WWU
MÜNSTER

The XENONnT cryogenic radon removal system

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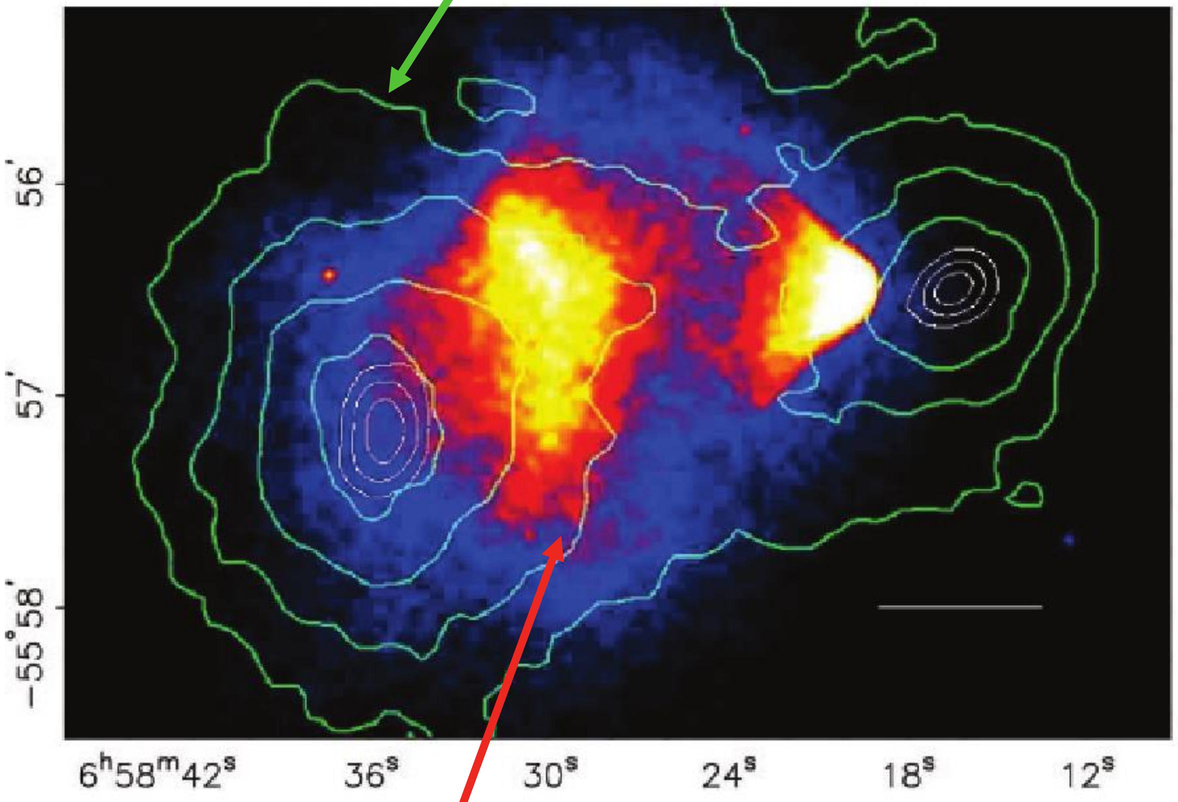
Bundesministerium
für Bildung
und Forschung

XENON

Motivation: WIMP dark matter

- A significant fraction of the energy content of the universe is composed of cold dark matter
- Weakly interacting massive particles (**WIMPs**) are promising candidates
- Arise naturally in many theoretical models
- Observational hints:
  - Data from strong **gravitational lensing** (e.g., Bullet cluster in figure)
- Very low interaction cross section ⇢ difficult to detect

Mass distribution



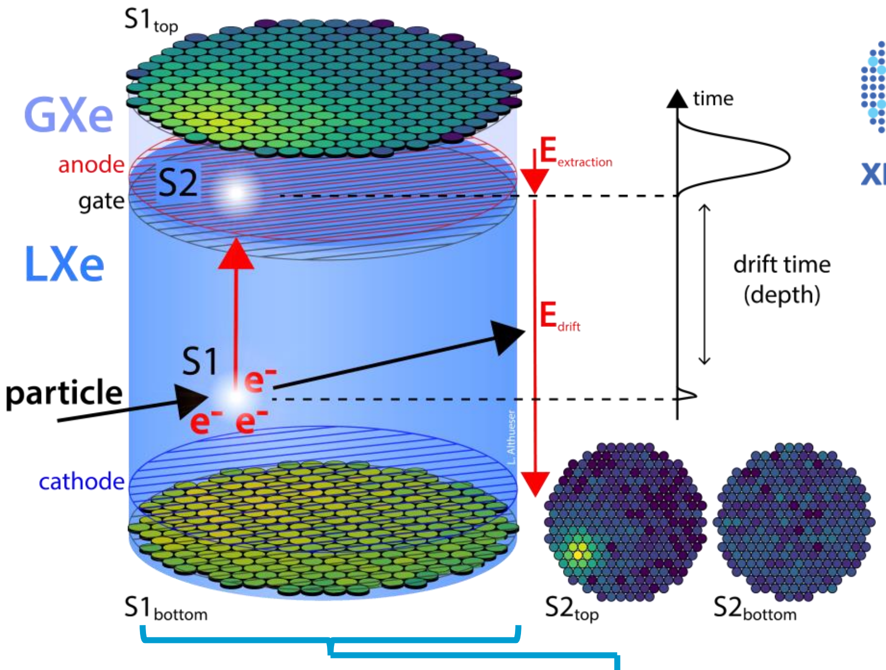
Hot-gas clouds (X-ray emission)

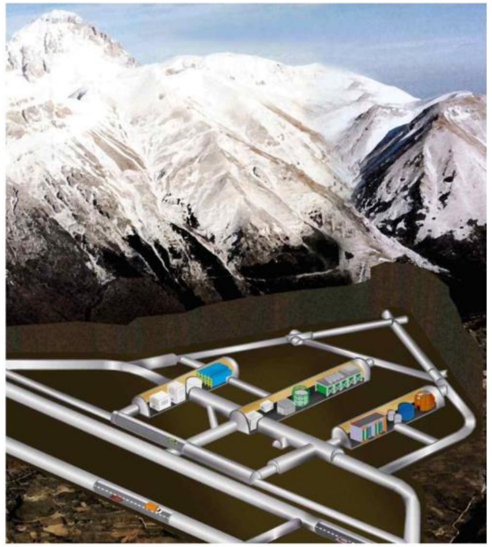
D. Clowe et al „A direct empirical proof of the existence of dark matter.“ Astrophys. J. 648 (2006) L109–L113

L. Roszkowski et al „WIMP dark matter candidates and searches—current status and future prospects.” 2018 Rep. Prog. Phys. 81 066201

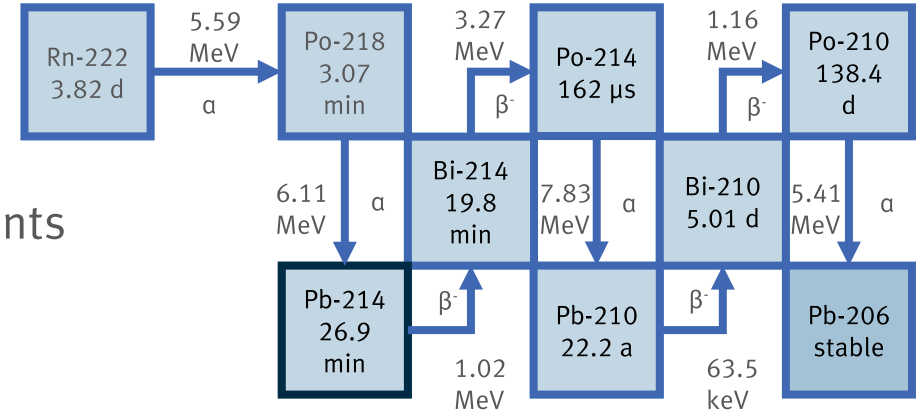
The XENONnT experiment

- Aimed at direct search for **WIMP** dark matter via nuclear recoils in xenon
- Under Gran Sasso, LNGS, Italy
- Uses a **LXe dual phase time projection chamber (TPC)** filled with 5.9 t of xenon
- **Full 3D position** reconstruction using two PMT arrays, *z*-position reconstructed via drift time between S1 and S2
- Search for rare events like WIMP nucleon scattering, double electron capture or double beta decay enabled by **Ultra-low background**
  - ⇢ Extensive material selection/screening
  - ⇢ **Cryogenic distillation**





Intrinsic ^{222}Rn background

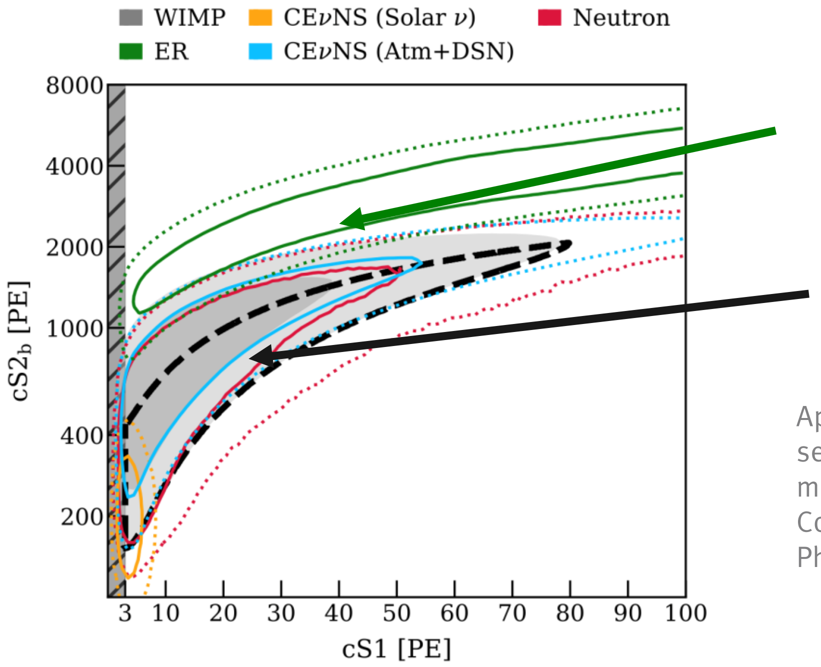


Radon in XENONnT

- Continuously emanated from detector material and components
- Half-life of 3.82 d ⇢ homogeneous distribution in detector
- ^{222}Rn daughters responsible for main background

^{222}Rn Decays to ^{214}Pb

- 1.02 MeV β^--emitter, decays to ground state ^{214}Bi
- Leakage of ER background from ^{222}Rn into NR region (ROI for WIMP search)



Aprile, E., et al. "Projected WIMP sensitivity of the XENONnT dark matter experiment." Journal of Cosmology and Astroparticle Physics 2020.11 (2020): 031.

