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Removing ^{222}Rn from xenon for large-scale rare event searches

Workshop on Xenon Detector $0\nu\beta\beta$ Searches, Steps Towards the Kilotonne Scale, Oct. 25-27, 2023, SLAC

- Background by ^{222}Rn & its progenies for dark matter and $0\nu\beta\beta$ searches
- Rn mitigation strategies
- Rn removal systems
- Online cryogenic distillation
- Conclusions

erc

living.knowledge

Christian Weinheimer – University of Münster
(member of XENON, DARWIN/XLZD, technical member of nEXO)

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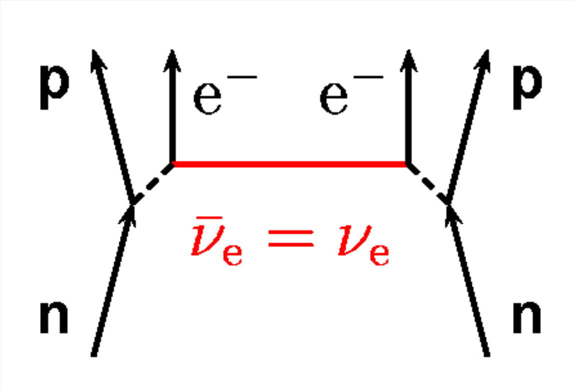
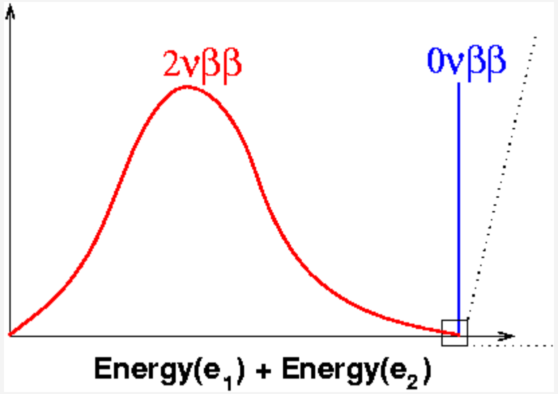
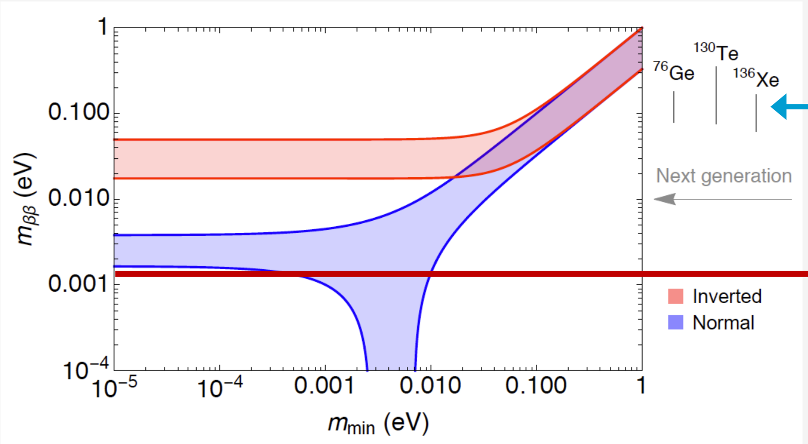
Rare event searches with large xenon detectors search for 0νββ and for dark mater

0νββ: sharp peak in 2e⁻ spectrum at *Q*-value



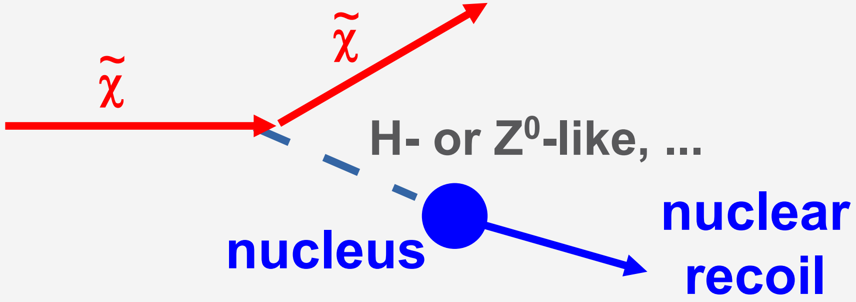


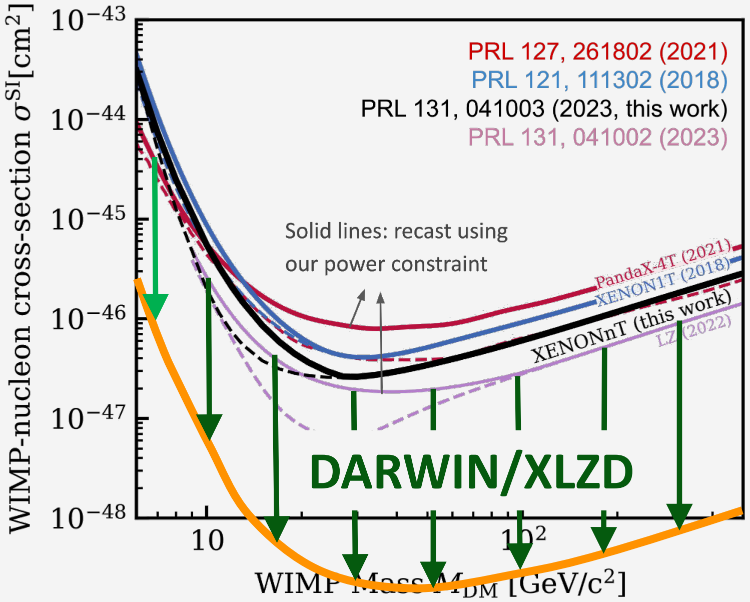


currently
$T_{1/2} \approx 10^{26}$ yr

final goal:
normal ordering

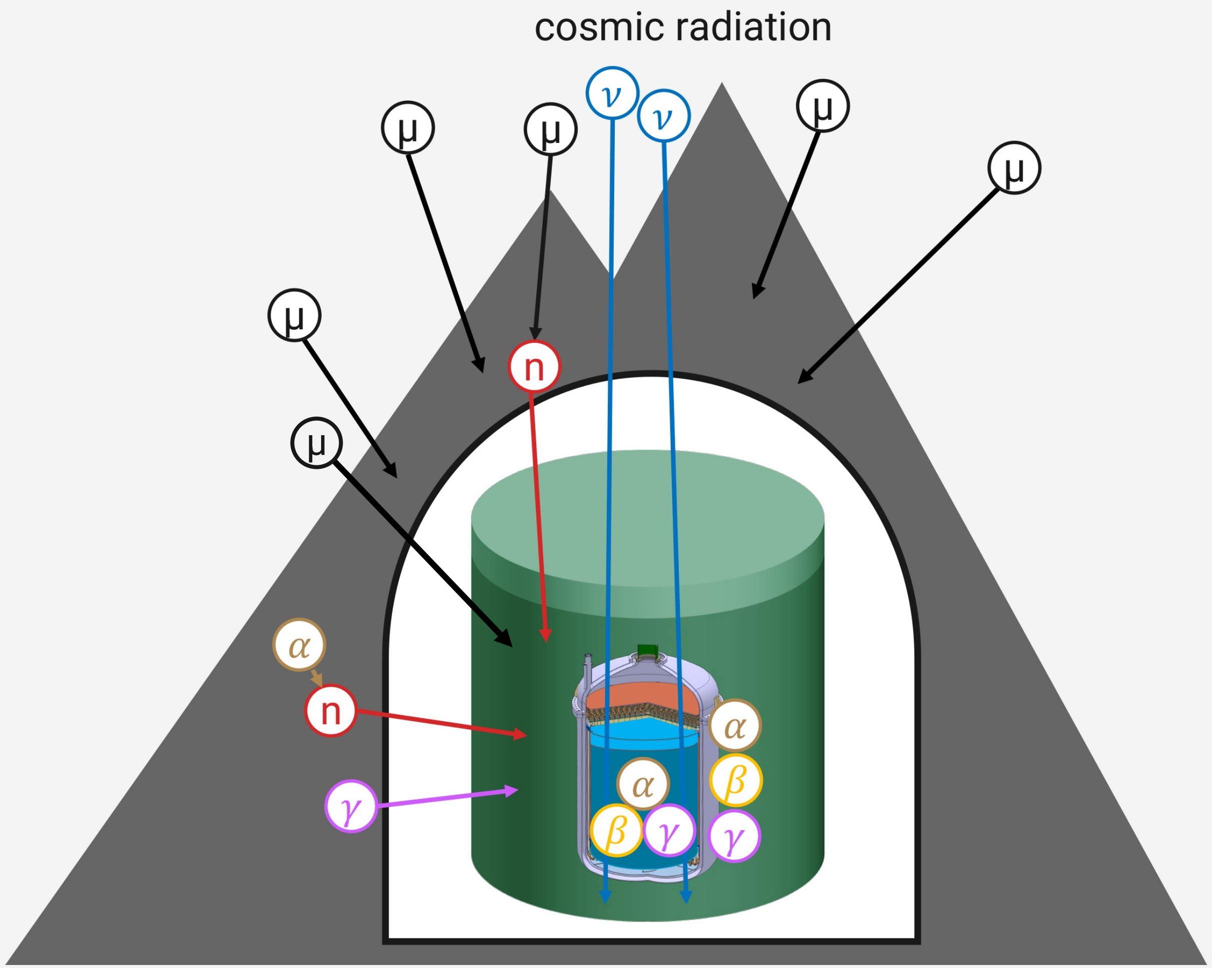
Dark matter: nuclear (electron) recoil





final goal: neutrino fog

Limiting backgrounds in xenon DM & 0νββ detectors



Expected dark matter scattering rate:

1 event per 10t and year

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

Most background problems solved by

- going underground
- extra (self-)shieldings & vetos

Two remaining backgrounds:

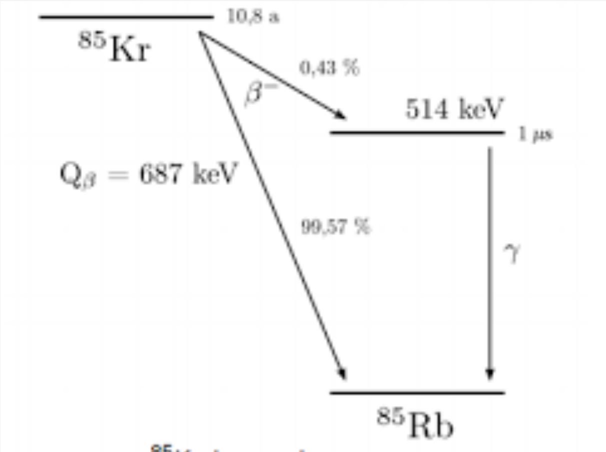
- solar neutrinos, non-shieldable
- **intrinsic radioactive noble gases:**
  ^{85}Kr, ^{222}Rn and progenies, (^{37}Ar, ^{39}Ar, ^{136}Xe)

A closer look to ^{85}Kr (^{39}Ar) and ^{222}Rn with its progenities

Why: intrinsic noble gas contaminants ^{85}Kr and ^{222}Rn (→ ^{214}Pb) (similarly ^{39}Ar, 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



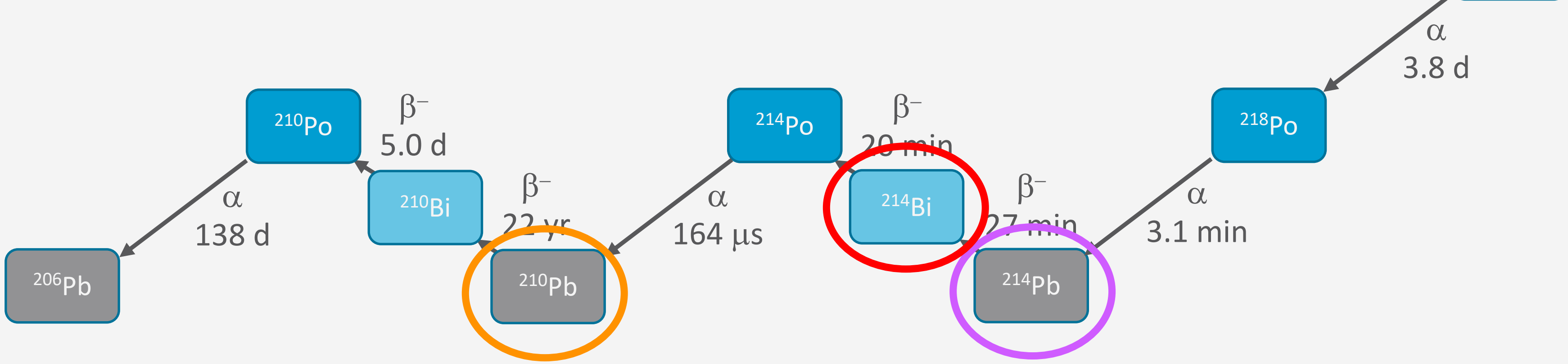
^{85}Kr decay scheme

^{39}Ar: $8 \cdot 10^{-16}$ (1 Bq per kg ^{nat}Ar)

Reduction needed also for 0νββ to reduce trigger rate ?

^{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



Event localisation in a xenon TPC and β-decays contributing to the background in dark matter searches

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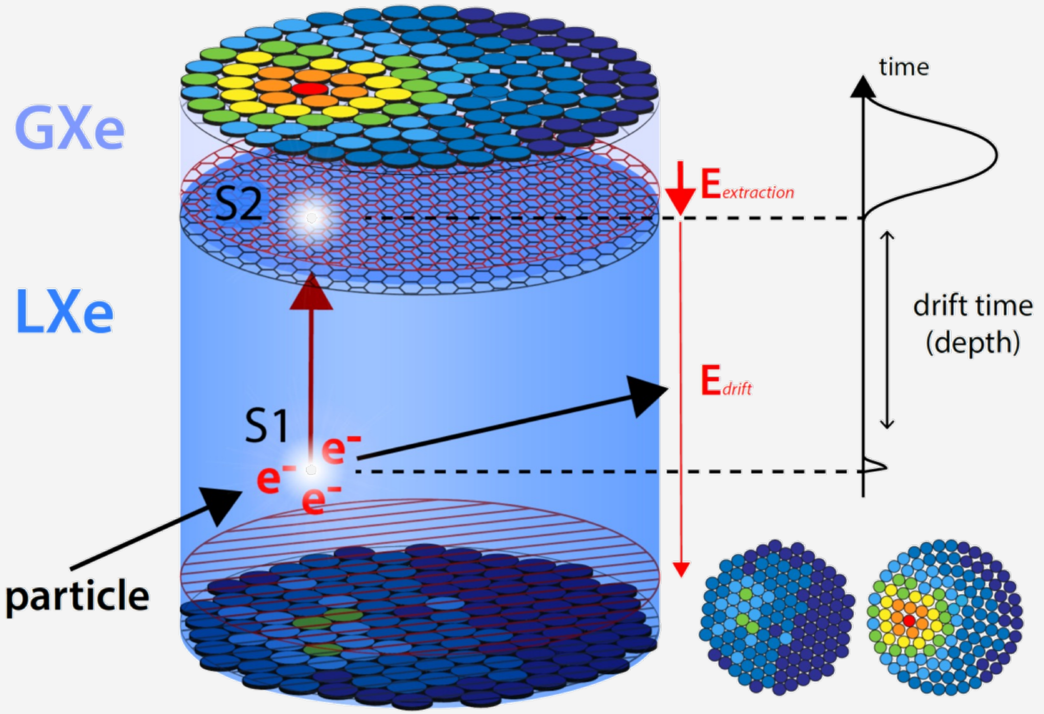


Image by L. Althüser

S1 light signal:

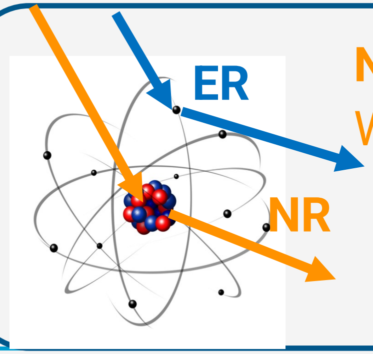
- prompt scintillation photons

S2 charge signal:

- secondary scintillation photons from electroluminescence in GXe due to drifted electrons

3D vertex reconstruction (-> fiducialisation):

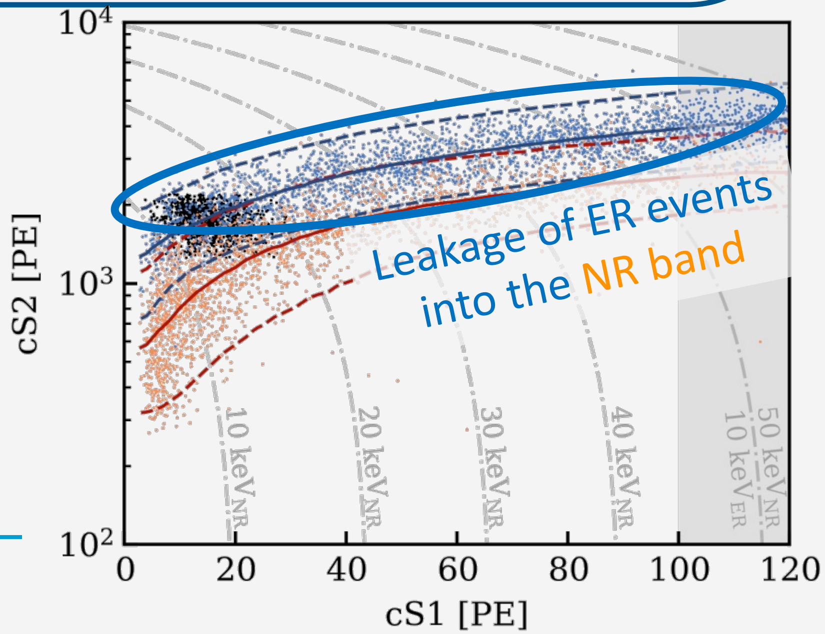
- X,Y: S2 hit pattern
- Z: drift time S2-S1



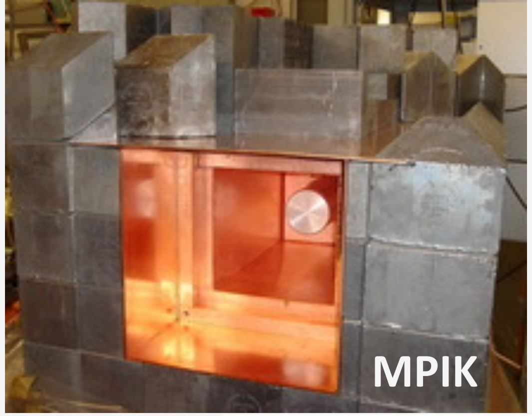
NR (Nuclear Recoils)
WIMP signal, neutrons, CEvNS

ER (Electronic Recoils)
γ, β backgrounds

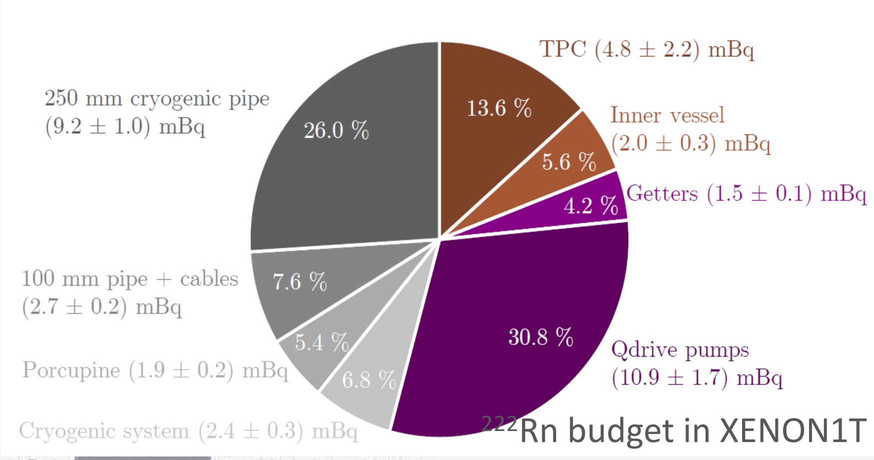
Discrimination from S2/S1
Larger for ER than NR



