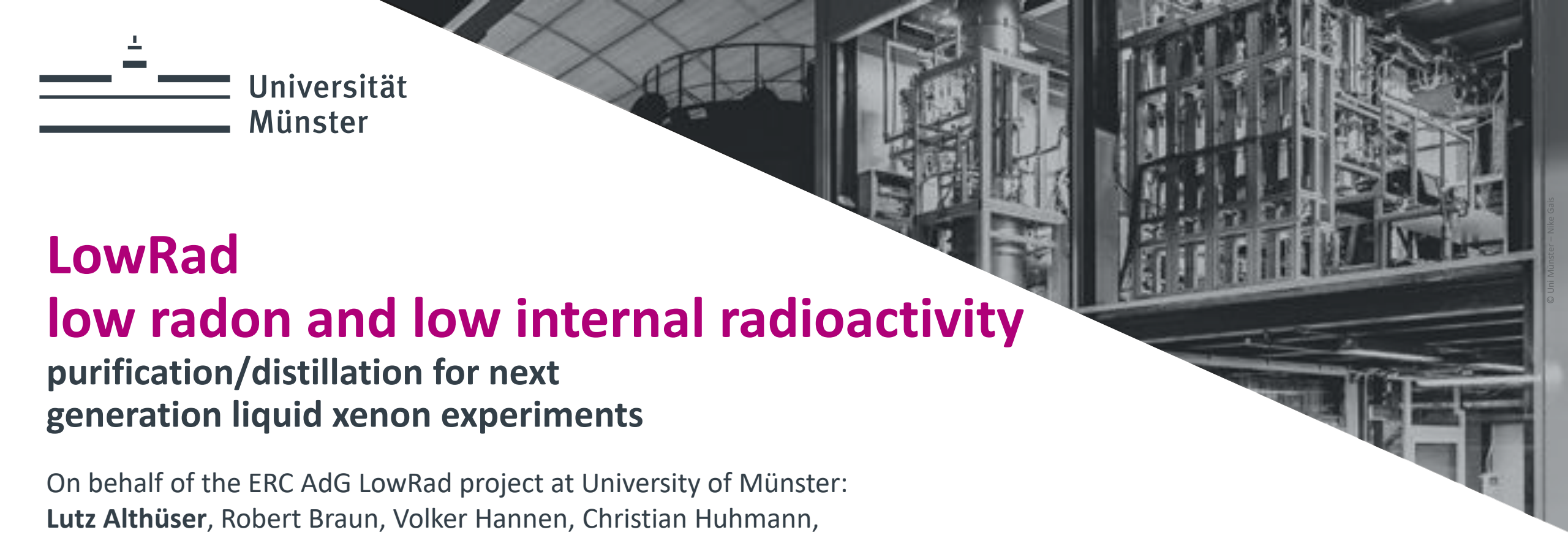
Universität Münster



LowRad
low radon and low internal radioactivity
purification/distillation for next generation liquid xenon experiments

On behalf of the ERC AdG LowRad project at University of Münster:
Lutz Althüser, Robert Braun, Volker Hannen, Christian Huhmann, David Koke, **Ying-Ting Lin**, Philipp Schulte, **Daniel Wenz**, ***Christian Weinheimer**

PostDocs
***PI**
Speaker

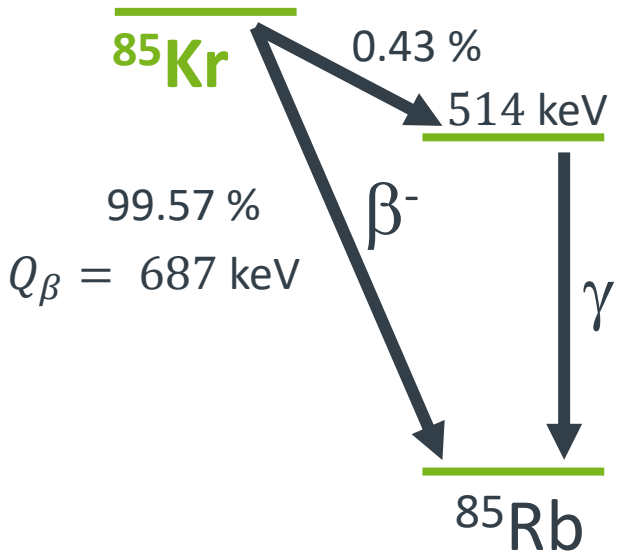
DFG

Bundesministerium für Bildung und Forschung

erc

Intrinsic backgrounds

- Anthropogenic ^{85}Kr ($T_{1/2} = 10.76$ years):
  - 2.33×10^{-11} ^{85}Kr in ^{nat}Kr
  - Commercial Xe: **^{nat}Kr/Xe > 10^{-9}** (ppb)
  - Needs to be removed once, but can reenter



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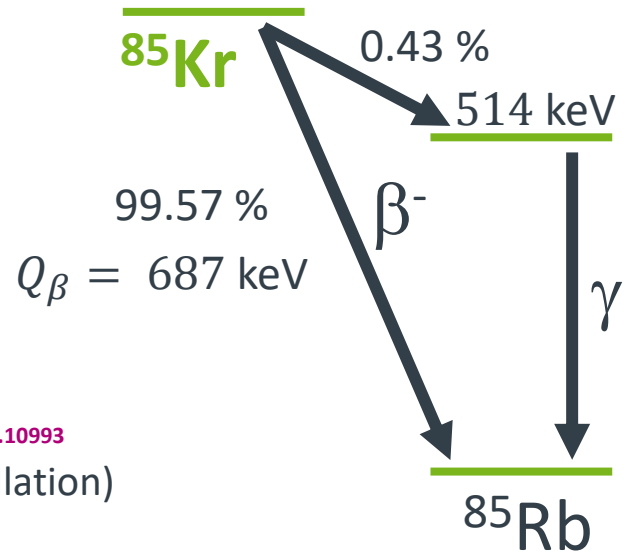
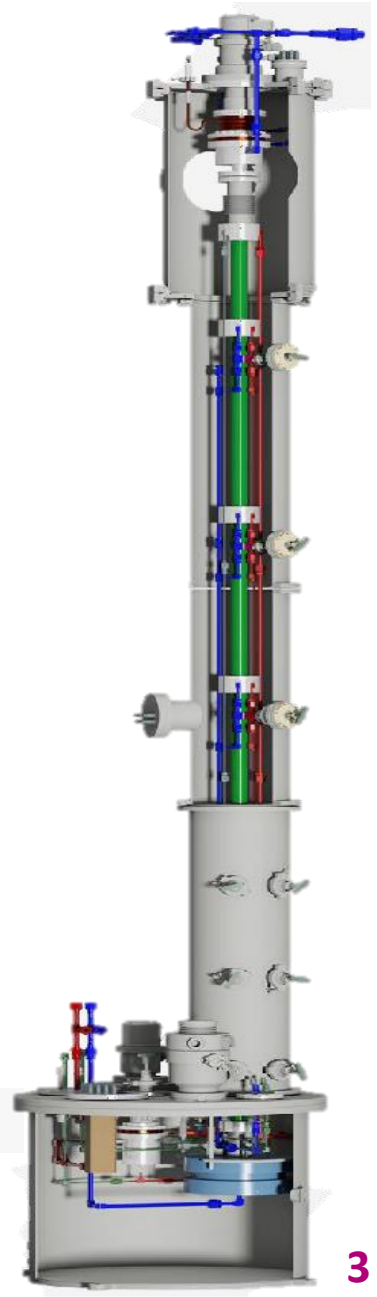
  - Commercial Xe: **^{nat}Kr/Xe > 10^{-9}** (ppb)
  - Needs to be removed once, but can reenter
- Achieved:
  - XENONnT: **^{nat}Kr/Xe < (56 ± 36) × 10^{-15}** (ppq) arXiv:2501.10993
    (26 ppq at local test in Münster via cryogenic distillation)
    PRL 129, 161805 (2022)
  - LZ: **^{nat}Kr/Xe < (186 ± 26) × 10^{-15}** (ppq) arxiv:2410.17036
    (via gas chromatography)
- XLZD requirement: **30 ppq** arXiv:2410.17137

