WWU MÜNSTER

Purifying xenon from radioactive noble gases

International Workhop on Applications of Noble Gas Xenon to Science and Technology

XeSAT2023, Nantes, June 5-9, 2023

Christian Weinheimer* – Institute for Nuclear Physics, University of Münster

* member of XENON, DARWIN/XLZD, technical member of nEXO

- Introduction
- Need to purify xenon (argon) from radioactive noble gases
- Kr (Ar) removal with charcoal chromatography and online cryogenic distillation
- Rn online removal with charcoal chromatography and cryogenic distillation
- Goal of ERC Advanced Grant „LowRad“
- Conclusions

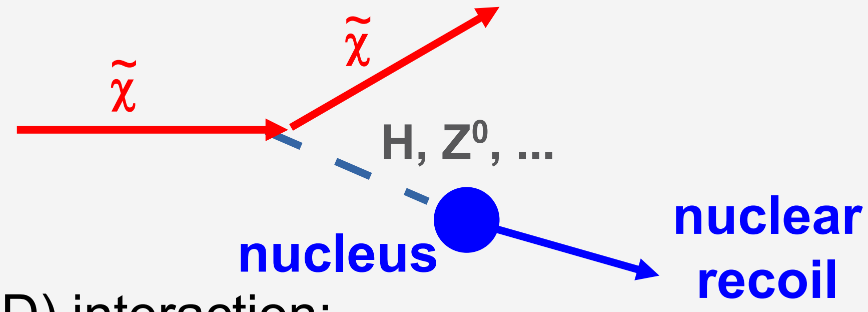
Experimental direct search for dark matter: WIMPs:

Search for nuclear recoil: energy transfer to nucleus by invisible particle

Elastic coherent scattering of the nucleus

mediated by a spin 0 (Higgs-like) or spin 1 (Z-like) propagator

Effectively a coherent spin-independent (SI) or spin-dependent (SD) interaction:



But two generic problems:

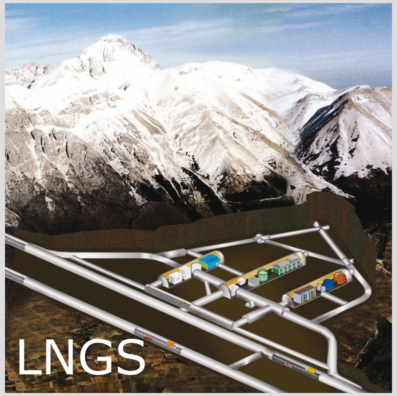
- **very low rate**

  → **go deep underground to avoid cosmic rays & secondary muons**

  & ultra-clean materials w.r.t. radioactivity

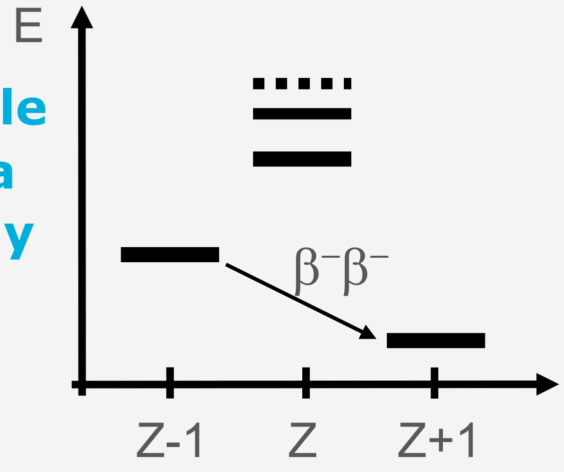
  & double read-out (light+charge or heat+charge or heat+light)
- **very low recoil energy**

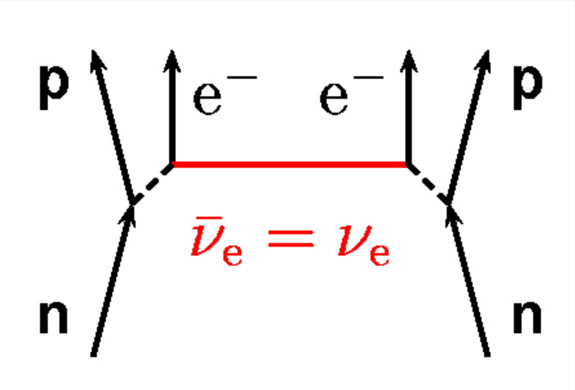
  → **ultra-sensitive detector**



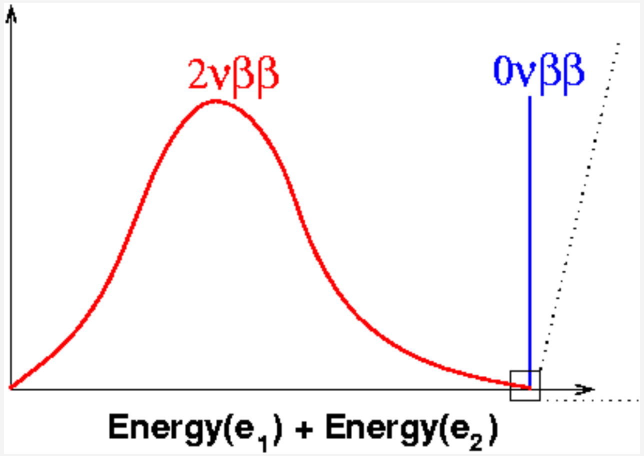
Experimental search for neutrinoless double beta decay

double beta decay





neutrinoless (0νββ)



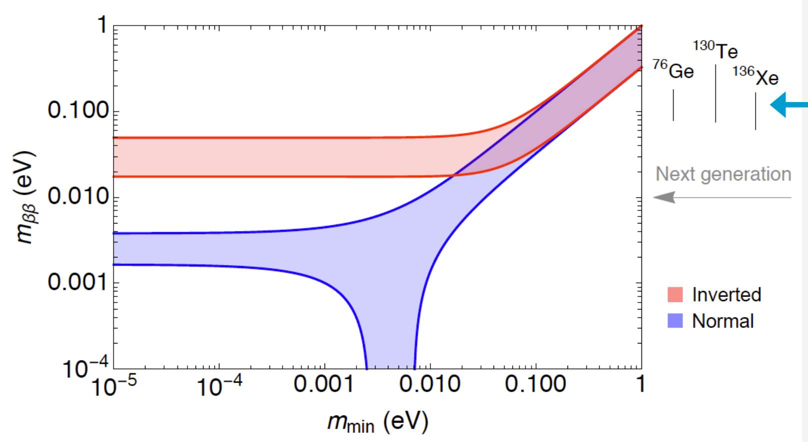
Signature: sum of both electron energies peak sharply at Q-value

Search for 0νββ: $m_{\beta\beta} \coloneqq \left|\sum_i U_{ei}^2 \cdot m(\nu_i)\right|$

sensitive to Majorana neutrinos only, challenge of uncertainties of nuclear matrix elements

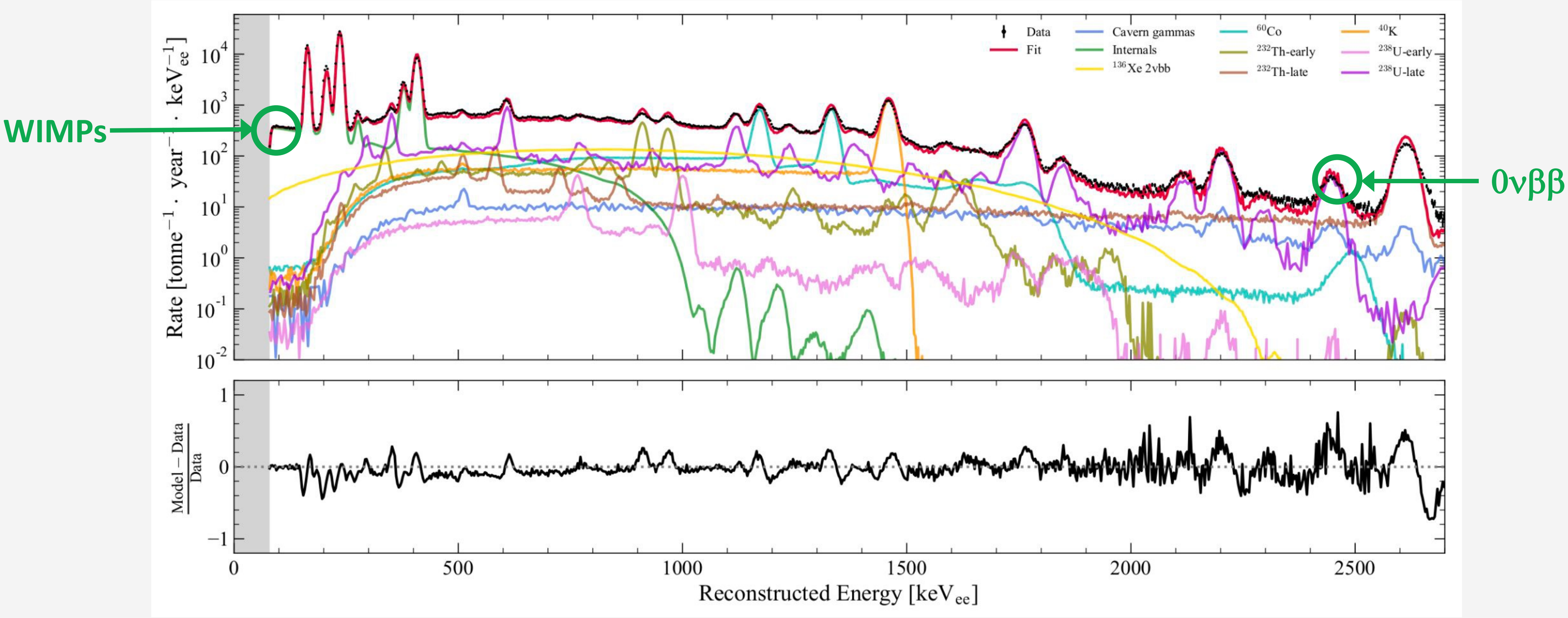
disclaimer: $m_{\beta\beta}$ are valid only, if 0νββ works dominantly via ν exchange

Discovery of 0νββ would proof lepton number violation !



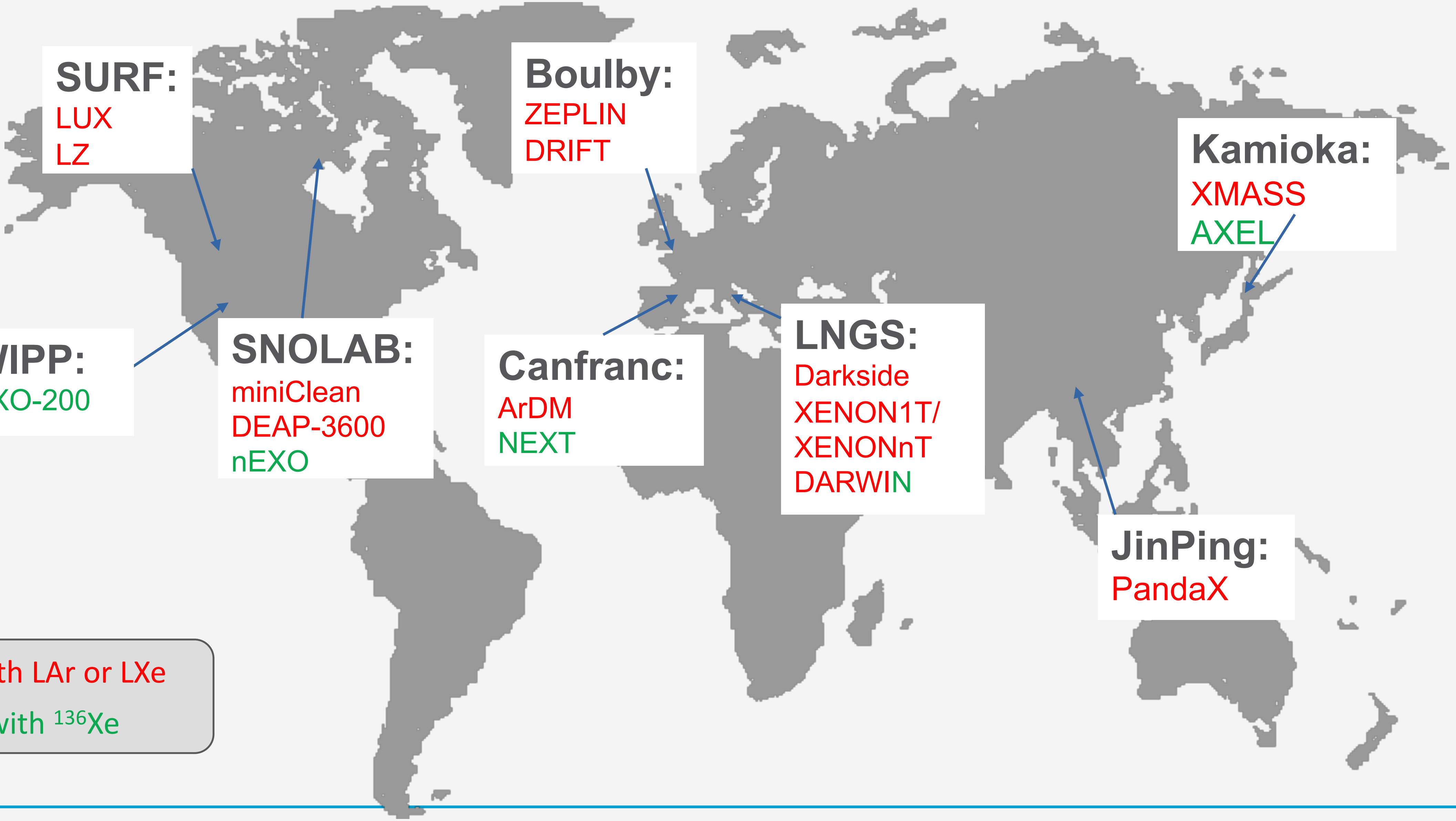
$T_{1/2} \approx 10^{26}$ yr

WIMPs and $0\nu\beta\beta$: rather different energy scales - different requirements as well?