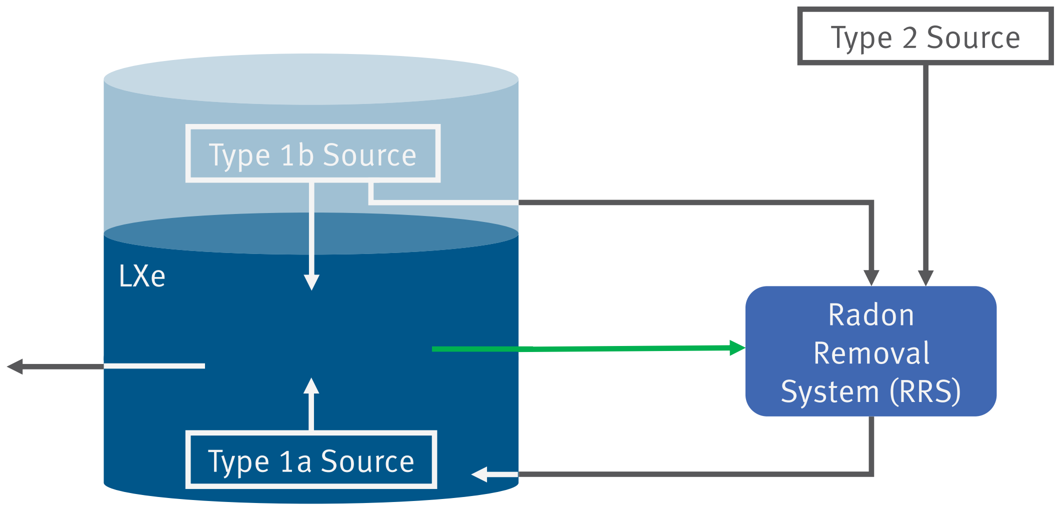
Background reduction concept

^{222}Rn Background reduction

- As a noble gas, Rn can not be removed by getter
- **Continuous active removal** via cryogenic distillation

- Employment of active radon **removal system (RRS)** to fight two kinds of sources
- **Type 1 sources**
  - Emanated into the detector before reaching the RRS
- **Type 2 Sources**
  - Emanating from components between the detector and the RRS
  - Can be effectively removed by the RRS

- **Two modes of the RRS:**
- LXe extraction
- GXe extraction
  - Convert Type 1b sources into Type 2 sources with efficiency ϵ



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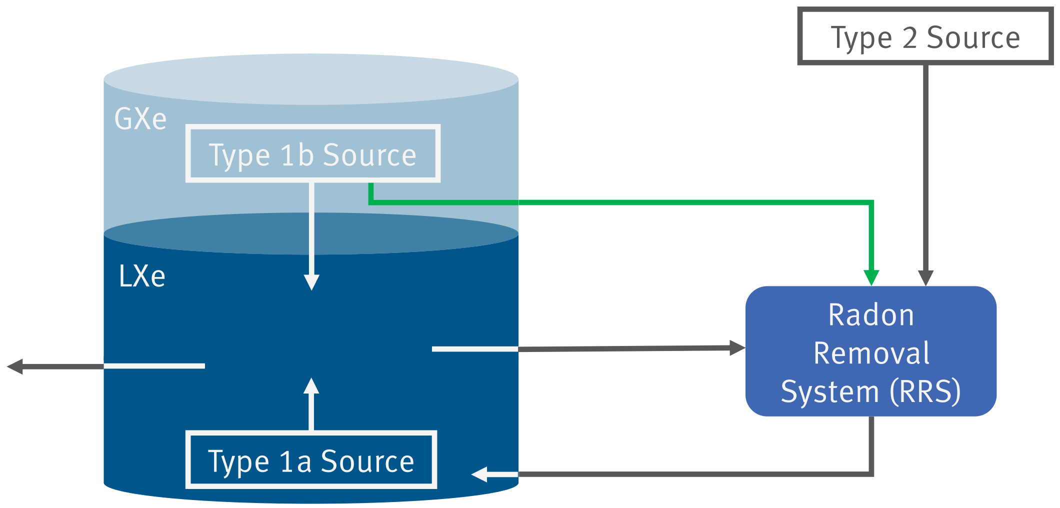

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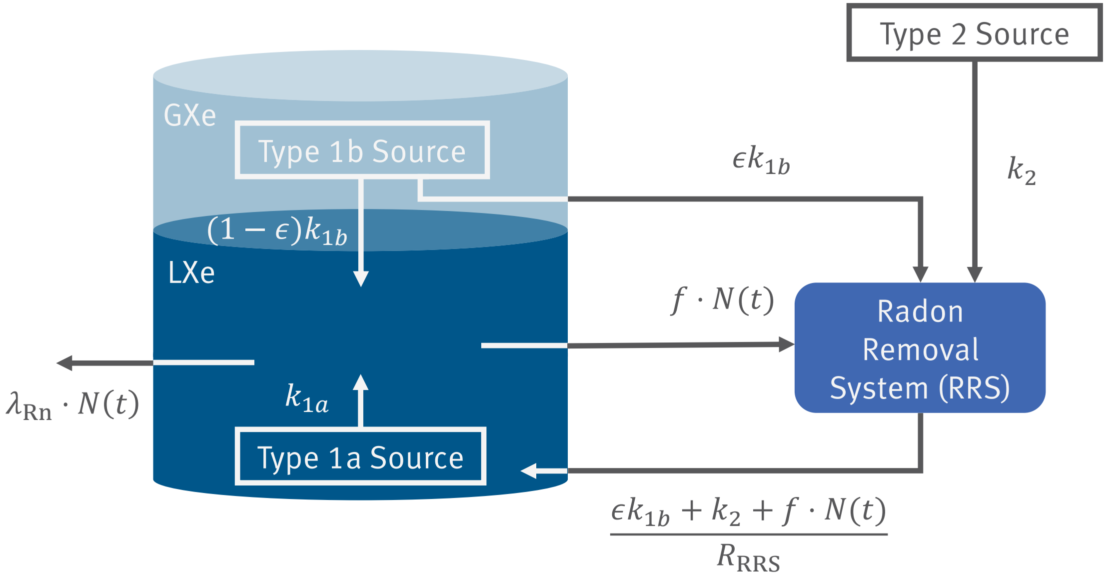


Equilibrium relation for number of Rn particles:

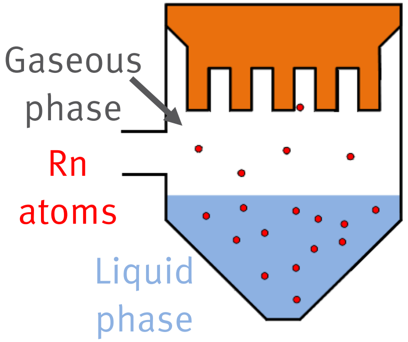
$$N_{equi} \overset{t, R_{\mathrm{RRS}} \to \infty}{\sim} \frac{1}{\lambda_{Rn} + f}$$

⇢ Very flow-dependent!

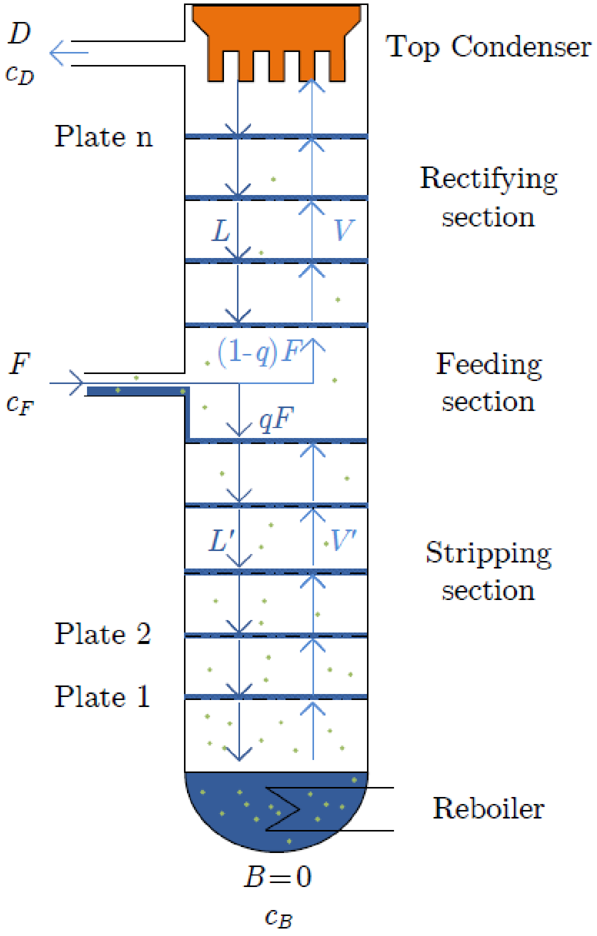
Cryogenic distillation: Theoretical concept

- Cryogenic distillation utilizes **difference in vapor pressure** between two components
- Relative volatility $\alpha = \frac{P_{\mathrm{Rn}}}{P_{\mathrm{Xe}}} = 0.1$ at -98°C (LXe temperature)
- **Raoults law** ⇢ Volatile Xe enriched in the gas, less volatile Rn enriched in liquid

Single distillation stage



Multistage distillation column



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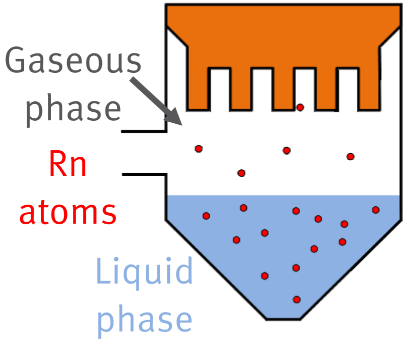

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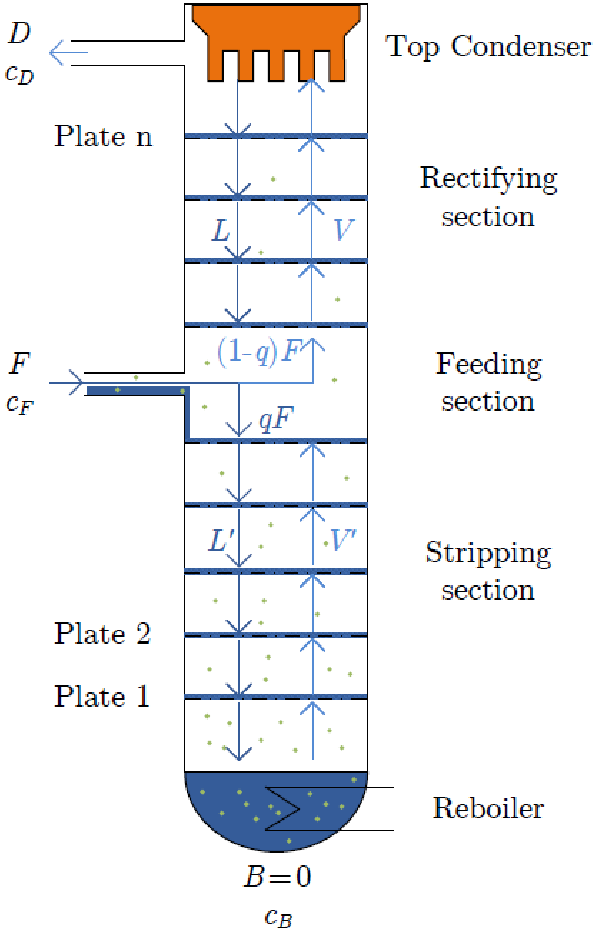

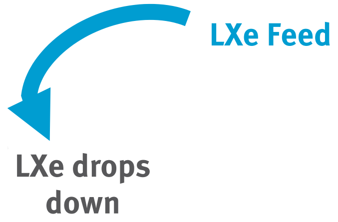

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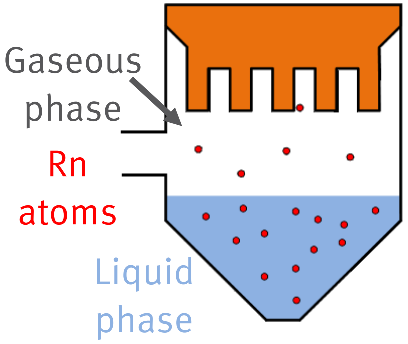

