 0νββ decay searches if not fully BiPo-tagged
- Additional backgrounds from plate-out of ^{210}Pb



Threefold way to ultra-low radon concentration in xenon

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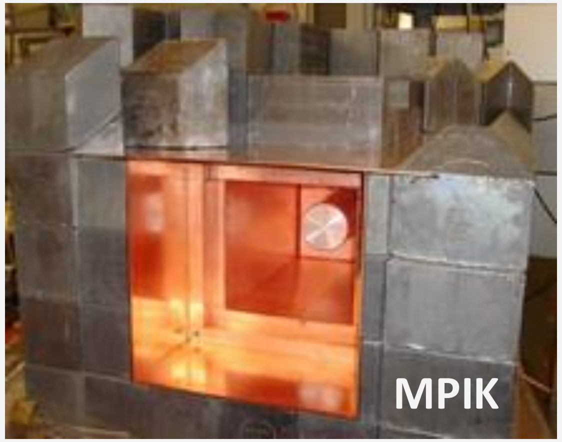
1) Avoid radioactive noble gas right from the beginning

^{222}Rn: Screen material, check for low ^{222}Rn emanation

F. Jörg
A.D. Fard



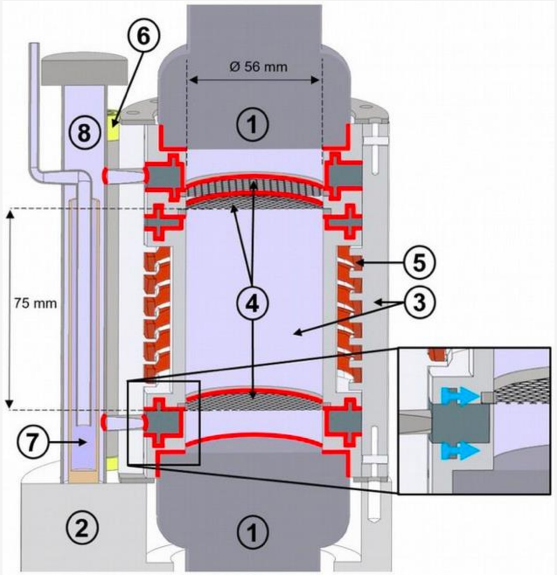
1) Mitigation

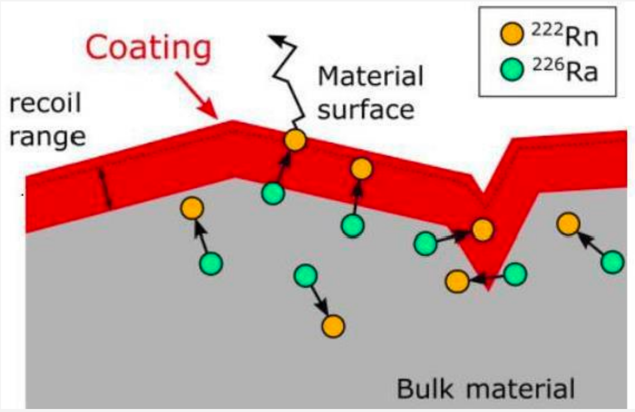
^{222}Rn: comes from materials:

- coating,
- detector design (hermetic, Xe ice, ...),
- ...

G. Volta
Y. Wu

EPJ C83 (2023) 9





Threefold way to ultra-low radon concentration in xenon

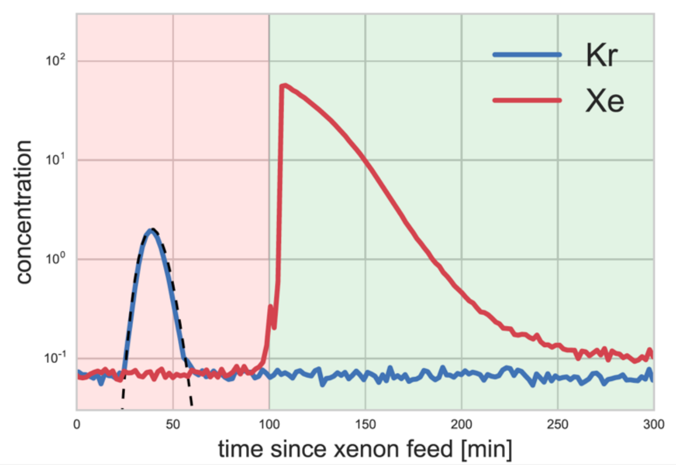
3) Active removal of radioactive noble gas from detector by using different properties of Kr/Xe/Rn:

a) Diffision: utilize different ad-/desorption times on porous materials

continuous adsorption and desorption processes depending on temperature, mass, charge radii of noble gas atoms, Van der Waals forces, ..

→ different drift times, chromatography

J. Busto



b) Cryogenic distillation: utilize different vapour pressures (volatility of the different noble gases)

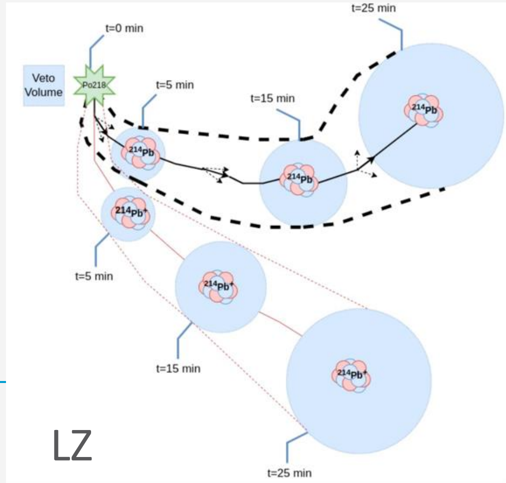
this talk

c) Virtual removing (offline tagging) of radon-induced background:

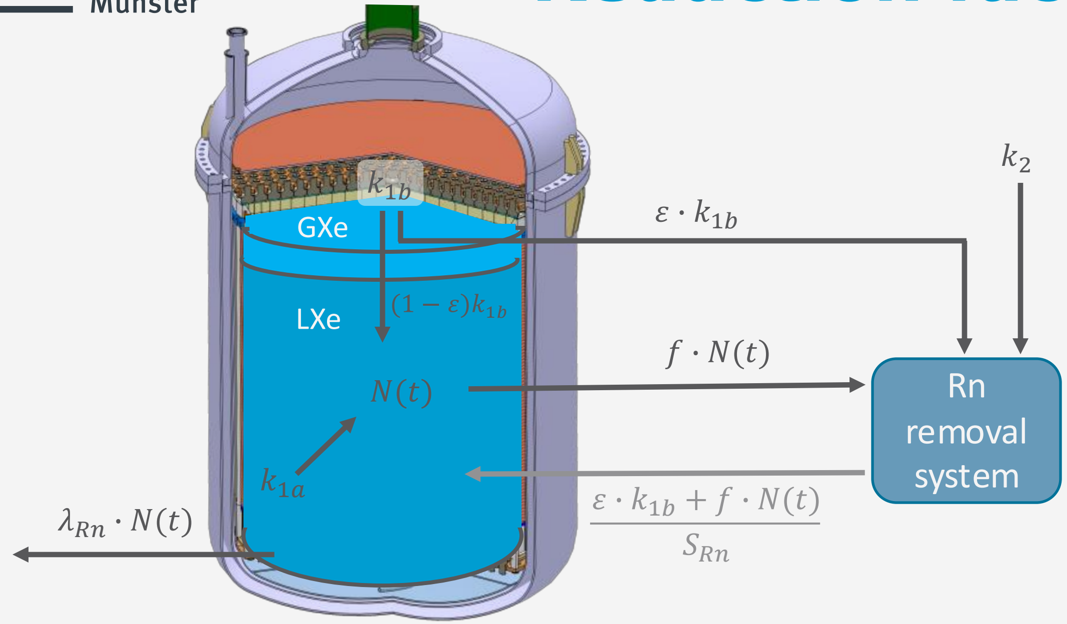
principle: [XENON] PRD 110 (2024) 012011

recent LZ offline-tagging result, reported at TEVPa 2024: **3.9 µBq/kg → 1.8 µBq/kg**

identifying ^{214}Pb decay by previous ^{222}Rn and ^{218}Po decay locations when applying very low convection flows in the LXe