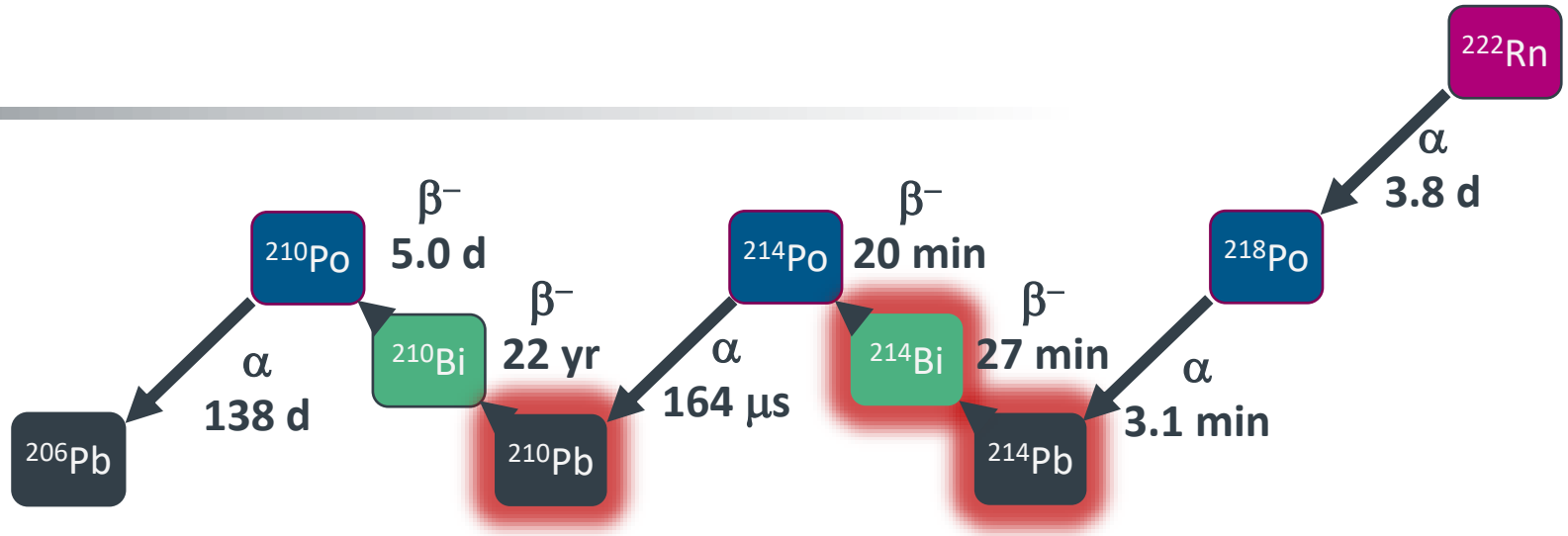


In realistic reach with current technology, few challenges when operated as "online" distillation



Intrinsic backgrounds

- **^{222}Rn** ($T_{1/2} = 3.8$ days):
  - Emanation from materials **(0.4 µBq/kg)**
  - Ways of mitigation:
    - **Avoid**: Screening, selection, design…
    - **Remove**: cryogenic distillation
    - **Tagging**: ^{218}Po-α tagging



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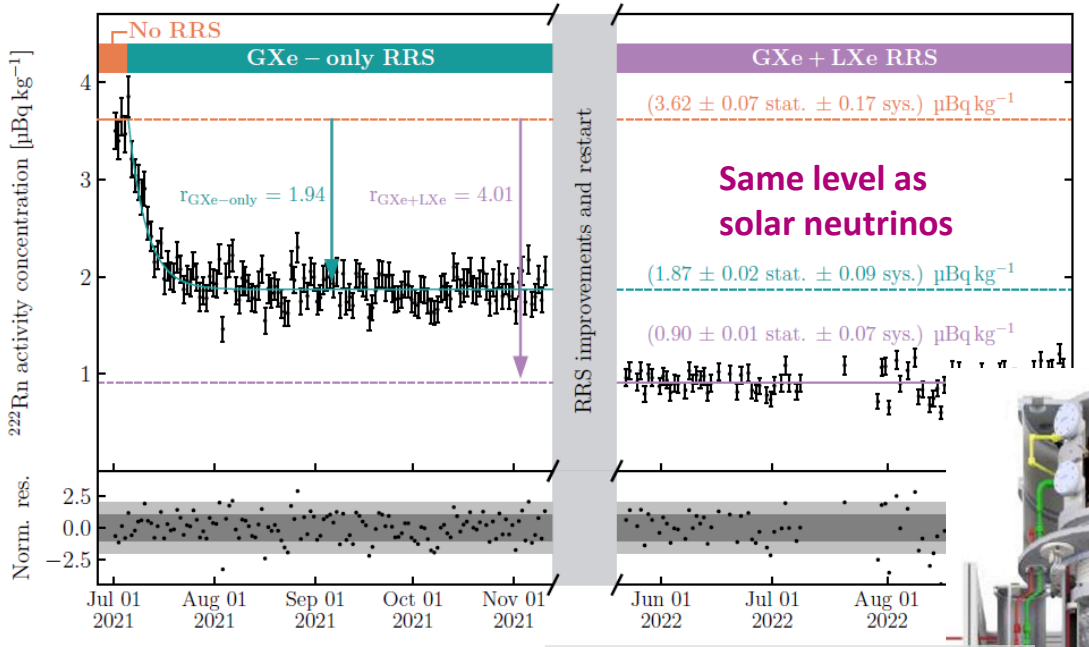
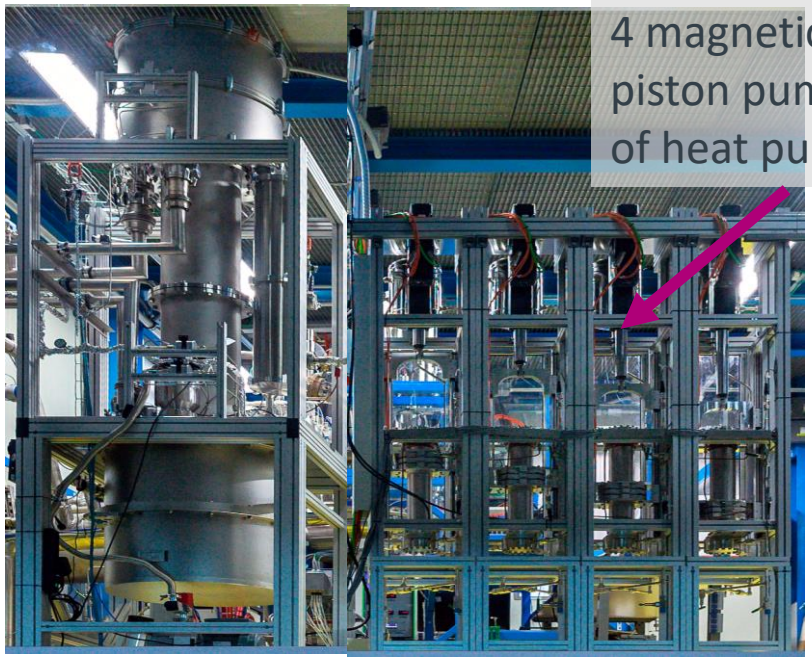
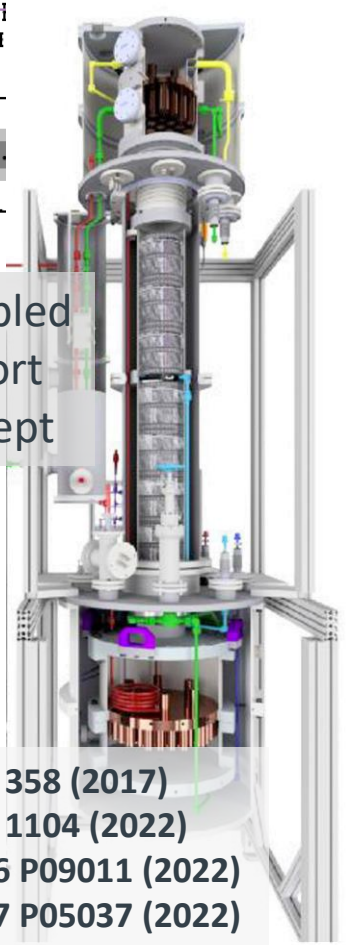
  - Ways of mitigation:
    - **Avoid**: Screening, selection, design…
    - **Remove**: cryogenic distillation
    - **Tagging**: ^{218}Po-α tagging
- Achieved:
  - XENONnT: **0.9 µBq/kg** arXiv:2502.04209
    (20 slpm GXe + 200 slpm LXe = 80 kg/h)
  - LZ: **1.8 µBq/kg** with rejection via tagging arXiv:2410.17137
- XLZD requirement: **0.1 µBq/kg** (10^{-26}) arxiv:2410.17036

Requires improvements on all fronts





4 magnetically coupled piston pumps for sort of heat pump concept



EPJ C77 358 (2017)
EPJ C82 1104 (2022)
JINST 16 P09011 (2022)
JINST 17 P05037 (2022)