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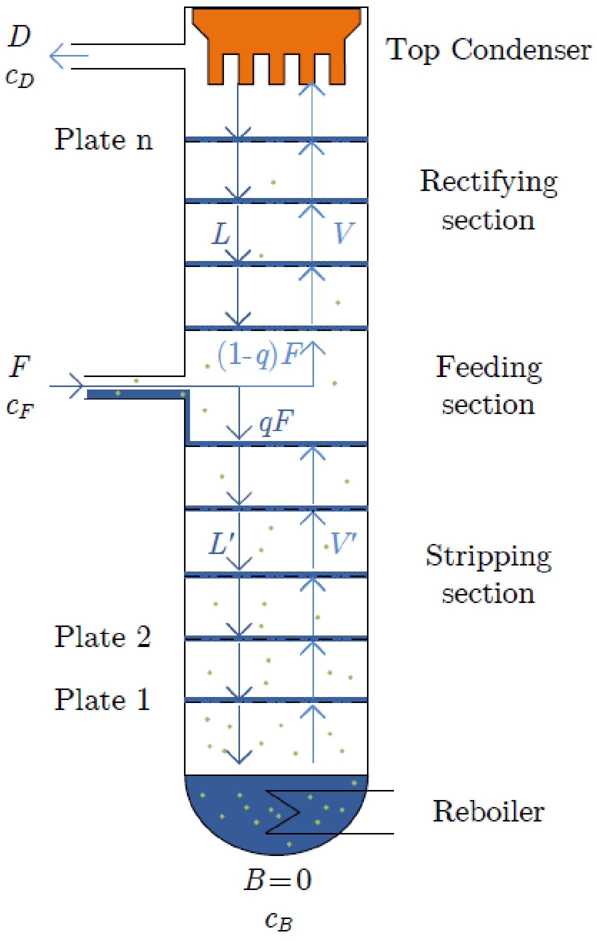

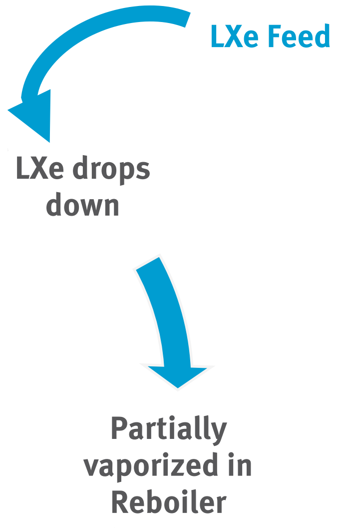

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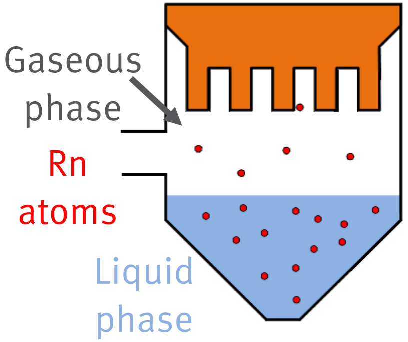

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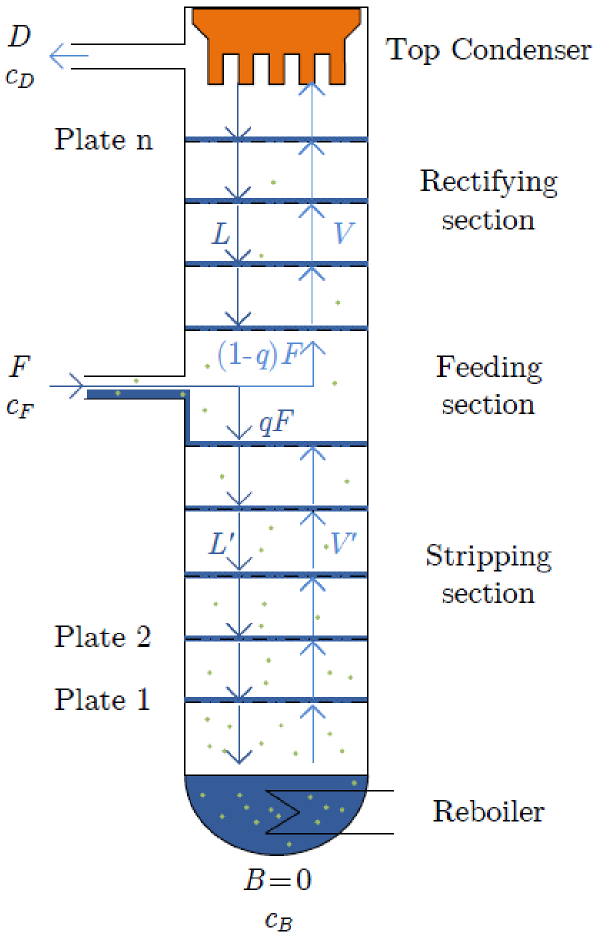

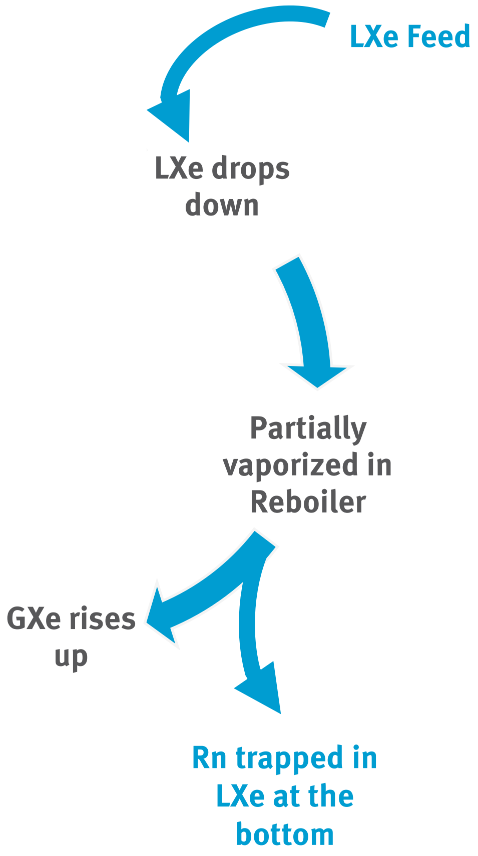

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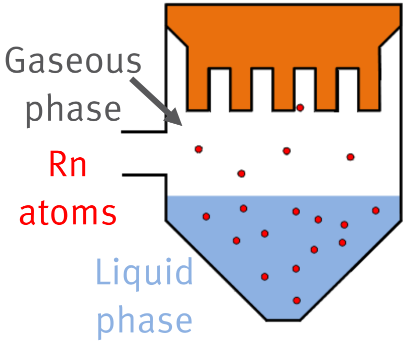

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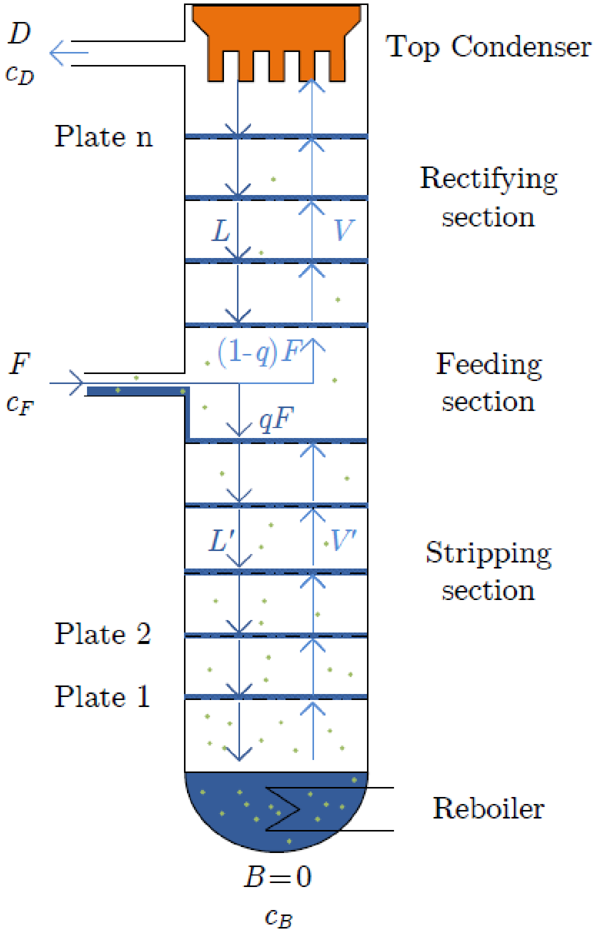

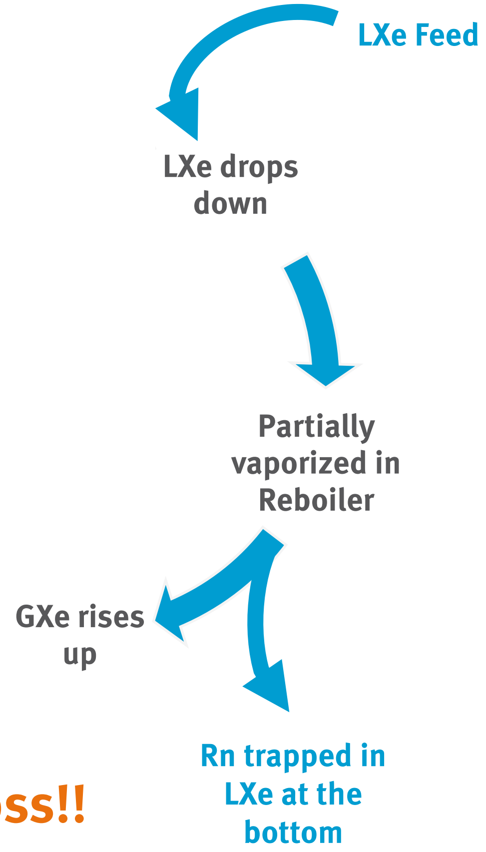

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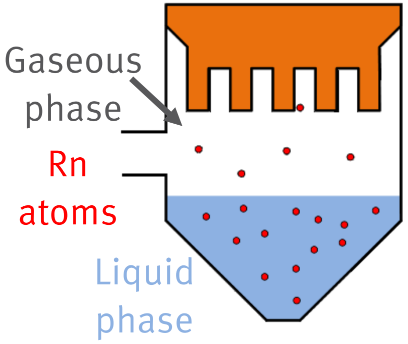

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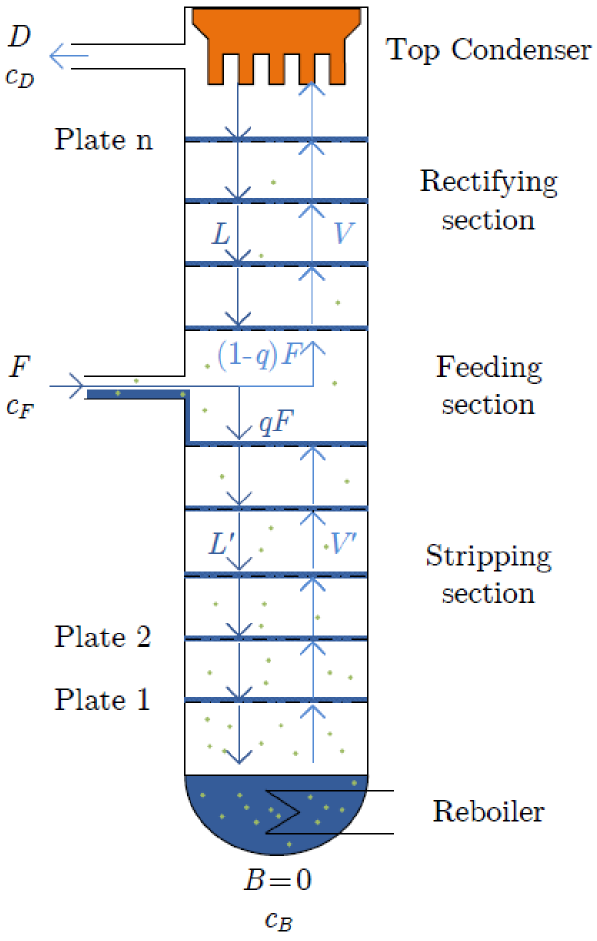