Reduction factor of ^{222}Rn removal system



Different Rn source types:

- Type 1b: enters the GXe phase with a rate k_{1b} from cables or lines to the outside, can be extracted directly with a fraction ε to the RRS
- Type 1a: directly enters the LXe phase in the detector with a rate k_{1a}, can be extracted with a relative low f to the RRS
- Type 2: enters the Rn removal system with a rate k_2 before the LXe phase

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

$\approx \mathbf{2} \cdot \mathbf{2} = \mathbf{4}$ for a XENONnT at a flow of $\approx$ 75 kg/h

LXe extraction reduction factor with total LXe exchange time $T = 1/f$:
$r_{LXe} \approx 1 + {}^{\tau_{Rn}}/_{T} \approx 2$ to 4

GXe extraction reduction factor, typically
$r_{GXe} \approx 2$ (XENONnT)

Online distillation:
E. Aprile et al. (XENON Collab.)
Prog. Theo. Exp. Phys. 5 (2022) 053H01

→ Need short Xe exchange time $T = 1/f = m_{Xe}/F_{Xe} \leq \tau_{Rn}$ and thus high throughput F_{Xe}

LZ: In-line Radon reduction system

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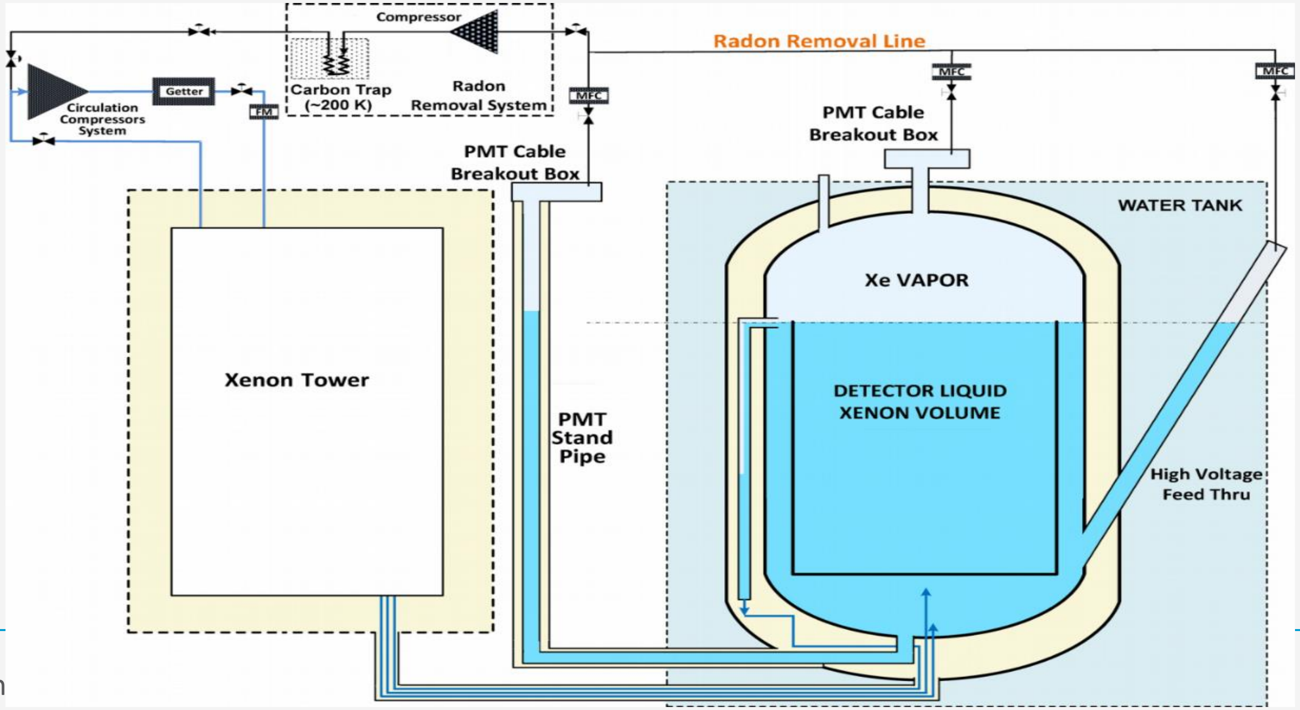
- reduce ^{222}Rn background from in warm parts only (feedthroughs, cables, etc.)
  i. tiny fraction of entire volume: 1 slpm (GXe) : 500 slpm (LXe)
  ii. expected to contribute ~50% of Rn burden in TPC
- not set up to purify all 10 t of LXe
- sequestration of atoms in activated carbon trap until most ^{222}Rn nuclei decay
  i. chromatographic separation: v(Xe)/ v(Rn) (-85 C) ≈ 1000
- to obtain reduction of 90% (10x), sequestration time ≥ ln(10)· τ_{Rn} = 12.7 days



courtesy:
Wolfgang Lorenzon
University of Michigan

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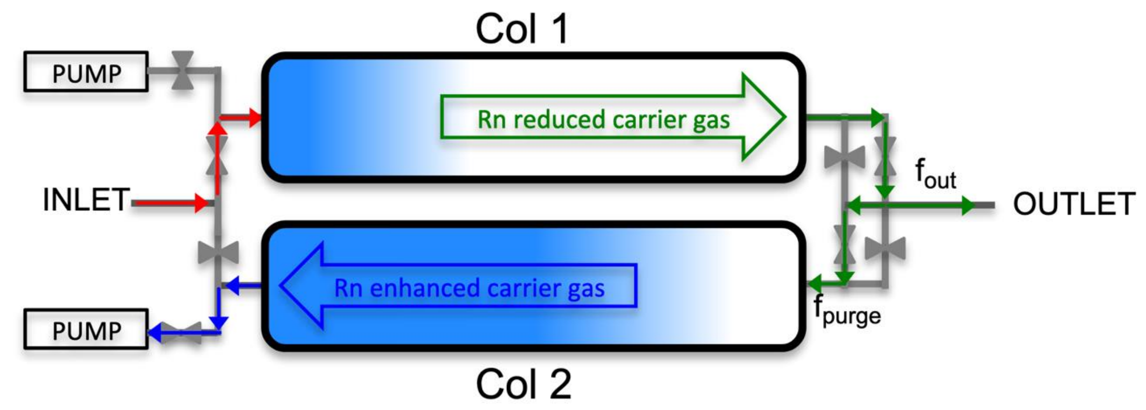
Radon removal by vacuum swing adsorption system (VSA) for larger throughputs