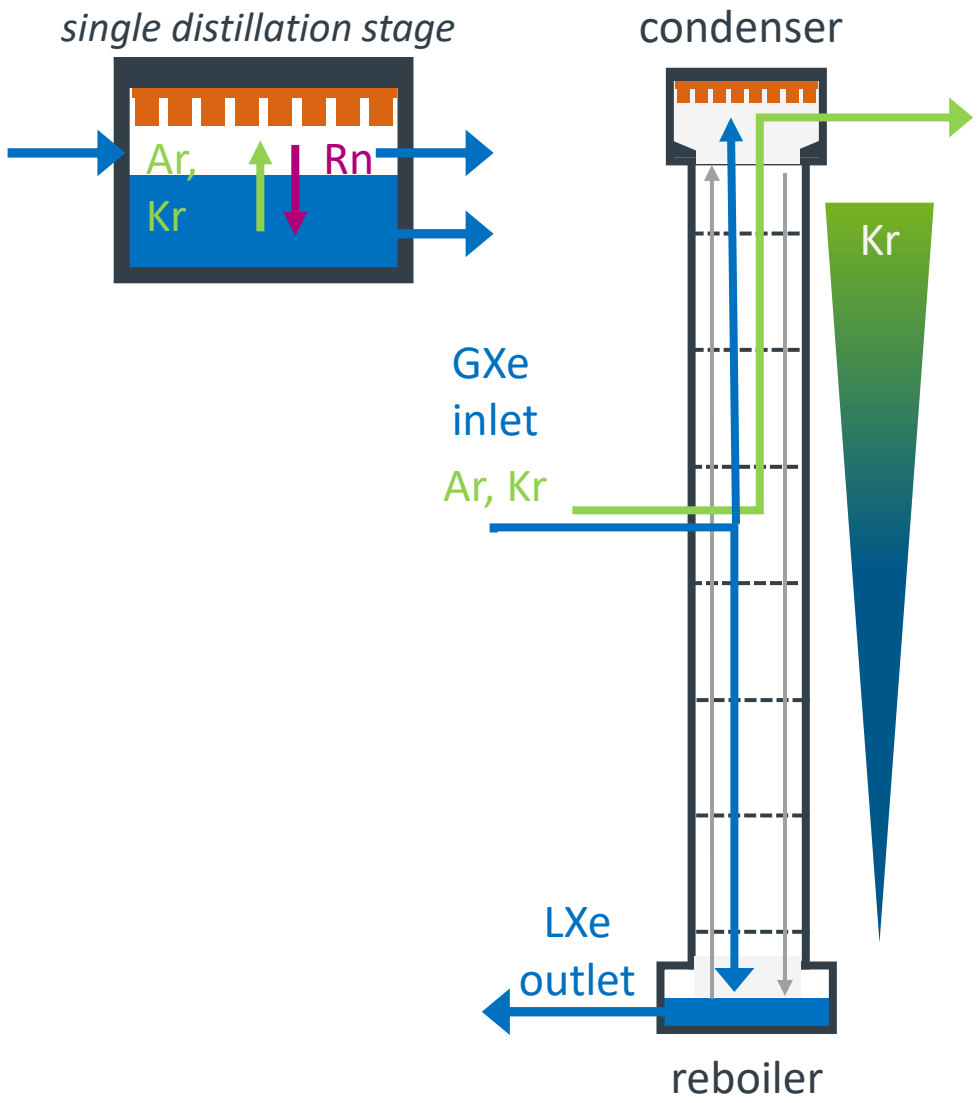
Cryogenic distillation in a nutshell

- Exploits difference in vapor pressure of fluids in mixture
  - Separation efficiency given by relative volatility

$$\alpha_i = \frac{p_i}{p_{\mathrm{Xe}}}$$

*at 173 K

  - **Krypton**: $\alpha_{Kr} = 10.5$*, extract…
    - …Kr-enriched offgas from the top
    - …clean xenon from the bottom



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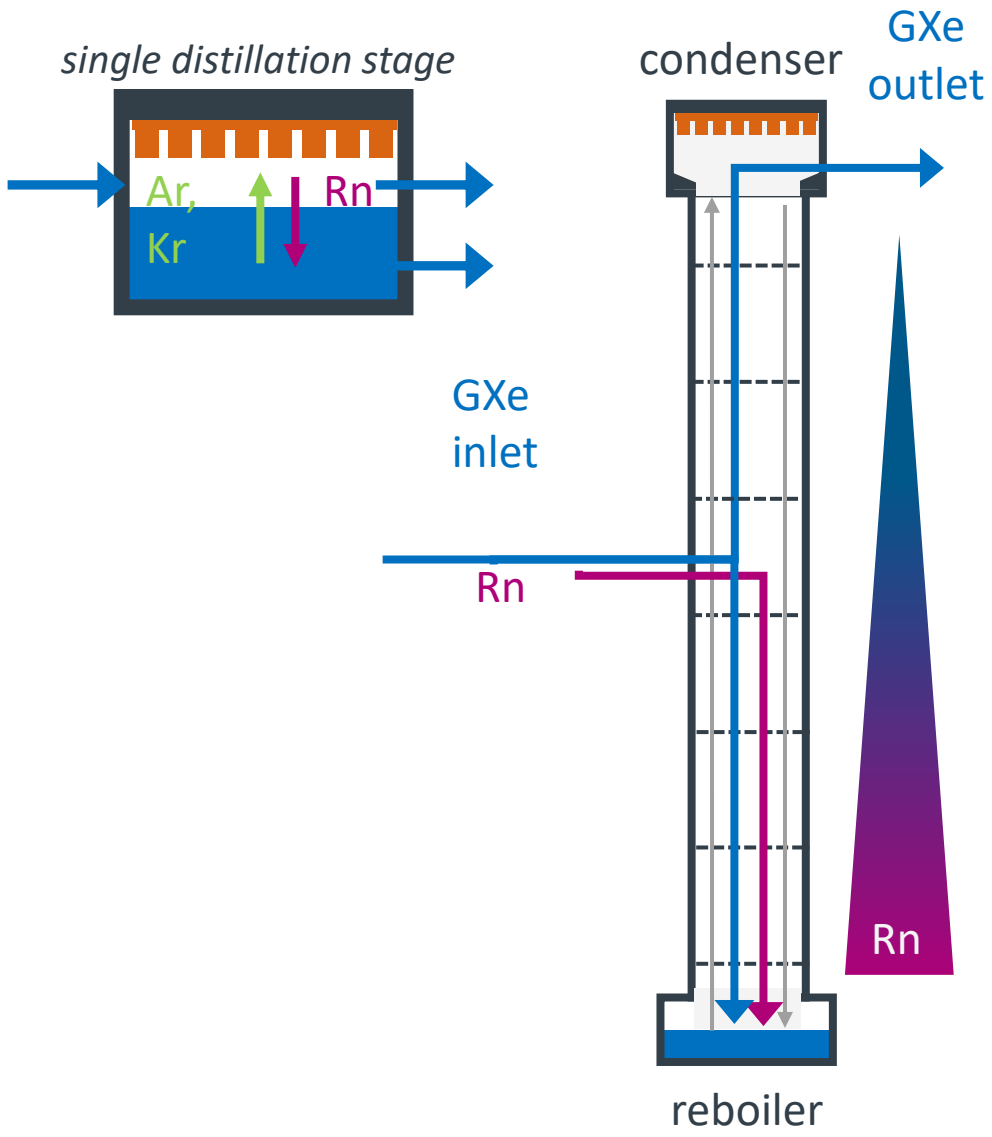
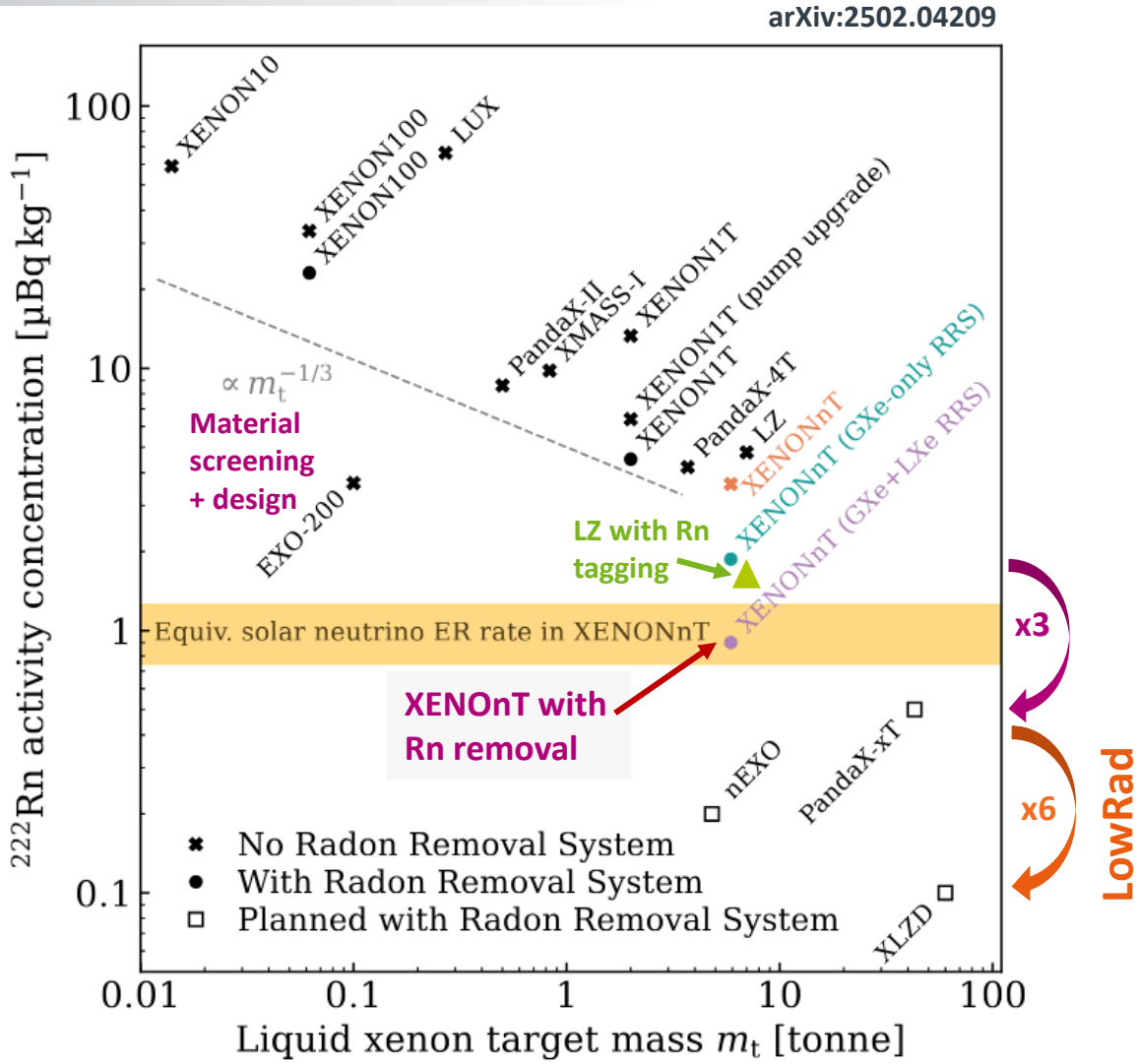
    - …Kr-enriched offgas from the top
    - …clean xenon from the bottom
  - **Radon**: $\alpha_{Rn} = 0.1$*, extract…
    - …clean xenon from the top
    - Let Rn decay inside of the reboiler ($T_{1/2} = 3.8$ days)