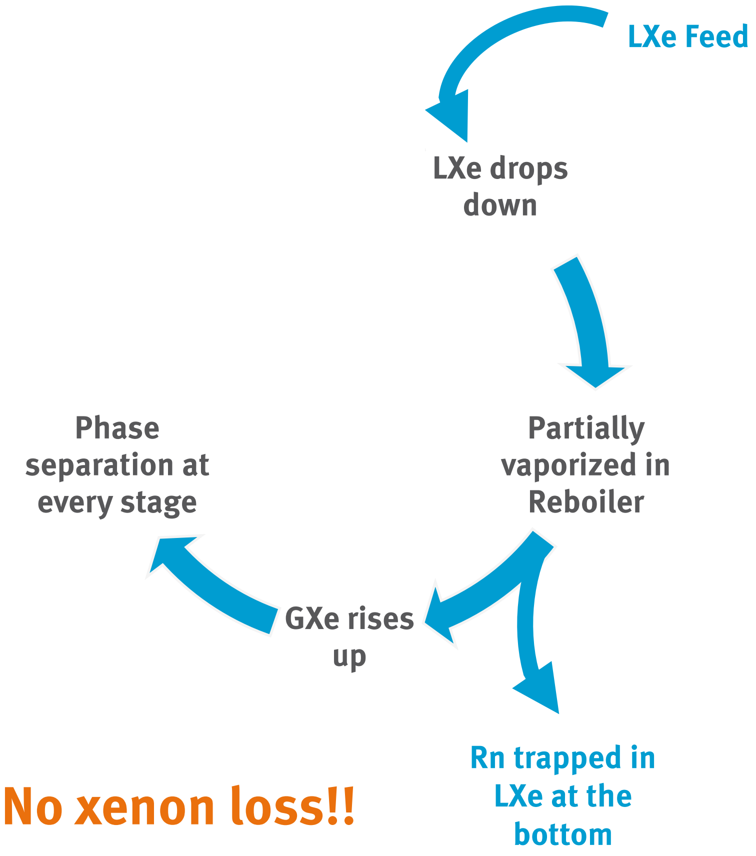

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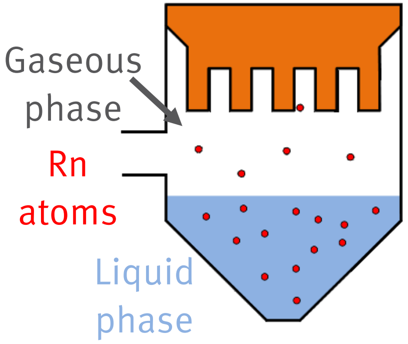

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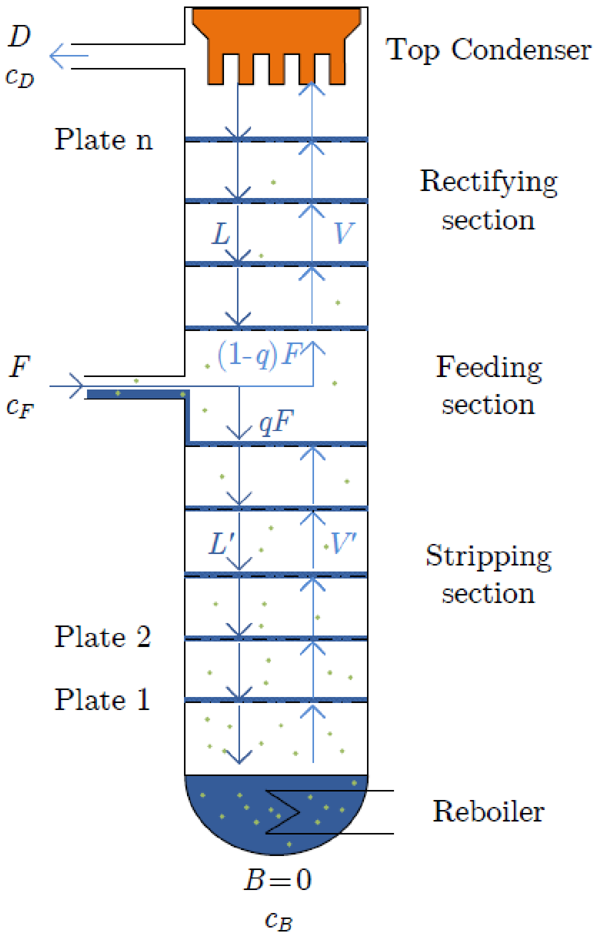

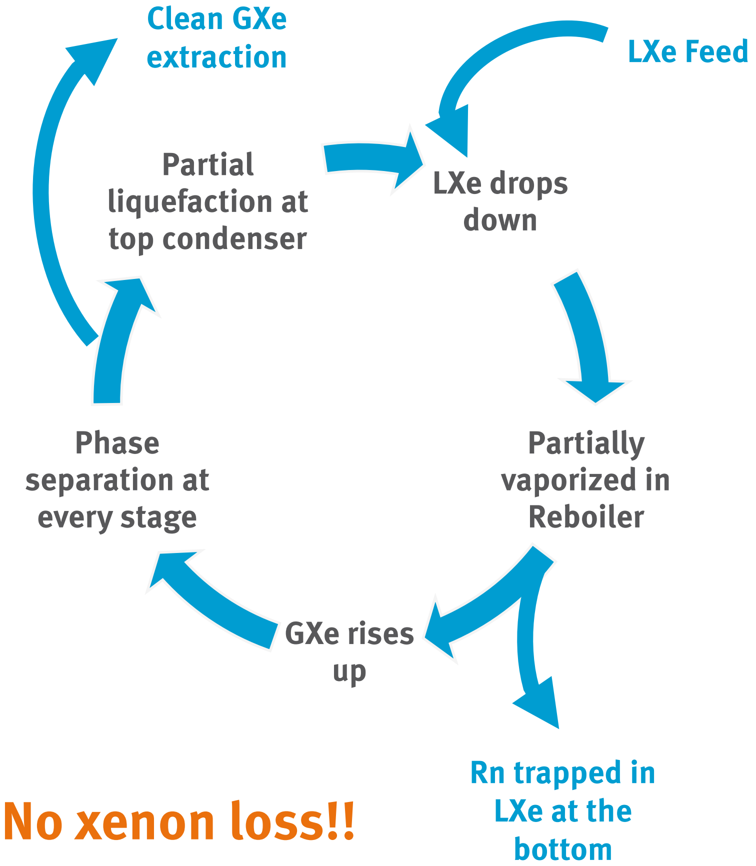

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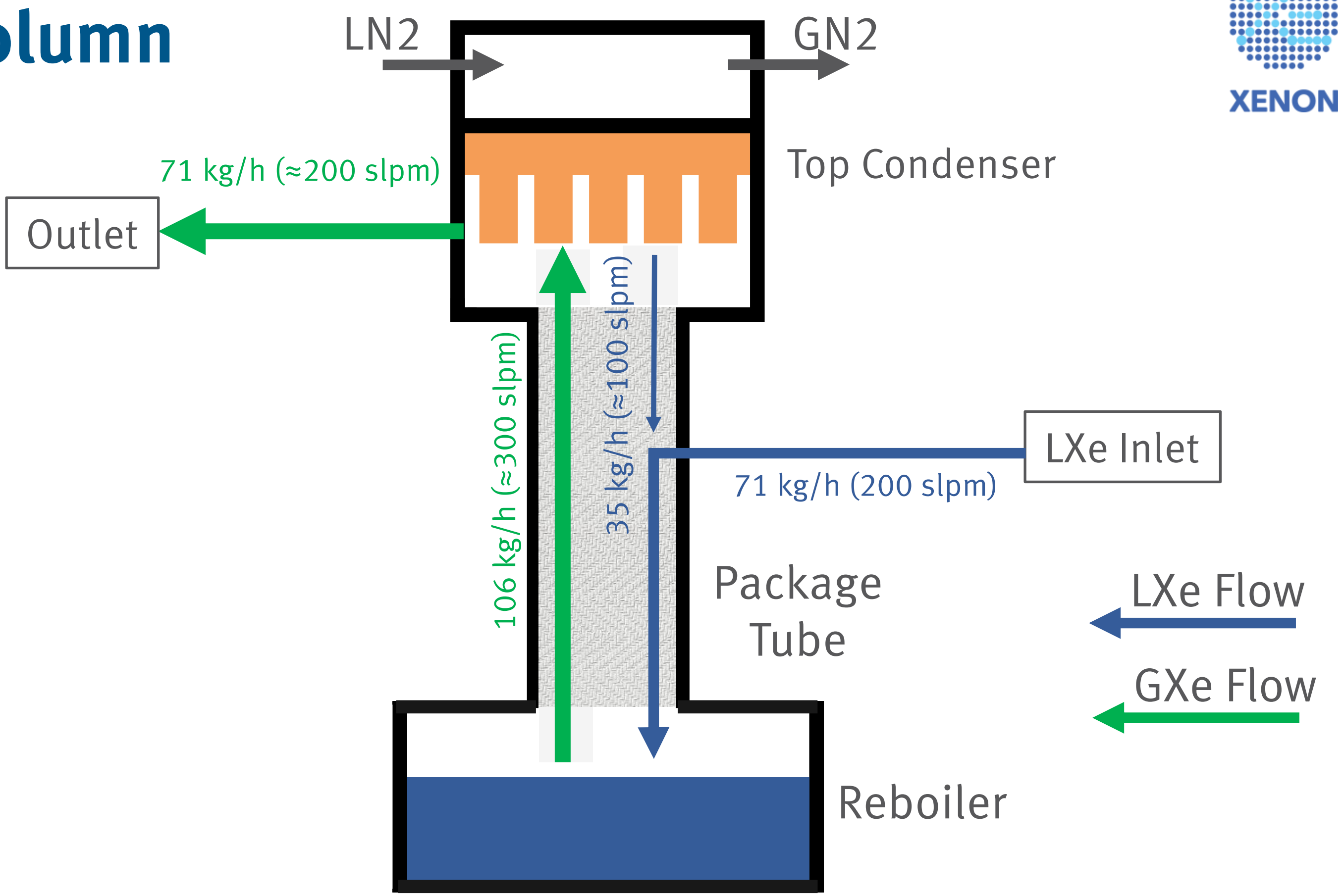
Radon distillation column

- Continuous **structured packaging material**
- Equivalent to 7 theoretical stages

- Incoming flow of **200 slpm** (71 kg/h) **LXe**
- Additional **25 slpm** (9 kg/h) of **GXe**
- **Reflux ratio of 0.5** at top condenser, 1kW of cooling power using **LN2**
- Liquefaction flow of 100 slpm (35 kg/h)
- Evaporation flow of 300 slpm (106 kg/h)
- Output flow of 200 slpm (71 kg/h) Lxe and 25 slpm (9 kg/h) GXe