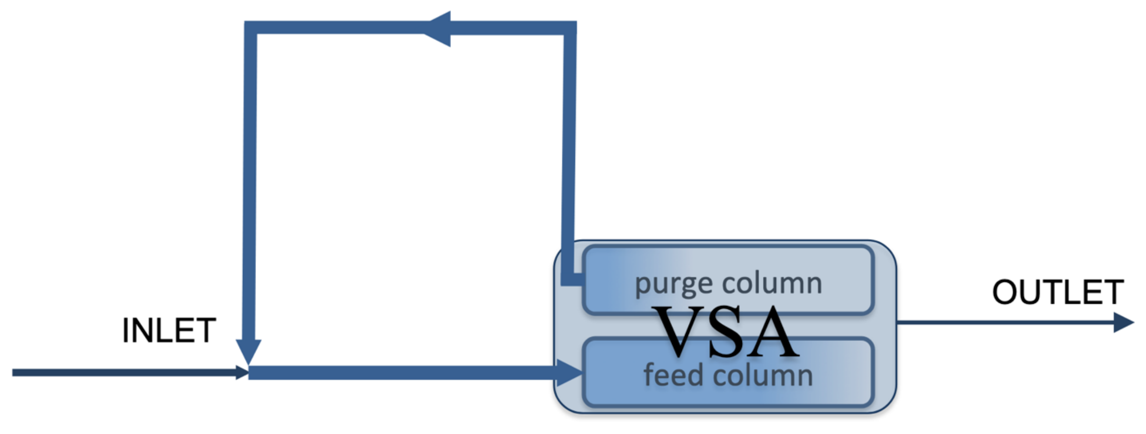
Example: Rn reduction from air:

- Air diffuses through a cold activated carbon column.
- Radon diffuses more slowly through the column than air, so that the column is closed before the radon breaks through.
- The closed column is then purged backwards with air low in radon.
- A two-column system allows continuous operation.



Rn reduction from xenon by a VSA:

- Similar, but xenon gas high in Rn needs to be recovered by collecting it at the input.



M. Arthurs et al., arXiv:2009.06069

Cryogenic distillation for removing noble gas impurities such as ^{85}Kr, ^{222}Rn (and ^{37}Ar, ^{39}Ar)

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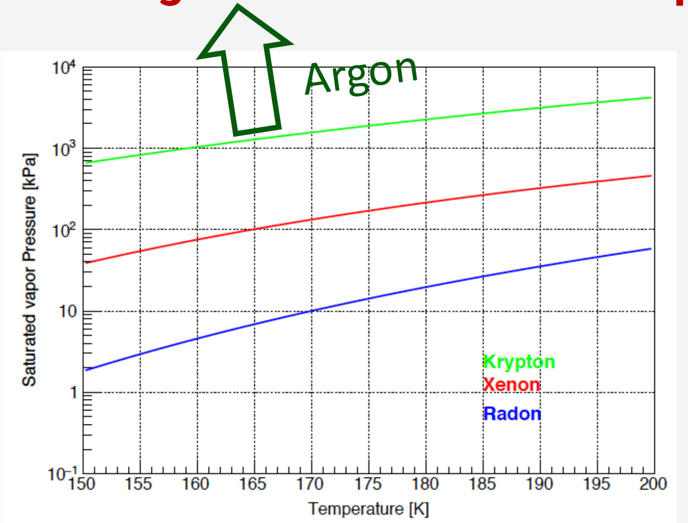
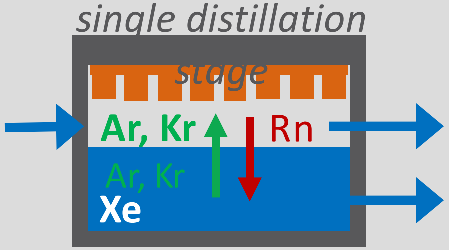
Making use of the different vapor pressure of the different noble gas elements



X. Cui et al. (PandaX Collaboration, JINST 16 (2021) P0704

Transition probabilities
of single noble gas atoms
from gas to liquid and vice versa:
volatility, saturation
vapor pressure



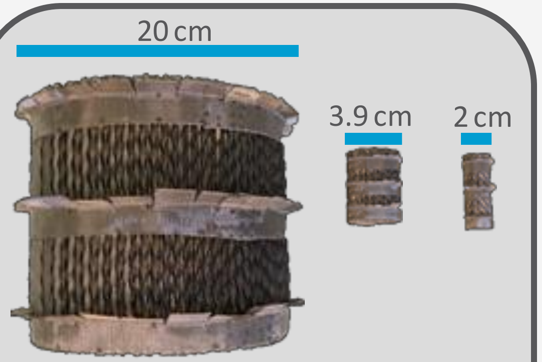
Brought into our field by XMASS for Kr removal:

Astropart. Phys. 31, 290-296 (2009)

introduced into XENON100 by Columbia University

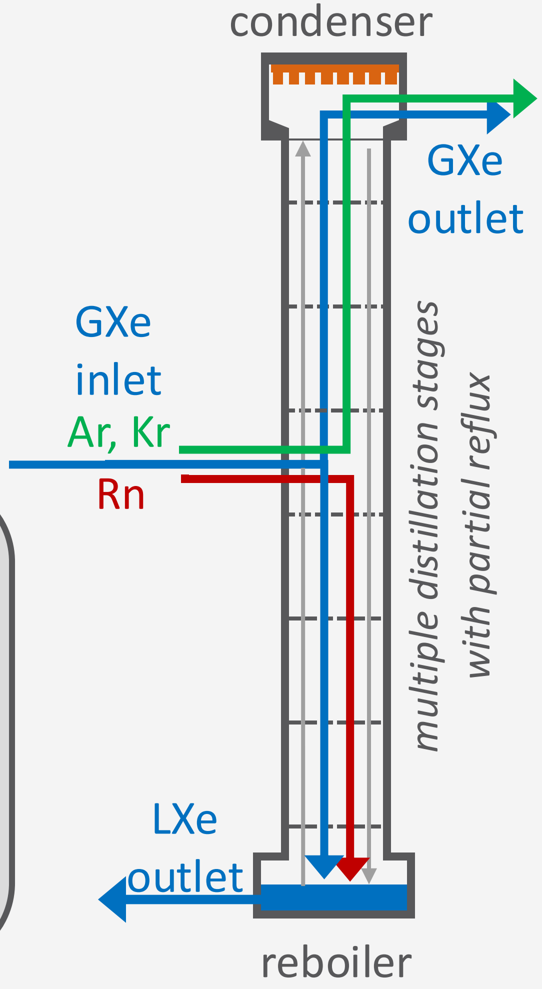
Further developed for XENON1T/nT for Kr & Rn by Münster group & enhanced to "online" removal

EPJ C 77, 277 (2017), EPJ C77 358 (2017), PTEP 2022 (2022) 053H01, EPJ C 82 (2022) 1104



in reality continuous package material

Multi-stage rectification column



Application of the different separation methods at Xe DM experiments

krypton | **radon**

Chromatographys:

Continuous adsorption & desorption processes depending on temperature, mass, charge radii of noble gas atoms, Van der Waals forces, ...

Cryogenic distillation:
Making use of the different vapor pressure essentially depending on the mass of the different noble gas elements

XENONnT:
Kr: 50 ppq, nearly sufficient for XLZD/DARWIN
^{222}Rn <1 µBq/kg, equal to ν_{solar} in [1,10] keV

Radon removal by cryogenic distillation at XENONnT

Novel radon removal system for XENONnT

Design parameters:

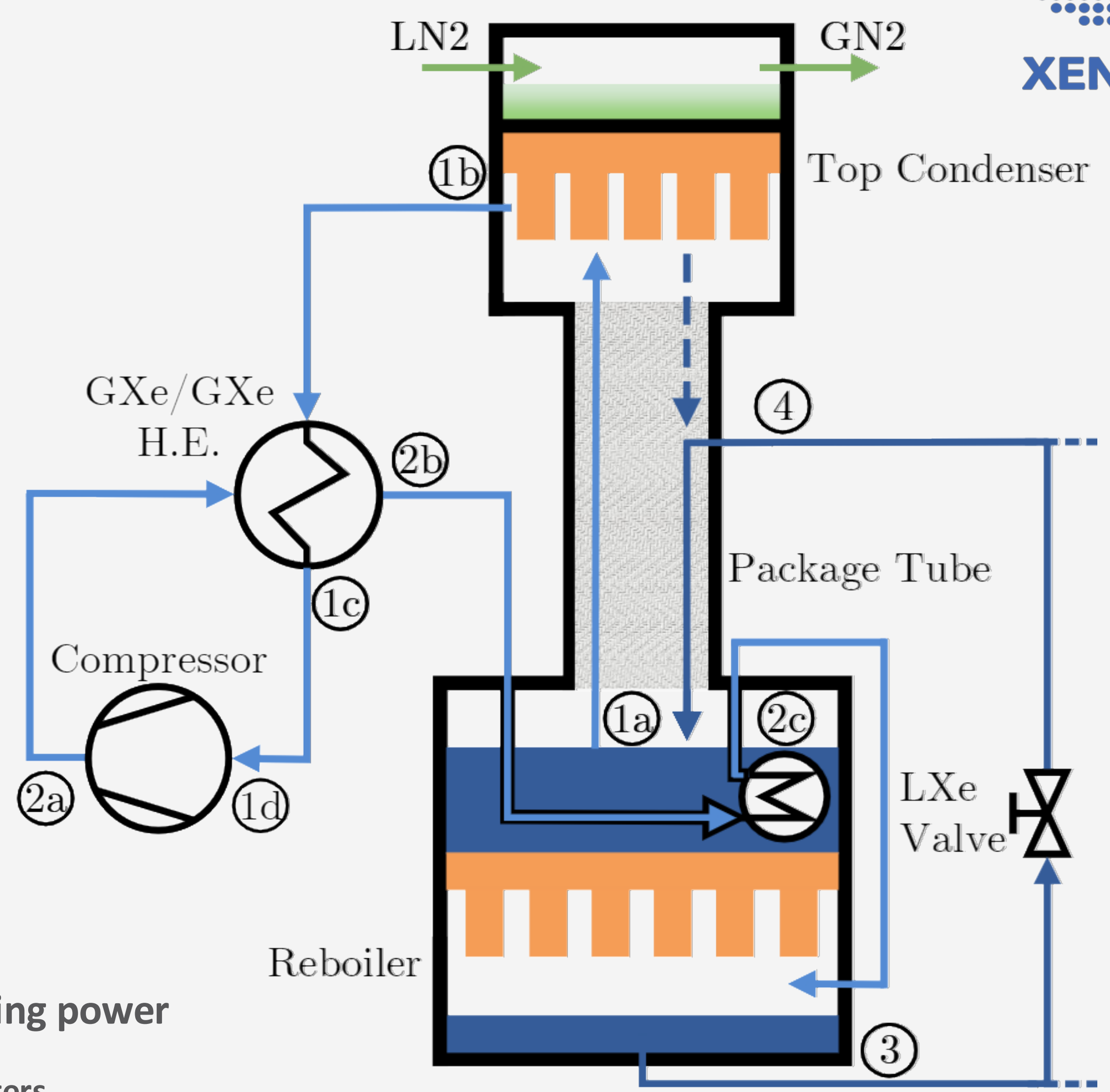
- **Target flow:** 72 kg/h (200 slpm)

- Requires 1 kW cooling power at top provided by LN_2
- LXe inlet and outlet require 2 kW cooling power

Thermodynamic concept:

- **Clausius-Rankine cycle** with phase changing medium xenon
- Reboiler acts as **heat exchanger** to liquefy Rn-depleted GXe with the stored Rn-enriched LXe
- Compressor acts as **heat-pump**

- Reduce required external cooling power from **3 kW to 1 kW**
- Drastically **reduce nitrogen consumption** and **electrical heating power**



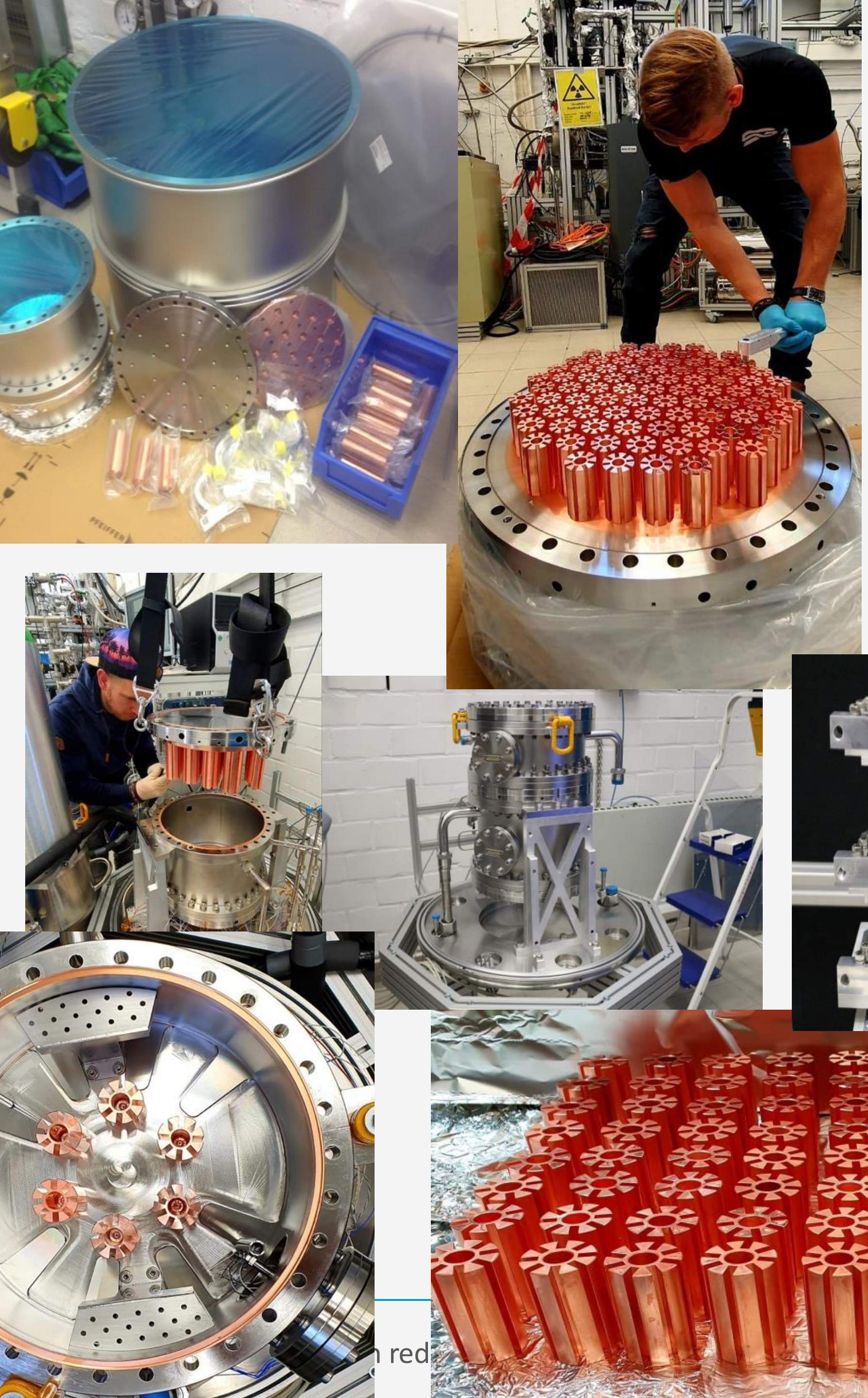
Low radon compressor
JINST 16 P09011 (2022), based on EPJ C78 604 (2018)