from LZ, see talk by P. Brás at XeSAT2023

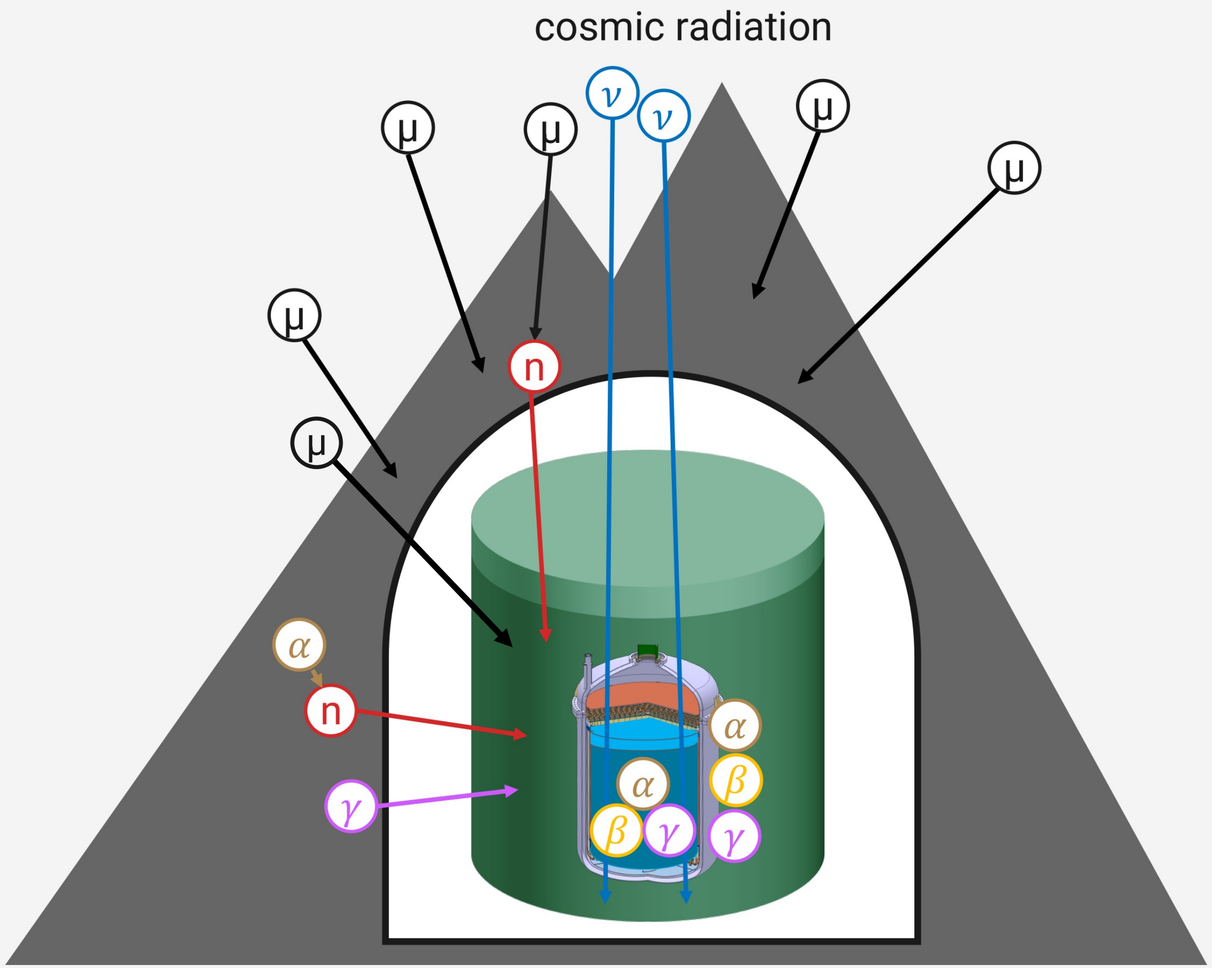
Direct Cold Dark Matter and $0\nu\beta\beta$ searches with noble gases



DM search with LAr or LXe

$0\nu\beta\beta$ search with ^{136}Xe

Limiting backgrounds in noble gas DM detectors



Expected dark matter scattering rate:

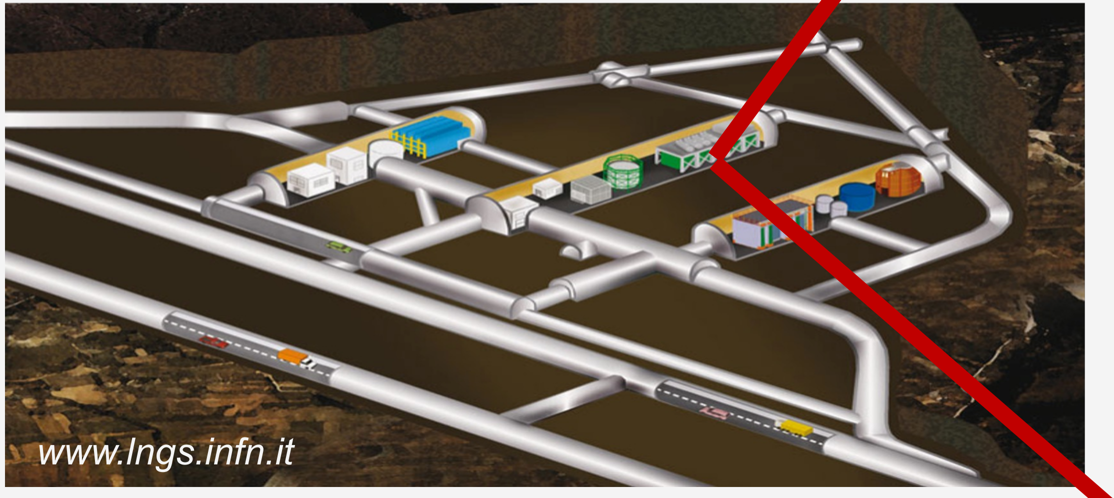
1 event per 10t and year

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

Most background problems solved by

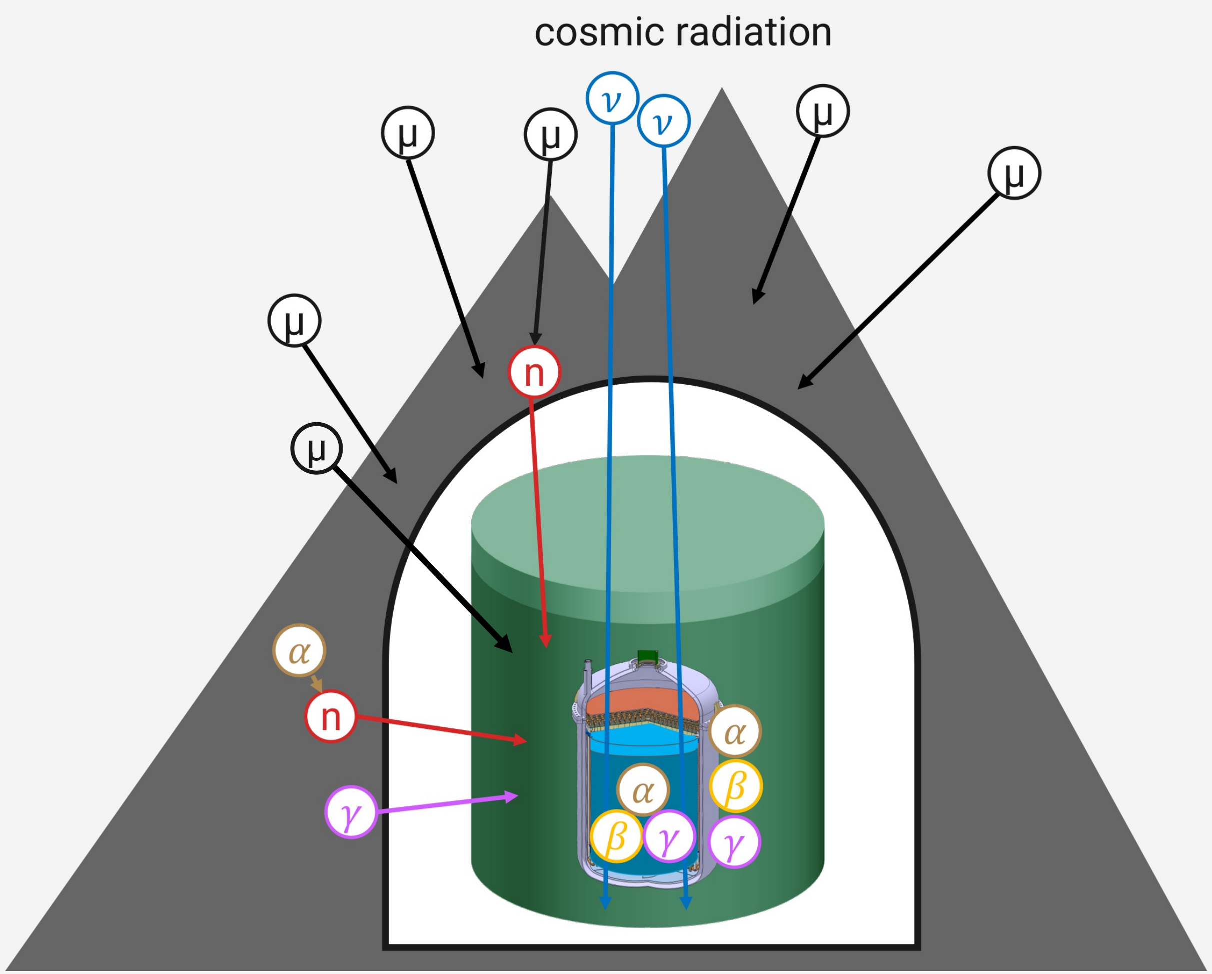
- going underground
- extra shieldings & vetos

Direct search for dark matter
XENON1T/nT @Laboratori Nazionali Gran Sasso (LNGS)



Laboratori Nazionali del Gran Sasso (LNGS), Italy

Limiting backgrounds in noble gas DM 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 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)

Dual Phase Xenon Time Projection Chamber

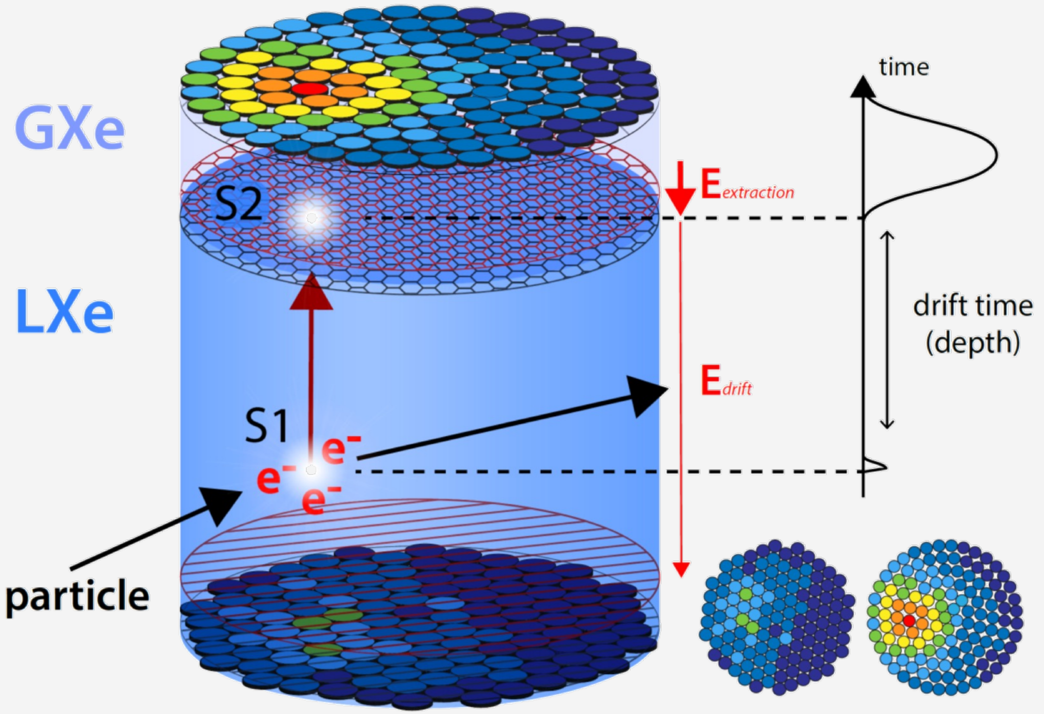
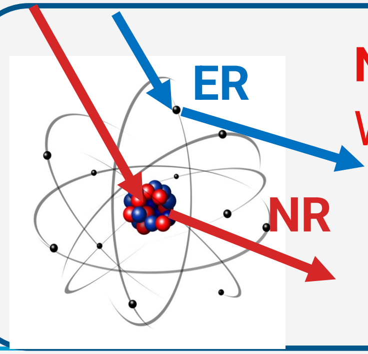


Image by L. Althüser

S1 light signal:
- prompt scintillation photons

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

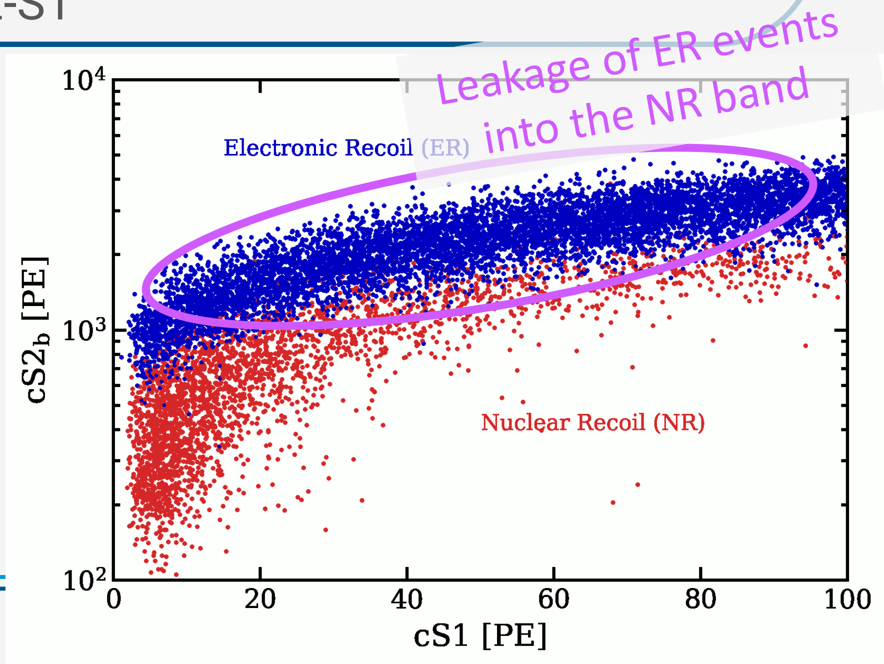
3D vertex reconstruction (-> fiducialisation):
- X,Y: S2 hit pattern
- Z: drift time S2-S1



NR (Nuclear Recoils)
WIMP signal, neutrons, CEvNs

ER (Electronic Recoils)
γ, β backgrounds

Discrimination from S2/S1
Larger for ER than NR

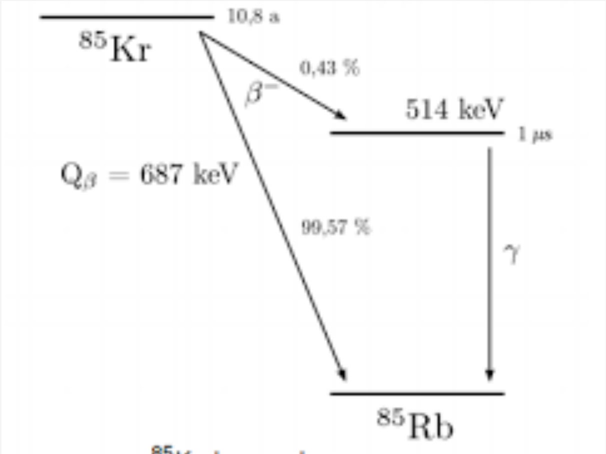


A closer look to ^{85}Kr and ^{222}Rn with its progenities

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

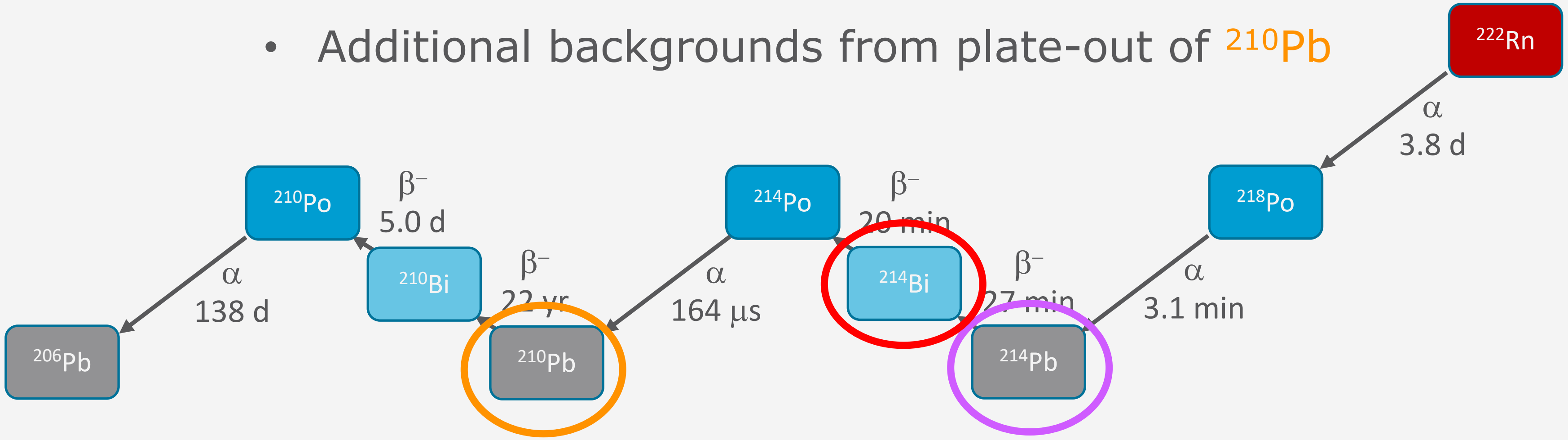
^{85}Kr: $1 - 2 \cdot 10^{-11}$ in ^{nat}Kr, man-made