Rn mitigation I

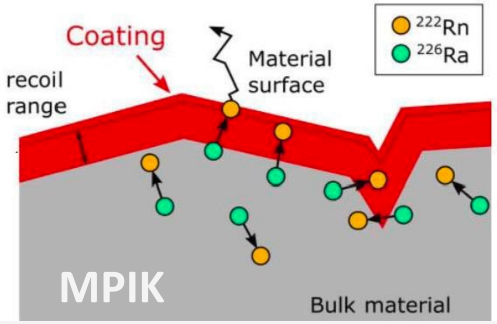


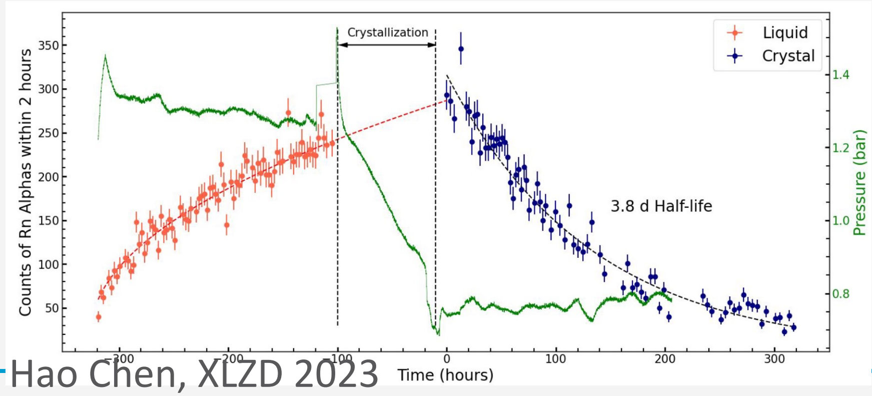
1. **Screen materials for gamma emission and radon emanation and selection**



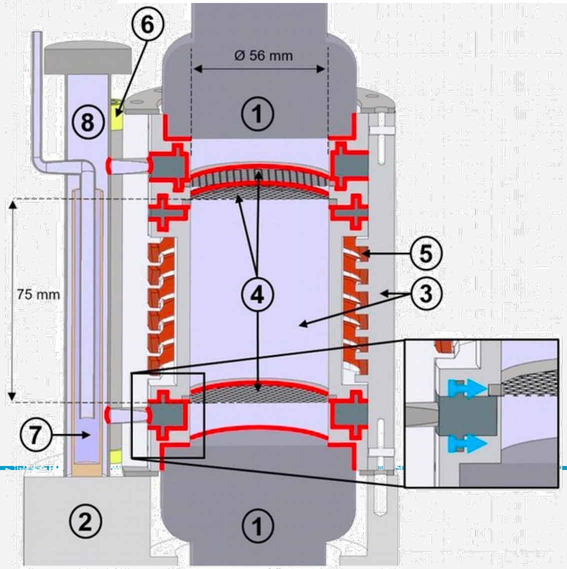
^{222}Rn budget in XENON1T

2. **Avoiding Rn to move into the LXe:**
   - **coating** (MPIK)
   - **hermetically-sealed TPC** (U Freiburg)
   - xenon ice (LBNL, U Texas)





Hao Chen, XLZD 2023



EPJ C83 (2023) 9

Rn mitigation II

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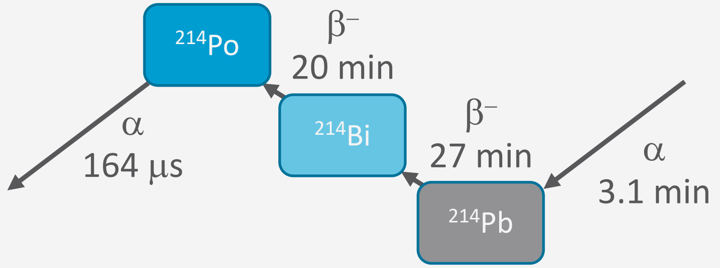
Profit from the larger volume of huge LXe detectors

3. **Use the larger volume-to-surface ratio reducing Rn emanation from walls further**

4. **Identify radon progeny decays by observing co-locoalized progenitor or progeny decays**



5. **Extract GXe from regions of large Rn emanation/injection** (e.g. cable entering TPC), **into Rn removal system** (e.g. by chromatography or distillation)

6. **High flow LXe extraction from detector into high through-put Rn removal system** (through-put time constant $\tau_{\mathrm{removal}} < \tau\ (^{222}\mathrm{Rn})$), e.g. cryogenic distillation at XENONnT

LZ: In-line Radon reduction system

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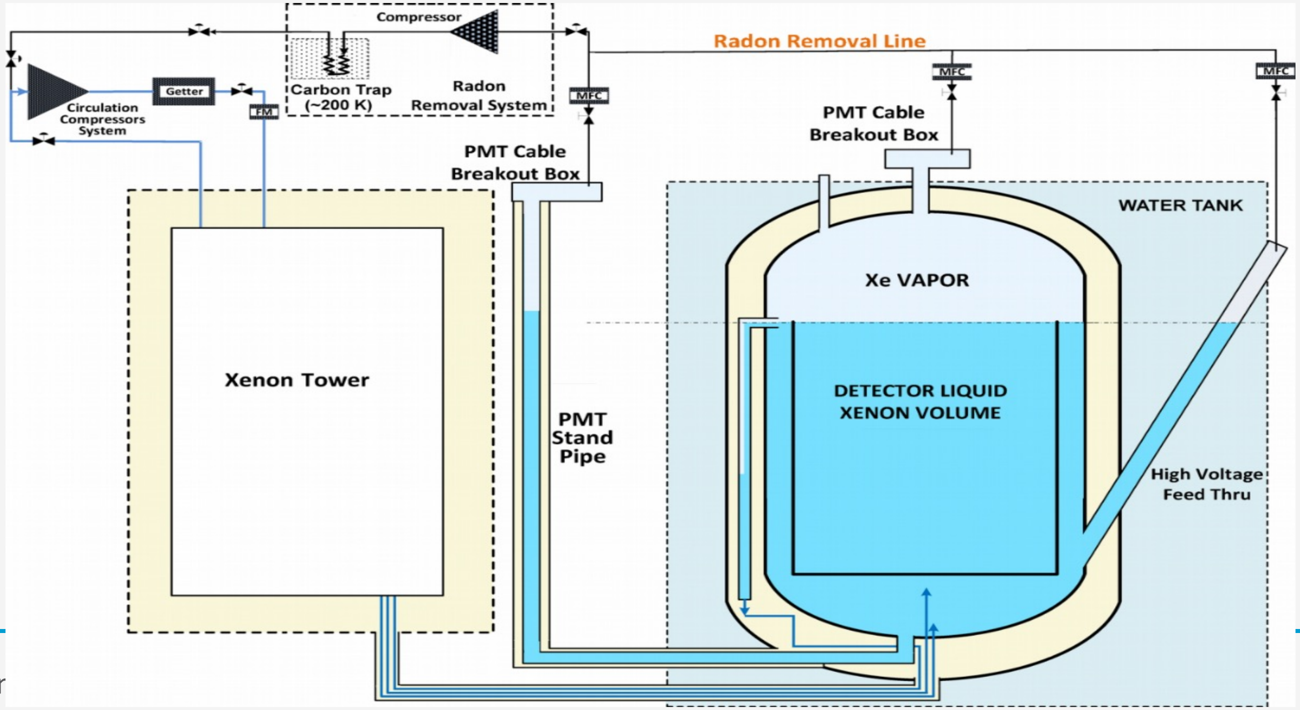
- reduce ^{222}Rn background from in warm parts only (feedthroughs, cables, etc.)
  i. tiny fraction of entire purification flow: 1 slpm (GXe) : 500 slpm (LXe)
  ii. expected to contribute ~50% of Rn burden in TPC
- not set up to purify all 10 t of LXe
- sequestration of atoms in activated trap (10 kg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