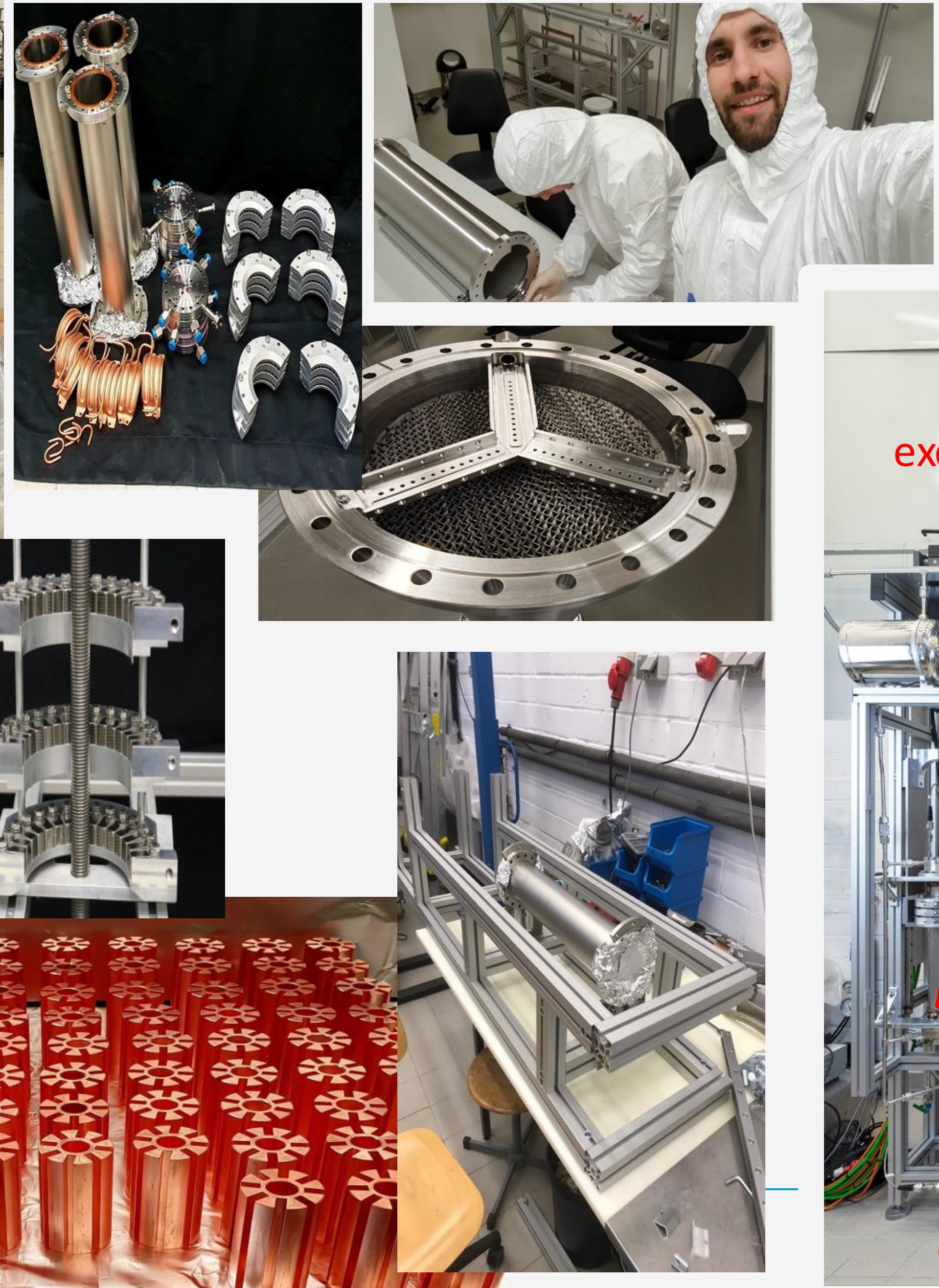
Low radon heat exchangers
JINST 17 P05037 (2022)

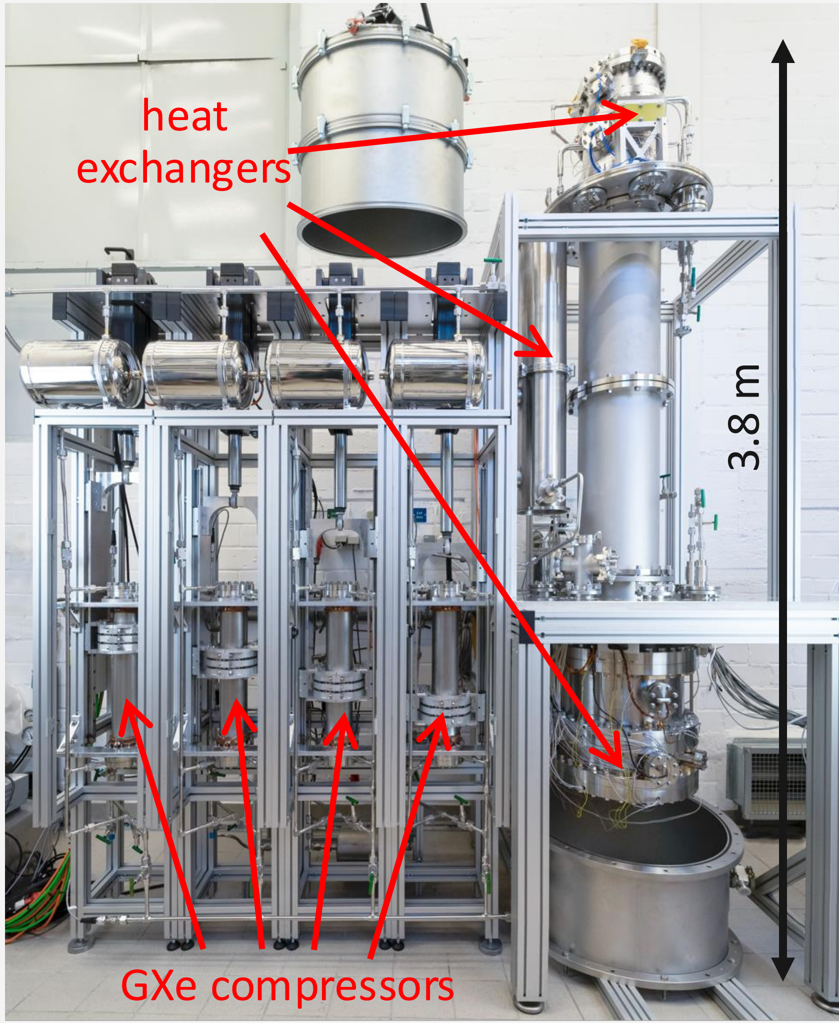
Eur. Phys. J. C 82, 1104 (2022)

Radon removal system

XENON







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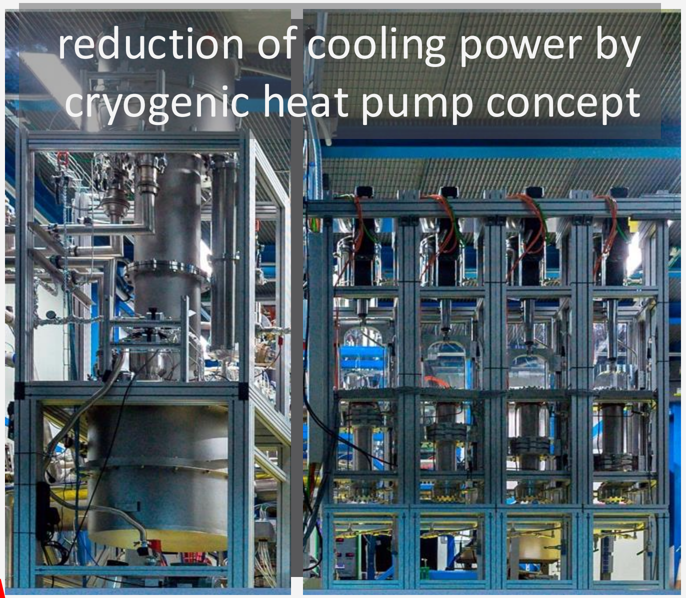
XENONnT – Novel radon removal system