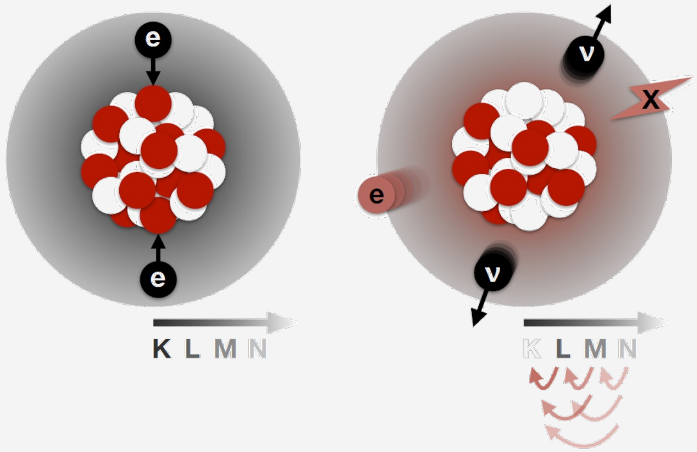
^{85}Kr decay scheme

^{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



XENON1T – Searches in the electronic recoil band

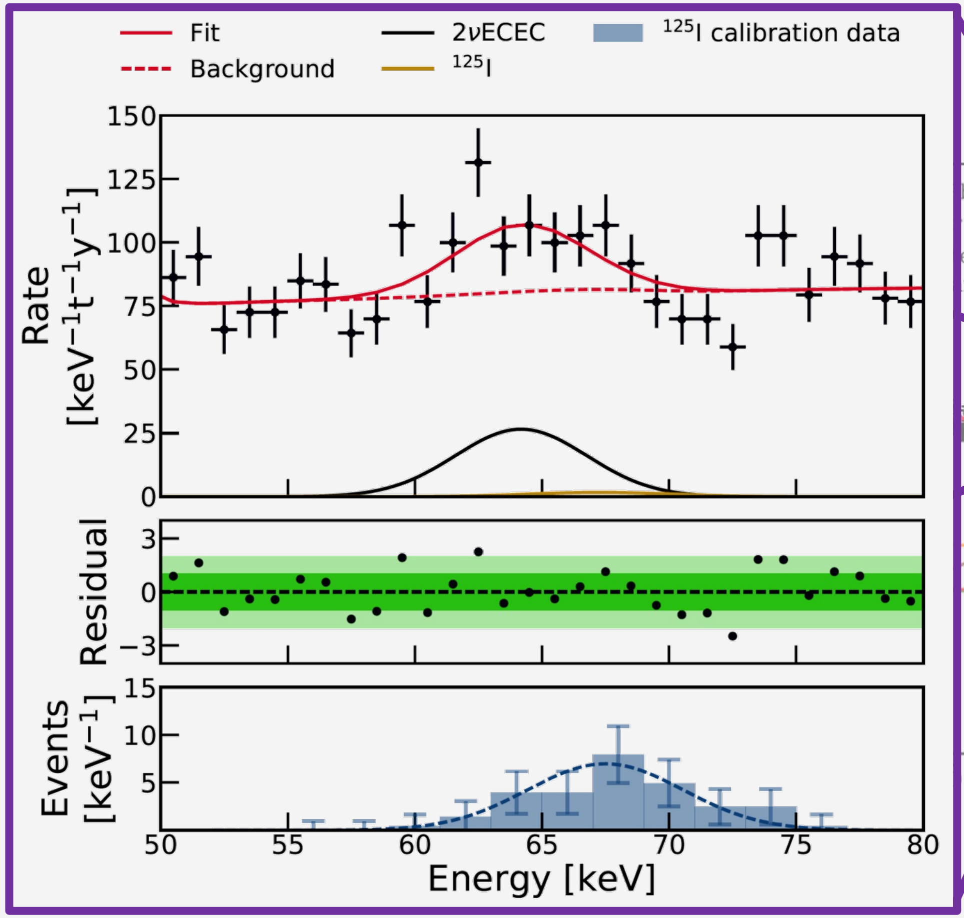


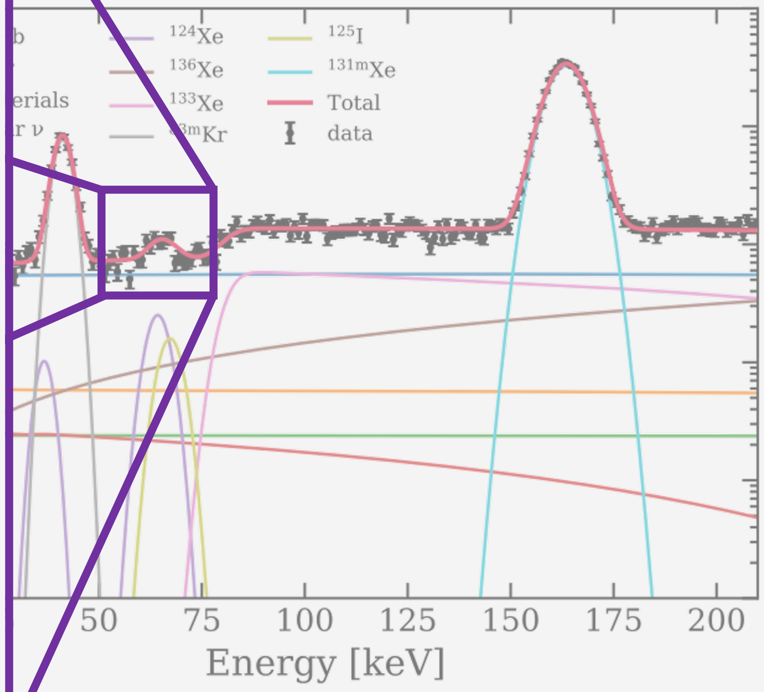
$^{124}Xe + 2e^{-} \rightarrow {}^{124}Te + 2\nu_e$

Double K-shell capture

- X-ray + Auger electrons create line at 64.3 keV

$T_{1/2}^{KK}$ = (1.8 ± 0.5_{stat} ± 0.1_{sys}) x 10^{22} yr





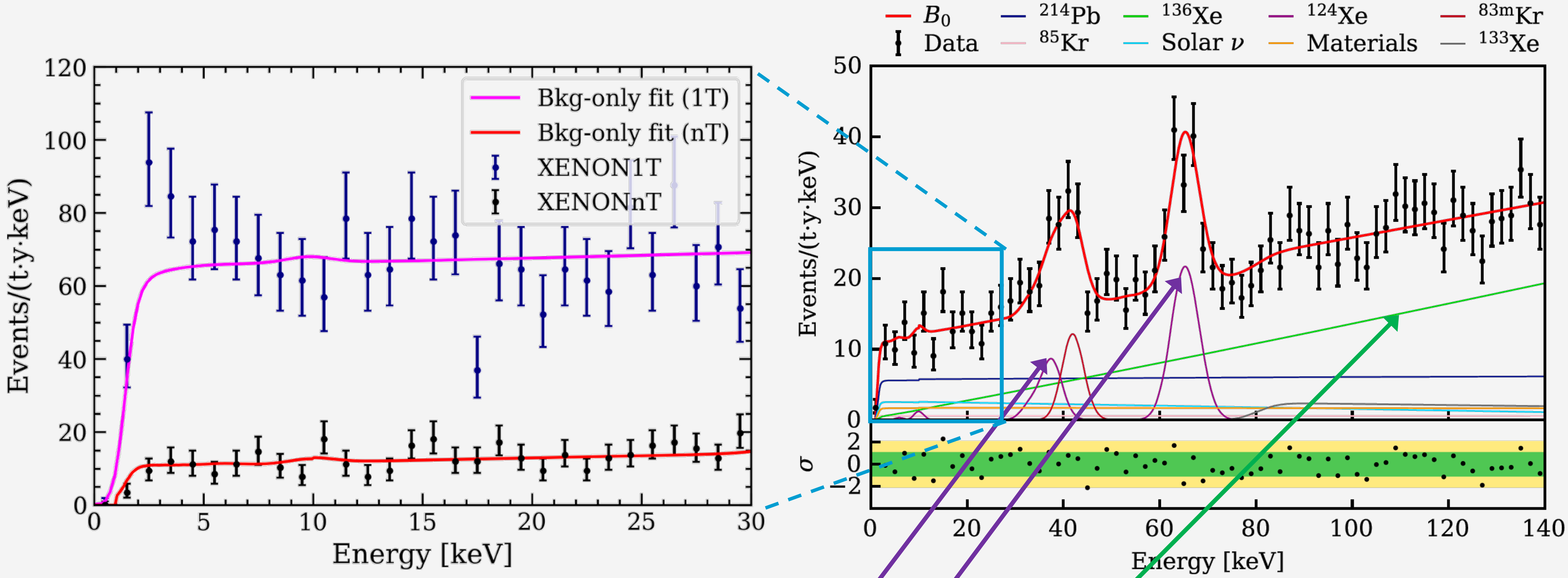
PRD 102, 072004 (2020)

Nature 568, 532-535 (2019)

Main authors: A. Fieguth, C. Wittweg, U Münster

WWU MÜNSTER

Significantly lower background of XENONnT



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

Much lower elecron recoil background:

- **Spectrum dominated by double weak decays (ECEC of ^{124}Xe, 2νββ of ^{136}Xe)**
- **XENON1T excess is gone, was likely tritium contamination, which now got purified**

Removal of Intrinsic radioactive contaminants: ^{85}Kr

Intrinsic noble gas contaminants Kr-85 and Rn-222 (Pb-214) inside the xenon

- ➔ electronic recoil events from the low energy β-spectrum of these radioactivities contaminate ROI for dark matter WIMP search
- ➔ searches for new physics using electronic recoil signals becomes possible when these radioactivities are drastically reduced
- ➔ Kr-85 originates from xenon extraction from air and needs to be **removed once** before the dark matter search to Kr-nat/Xe < 0.2 ppt
- ➔ commercial xenon comes with ^{nat}Kr-/Xe > 1 ppb with ^{85}Kr-85 / ^{nat}Kr ~ 2 x 10^{-11}

XENON1T/nT

Cryogenic Distillation "online" at LNGS

- Initial Kr removal during filling
- Online removal by distilling the GXe inside the cryostat
- Online mode also removes radioactive Ar-37
- Kr/Xe < 0.05 ppt

LZ

Gas charcoal chromatography "offline" at SLAC

- Xe then shipped to SURF
- Handle Xe of varying initial Kr contamination - multiple passes if necessary
- Kr/Xe = 0.14 ppt

PandaX-4T

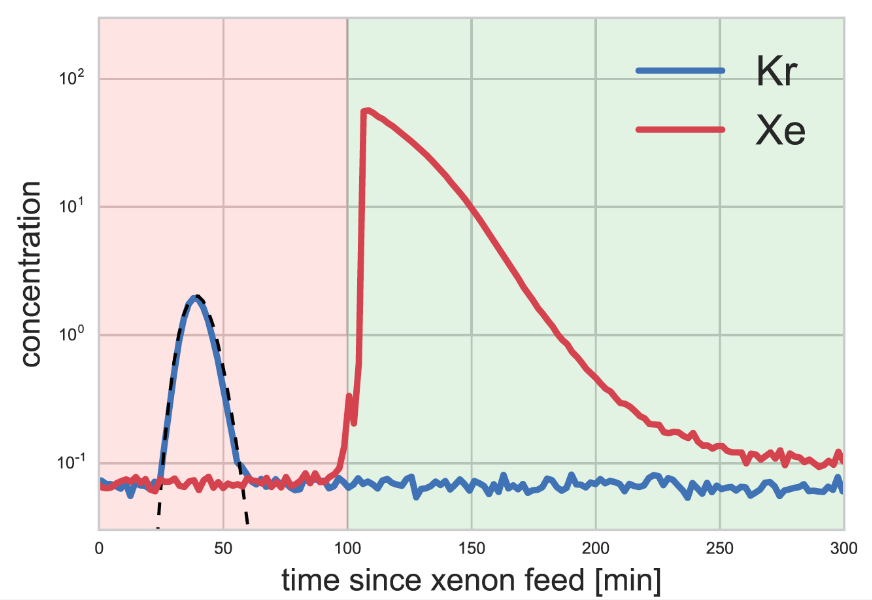
X. Cui *et al* 2021 JINST 16 P07046

Cryogenic Distillation "online" at CJPL

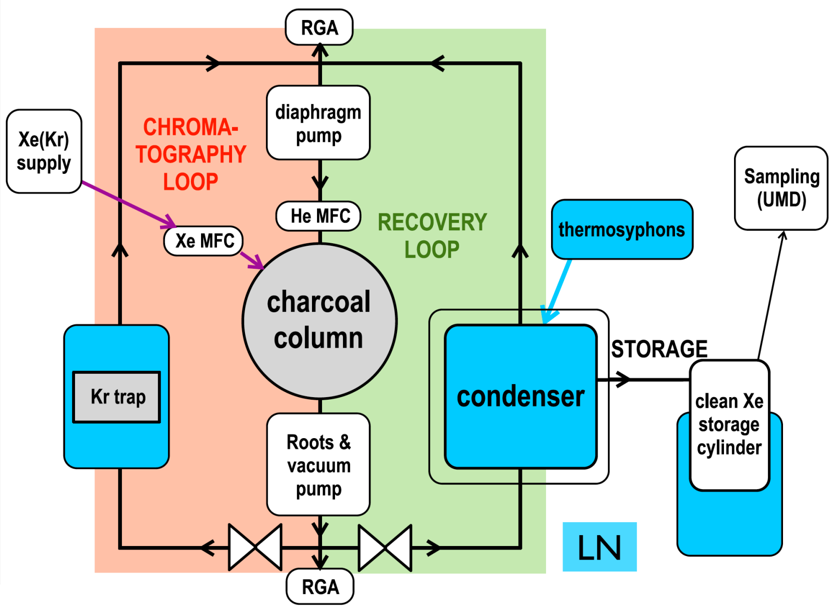
- Initial Kr removal during filling
- Online removal by distilling the GXe inside the cryostat
- Online mode also removes radioactive Ar-37
- Kr/Xe = 0.33 ppt