Goals of ERC Advanced Grant LowRad of C. Weinheimer

- Develop technologies for:
  - Next-generation experiments with around 75 t of LXe
  - Continuous/online ^{85}Kr removal (30 ppq ^{nat}Kr)
  - Another factor 10* in ^{222}Rn reduction (0.1 µBq/kg)
- R&D for novel purification methods
- Methods for physics searches/analyses
- Pave the way for an all-in-one purification & distillation system
- Complete purification & distillation demonstrator

*A **factor 6 through active removal** times
a **factor 3 by avoidance and tagging**

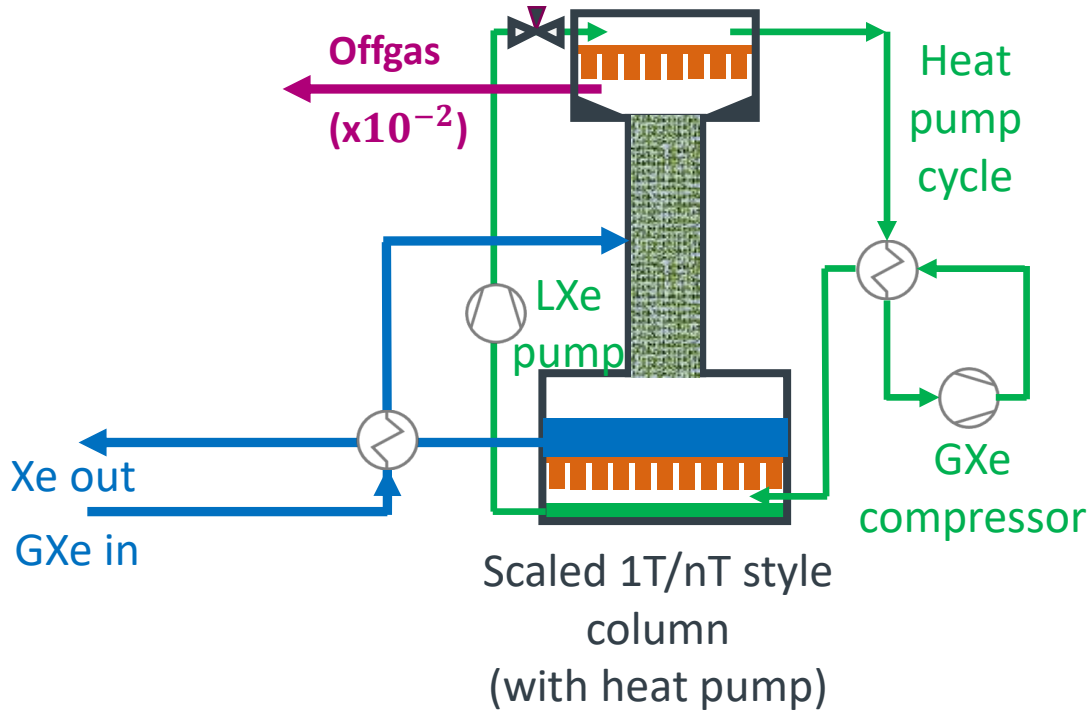


Loss-free online Krypton removal

- Why continuous Kr removal?
  - Contamination due to Air “leaks” ($\propto$ #Flanges), or operations e.g. in XENONnT
  - Enables regular ^{37}Ar ($T_{1/2} = 35$ d) low energy calibration (To study efficiency near detector threshold)
- Challenge:
  - Requires 1 % offgas:

$$2.9\,\frac{\text{kg}}{\text{h}} \cdot \frac{75\ \text{tonne}}{8.6\ \text{tonne}} \cdot \mathbf{10^{-2}} \approx 0.26\,\frac{\text{kg}}{\text{h}} \Rightarrow 6\,\frac{\text{kg}}{\text{d}}$$

Scale flow to XLZD size



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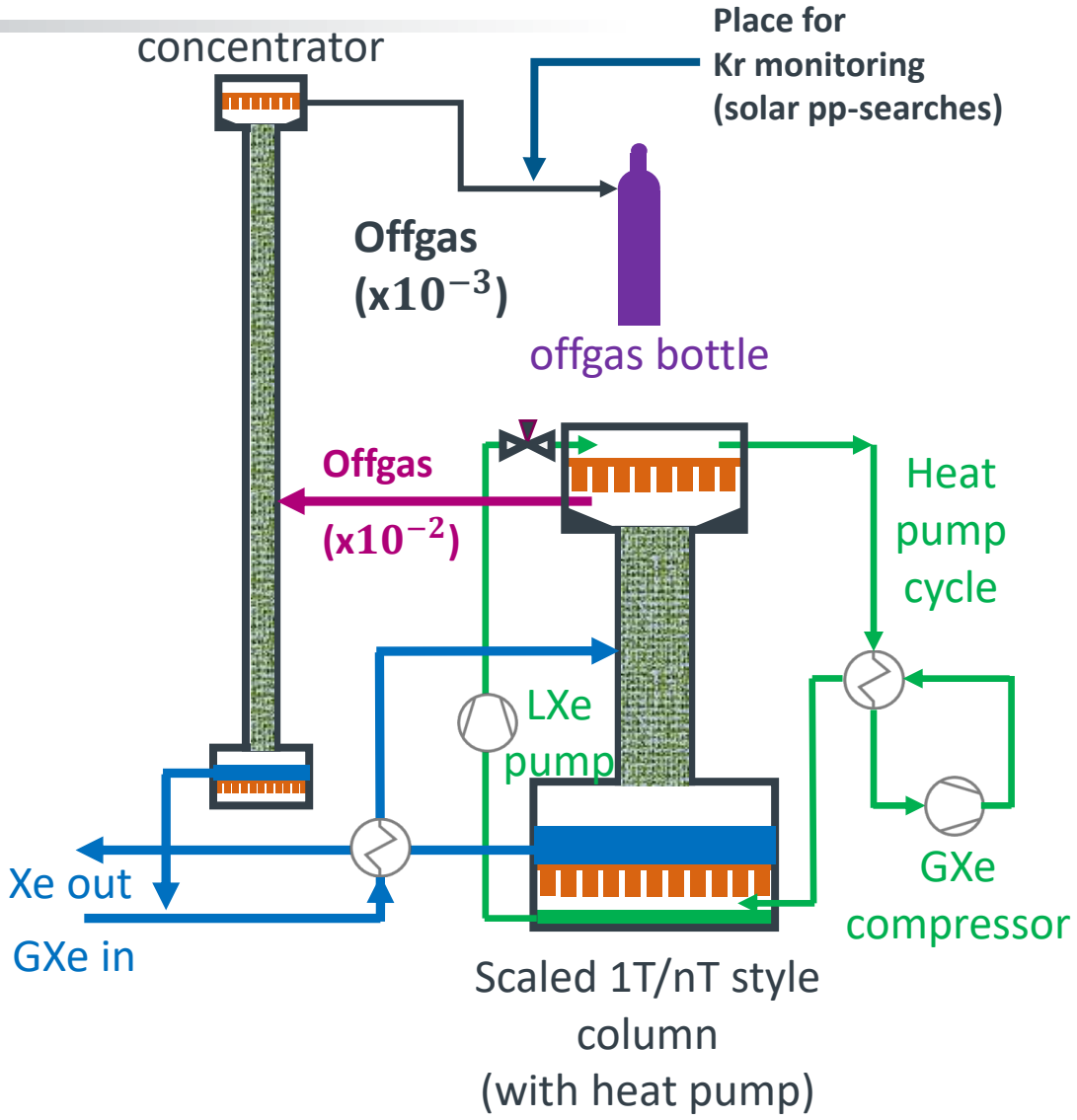
Scale flow to XLZD size