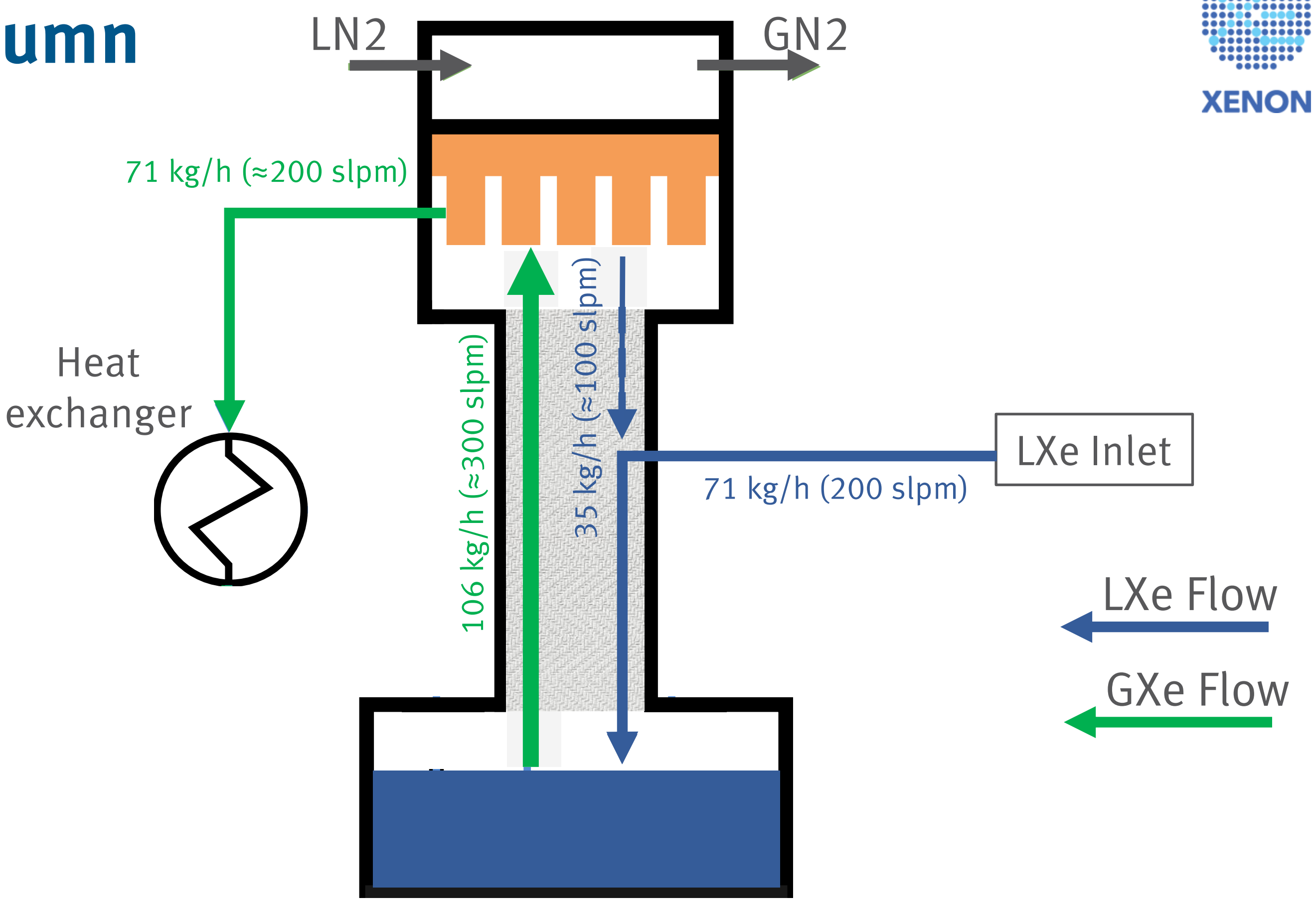
- **Rn Depletion factor R_{RRS}=100** at outlet
- Rn Enrichment factor 1000 in reboiler



Murra, M. et al. „Design, construction and commissioning of a high-flow radon removal system for XENONnT", Eur. Phys. J. C (2022) 82:1104

Radon distillation column

- Challenge: Cleaned **GXe must be liquefied** before entering the detector
  - **Compression** of Lxe with Δp ≈3 bar
  - Pre-cooling by **heat exchanger**
  - Pre-cooling by **spiral** in reboiler
  - **Thermal connection** (copper fins) between top and bottom reboiler vessels ⇢ use vaporization of Rn enriched LXe to liquefy Rn depleted GXe



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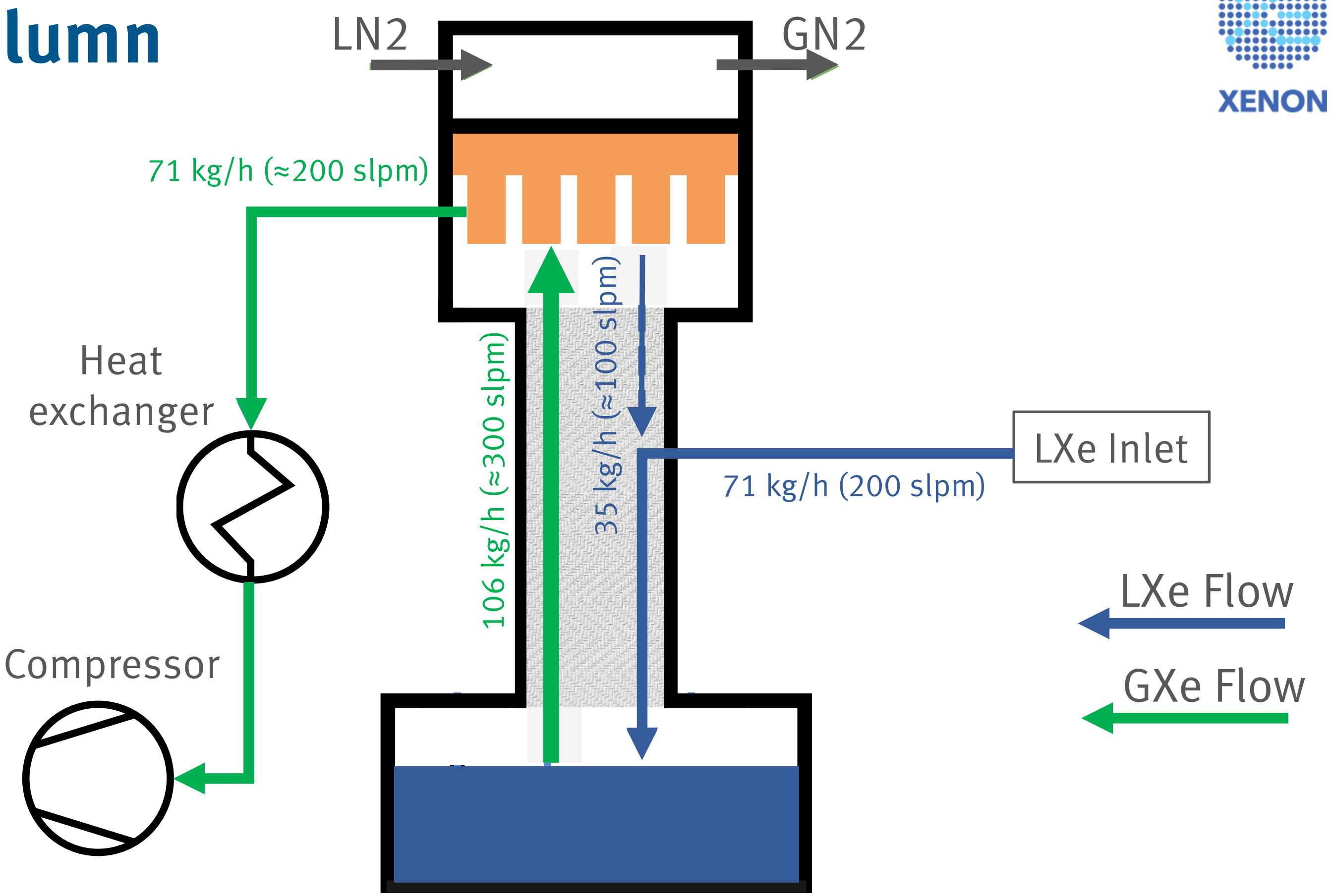

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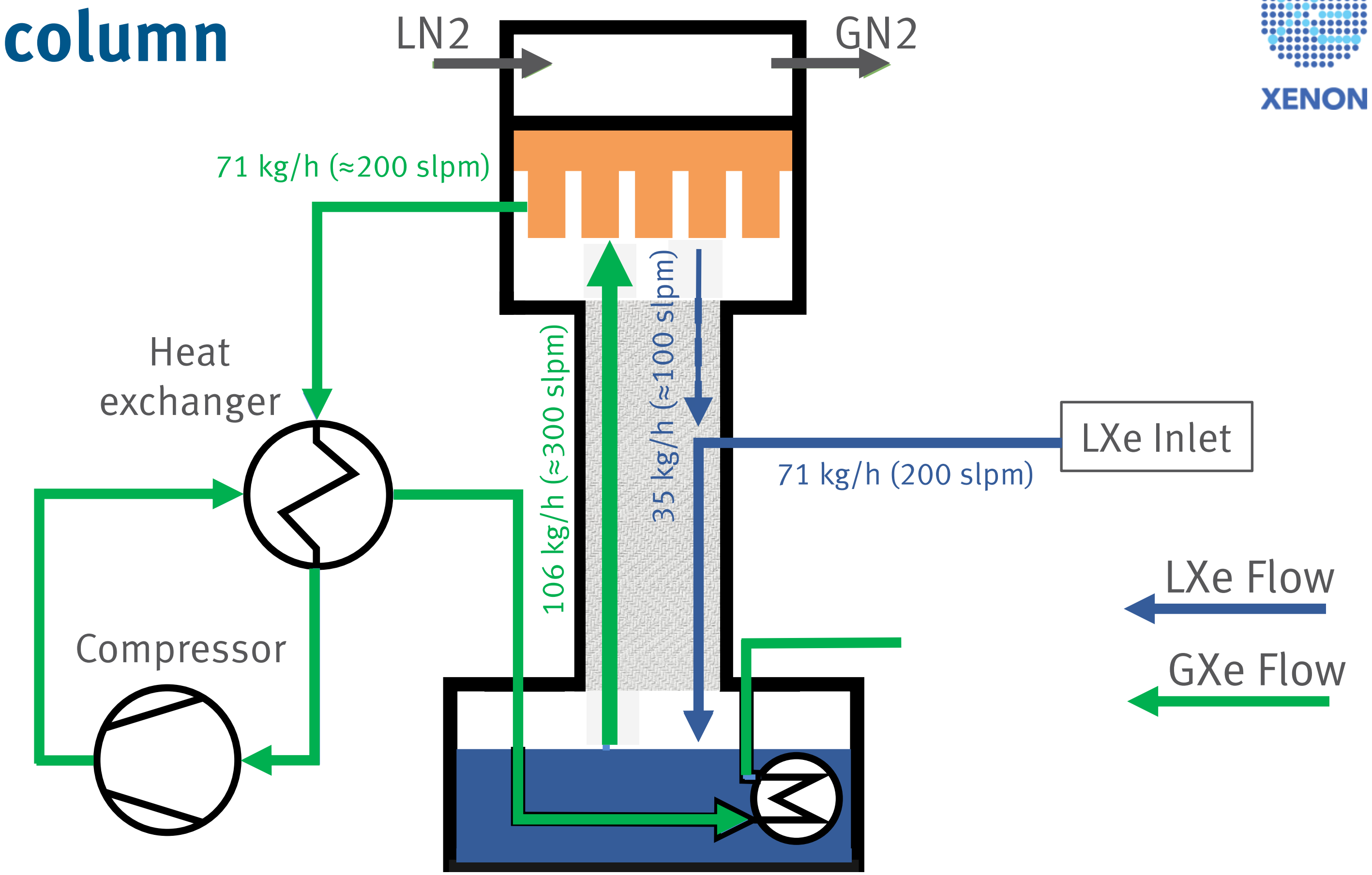