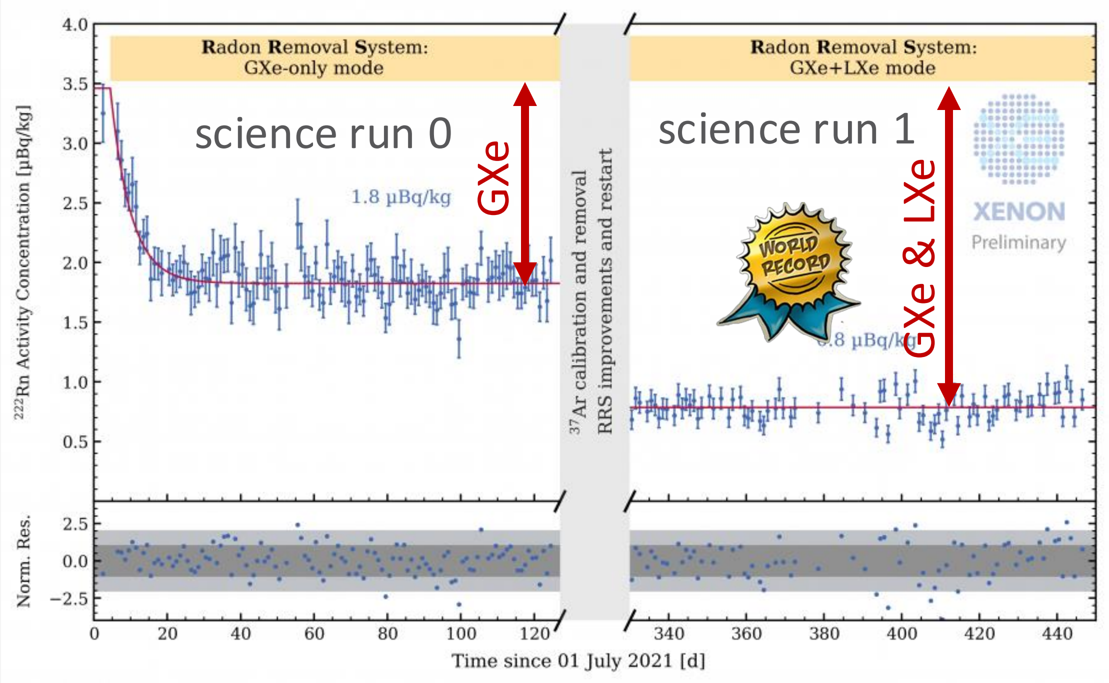
XENON

Cryogenic distllation system - key parameter:

- ➢ liquid xenon inlet (and gaseous Xe inlet) and outlet
- ➢ flow of 0.4 l/min LXe = 200 SLPM ≈ 70 kg/h
- ➢ **reduction by factor of 2** for sources within detector by LXe extraction
- ➢ **another reduction factor 2** for warm Rn sources by GXe extraction → **as low as solar ν-induced ER bg !**



Radon concentration at XENONnT



Proof of basic removal concept:
Eur. Phys. J C77, 358 (2017)
Design of XENONnT system:
Eur. Phys. J. C82, 1104 (2022)

Low radon and low internal radioactivity
for dark matter and rare event xenon detectors
ERC AdG LowRad (PI: C. Weinheimer)

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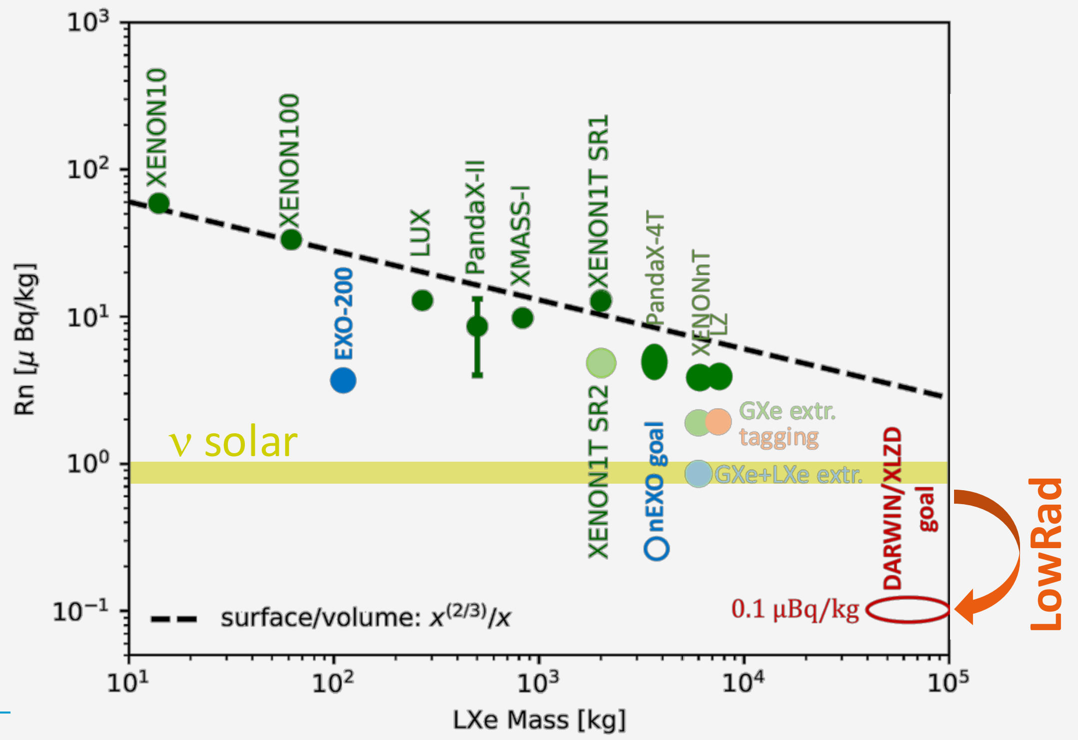
Goal: Develop and demonstrate the Kr and Rn removal technologies for the next generation dark matter experiment DARWIN/XLZD with a sensitivity down to the neutrino fog (and for more channels, e.g. 0νββ)

Challenges/tasks for reaching background rates by ^{85}Kr and ^{222}Rn being 10-times smaller than by ν_{solar}

- Continuous/**online nearly lossless ^{85}Kr removal** (30 ppq ^{nat}Kr)
- Another **factor 10** in **^{222}Rn reduction** (0.1 μBq/kg), factor 6 by cryogenic distillation
- Use fact, that cryogenic distillation enhances concentration on one side → **sensitive online diagnostics**
- R&D for novel purification methods
- Pave the way for an **all-in-one** purification & distillation system
- Complete **purification & distillation demonstrator**

Reach: "less than 1 Radon atom in 160 mol of xenon"



Key aspects of the LowRad project

How to purify 50 t of Xe from Rn in ≤ 2d ?