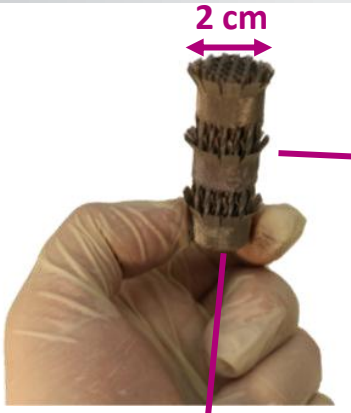
$$\cdot\,\mathbf{10^{-3}} \rightarrow 6\,\frac{\text{g}}{\text{d}}$$

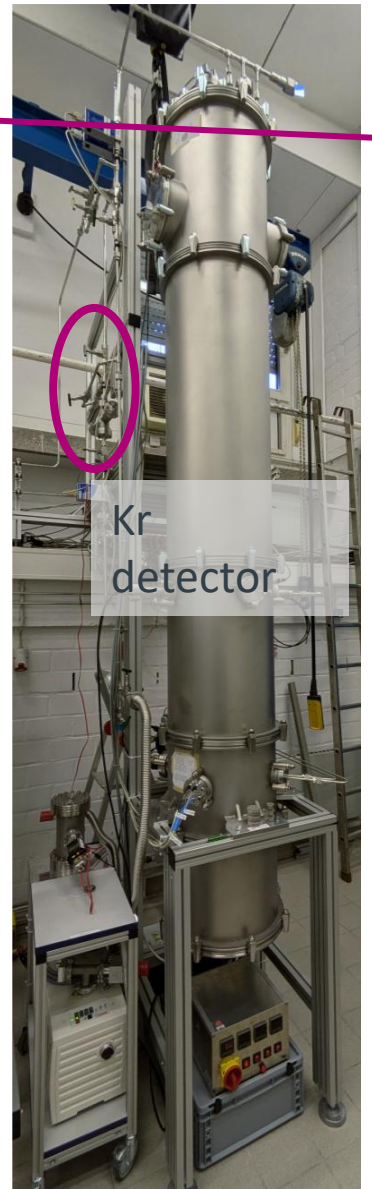
Manageable offgas plus place for online Kr monitoring

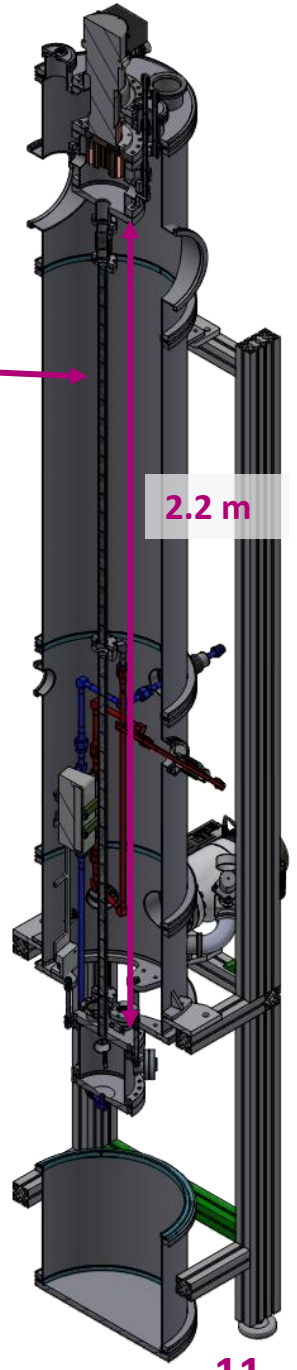


Loss-free online Krypton removal

- Developed McCabe-Thiele calculator based on TESPy and CoolProp
- Designed demonstrator column with
  - Input: 1 kg/h with ^{nat}Kr/Xe of 5×10^{-12} (ppt)
  - Output: ^{nat}Kr/Xe of 5×10^{-15} (ppq)
  - Offgas: 0.1 % of input with ^{nat}Kr/Xe of 5×10^{-9} (ppb)
  - (Column: 1200 Reflux with 9 stages)







Concentrator column was built and is currently being characterized using ^{83m}Kr. First results look good!

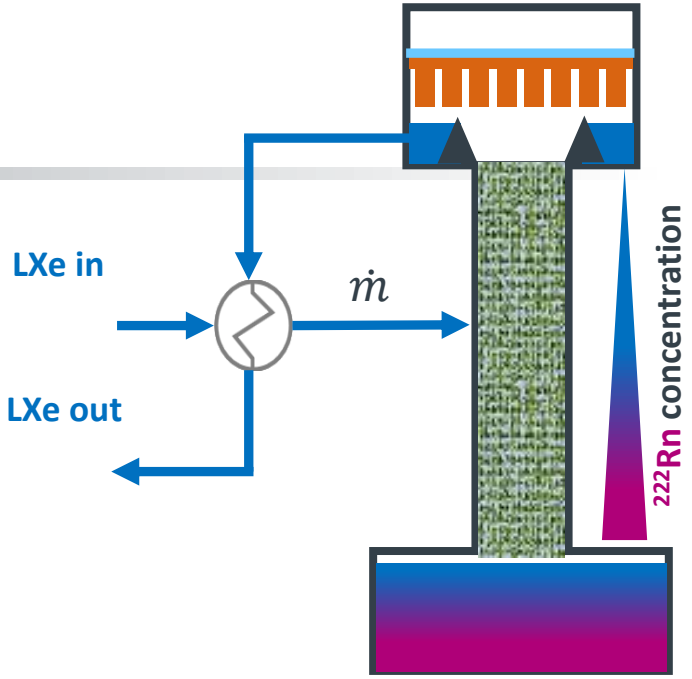
High flow radon removal system

- Why higher flow for increased Rn reduction?
  - Reduction factor is given by

$$r = \underbrace{r_{GXe}}_{\approx 2^*} \cdot \underbrace{\frac{\lambda_{Rn}+f}{\lambda_{Rn}}}_{\approx 3} \approx 6$$

*assumes similar Rn distribution as in XENONnT

$$\dot{m} = 75\,\mathrm{t} \cdot \underbrace{0.362\,\frac{1}{\mathrm{d}}}_{f} \approx 1130\,\frac{\mathrm{kg}}{\mathrm{h}}$$



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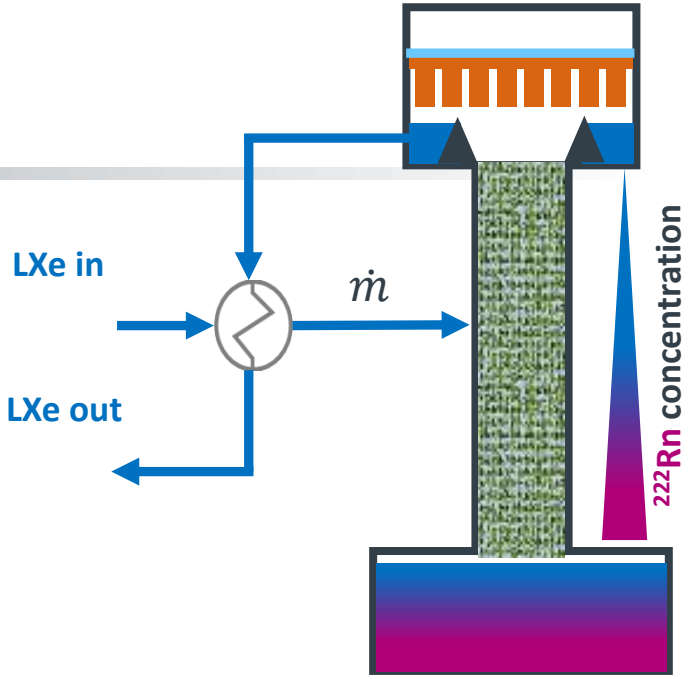

- Requires large cooling and heating power!