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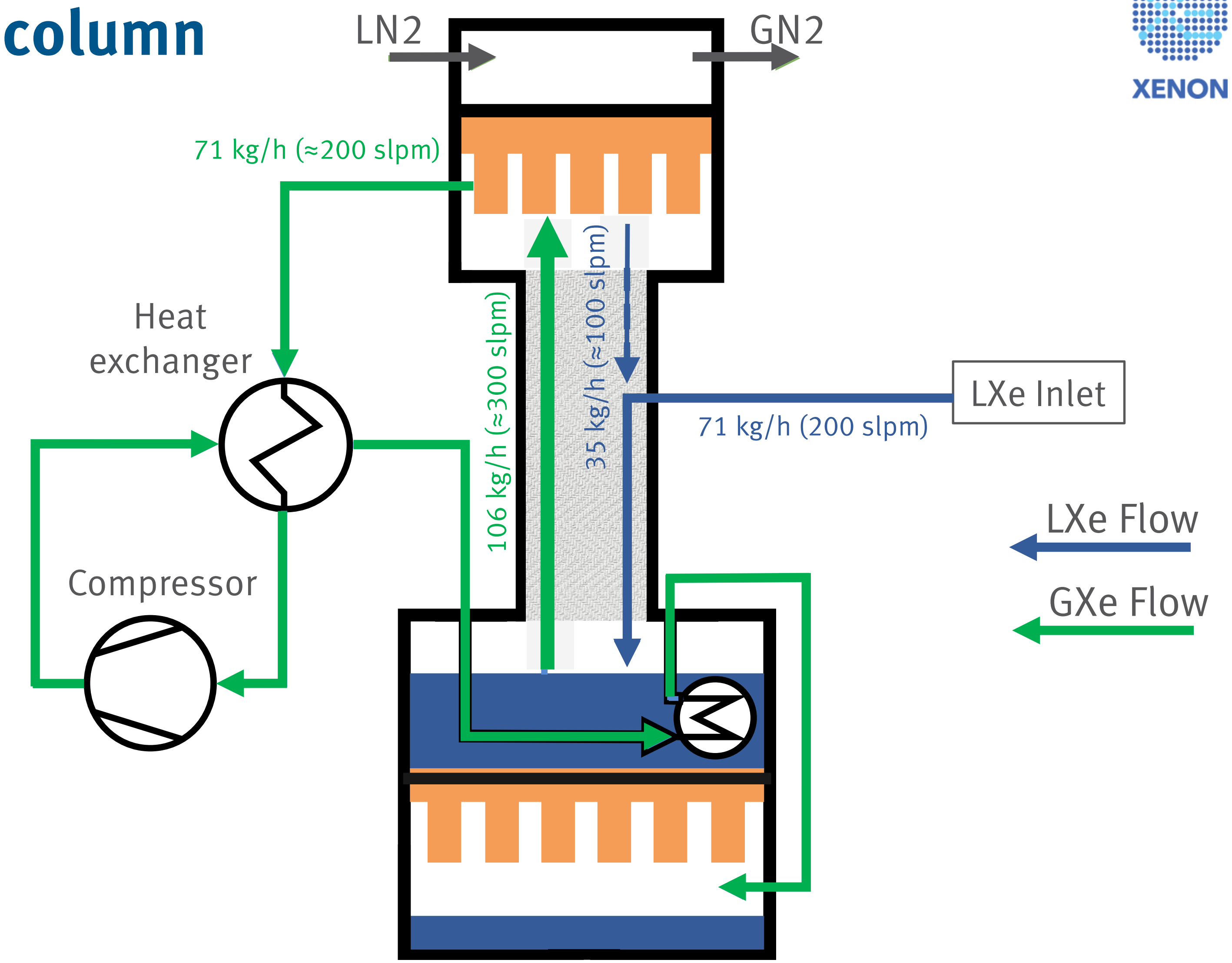

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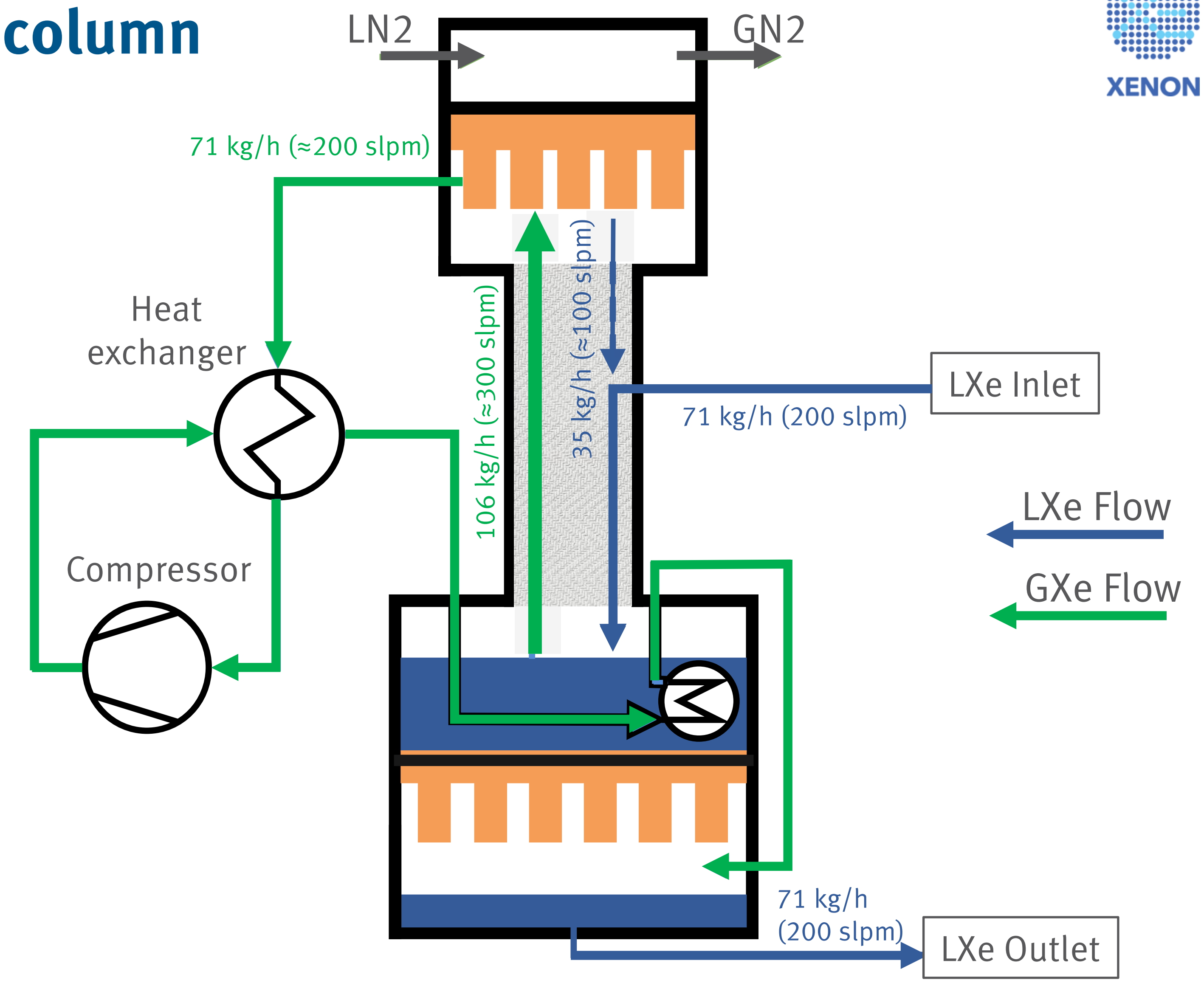

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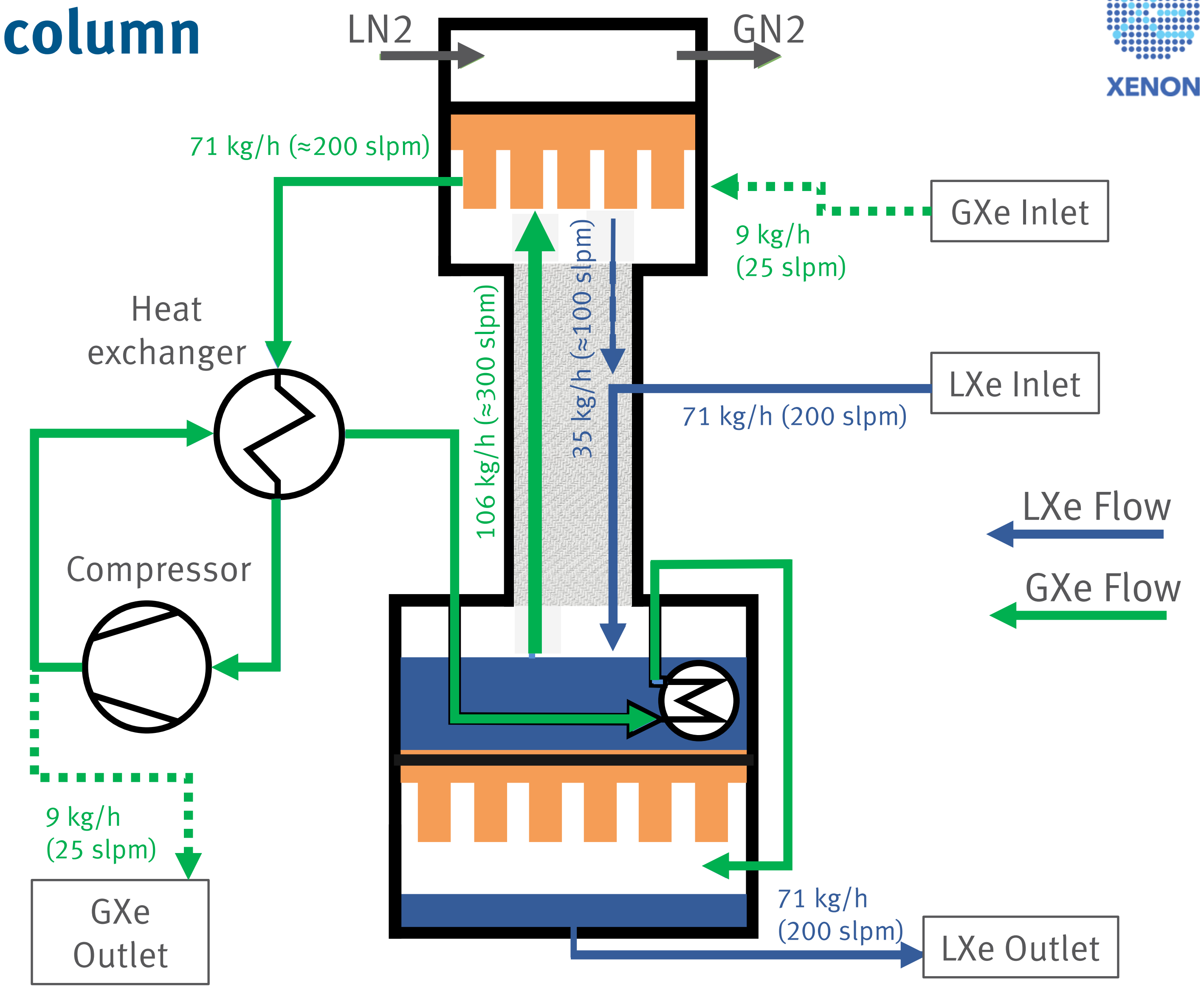