- **Full heat pump** to achieve enormous cooling

  throughput: **75 kg/h (LowRad demonstrator)**

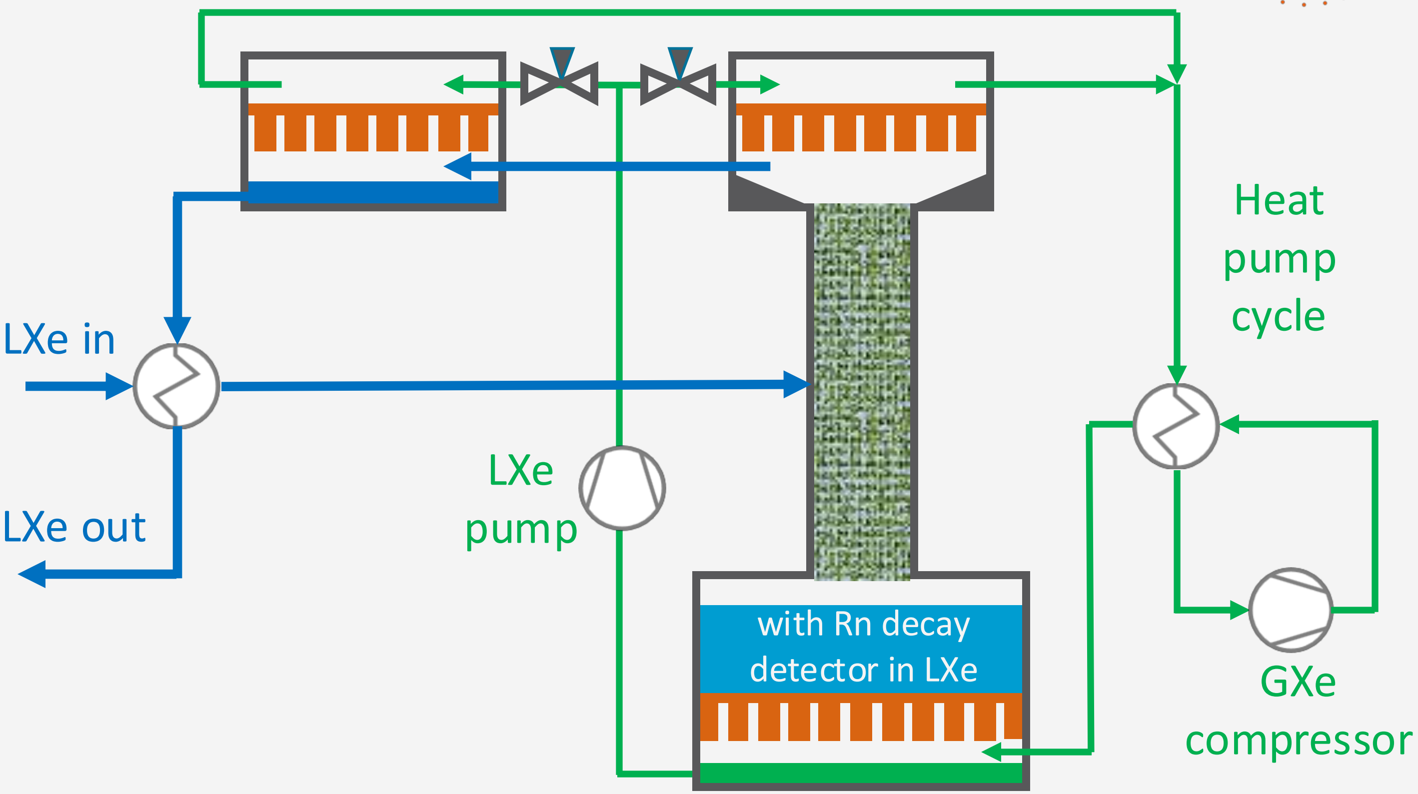
  750 kg/h (final system)

Demonstrator

- Radon-free heat exchangers
- 2nd Xe **heat pump** cycle
- With online **Rn decay monitor**

Final system

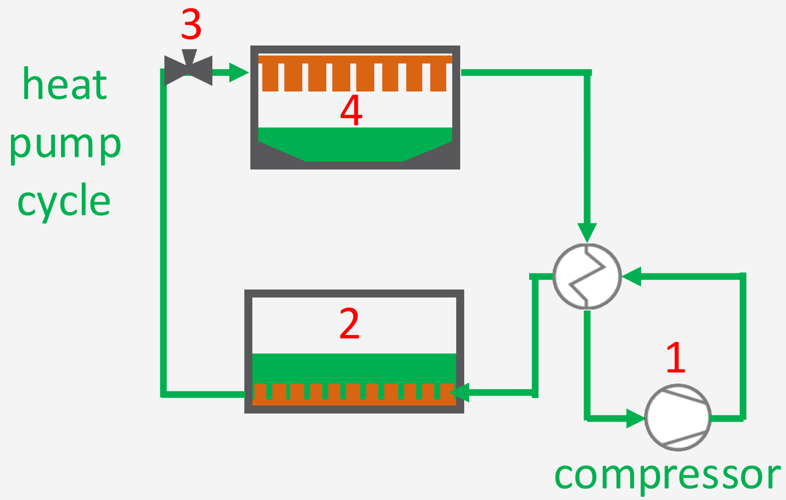
- Should be integrated with **purification system** for removal of electronegative impurities
- With **nearly lossless online Kr removal system**
- Installed in a **water shield** to avoid Xe activation



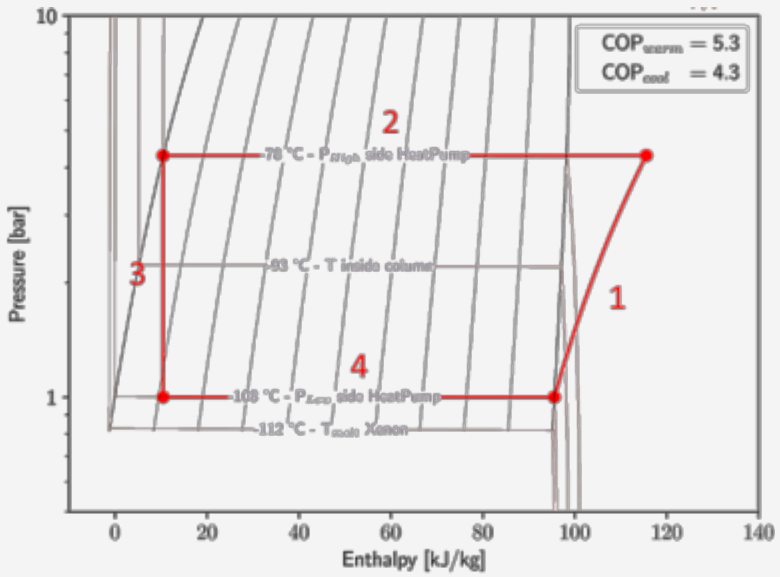
R&D currently focusing on:

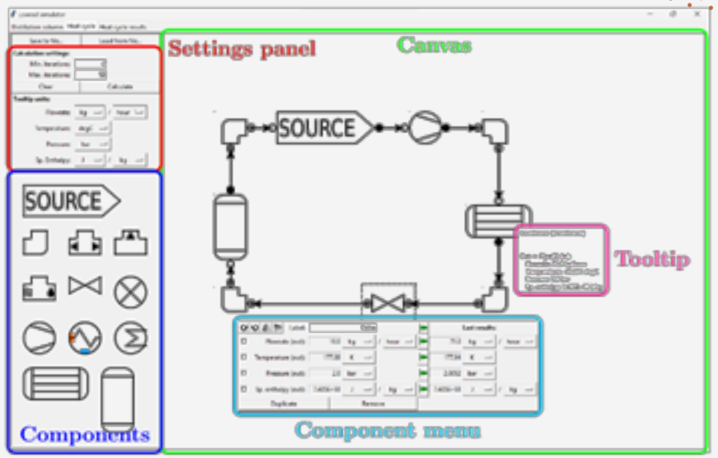
- **Kr-concentrator** for an online distillation system
- Demonstration of a **Xe heat pump** concept
- **Rn-decay detectors** for online monitoring