courtesy:
Wolfgang Lorenzon
University of Michigan

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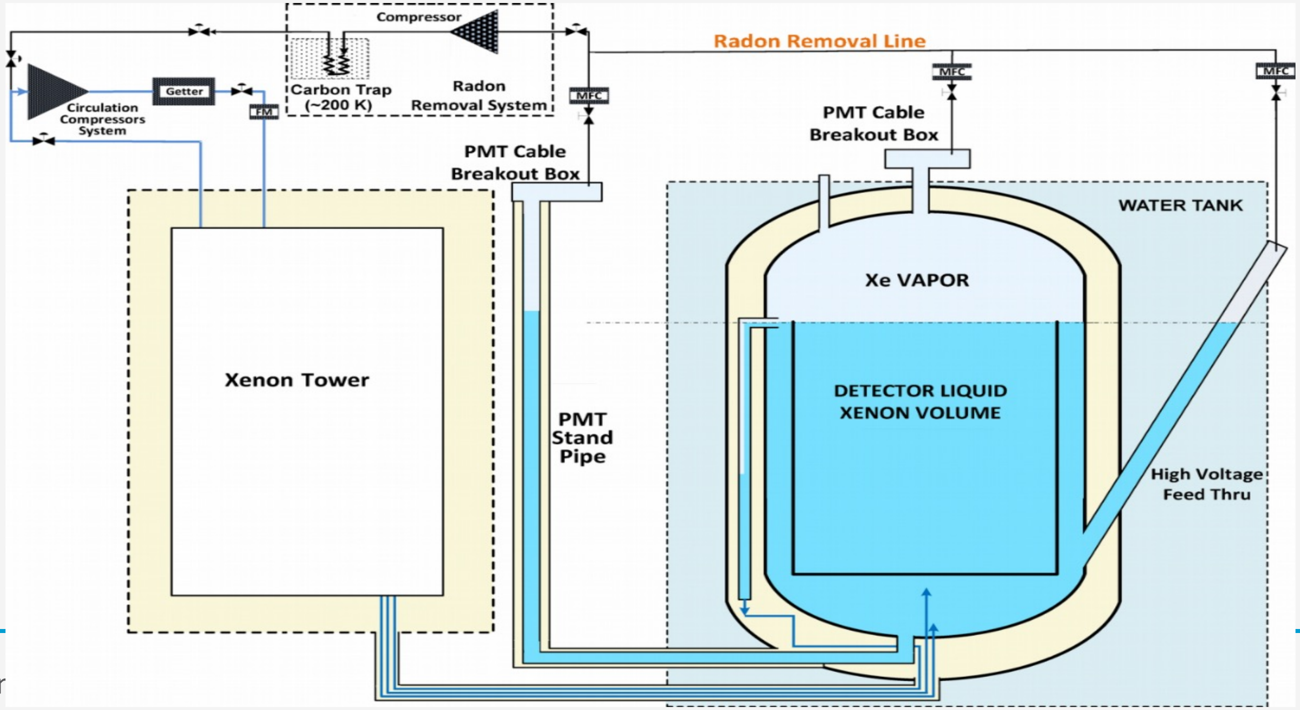
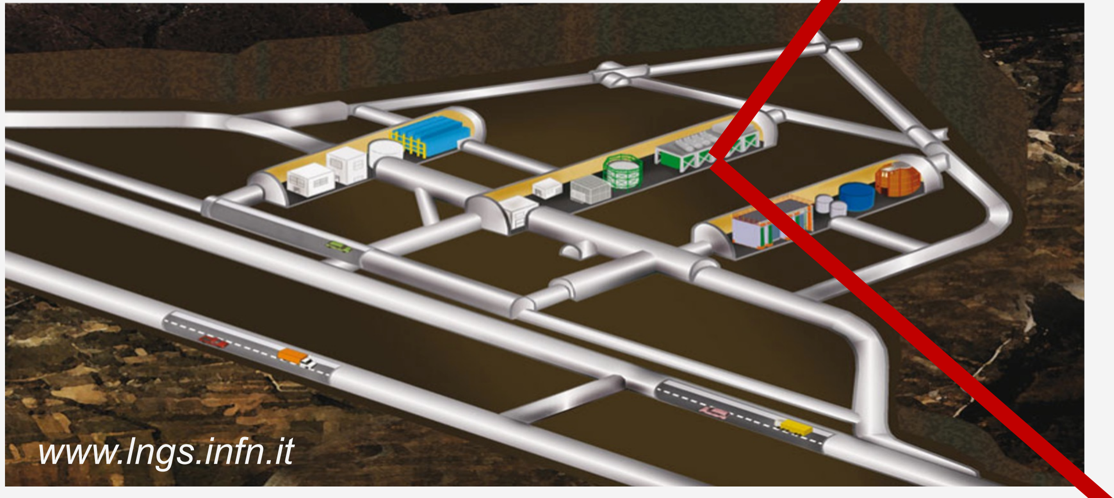


LXe swing system for radon removal under investigation

Delopments for large flow xenon capture from air might lead to a much more efficient materials to separate radon from xenon

courtesy:
Wolfgang Lorenzon
University of Michigan

Direct search for dark matter
XENONnT @Laboratori Nazionali Gran Sasso (LNGS)



Laboratori Nazionali del Gran Sasso (LNGS), Italy

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

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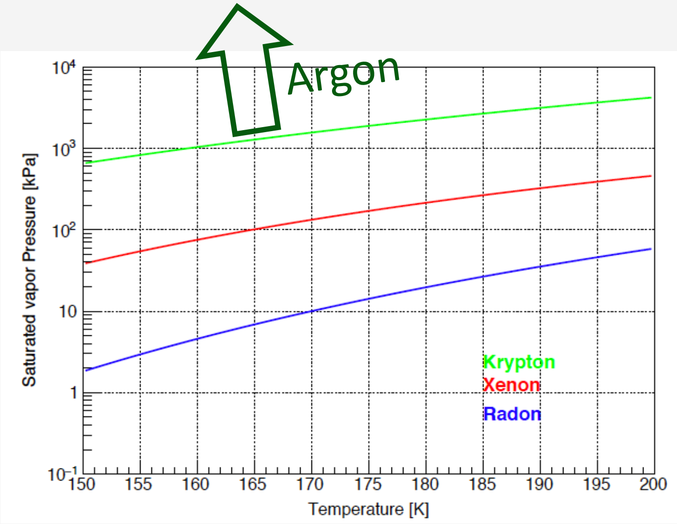
How: Making use of the different vapor pressure of the different noble gas elements

- brought into our field by **XMASS** for Kr removal:

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

- continued by **XENON** and enhanced to "online" Kr & Rn removal:

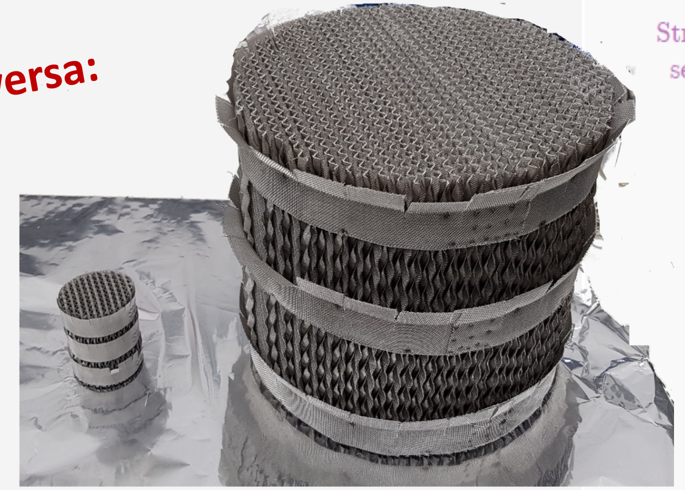
  EPJ C 77, 277 (2017), EPJ C77 358 (2017), PTEP 2022 (2022) 053H01, EPJ C 82 (2022) 1104

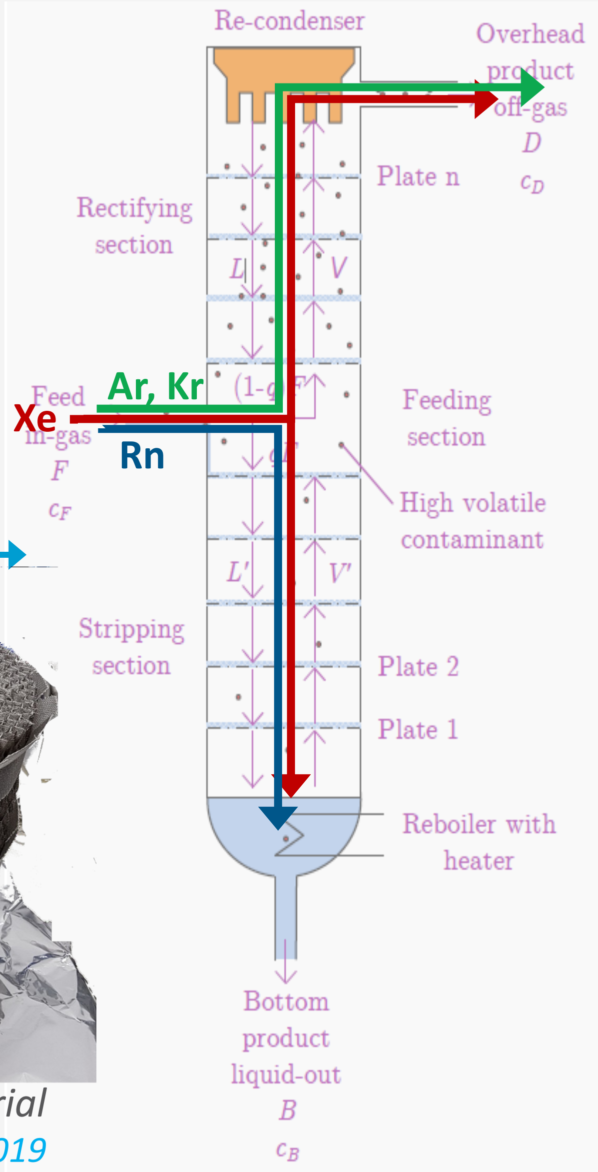


X. Cui et al. (PandaX Collaboration, JINST 16 (2021) P0704

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

Ø 20cm





Multi-stage rectification column: in reality continuous package material

M. Murra, PhD thesis, University of Münster 2019

Removing Kr by cryogenic distillation at XENON1T/nT

Make use of the different vapour pressures (volatilities) of Kr, Xe and Rn

Processing flow rate: up to 6.5 kg/h (18 SLPM)

Separation factor for Kr: $6.4^{+1.9}_{-1.3} \cdot 10^5$

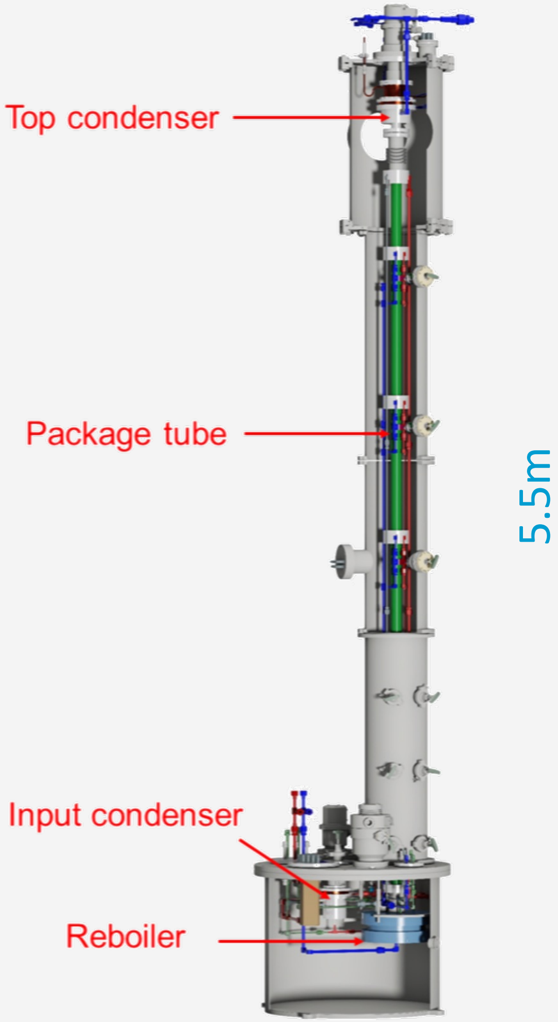
Kr removal (XENONnT): $\frac{^{nat}\mathrm{Kr}}{\mathrm{Xe}} < 2 \cdot 10^{-13}$,

achieved: $\frac{^{nat}\mathrm{Kr}}{\mathrm{Xe}} < 4.8 \cdot 10^{-14} = 48$ ppq

Kr removal achieved by “online distillation”:

Prog. Theo. Exp. Phys. 5, 053H01 (2022)

Eur. Phys. J. C77, 275 (2017)



Reduction by a continuous ^{222}Rn removal system

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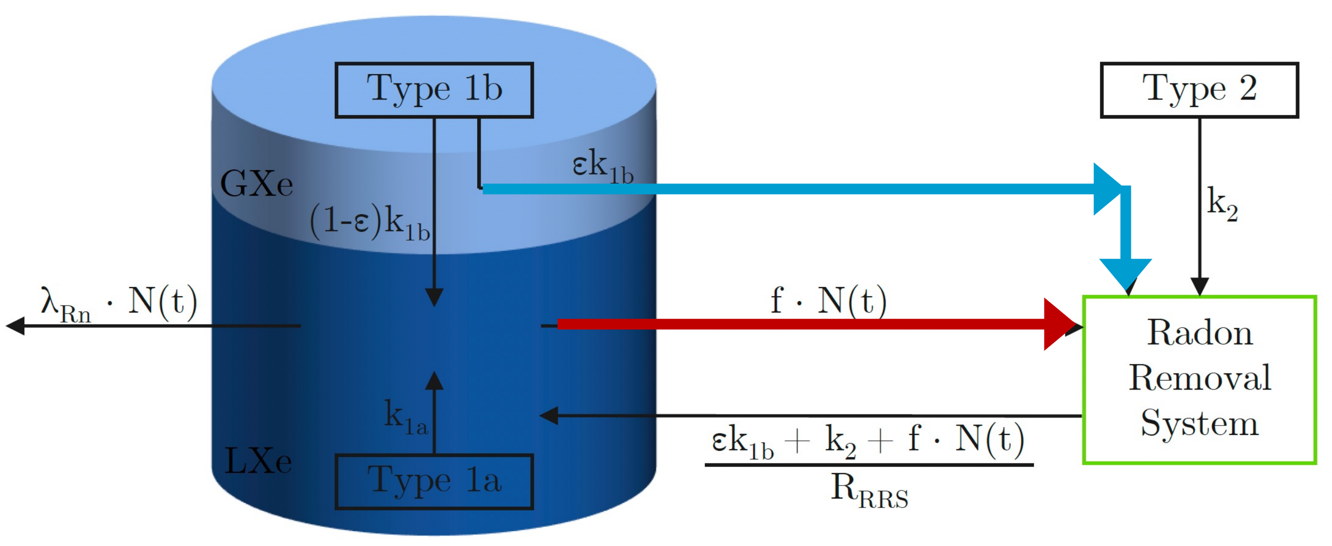


$$r(R_{RRS} \to \infty, f, \epsilon) = \frac{\lambda_{Rn} + f}{\lambda_{Rn}} \cdot \frac{k_{tot}}{k_{1a} + (1-\epsilon)k_{1b}}$$

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

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

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

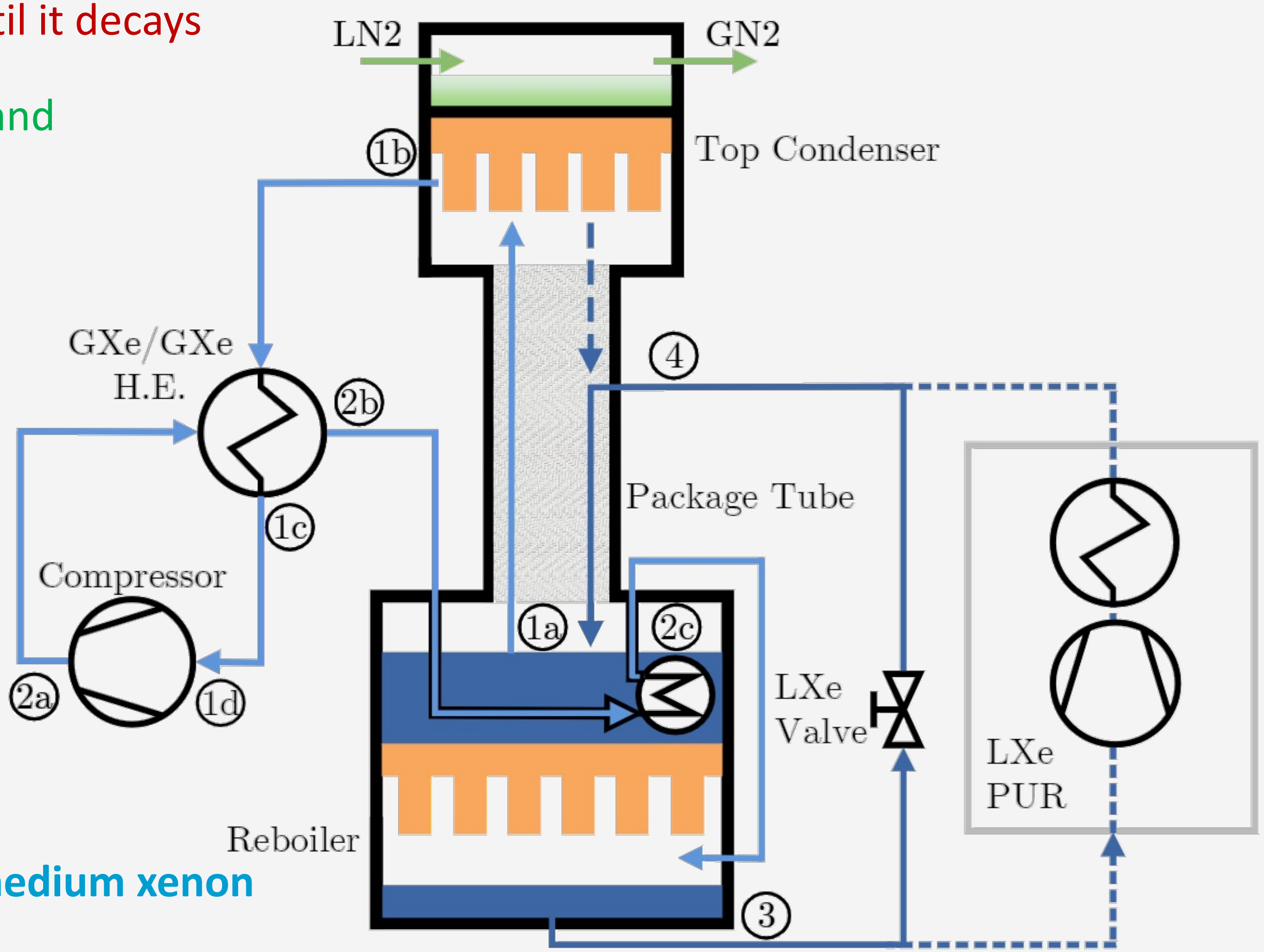
Different Rn source types:

- 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 Rn removal system
- 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

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

Radon removal system for XENONnT

- Radon as less volatile noble gas is trapped in reboiler until it decays
- Radon-depleted GXe extracted from the top condenser and reliquified in the bottom reboiler
- Target flow: 80 kg/h (225 slpm) ($T < \tau_{Rn}$)
- Reduction factor: 100 between inlet and top
- Enrichment factor: 1000 between inlet and bottom
- Reflux ratio: 0.5
- 1 kW cooling power required at top
- LXe inlet and outlet → require additional
  > 2 kW cooling power for LXe outlet
  Solution: Clausius-Rankine cycle with phase changing medium xenon (kind of heat pump)



Radon removal system for XENONnT

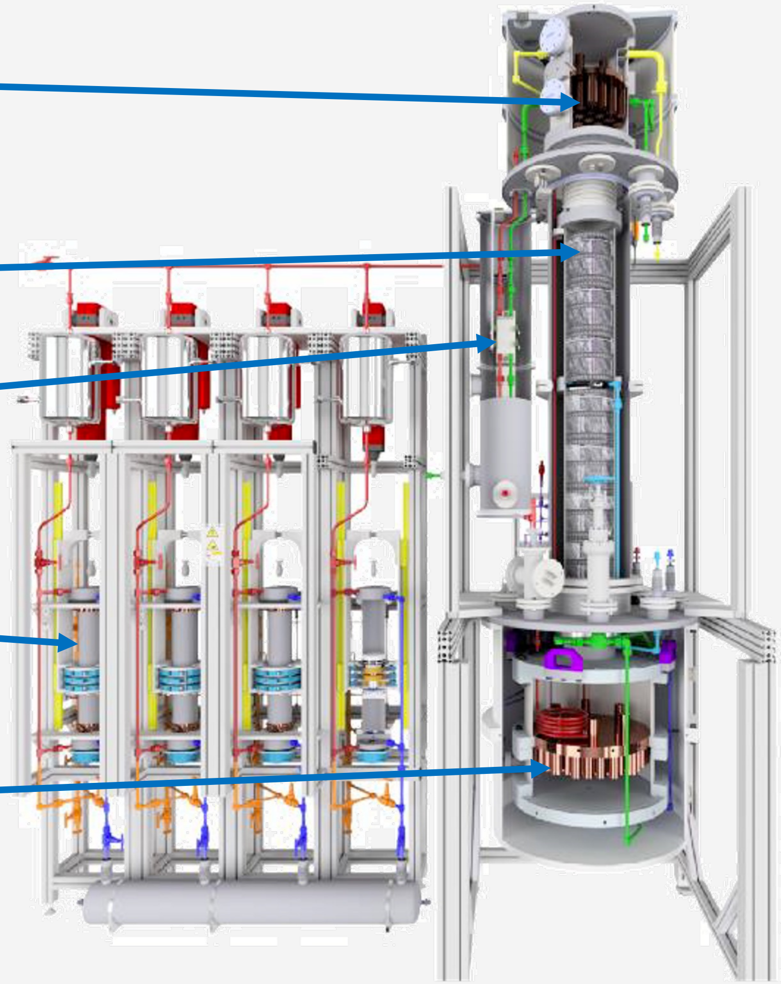
Top Condenser
Custom bath-type LN_2/GXe heat exchanger
JINST 17 (2022) P05037