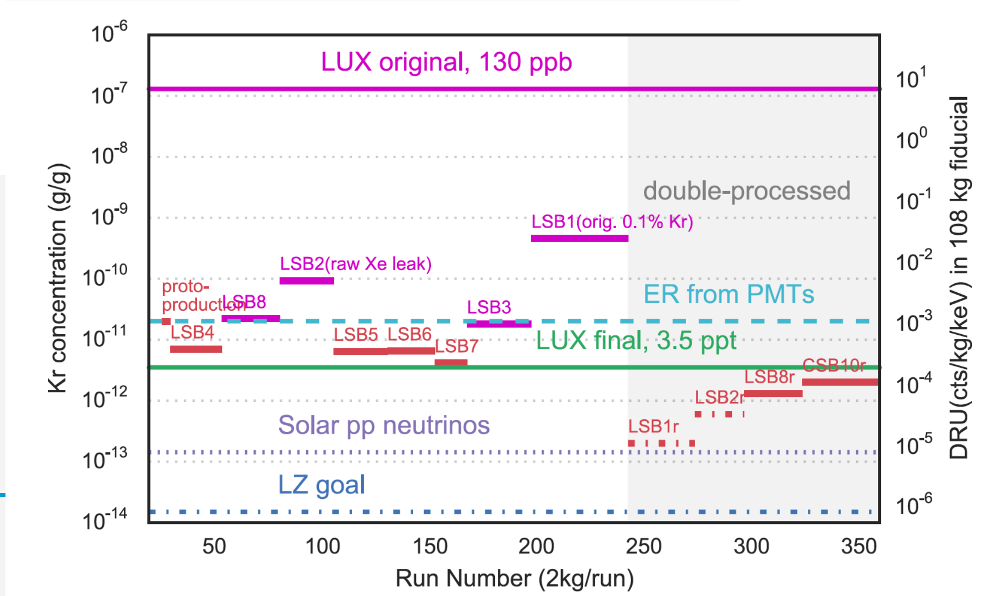
courtesy: Elena Aprile

^{85}Kr removal by charcoal chromatography for LZ before the start of the experiment



J. Albers et al., arXiv:2211.17120





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

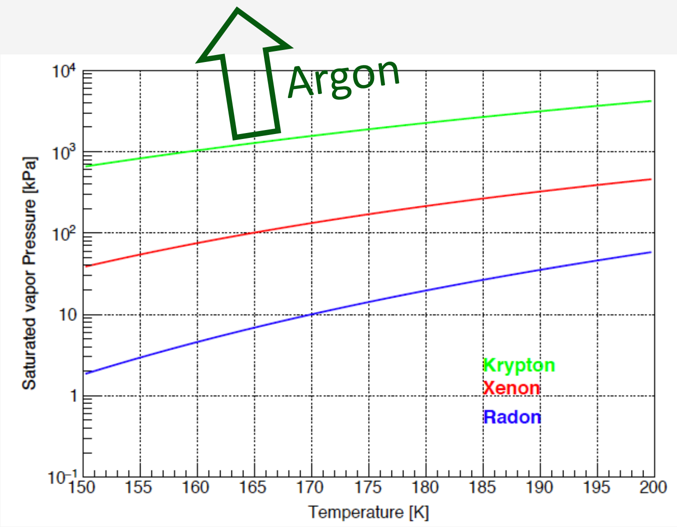
How: Making use of the different vapor pressure of the different noble gas elements

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

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

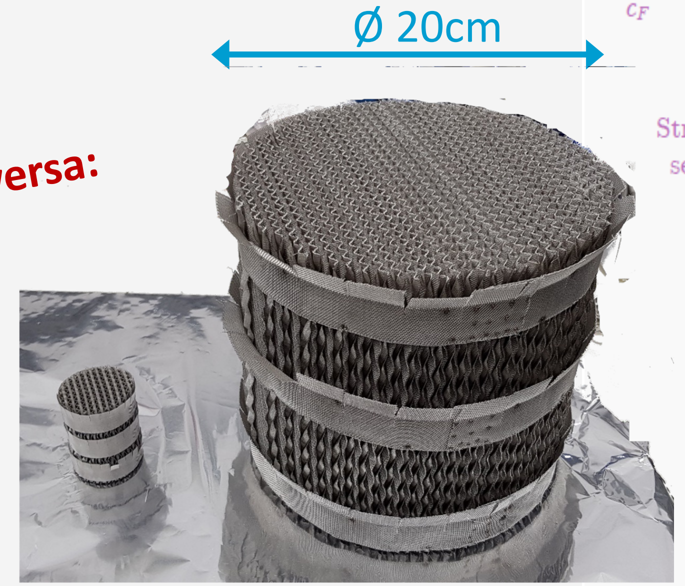
- continued by **XENON** and enhanced to "online" Kr & Rn removal:

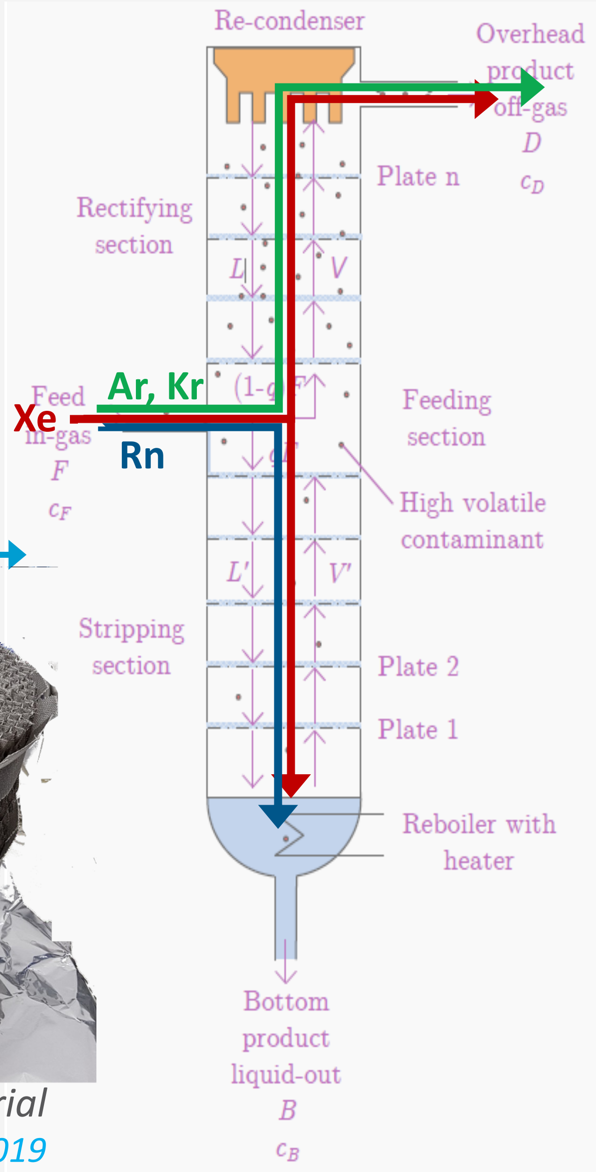
  EPJ C 77, 277 (2017), EPJ C77 358 (2017), PTEP 2022 (2022) 053H01, EPJ C 82 (2022) 1104



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





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

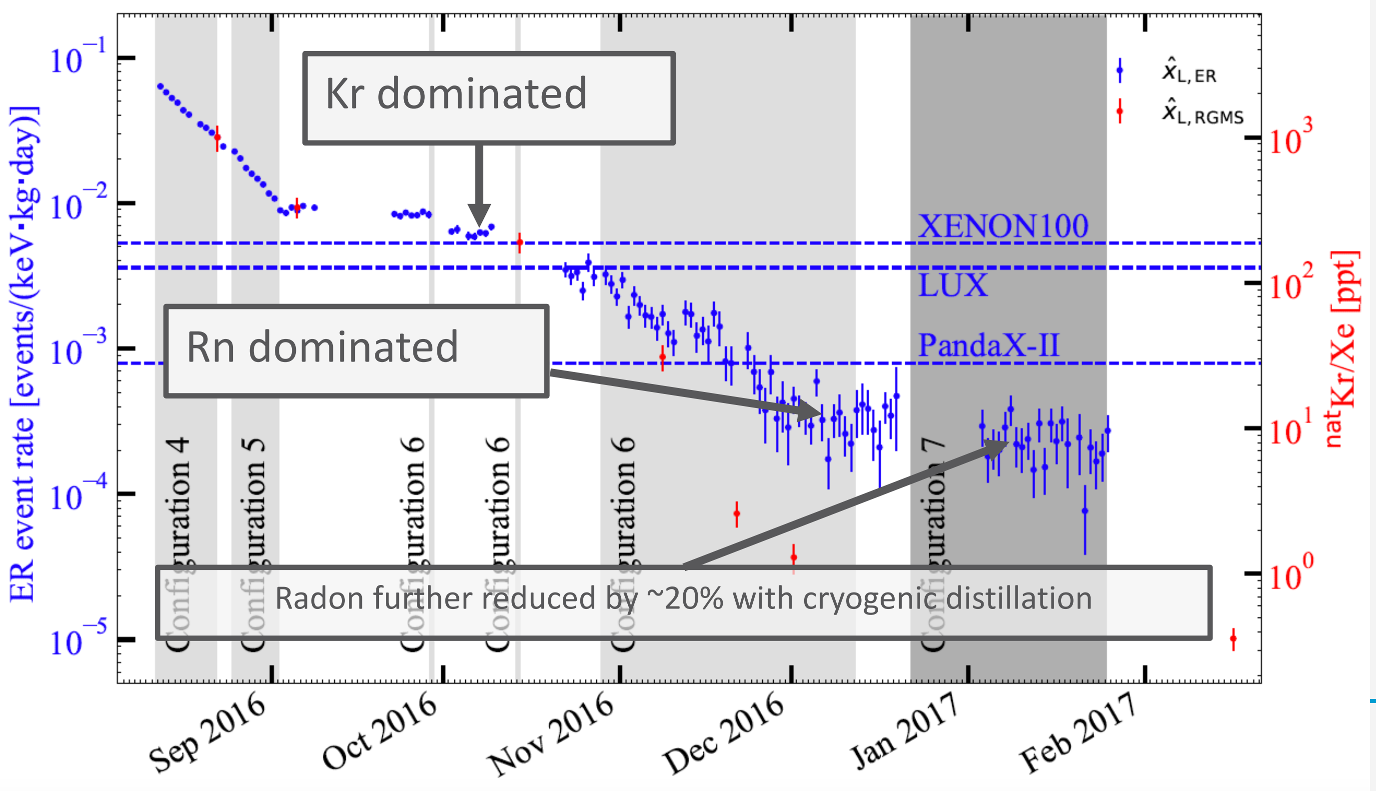
Make use of the different vapour pressures (volatilities) of Kr, Xe and Rn

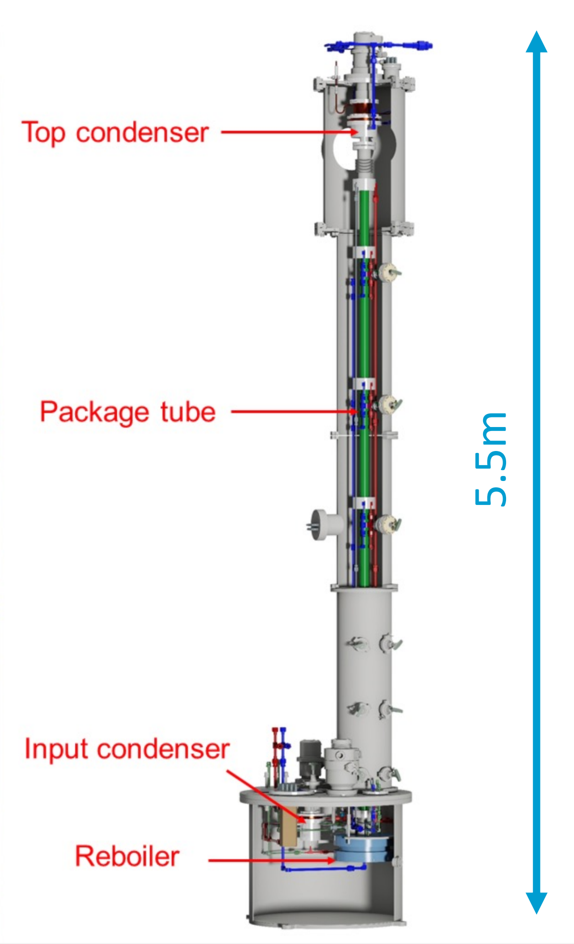
Processing flow rate: up to 6.5 kg/h (18 SLPM)

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

Kr removal (XENONnT): $\frac{^{nat}\mathrm{Kr}}{\mathrm{Xe}} < 2 \cdot 10^{-13}$, achieved: $\frac{^{nat}\mathrm{Kr}}{\mathrm{Xe}} < 4.8 \cdot 10^{-14} = 48\ \mathrm{ppq}$

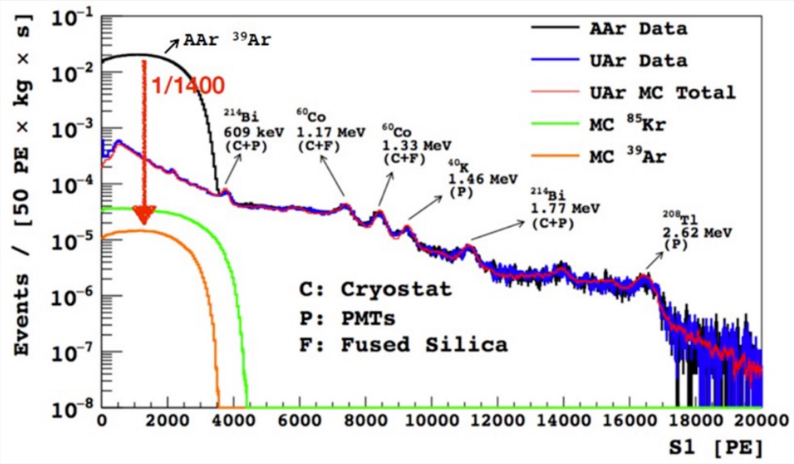
Kr removal achieved by "online distillation": E. Aprile et al., PTEP 5, 053H01 (2022)





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

Low ^{39}Ar – UAr & ARIA project



^{39}Ar: typically 1 Bq/kg

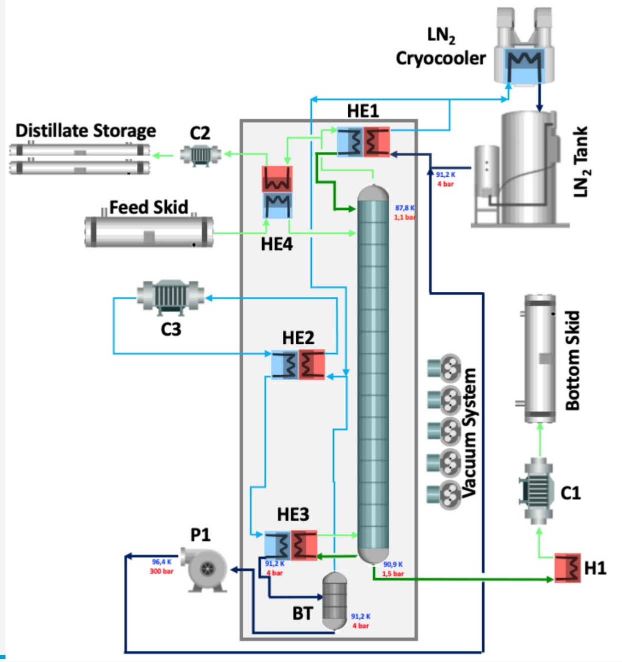
β emitter, $T_{1/2}$ = 269 yr, E_0 = 565 keV