$(\Delta h|_{\mathrm{evap.}} = 95.7\,\frac{\mathrm{kj}}{\mathrm{kg}}$ @ 1 bar)

$$\Rightarrow \dot{Q}_C = 45^*\ \mathrm{kW}$$
$$\dot{Q}_E = 45^*\ \mathrm{kW}$$

*assumes similar reflux of R=0.5 as in XENONNT (So total flow will be $1.5\dot{\cdot}\, m$)

- Cooling cannot be provided by LN2 or Cold Heads

$(\Delta h|_{\mathrm{evap.}} = 199\,\frac{\mathrm{kj}}{\mathrm{kg}}$ @ 1 bar)

$$\Rightarrow \dot{m}_{\mathrm{LN2}} \approx 20\,\frac{\mathrm{tonne}}{\mathrm{day}}$$

Use full heat pump concept to drive distillation

High flow radon removal system

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  - Reduction factor is given by

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$$\Rightarrow \dot{m} = 75\,\mathrm{t} \cdot \underbrace{0.362\,\frac{1}{\mathrm{d}}}_{f} \approx 1130\,\frac{\mathrm{kg}}{\mathrm{h}}$$

- Requires large cooling and heating power!

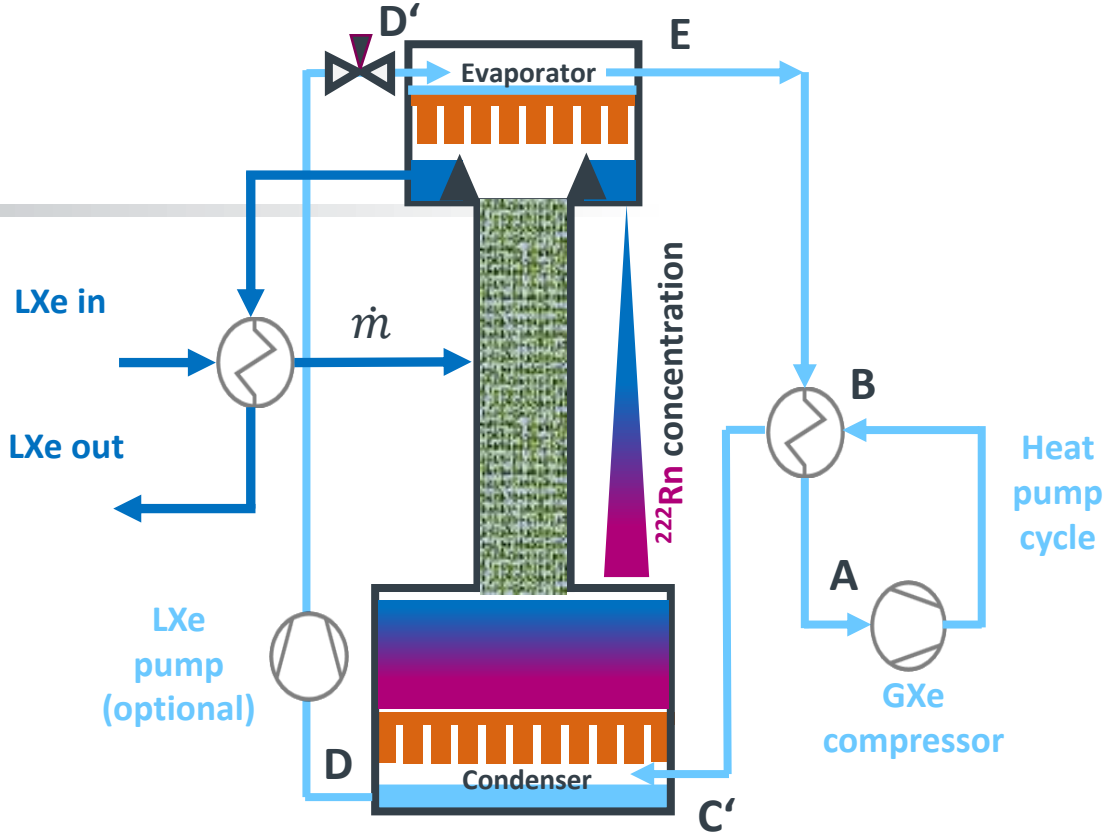
$(\Delta h|_{\mathrm{evap.}} = 95.7\,\frac{\mathrm{kj}}{\mathrm{kg}}$ @ 1 bar) $\Rightarrow$ $\dot{Q}_C = 45^*\ \mathrm{kW}$, $\dot{Q}_E = 45^*\ \mathrm{kW}$

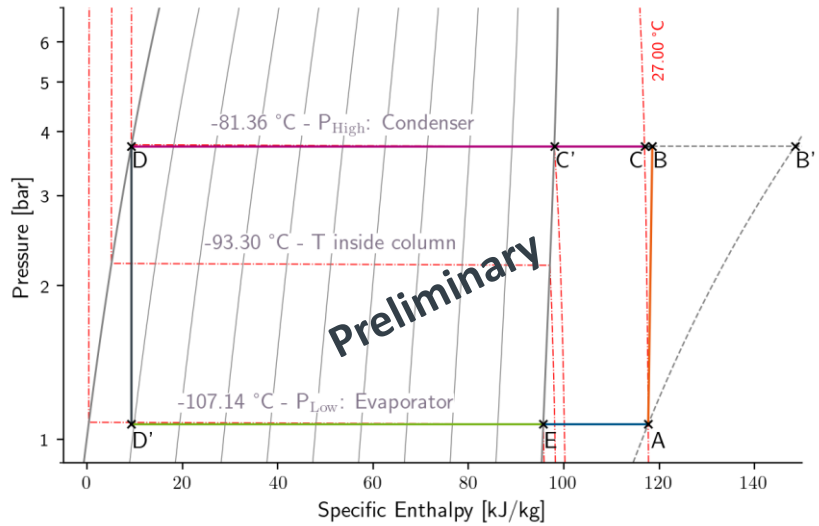
*assumes similar reflux of R=0.5 as in XENONNT (So total flow will be $1.5 \cdot \dot{m}$)

- Cooling cannot be provided by LN2 or Cold Heads

$(\Delta h|_{\mathrm{evap.}} = 199\,\frac{\mathrm{kj}}{\mathrm{kg}}$ @ 1 bar) $\Rightarrow$ $\dot{m}_{\mathrm{LN2}} \approx 20\,\frac{\mathrm{tonne}}{\mathrm{day}}$