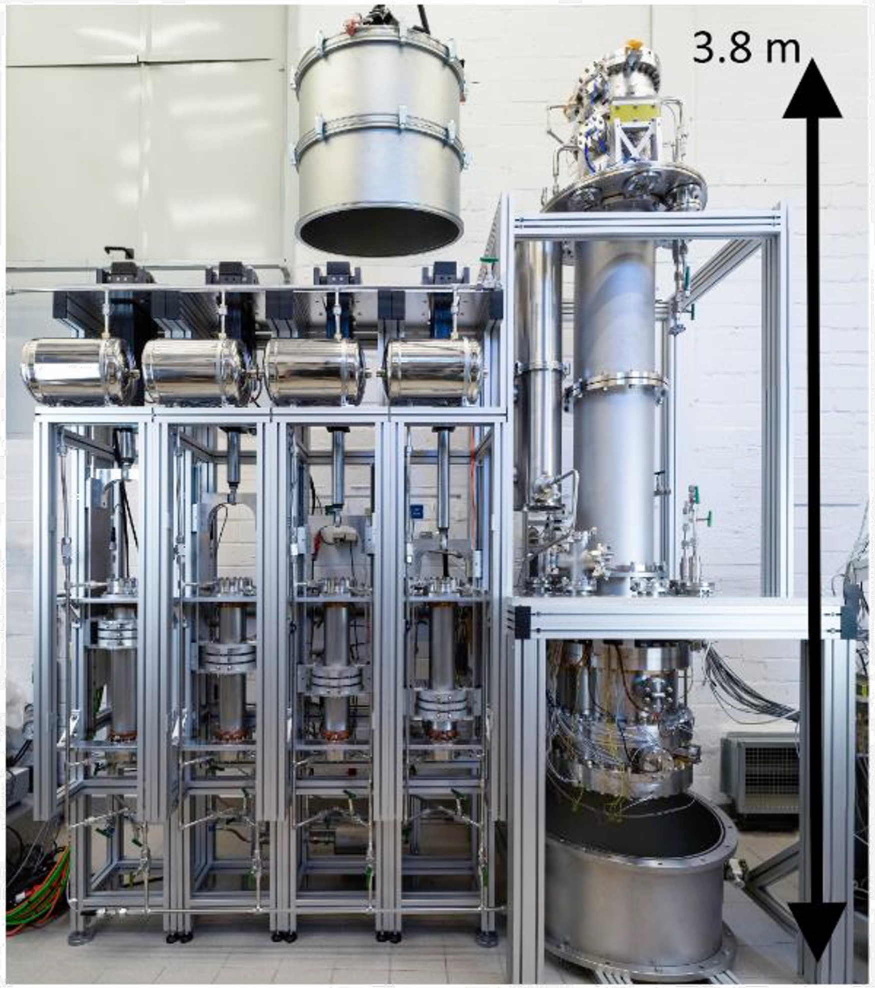
PackageTube
Large-surface package material

Auxiliary
Commercial GXe/GXe heat exchangers

Compressor
Custom four cylinder magnetically-coupled piston pump: JINST 16 (2021) P09011

Reboiler
Custom bath-type Xe/Xe heat exchanger
JINST 17 (2022) P05037





Overall system: EPJ C82 (2022) 1114

XENONnT – Novel radon removal system

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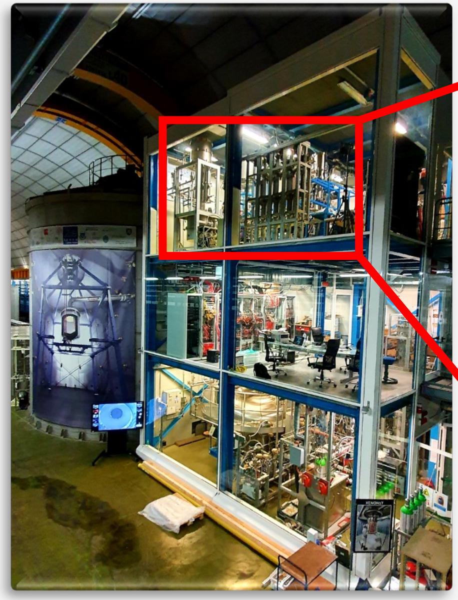
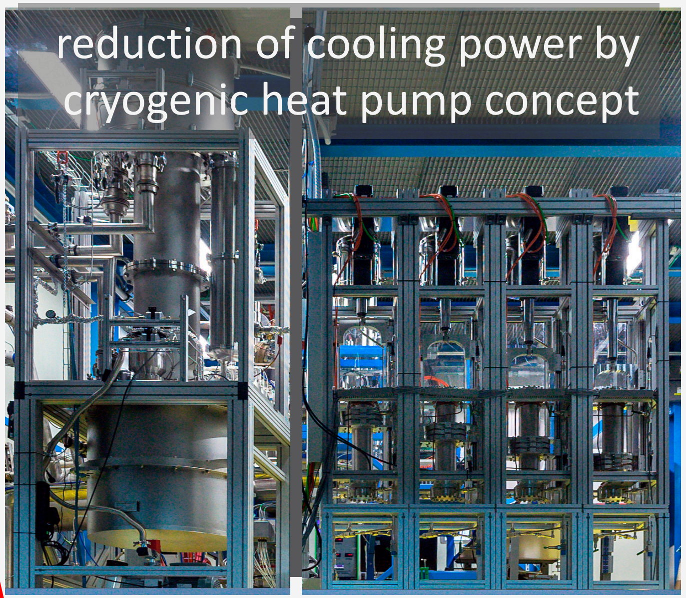
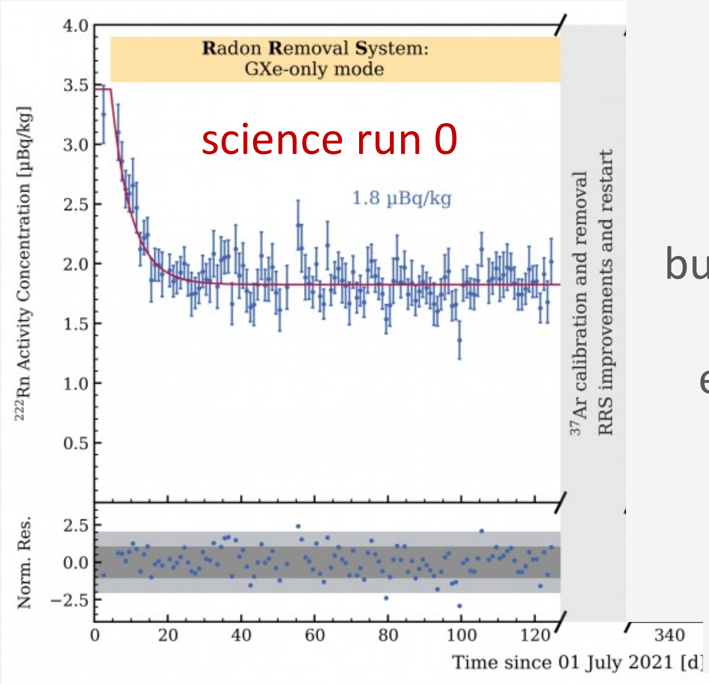
Again cryogenic distllation - key parameter:

- liquid xenon inlet and outlet allowing high flow
- flow of up to 0.4 l/min LXe = 225 slpm ≈ 80 kg/h
- **reduction factor 2** for cryogenics‘ sources by GXe extraction at 25 slpm





Radon concentration at XENONnT



similarly to LZ but at ≈ 50 times higher GXe extraction flux

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

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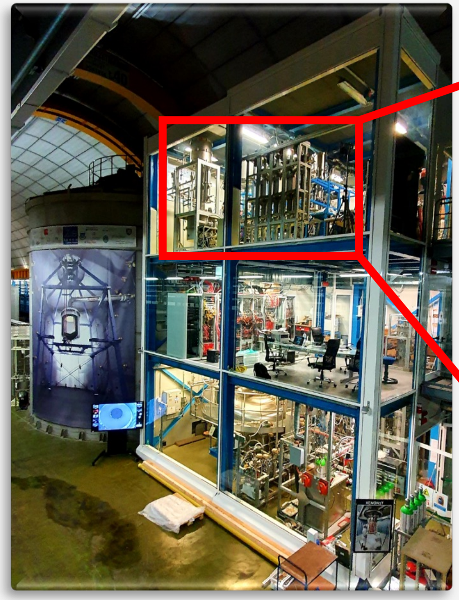
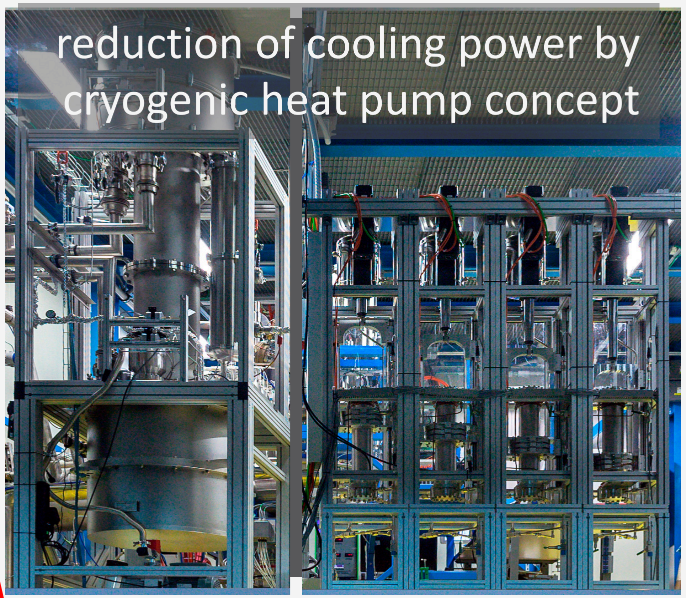
- **another reduction by factor of 2** for sources within detector by high-flow LXe extraction at 200 slpm