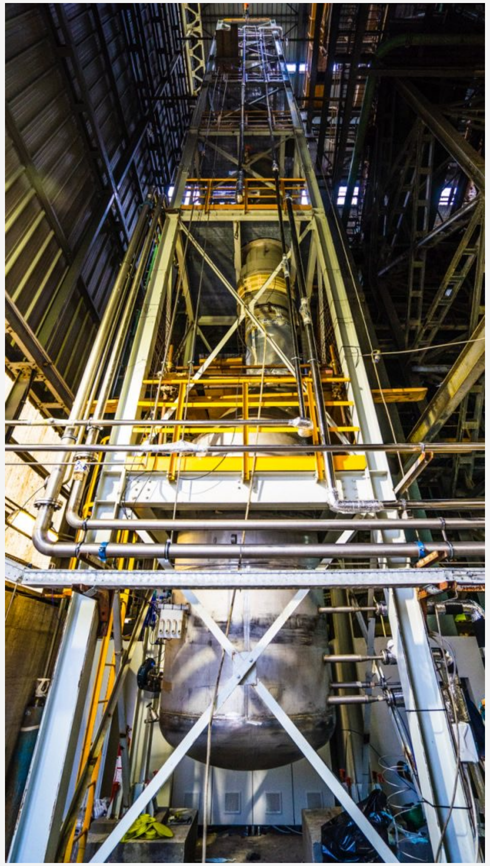
-> too much background rate for dark matter searches

A first approach:

Use underground Ar (UAr)
from Urania plant in Cortez/USA
with a reduction in ^{39}Ar by a factor 1400
clean the Argon by using the ARIA distillation column
at Sardinia

EPJ C81 (2021) 359

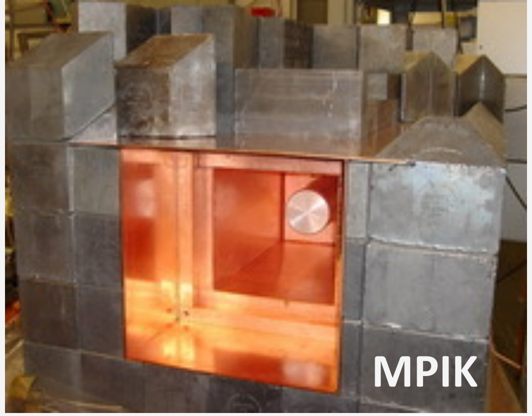




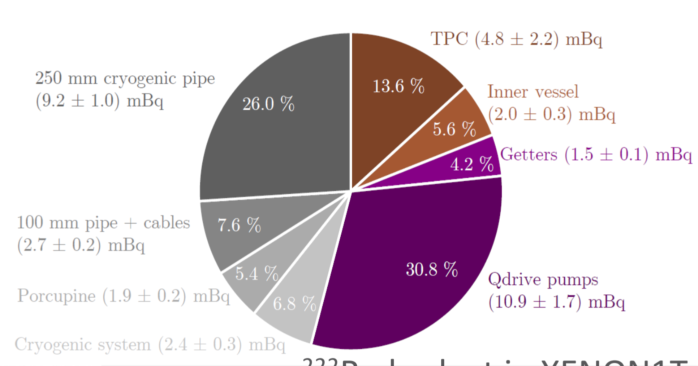
To go even lower in ^{39}Ar:

Cryogenic distillation for isotope sepearation:
ARIA-project: Factor 10 per pass, about 10 kg/d

Rn mitigation

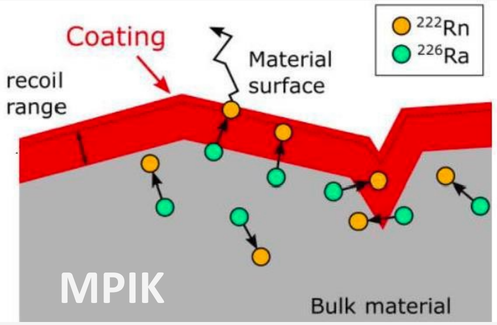


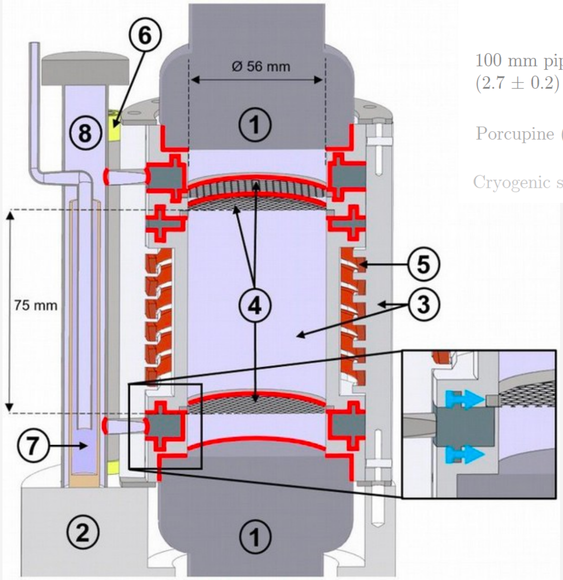
1. Screen materials for gamma emission and radon emanation and selection



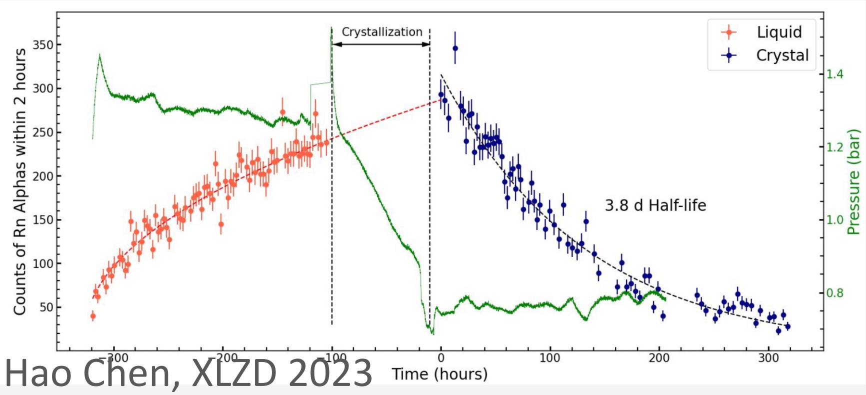
^{222}Rn budget in XENON1T

2. Avoiding Rn to move in:
   - coating (MPIK)
   - hermetic TPC (U Freiburg)
   - xenon ice (LBNL,, U Texas)





EPJ C83 (2023) 9



Hao Chen, XLZD 2023

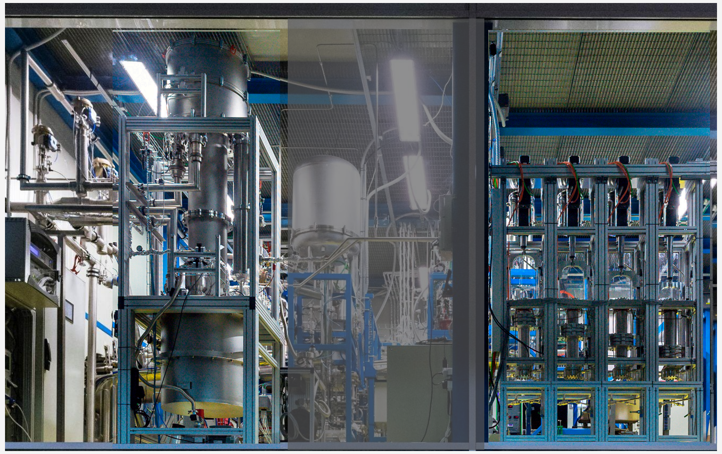
3. Online removal by cryogenic distillation
   also needed for $0\nu\beta\beta$ because of Bi-214 (BiPo tagging and self-shielding is not 100%)

Removal of Intrinsic radioactive contaminants: ^{222}Rn

Intrinsic noble gas contaminants ^{85}Kr and ^{222}Rn (^{214}Pb) inside the xenon

- ➔ Electronic recoil events from the low energy β-spectrum of these radioactivities contaminate ROI for dark matter WIMP search
- ➔ Searches for new physics using electronic recoil signals becomes possible when these radioactivities are drastically reduced
- ➔ ^{222}Rn emanates from detector materials and needs to be **avoided or removed continuously**
- ➔ Material screening and selection to avoid ^{222}Rn in the first place
- ➔ Main background in XENON1T, LUX and PandaX at ^{222}Rn/Xe ~ 10µBq/kg - challenge for current experiments to reach 1µBq/kg
- ➔ Challenge met with continuous Rn removal by cryogenic distillation (XENONnT and PandaX) or by gas chromatography (LZ)

XENONnT



courtesy: Elena Aprile

Cryogenic Distillation done "online" at XENONnT
- High-flow distillation column with LXe and GXe in- and outlets
- 200 slpm (1.8 t/d) LXe-phase mode and 25 slpm (0.2 t/d) GXe-phase mode
- ^{222}Rn/Xe = 1.7 µBq/kg (GXe-only mode)
- ^{222}Rn/Xe = 0.8 µBq/kg (GXe+LXe mode)

LZ

J. Aalbers et al, arXiv:2211.17120, 2022

Gas chromatography done "online" at LZ
- 0.5 slpm from gas conduits run to 10 kg cold synthetic charcoal
- keep Rn in charcoal for >3 half-lives
- Ongoing R&D to further suppress Rn
- ^{222}Rn/Xe = 4.6 µBq/kg

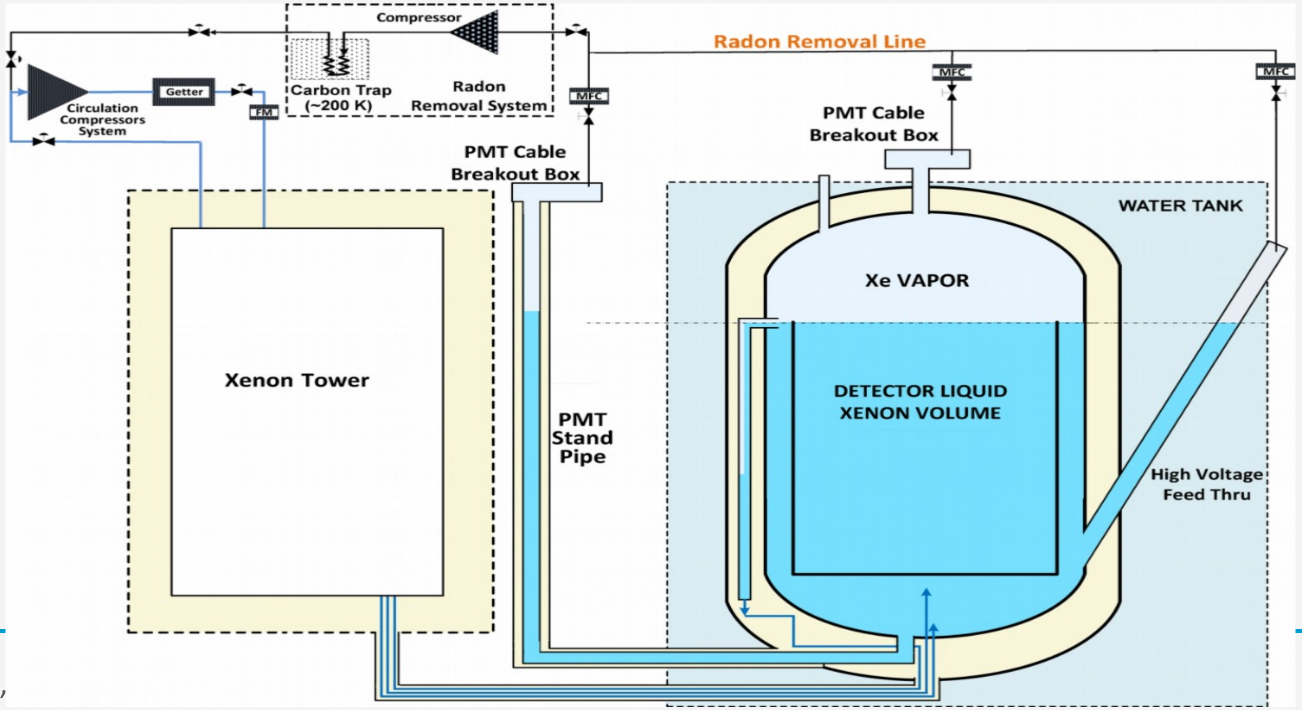
PandaX-4T

X. Cui *et al* 2021 JINST 16 P07046

Cryogenic Distillation done "online" at PandaX-4T
- Same as Kr removal system, but in reverse mode
- GXe in- and outlets
- 160 slpm (1.4 t/d)
- ^{222}Rn/Xe = 4.2 µBq/kg

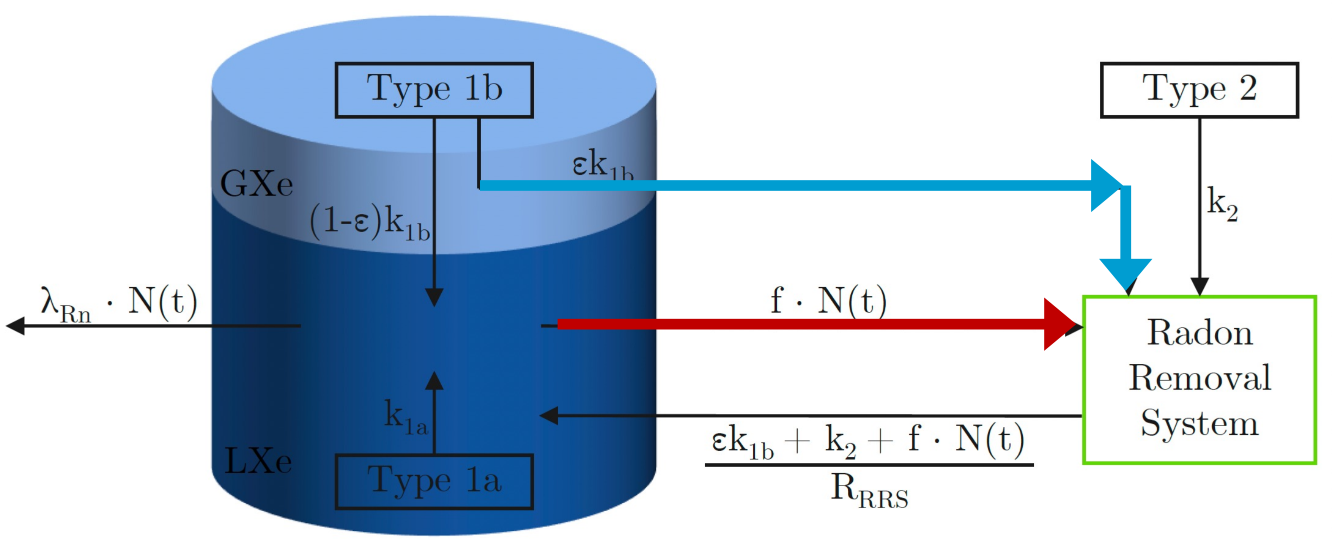
LZ: In-line Radon reduction system

- 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

Reduction of a continuous ^{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