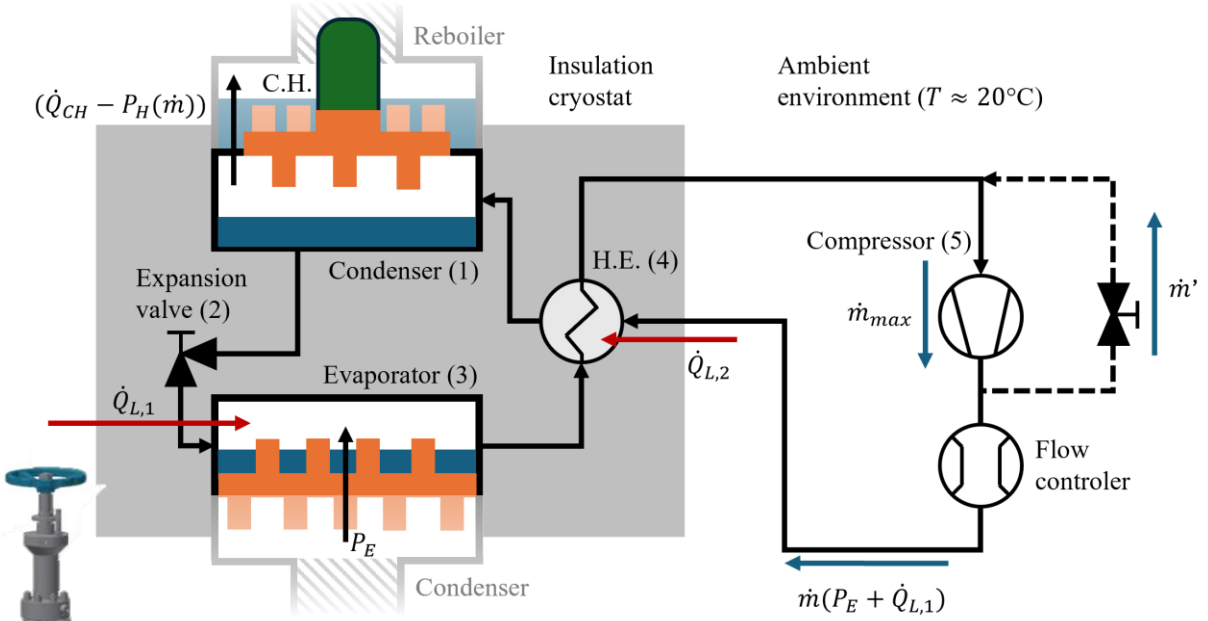
- **Separate heat pump with xenon as working medium to provide cooling and heating power!**

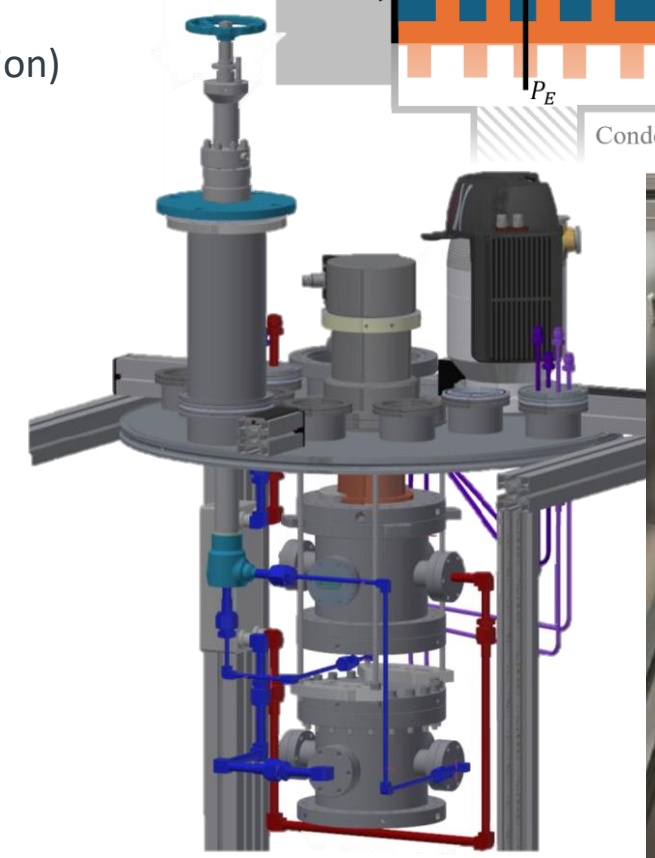


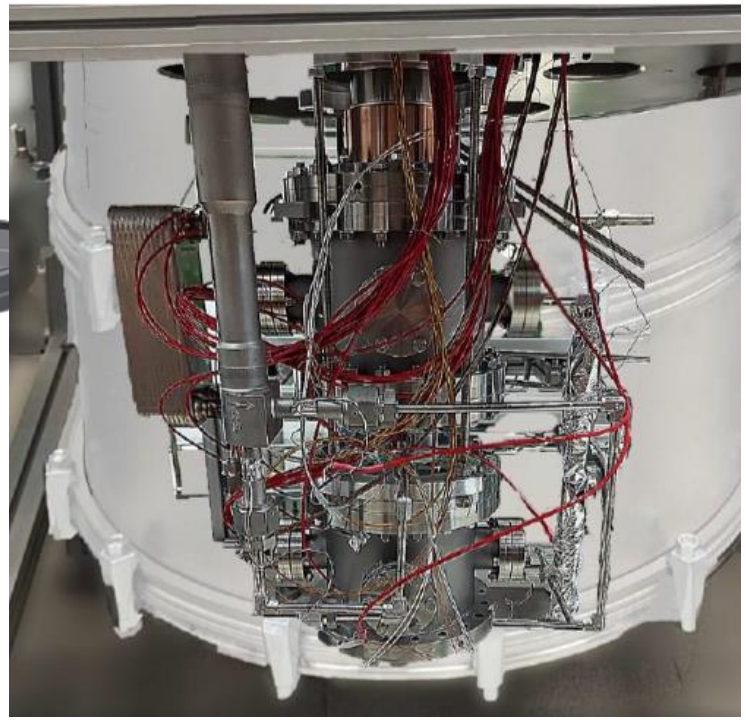


High flow radon removal system

- Small scale demonstrator to study technical challenges (flow: 4 kg/h equivalent column)
  - Designed to deliver up to 130 W of cooling and heating power
  - First test concluded successful (paper under preparation)