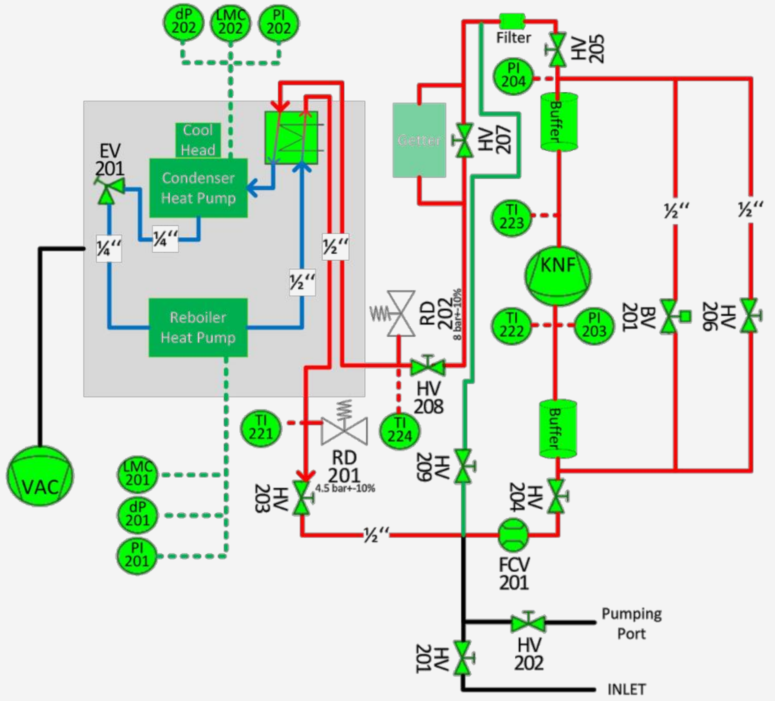
LowRad Xe heat pump demonstrator



1: compression
2: condensation
3: expansion
4: evaporation



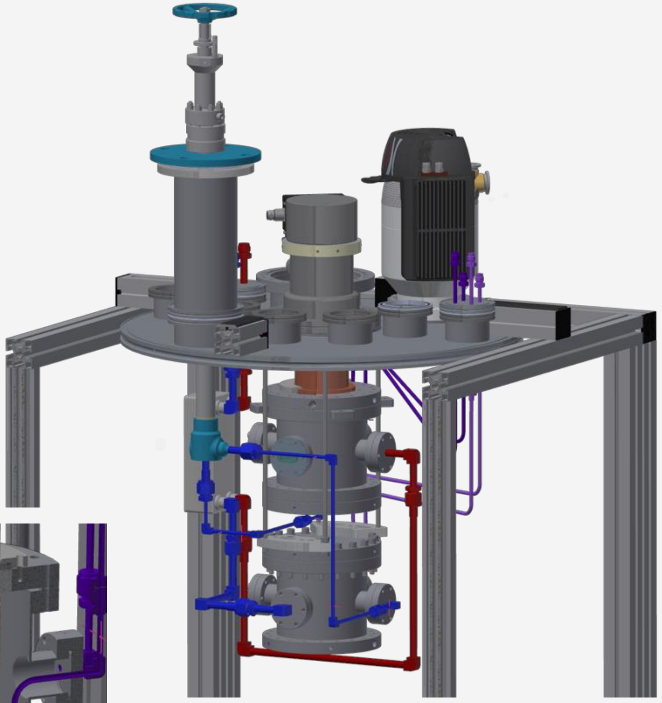


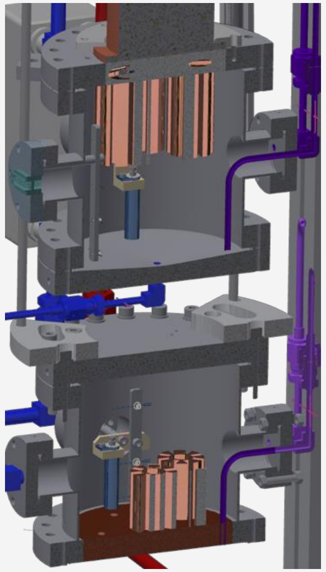


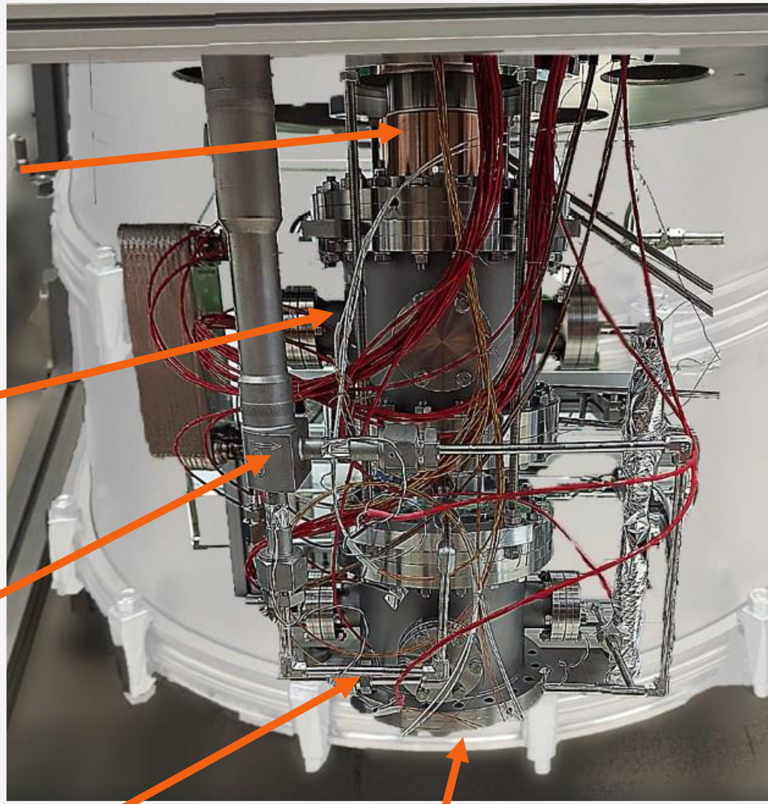
Design of a heat pump cycle

- Investigating several process gases including **Xe**
- Need to supply the required heating and cooling power at reboiler and condenser (roughly 10 W per 1 slpm)
- Design using custom numerical calculator for heat pump concepts/heat cycles

LowRad Xe heat pump demonstrator







cold head

condenser vessel
2

expansion valve
3

reboiler vessel
4

heating elements (simulating a column condenser)

1: compression
2: condensation
3: expansion
4: evaporation

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Conclusions

- Clear need for removal of radioactive noble gases from xenon for search for dark matter and $0\nu\beta\beta$:
  ^{85}Kr, ^{222}Rn and progenies, (^{37}Ar, ^{39}Ar, ^{136}Xe)
  (some overlap with LAr dark matter experiments)
- Charcoal chromatography can reach the low concentrations but quite some effort
  → will stay very important for diagnostics and very dirty samples,
  but maybe even more by LXe Rn removal by a "swing" system and/or by finding ideal porous material
- Cryogenic distillation is a robust and efficient scalable method yielding ultralow concentrations at XENONnT:
  ^{85}Kr ($\approx$100 ppq ^{nat}Kr) and ^{222}Rn ($\approx$1 µBq/kg)
  Should be the default method for DARWIN/XLZD (and nEXO)
  after all primary mitigation strategies have been explored:
  material screening and ^{222}Rn emanation tests as well as selection, coating, apparatus design
- LowRad ERC AdG project: developing the cryogenic distillation technology for DARWIN/XLZD (^{85}Kr, ^{222}Rn)
  Goals: full cryogenic heat pump for large scale, in situ diagnostics, nearly lossless Kr removal, ...

This research at U Münster is funded by

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