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

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

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

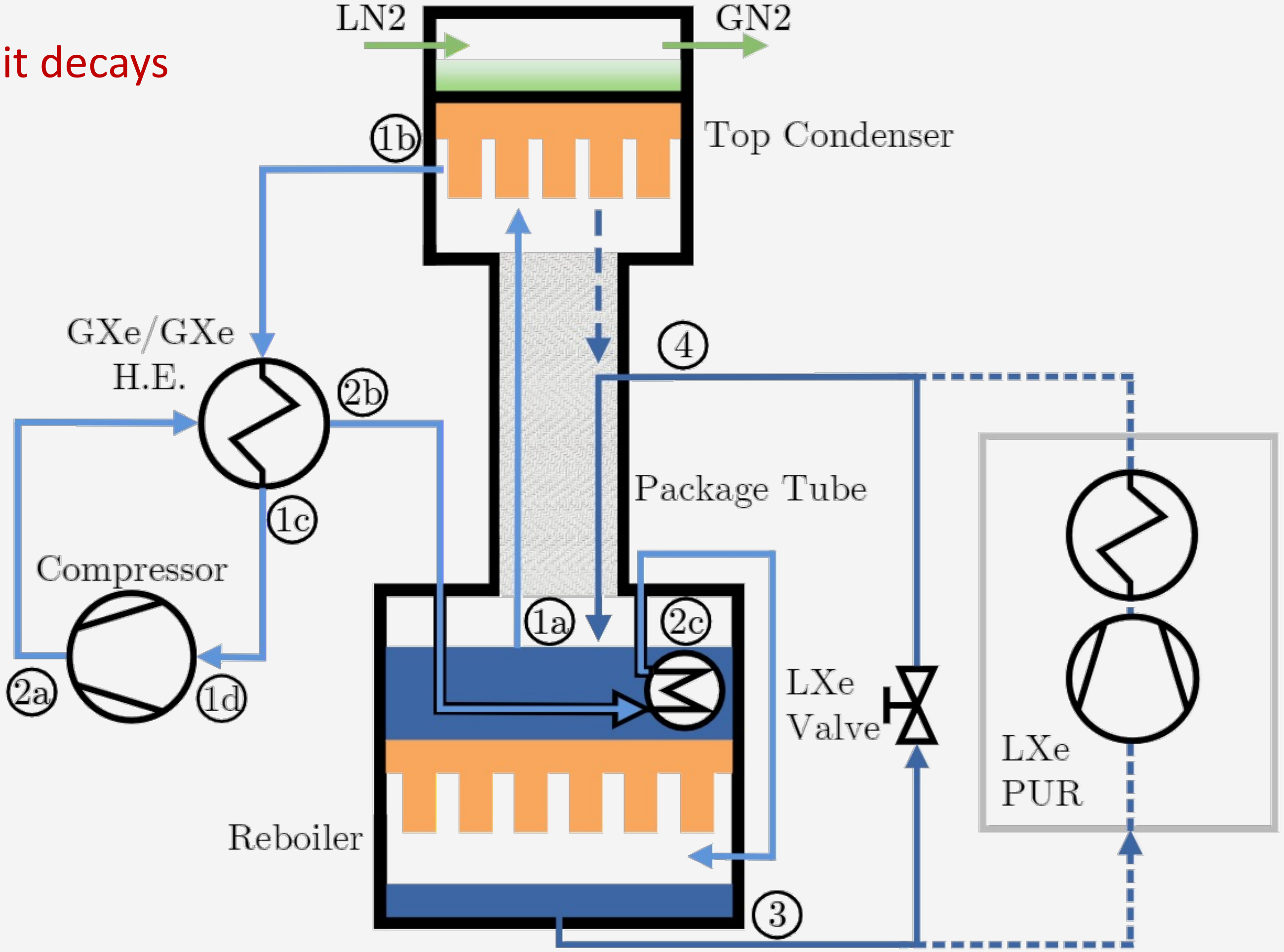
GXe extraction reduction factor, typically
$r_{GXe} \approx 2$ (XENONnT)

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

Radon removal system for XENONnT

High-flow radon removal distillation column

- Radon as less volatile noble gas is trapped in reboiler until it decays
- Radon-depleted GXe extracted from the top condenser
- Target flow: 72 kg/h (200 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
- Requires additional >2 kW cooling power for LXe outlet



Radon removal system for XENONnT

Thermodynamic concept:

- Kind of heat pump: Clausius-Rankine cycle
  with phase changing medium xenon

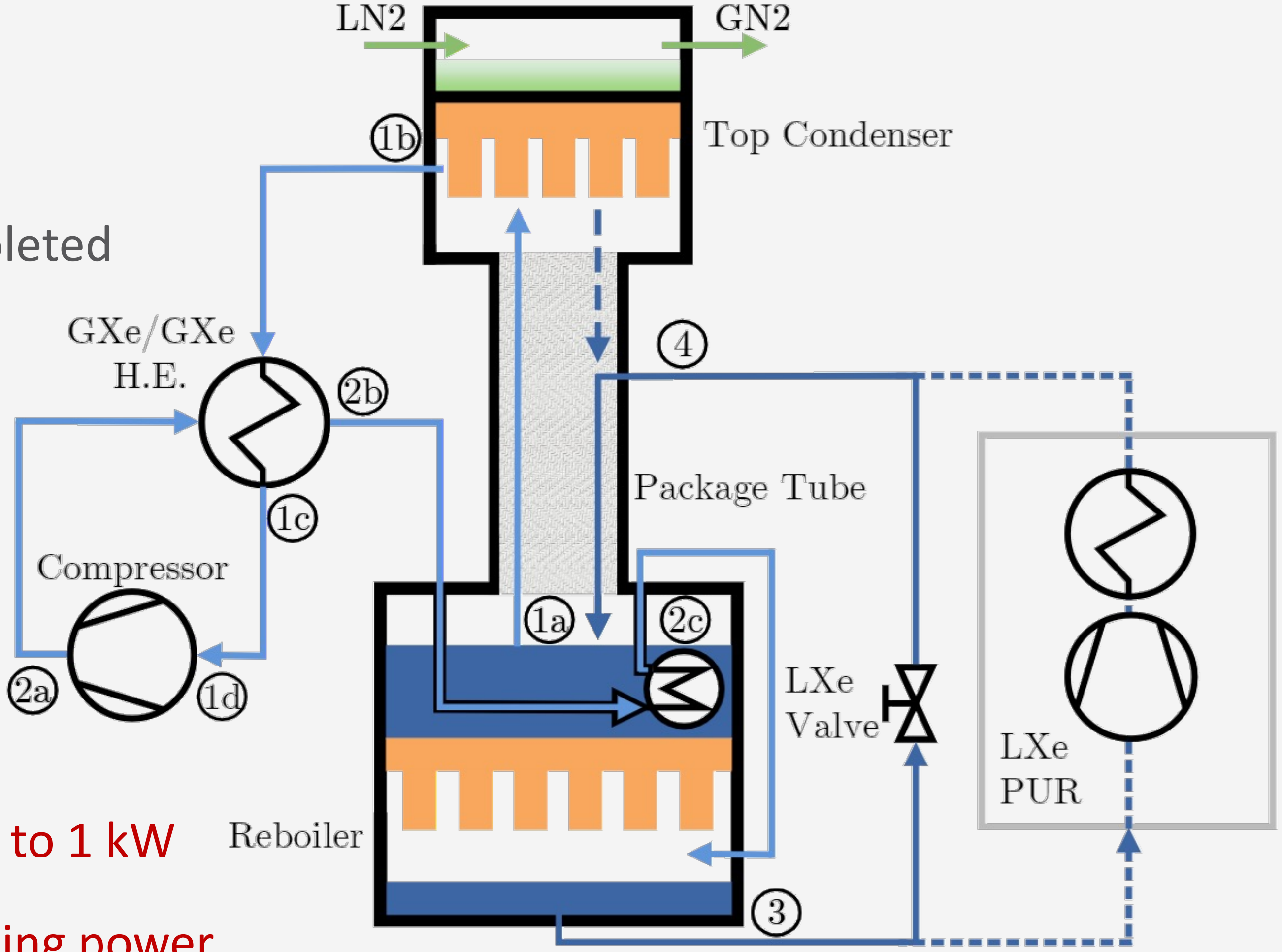
- Reboiler acts as heat exchanger to liquefy radon-depleted
  GXe with stored radon-enriched LXe

- Compressor acts as heat-pump

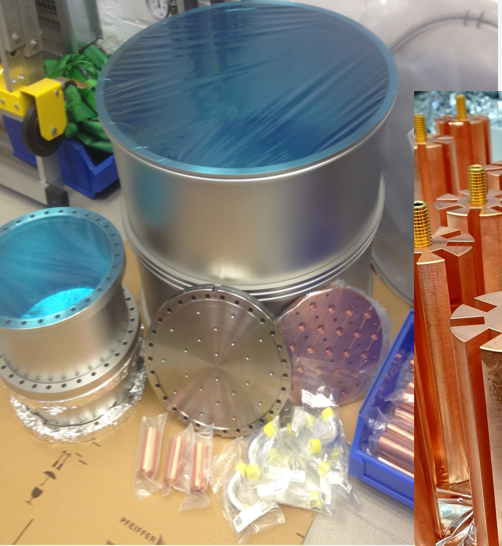
- Requires two special hardware developements
  - Radon-free compressor
  - Radon-free heat exchangers

- Reduce required external cooling power from >3 kW to 1 kW

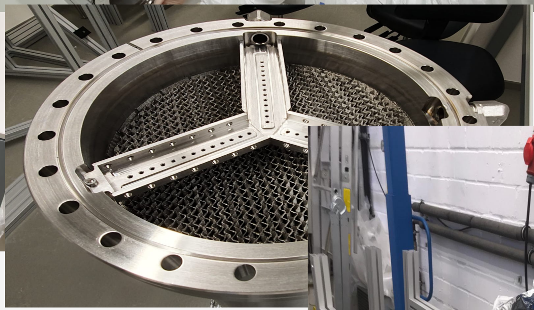
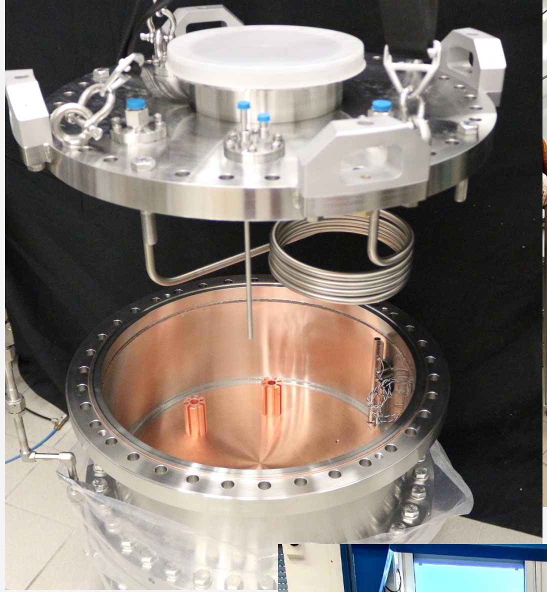
- Drastically reduce LN_2 consumption & electrical heating power

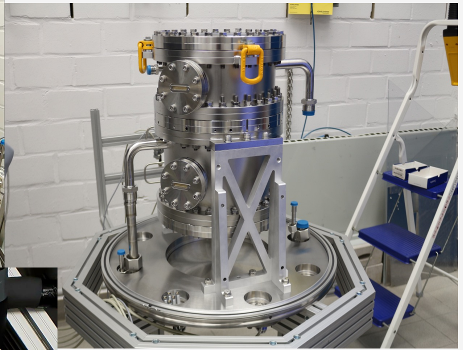
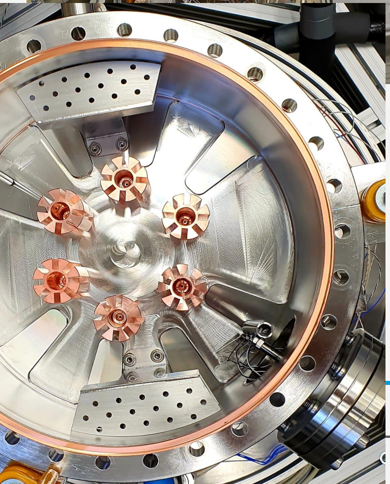


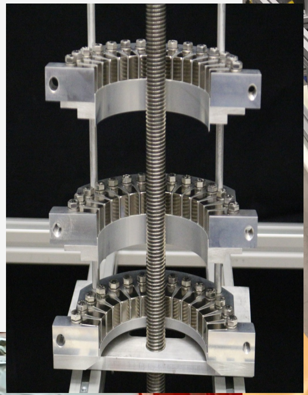
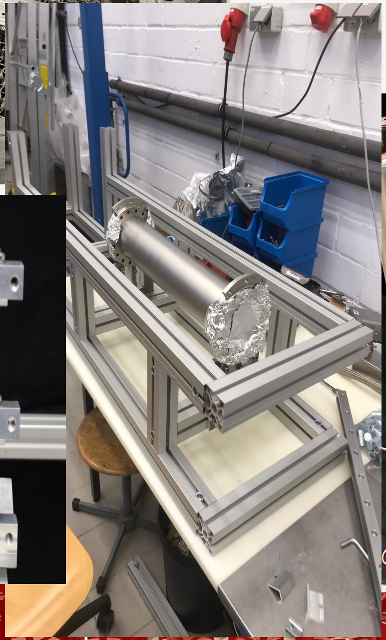
Radon removal system






Radon removal system for XENONnT

Top Condenser
Custom bath-type LN_2/GXe heat exchanger
(arXiv:2203.01026)

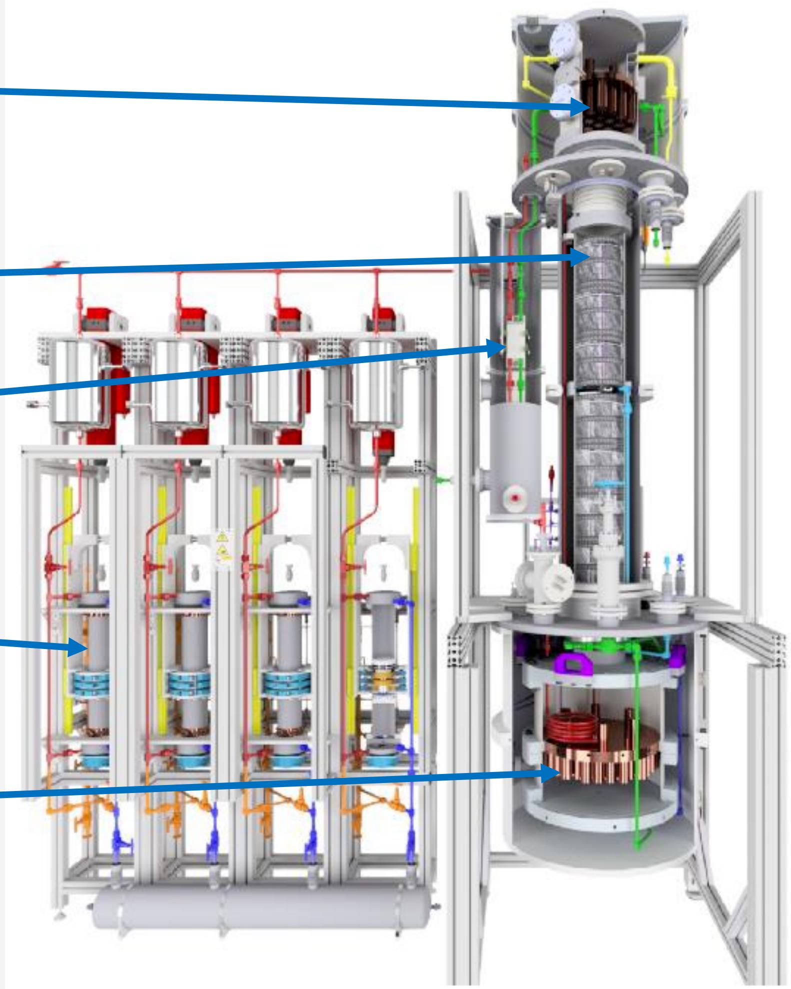
PackageTube
Large-surface package material