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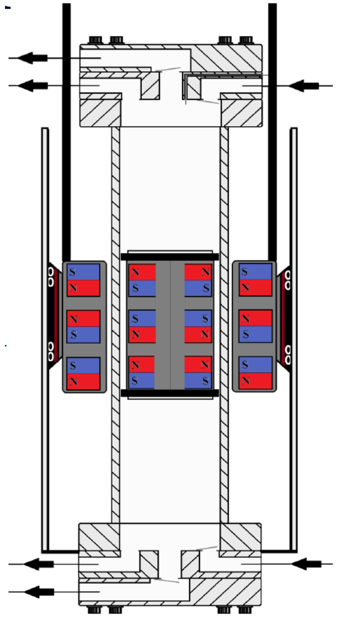
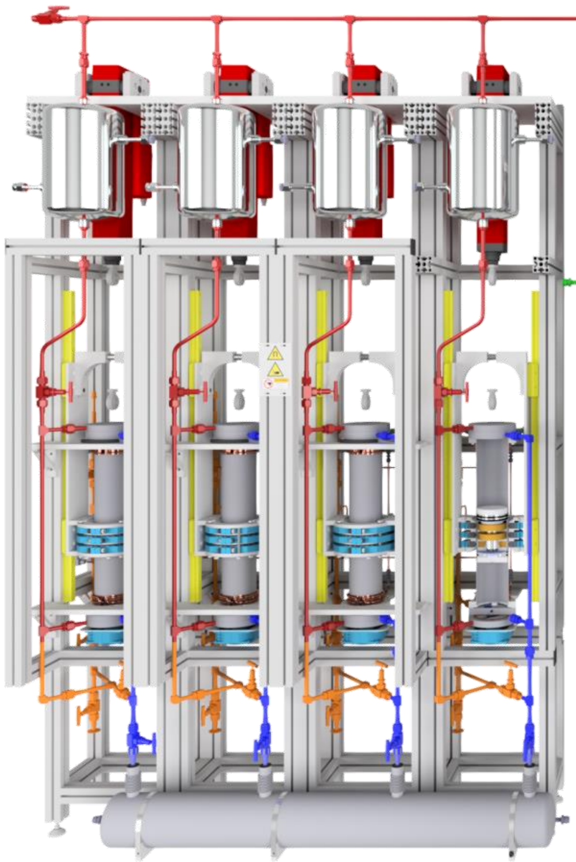
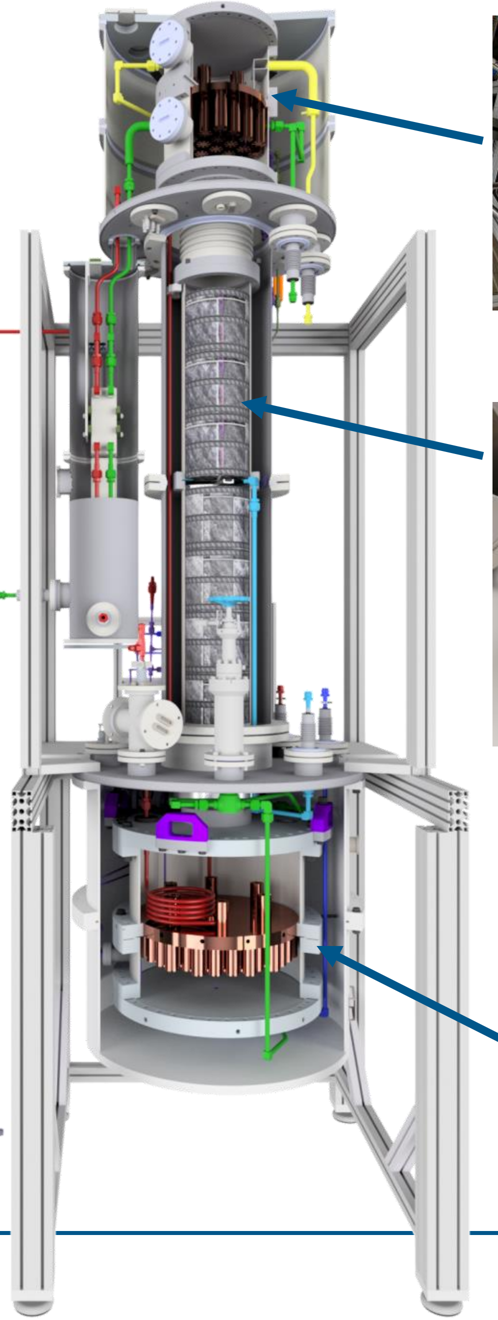
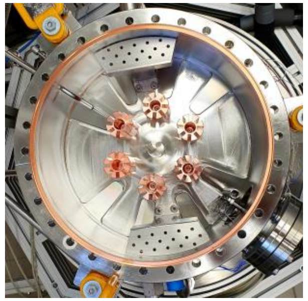
Hardware design

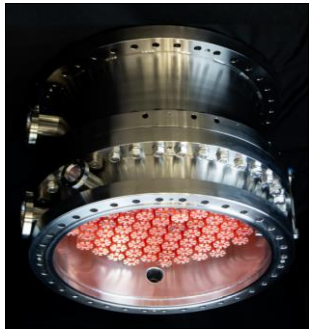
- Compression by **four piston pumps**
- **Magnetically-coupled drive mechanism**
- Complete isolation of drive mechanism from gas



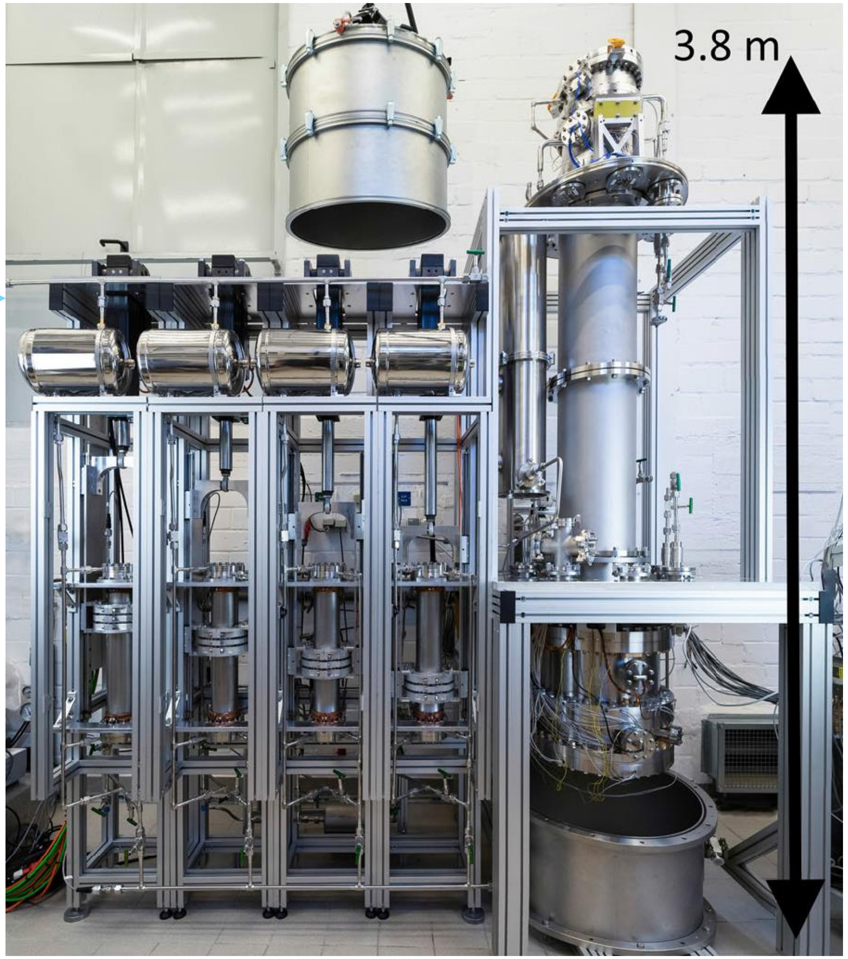








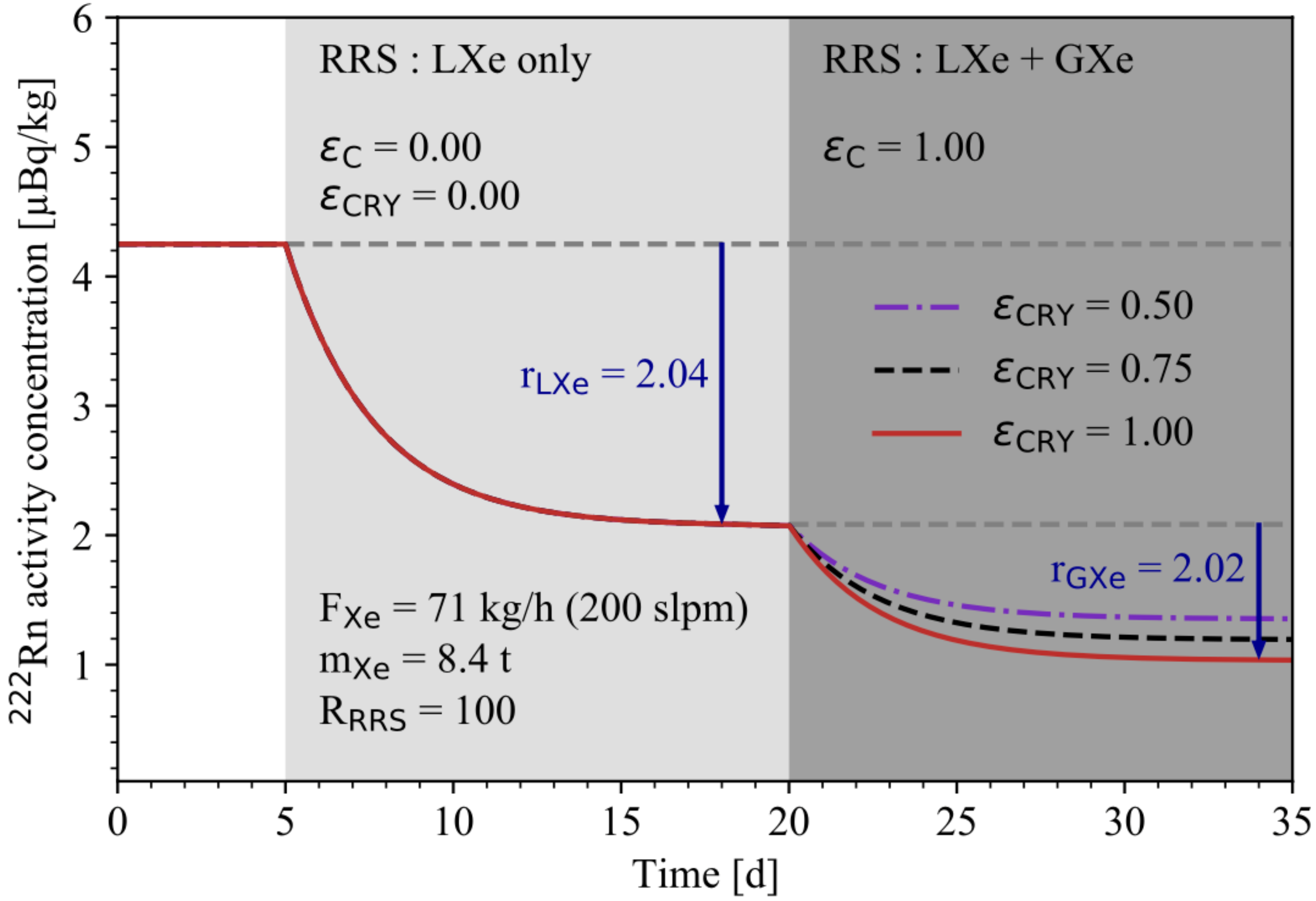
Location in XENONnT infrastructure



Expected performance in XENONnT

- **LXe**-mode:
- ⇢ **Rn reduction factor 2** assuming designed flow of 200 slpm (1.7 t/d) (5.5 days to circle whole detector volume)