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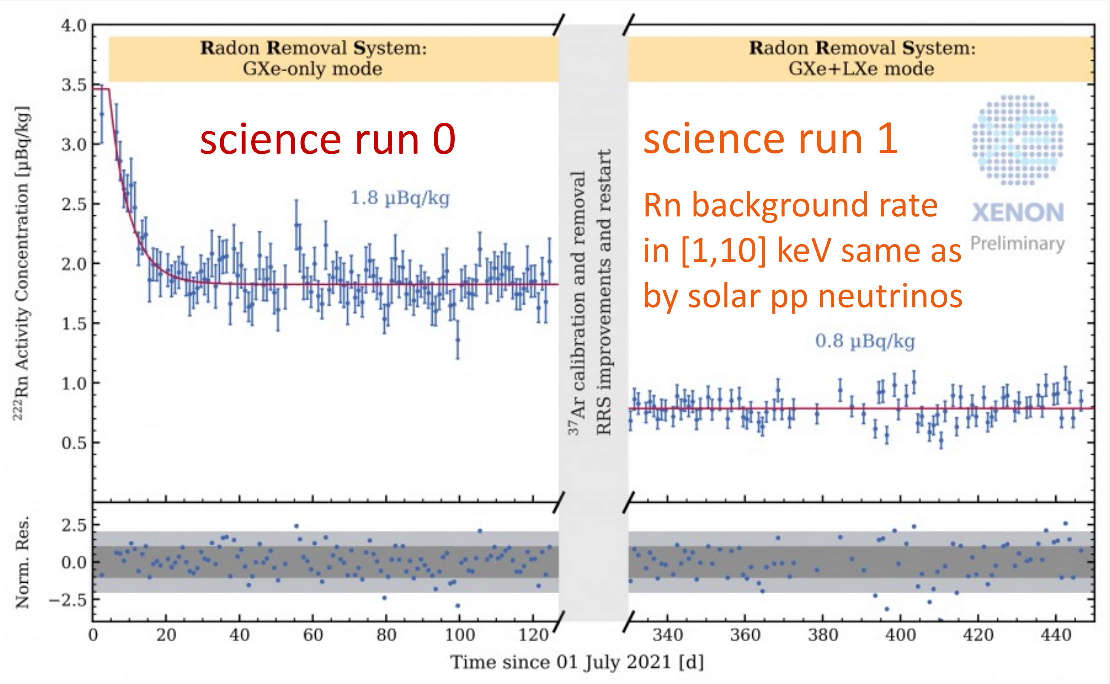

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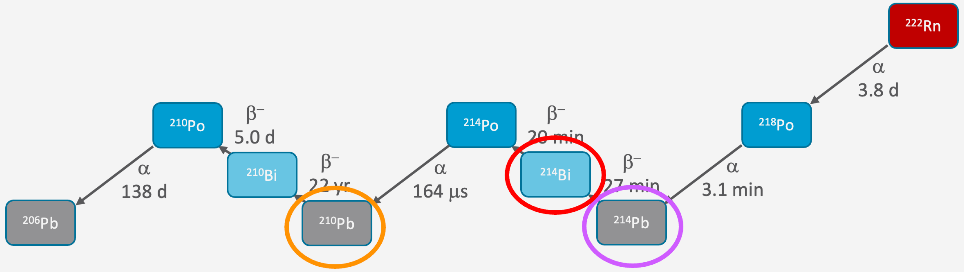
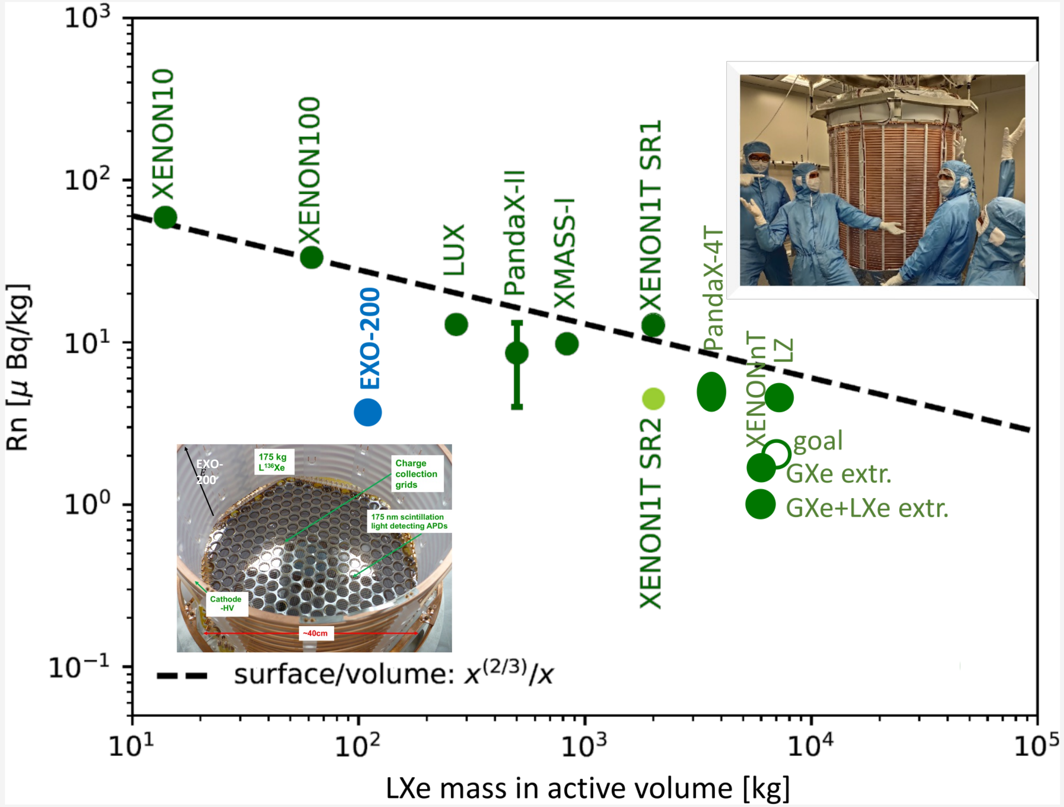
Rn requirements for xenon-based dark matter exp.

^{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 $0\nu\beta\beta$ decay searches if not fully BiPo-tagged
- Additional backgrounds from plate-out of ^{210}Pb

^{222}Rn concentrations achieved so far



Yamashita-san plot

Rn requirements for xenon-based dark matter exp.

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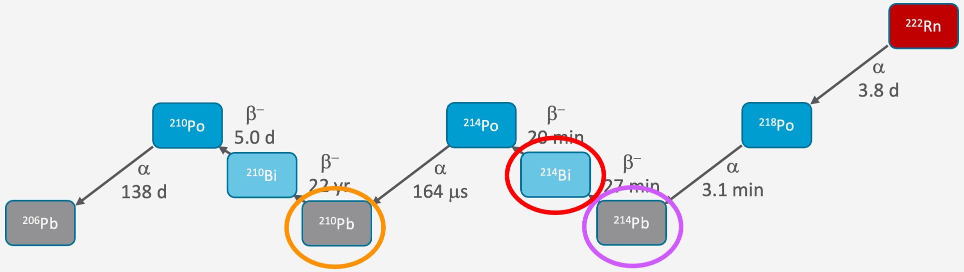

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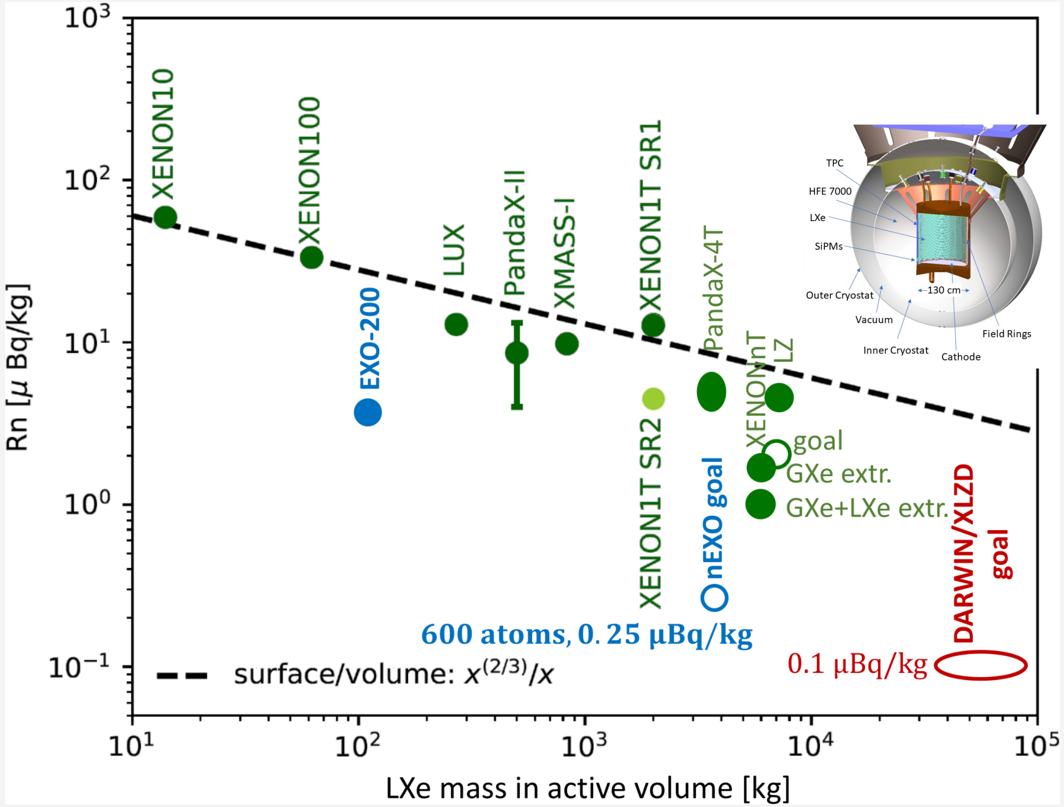