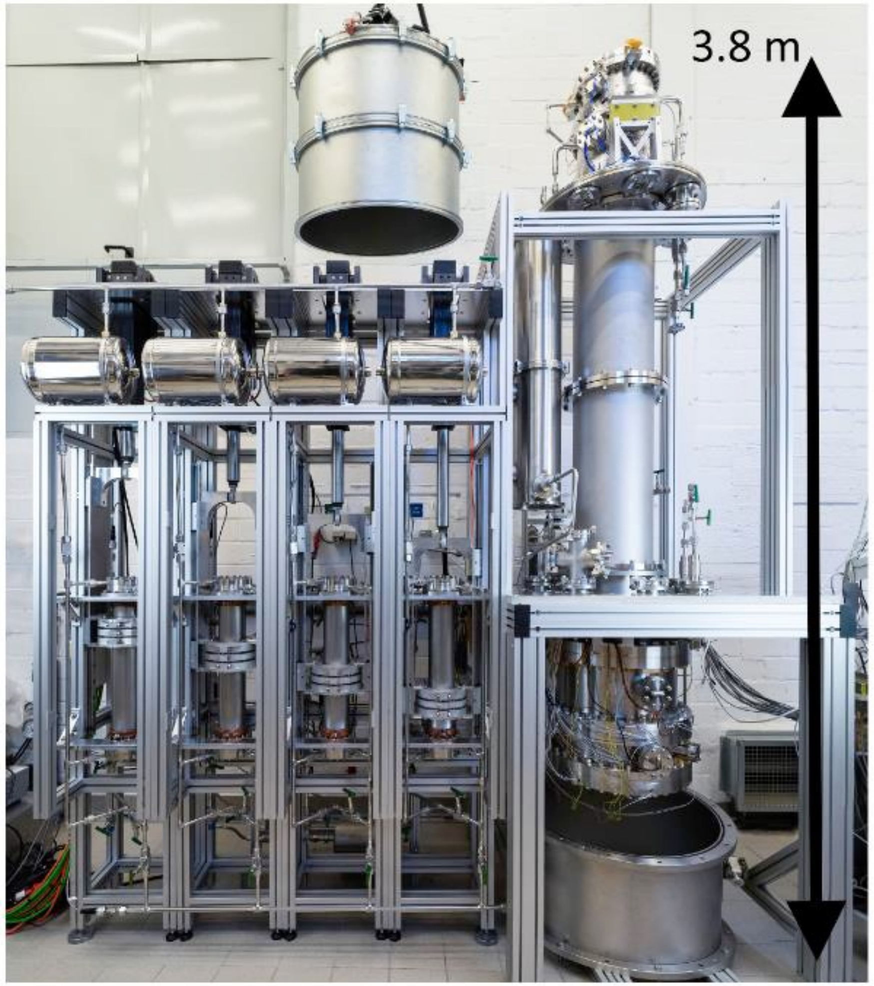
Auxiliary
Commercial GXe/GXe heat exchangers

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



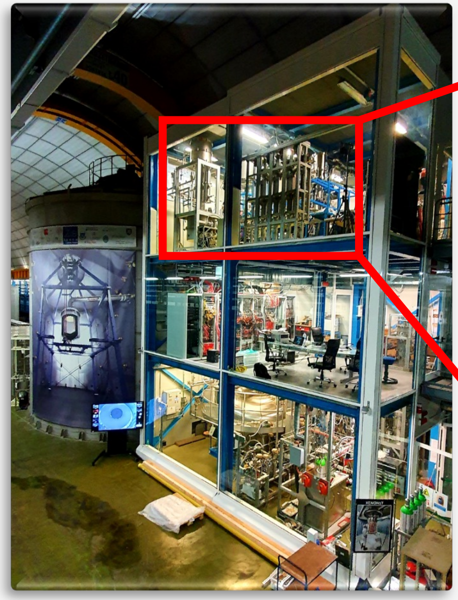


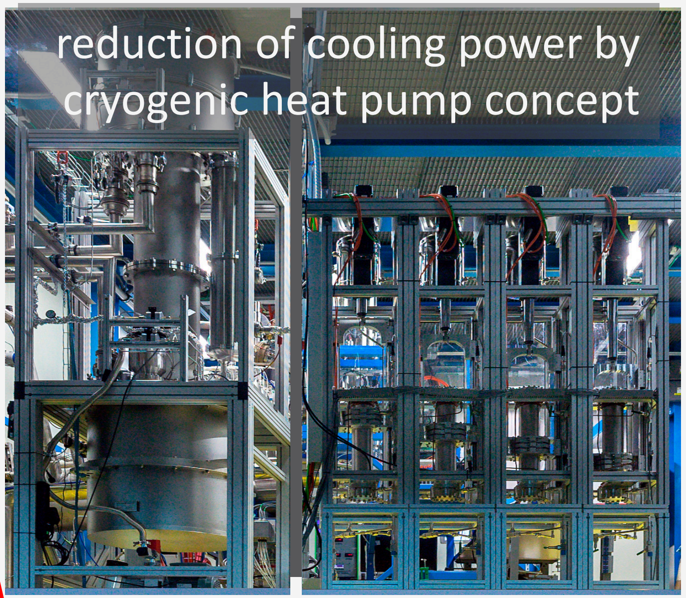
WWU MÜNSTER

XENONnT – Novel radon removal system

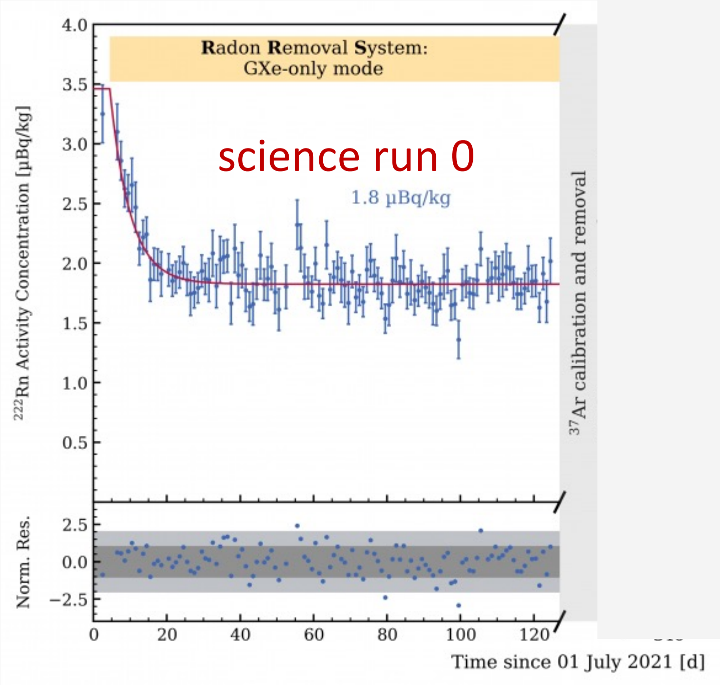
Again cryogenic distllation - key parameter:

- ➢ liquid xenon 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 cryogenics‘ sources by GXe extraction





Radon concentration at XENONnT

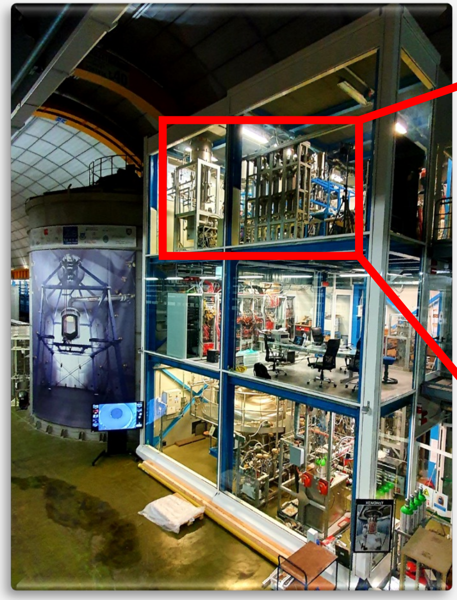


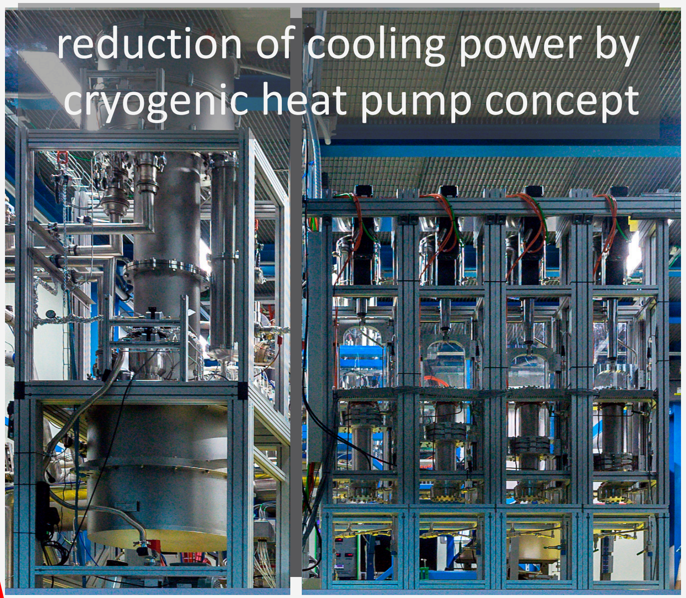
Proof of basic removal concept:
Eur. Phys. J C77, 358 (2017)
Design of XENONnT system:
Eur. Phys. J. C82, 1104 (2022)

XENONnT – Novel radon removal system

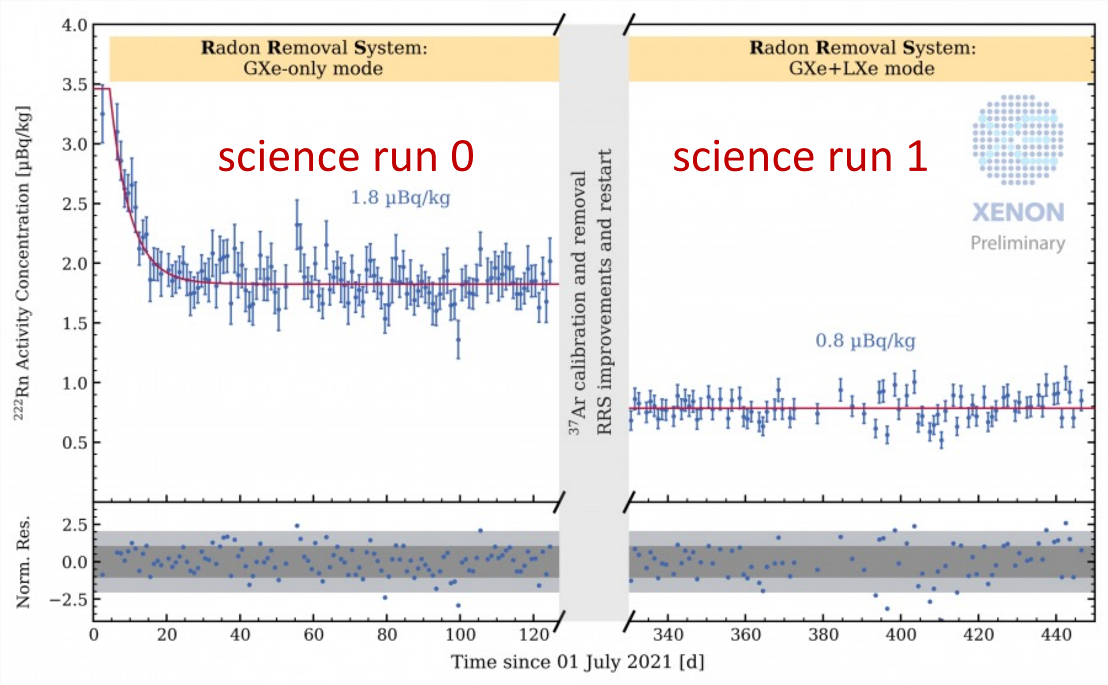
Again cryogenic distllation - key parameter:

- liquid xenon 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 cryogenics‘ sources by GXe extraction





Radon concentration at XENONnT



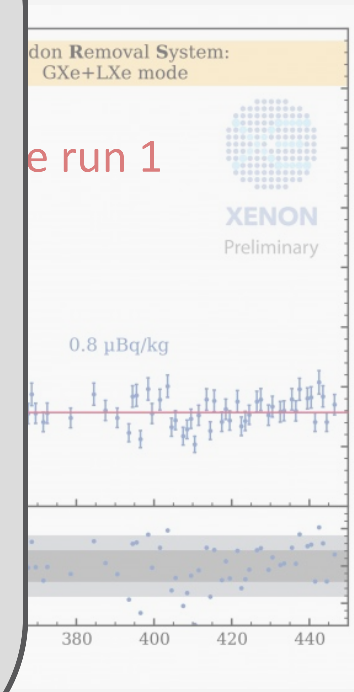
Proof of basic removal concept:
Eur. Phys. J C77, 358 (2017)
Design of XENONnT system:
Eur. Phys. J. C82, 1104 (2022)

XENONnT – Novel radon removal system

Again cryogenic distllation - key parameter:

- liquid x
- flow o
- **reduc** by LX
- **anoth** GXe e

Radon concentration at XENONnT

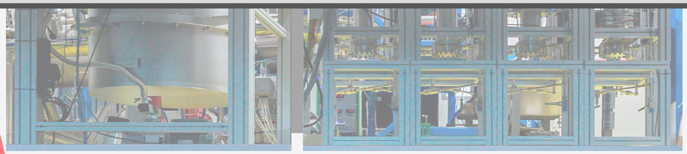


Key feature 1: Ultra-high vacuum technology and ultra-pure materials
- absolute leak tightness
- very low emanation of inpurities
- material control (Rn emanation measurements (MPIK), most components custom-built)

Key feature 2: Online diagnostics
- process control: level meter, flow, (differential) pressure, temperature, …
- Rn concentration by decay measurements in XENONnT

Key feature 3: Cooling power
- heat-exchangers, heat pump concept, LN_2 evaporation

Key feature 4: Liquid xenon flow
- very high flows require LXe from the detector to the radon removal system and back



Eur. Phys. J C77, 358 (2017)

Design of XENONnT system: Eur. Phys. J. C82, 1104 (2022)

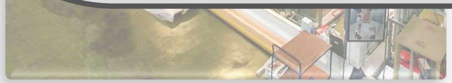
XENONnT – Novel radon removal system

Kryogenic distillation was brought into our field by **XMASS** for Kr removal: Astropart. Phys. 31, 290-296 (2009)

This technology was taken over by the Columbia University group for XENON100
and taken over for XENON1T/nT by Münster University.