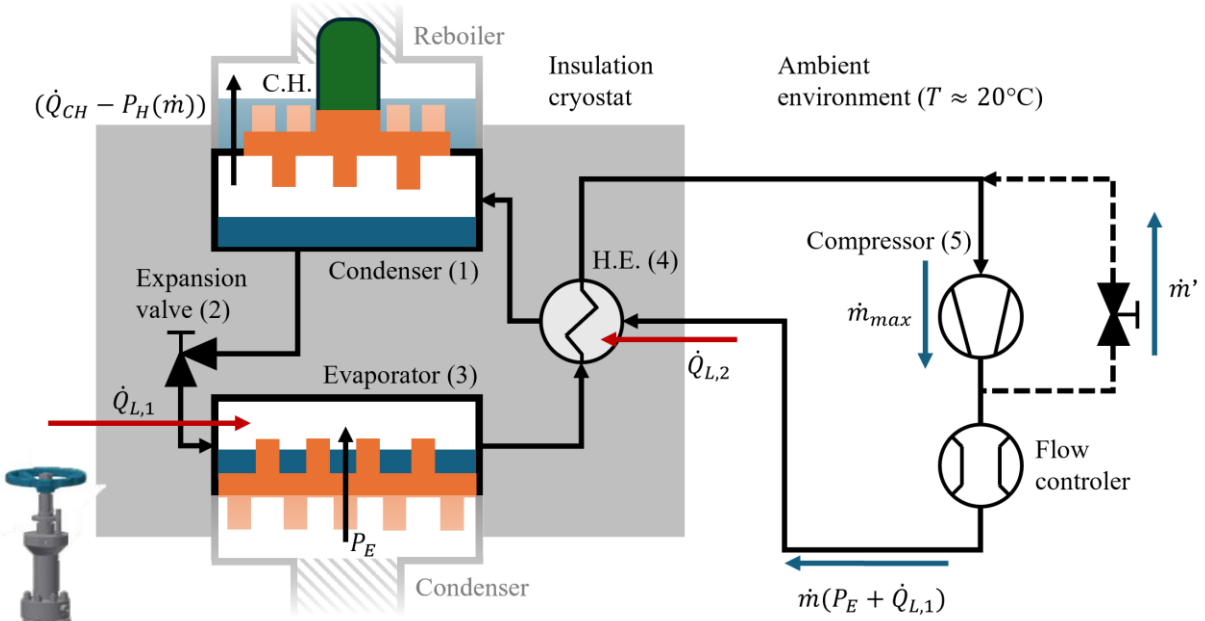


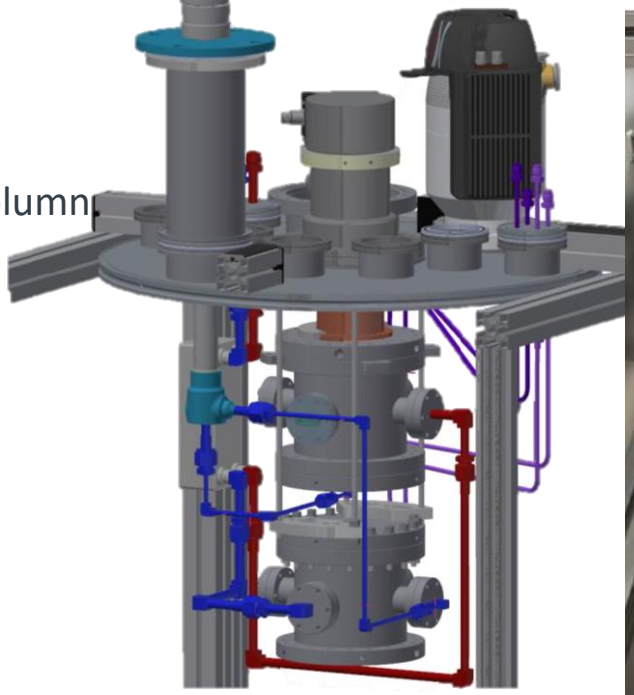


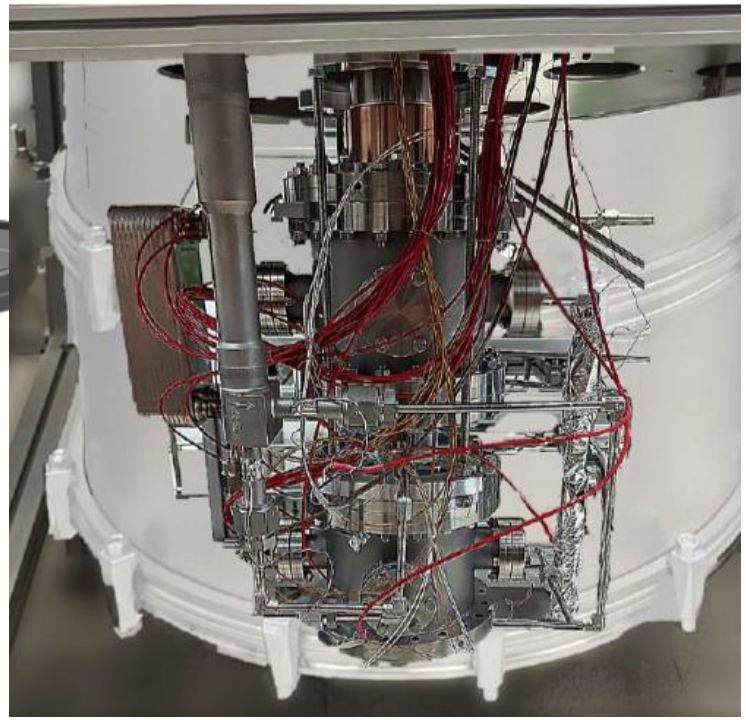


High flow radon removal system

- Small scale demonstrator to study technical challenges (flow: 4 kg/h equivalent column)
  - Designed to deliver up to 130 W of cooling and heating power
  - First test concluded successful (paper under preparation)
- Next step:
  - Scale technology by a factor x15 to 70 kg/h (2 kW to 3 kW of cooling/heating power)
  - Fully integrated into a XENONnT sized Rn distillation column at Münster
  - Rn concentration monitor
  - Make first design choices towards optimization:
    - More efficient compressor
    - Reduce flow loss through compressor bypass

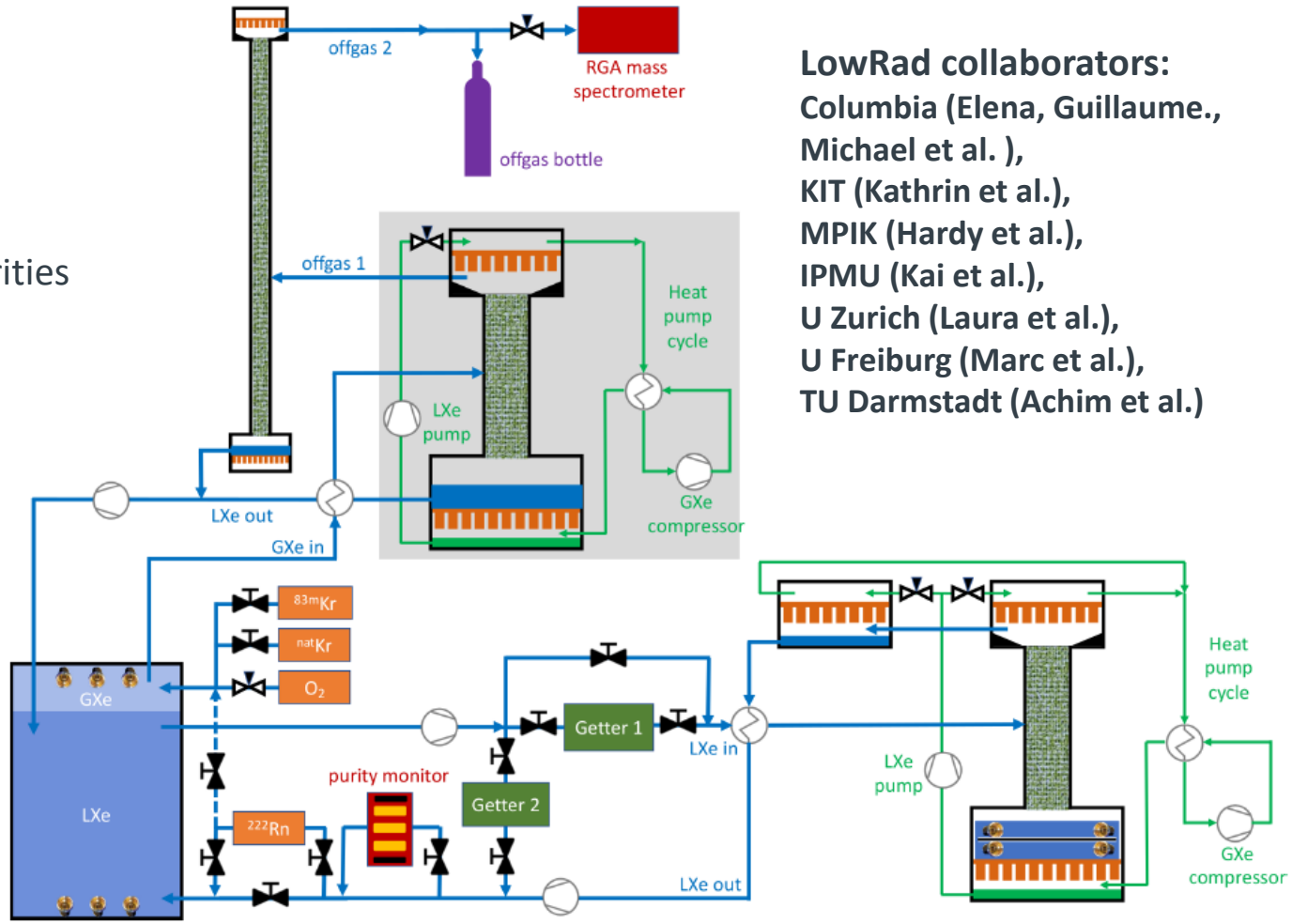






Compact purification and monitoring:

- Demonstrator for a compact all-in-one purification, distillation and monitoring unit.
  - LXe detector volume instrument with light sensors for monitoring
  - Includes GXe/LXe purification for electronegative impurities
  - Various calibration sources to study performance of subsystems
  - Neutron shielding design study to mitigate ^{137}Xe
  - A test facility for high-flow LXe distribution and low maintenance LXe pumps



LowRad collaborators:
Columbia (Elena, Guillaume., Michael et al.),
KIT (Kathrin et al.),
MPIK (Hardy et al.),
IPMU (Kai et al.),
U Zurich (Laura et al.),
U Freiburg (Marc et al.),
TU Darmstadt (Achim et al.)

Please let us know if you would like to contribute!

Compact purification and monitoring:

- Space requirement:
  - Krypton removal system (height ~5.5 m)
    - (XENONnT sized Rn column) + concentrator column: 0.7 m² + 0.7 m²
    - (XENONnT sized compressor for heatpump): 0.7 m²
  - Rn column (height ~4 m):
    - XENONnT sized Rn column sized by flux: $15 \cdot 0.7$ m² = 10.5 m²
    - Compressor sized by flux: $15 \cdot 0.7$ m² = 10.5 m²
  - Additional infrastructure:
    - GXe/LXe purification, LXe monitor, etc. +??? m²
- Electrical power requirement:
  - Goal: less than 100 kW
  - Using large efficient turbine compressors

about 6 x 6 x 6 m³
(+ 0.5 m of PE
neutron shield)

Conclusion

- **Develop technologies** for:
  - Continuous/**online ^{85}Kr removal** (30 ppq ^{nat}Kr), enable high statistics **^{37}Ar calibration**
  - Another **factor 6** in **active ^{222}Rn reduction towards** 0.1 µBq/kg
  - Online **concentration monitoring**
- Design of a combined and compact **purification & distillation** unit (75 kg/h)
- Other **LowRad R&D at Münster** not shown today:
  - Computing tools for the design of cryogenic distillation and heat pumps
  - Kr- and Rn-decay monitoring systems
  - Ultra clean gas and liquid xenon pumps
  - Xenon gas purity monitoring systems