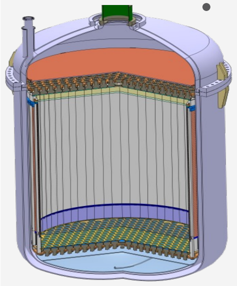

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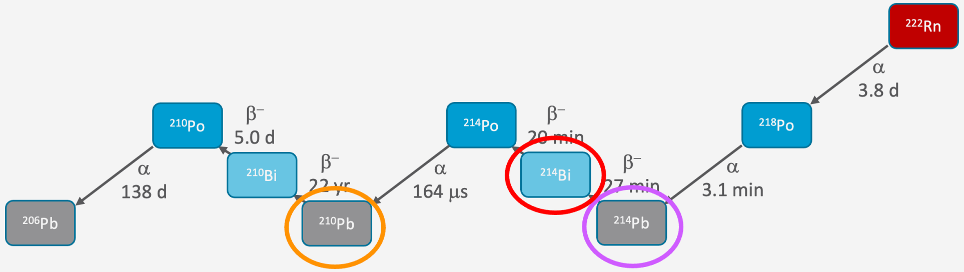

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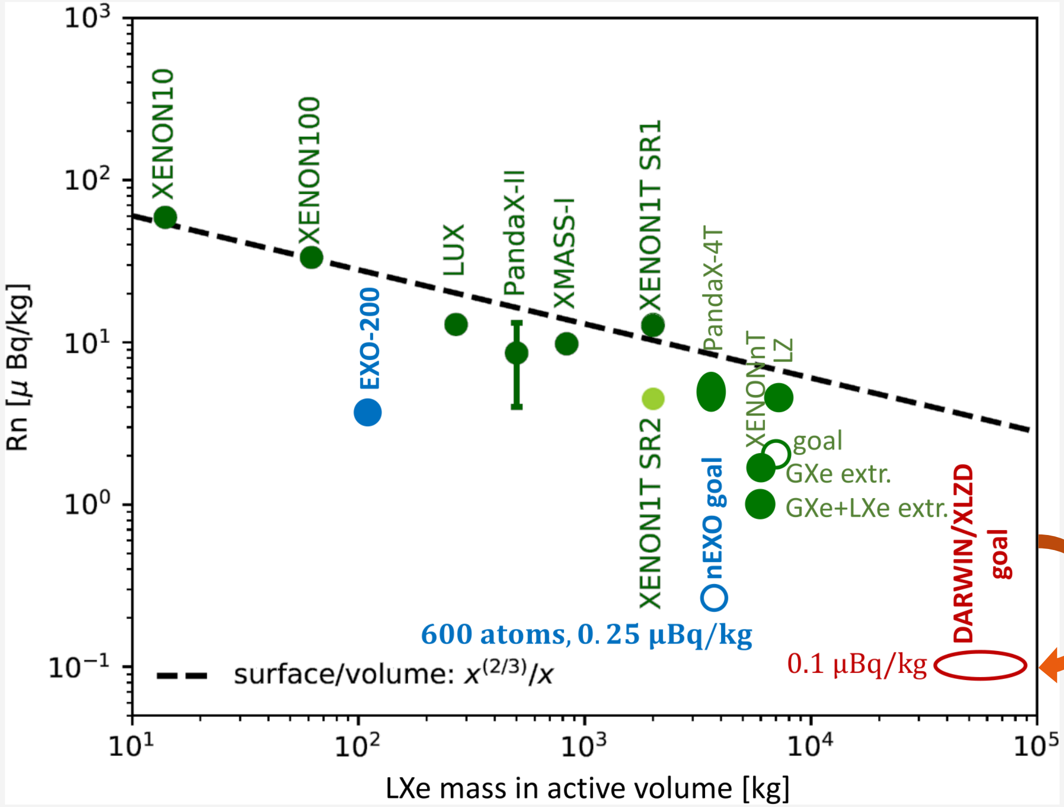
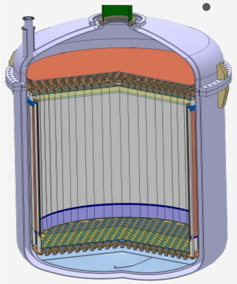
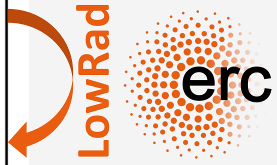




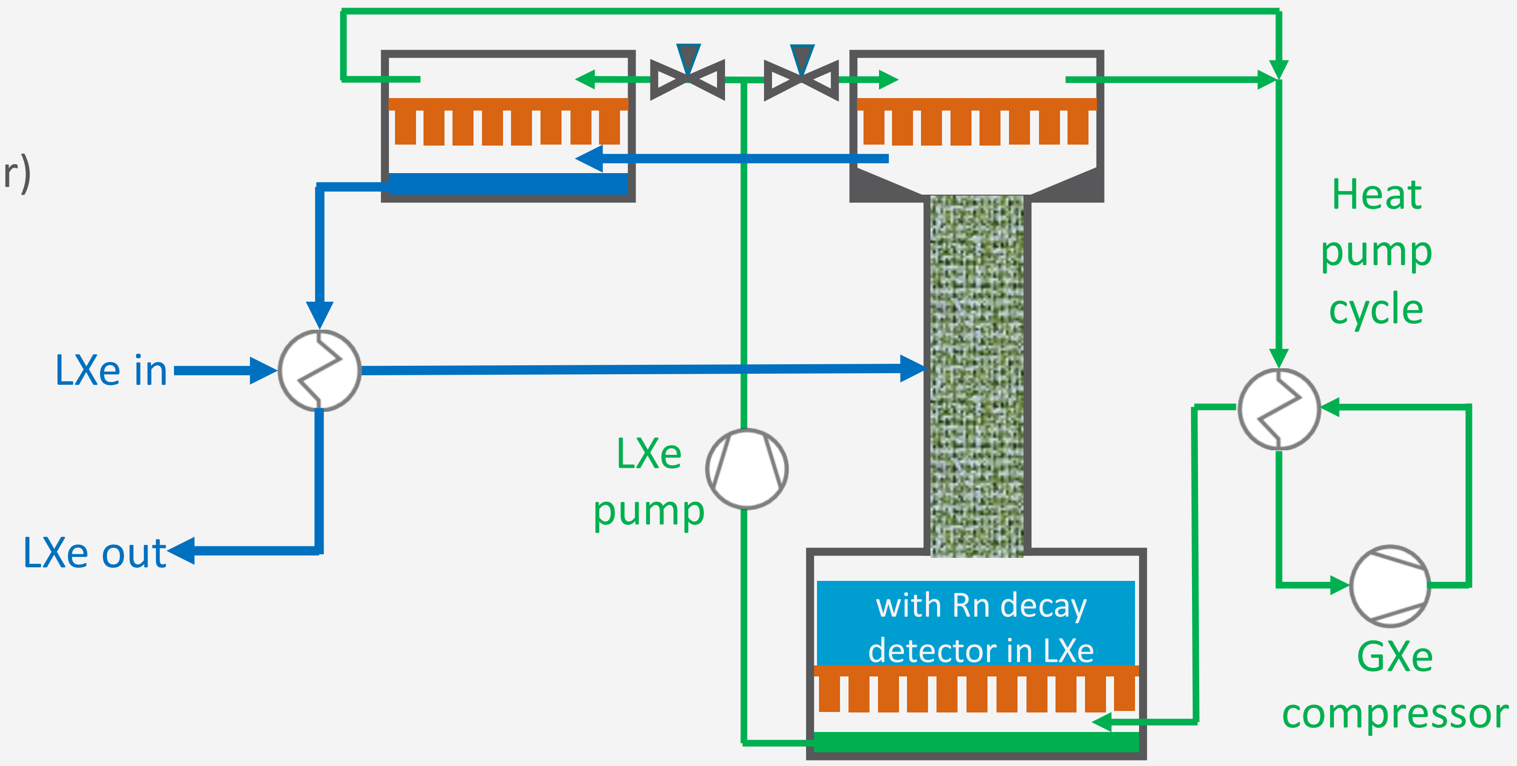


LowRad goals:
Develop technologies to reach another factor 10 reduction in ^{85}Kr (30 ppq ^{nat}Kr) and ^{222}Rn (0.1 µBq/kg) by online removal:
"less than 1 Rn atom in 100 mol of xenon"

Cryogenic distillation system for DARWIN/XLZD

How to purify 50 t of Xe from Rn in $\leq$ 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
  should include online Rn decay monitor
- Final system:
  should be integrated with purification system
  from electronegative impurities
  and with online Kr removal system
  should be installed in a water shield to avoid Xe activation



- R&D and demonstrator within ERC AdG LowRad

Conclusion

- **Radon mitigation needs to start with material screening & selection as well as smart detector design**, all Xe-systems including purification system must be "Rn emanation free"
- **Rn-progenies decays in large Xe detectors should be identified** by spatial & delayed coincidences
- **Online Rn removal is the last step**, two cases
  - a) **Xe extraction at places with high Rn emanation/injection:** can be handled by moderate flow systems
  - b) **High flow Xe extraction** is ultima ratio, requires large through-put systems, probably LXe flow
- **Rn removal from Xe by**
  - a) chromatography: demonstrated by LZ at $\mathcal{O}$(1 slpm)
  - b) LXe swing system under development at LZ for larger flows

  } could be very efficient with the right adsorption material

  - c) Cryogenic distillation system demonstrated at XENONnT at $\mathcal{O}$(80 kg/h = 225 slpm)
  - d) Advanced cryogenic distillation system is being developed within ERC AdG LowRad for concentrations down to 0.1 µBq/kg and flows of $\mathcal{O}$(750 kg/h) → enough for a kilotonne xenon experiment for Xe extraction from high Rn injection places

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