- **Gxe**-mode:
- ⇢ Additional **Rn reduction factor 2,** depending on extraction flow from cryogenic system



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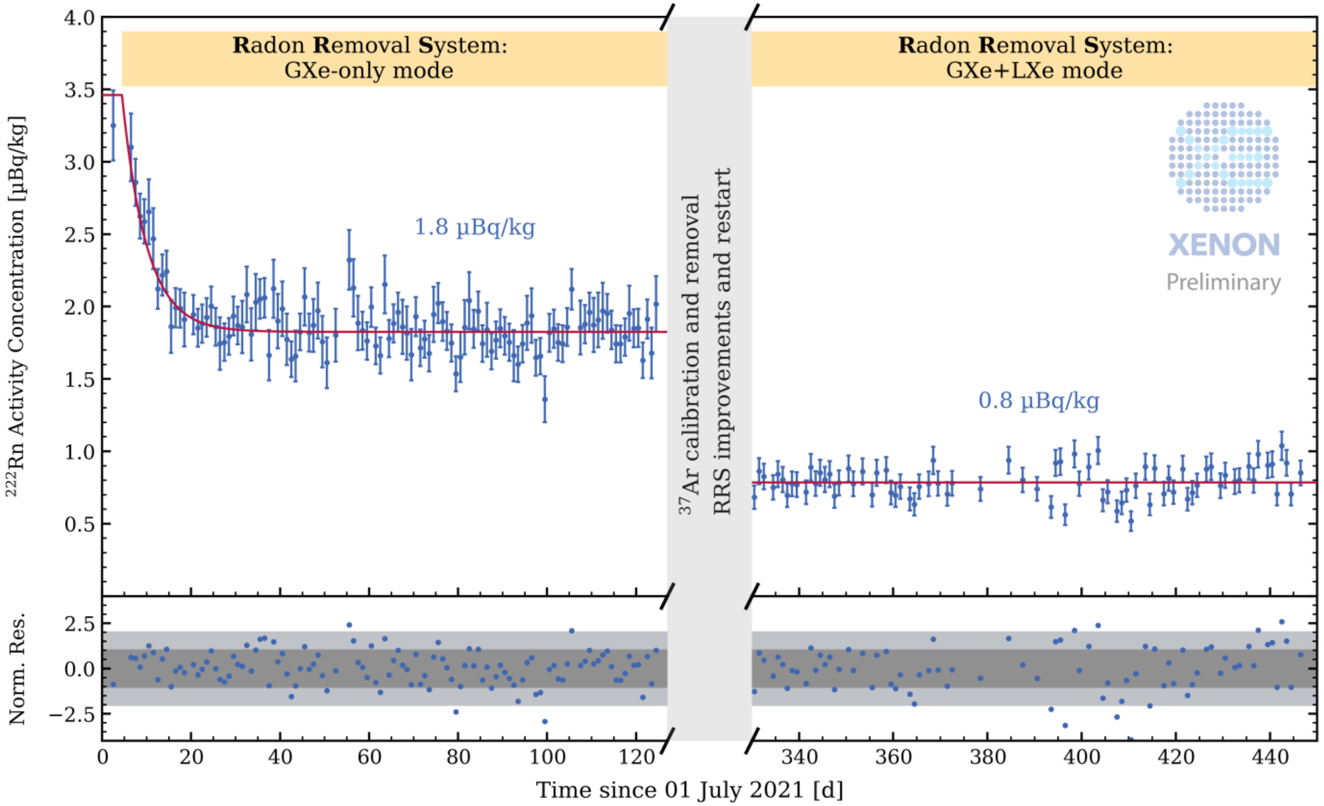
Measured performance in XENONnT

- ^{222}Rn concentration without distillation system: 3.3 µBq/kg

- During SR0: **GXe**-mode only: **1.8 µBq/kg**
- ⇢ **Rn reduction factor 2** (close to 100% efficient in suppressing Rn emanated into gas phase)

- During SR1: **GXe+LXe** mode: **0.8µBq/kg**
- ⇢ another **Rn reduction factor 2**

- Marks a **new world record** for any xenon dark matter experiment



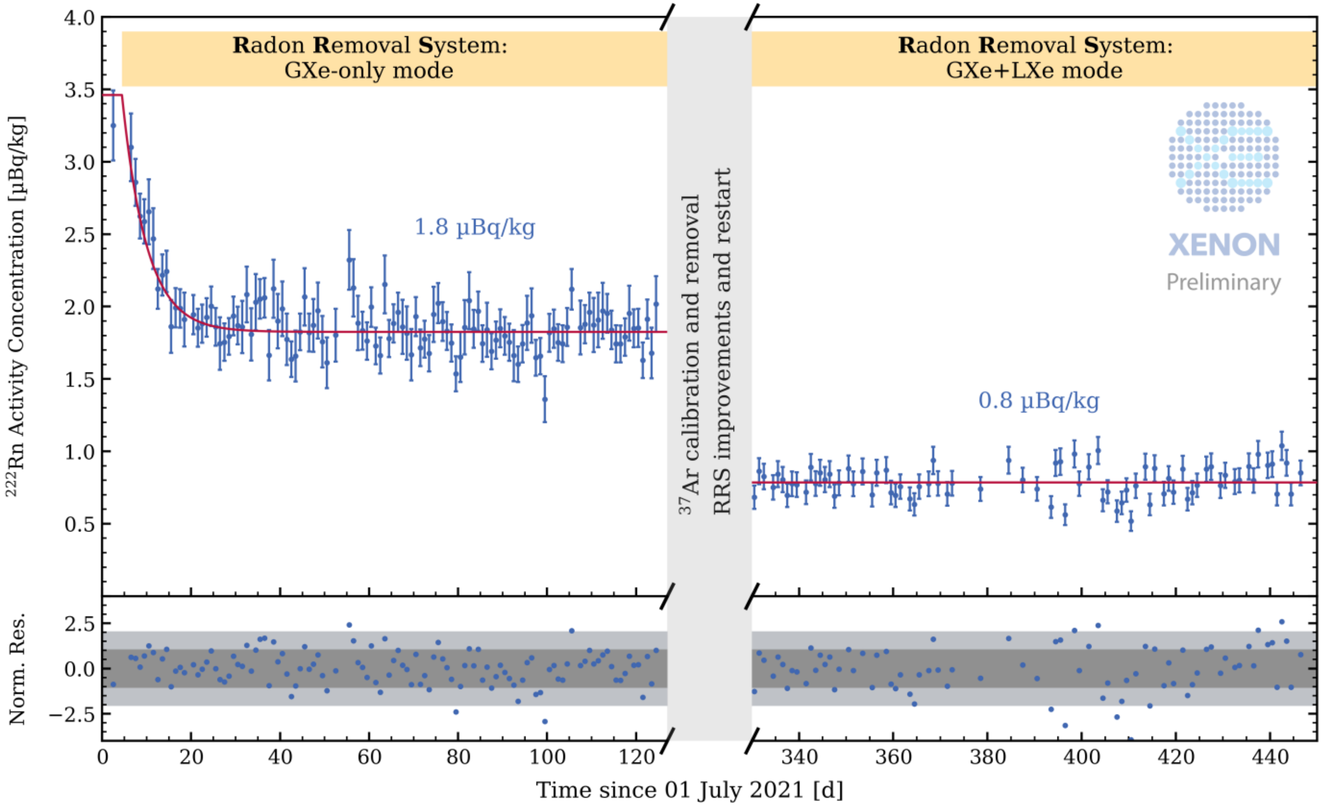
Measured performance in XENONnT

- ^{222}Rn concentration without distillation system: 3.3 µBq/kg

- During SR0: **GXe**-mode only: **1.8 µBq/kg**
- ⇢ **Rn reduction factor 2** (close to 100% efficient in suppressing Rn emanated into gas phase)

- During SR1: **GXe+LXe** mode: **0.8µBq/kg**
- ⇢ another **Rn reduction factor 2**

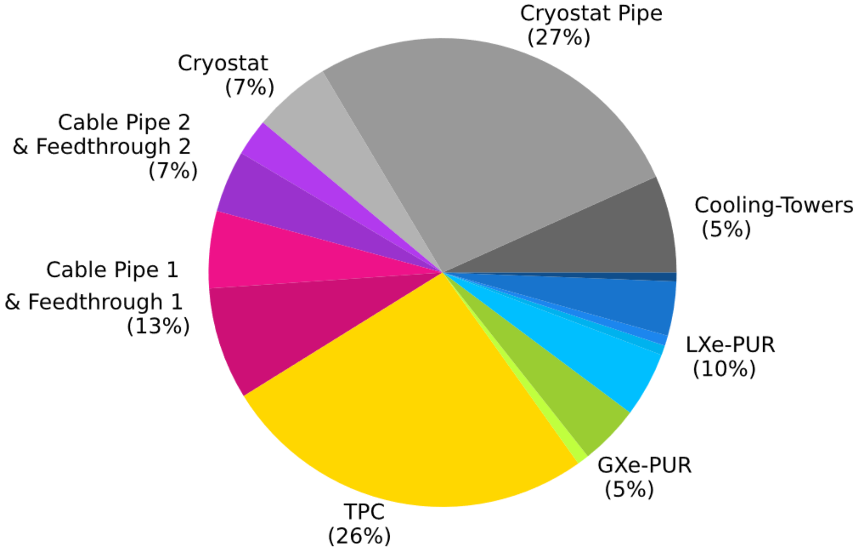
- Marks a **new world record** for any xenon dark matter experiment



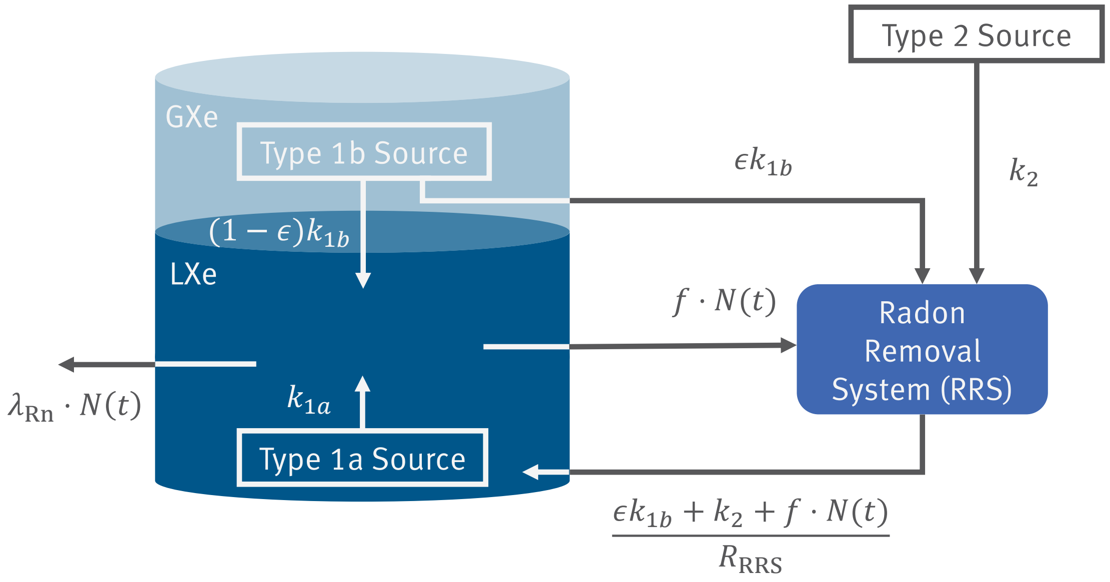
Thanks!

Backup

Background reduction concept



Aprile, E. et al. „Material radiopurity control in the XENONnT experiment", Eur. Phys. J. C (2022) 82:599



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