Publications on cryogenic distillation related topics by Münster group/XENON:

1. M. Murra, D. Schulte, C. Huhmann, *C. Weinheimer, Design, construction and commissioning of a high-flow radon removal system for XENONnT*, Eur. Phys. J. C 82 (2022) 1104
2. M. Murra, D. Schulte, I. Cristescu, J.-M. Disdier, C. Huhmann, D. Tatananni, C. Weinheimer, *Cryogenic bath-type heat exchangers for ultra-pure noble gas applications*, JINST 17 (2022) P05037
3. E. Aprile et al. [XENON Collaboration|, *Application and modeling of an online distillation method to reduce krypton and argon in XENON1T*, Prog. Theor. Exp. Phys. 2022 (2022) 053H01
4. D. Schulte, M. Murra, P. Schulte, C. Huhmann, C. Weinheimer, *Ultra-clean radon-free four cylinder magnetically-coupled piston pump*, JINST 16 (2021) P09011
5. E. Aprile et al. [XENON Collaboration], *^{222}Rn emanation measurements for the XENON1T experiment*, EPJ C 81 (2021) 337
6. E. Brown, A. Buss, A. Fieguth, C. Huhmann, M. Murra, H.-W. Ortjohann, S. Rosendahl, A. Schubert, D. Schulte, D. Tosi, G. Gratta, C. Weinheimer, *Magnetically-coupled piston pump for high-purity gas applications*, Eur. Phys. J. C 78 (2018) 604
7. E. Aprile et al. [XENON Collaboration], *Online ^{222}Rn removal by cryogenic distillation in the XENON100 experiment*, Eur. Phys. J. C 77 (2017) 358
8. E. Aprile et al. [XENON Collaboration], *Removing krypton from xenon by cryogenic distillation to the ppq level*, Eur. Phys. J. C 77 (2017) 275
9. R. Rosendahl et al., *Determination of the separation efficiencies of a single-stage cryogenic distillation setup to remove krypton out of xenon by using a ^{83m}Kr tracer method*, Rev. Scient. Instr. 86 (2015) 11, 115104
10. S. Rosendahl, K. Bokeloh, E. Brown, I. Cristescu, A. Fieguth, C. Huhmann, O. Lebeda, C. Levy, M. Murra, S. Schneider, D. Venos and C. Weinheimer, *A novel ^{83m}Kr tracer method for characterizing xenon gas and cryogenic distillation systems*, JINST 9 (2014) 10, P10010
11. E. Brown, S. Rosendahl, C. Huhmann, C. Weinheimer and H. Kettling, *In situ measurements of Krypton in Xenon gas with a quadrupole mass spectrometer following a cold-trap at a temporarily reduced pumping speed*, JINST 8 (2013) P02011

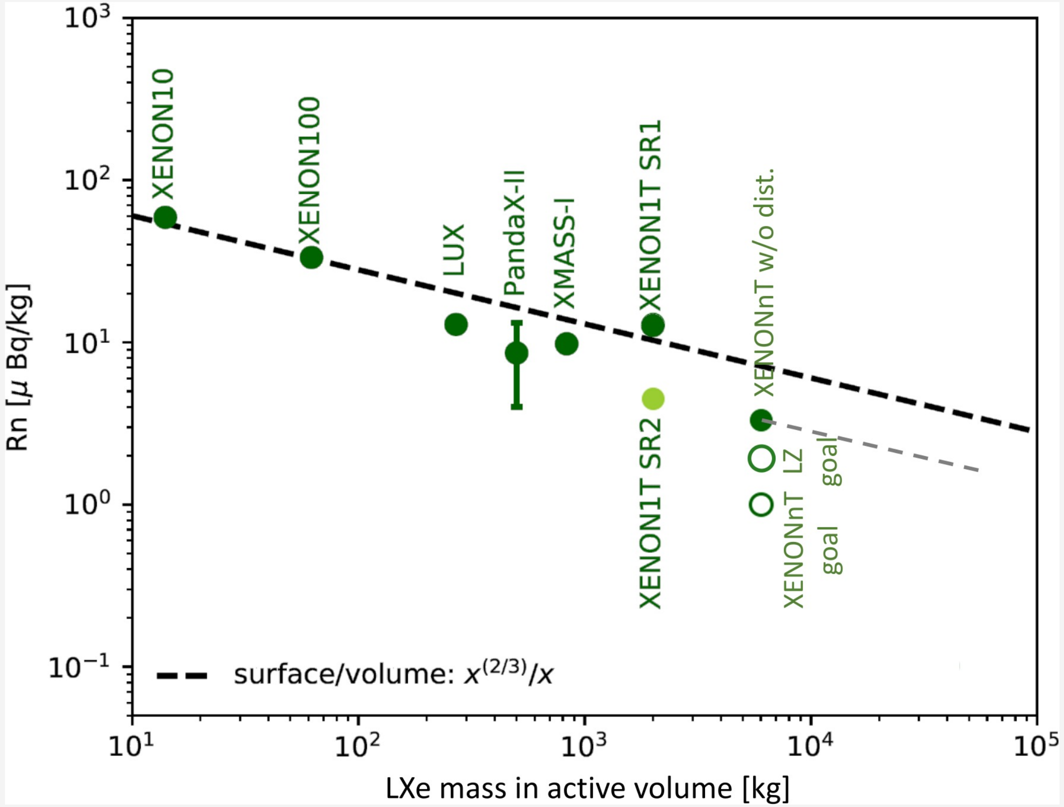


Design of XENONnT system:
Eur. Phys. J. C82, 1104 (2022)

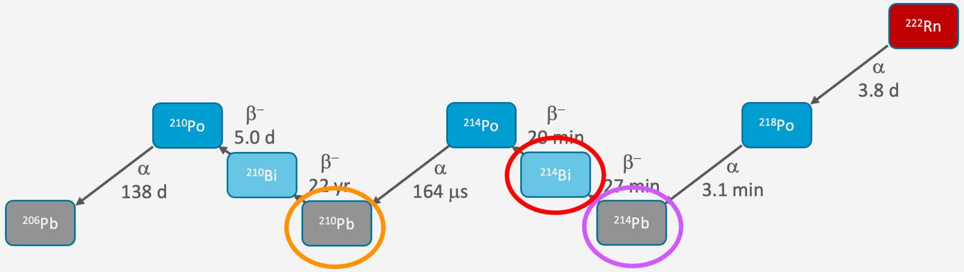
Rn requirements for xenon-based dark matter exp.

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

^{222}Rn concentrations achieved so far



Yamashita-san plot



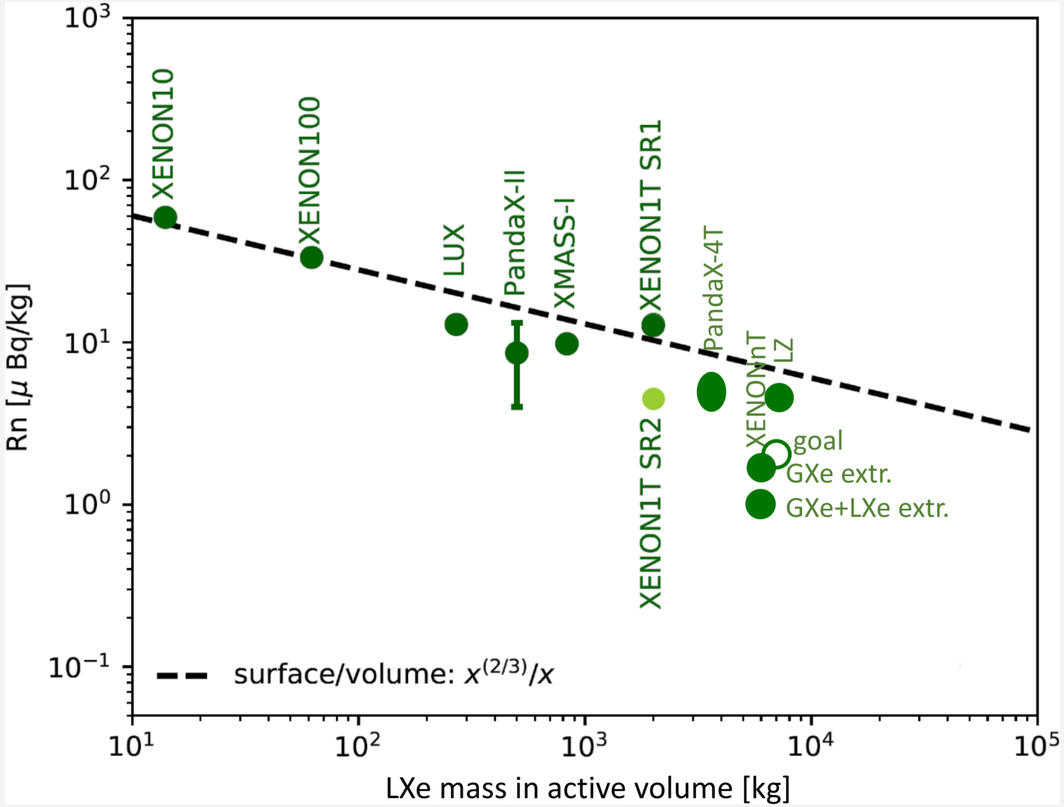
- Background from β-decay of ^{214}Pb which cannot be identified by accompanying α-decay
- Background from γ-decay of ^{214}Bi for 0νββ decay searches if not fully BiPo-tagged
- Additional backgrounds from plate-out of ^{210}Pb

Rn requirements for xenon-based dark matter exp.

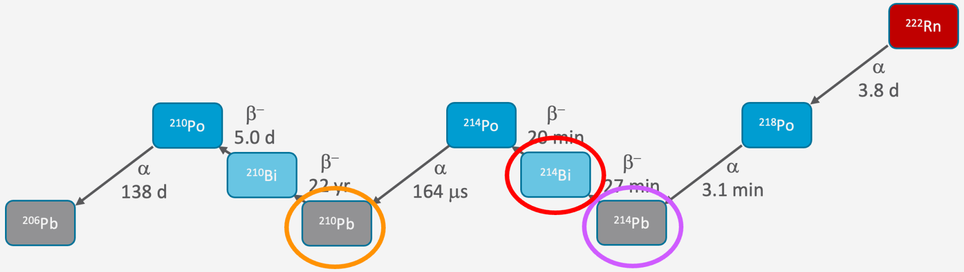
^{222}Rn: $t_{1/2} = 3.8$ d,

continuously emanating from detector materials

^{222}Rn concentrations achieved so far



Yamashita-san plot



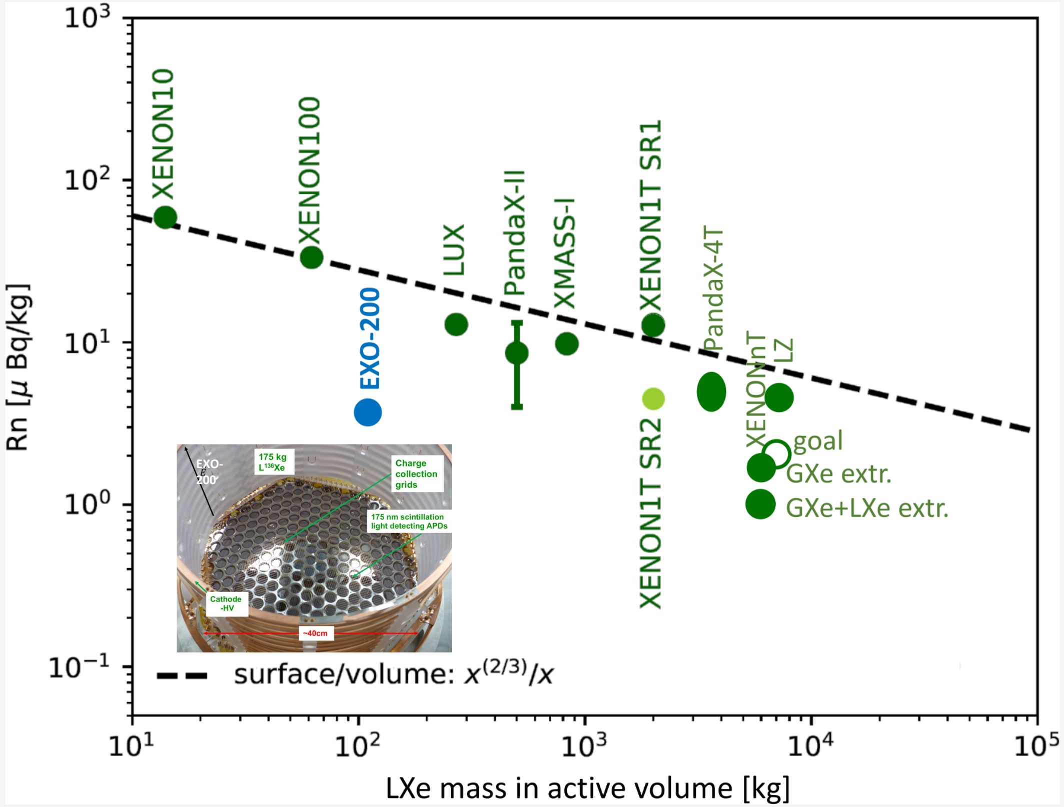
- Background from β-decay of ^{214}Pb which cannot be identified by accompanying α-decay
- Background from γ-decay of ^{214}Bi for $0\nu\beta\beta$ decay searches if not fully BiPo-tagged
- Additional backgrounds from plate-out of ^{210}Pb

Rn requirements for xenon-based dark matter exp.

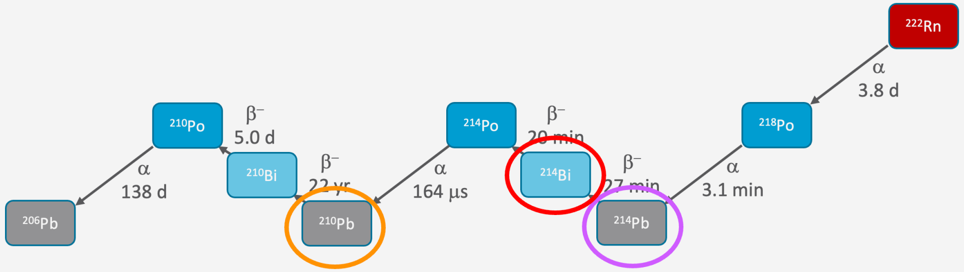
^{222}Rn: $t_{1/2} = 3.8$ d,

continuously emanating from detector materials

^{222}Rn concentrations achieved so far

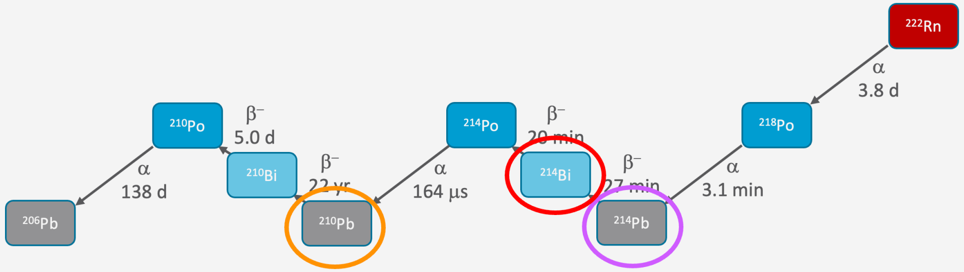


Yamashita-san plot



- 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

Rn requirements for xenon-based dark matter exp.



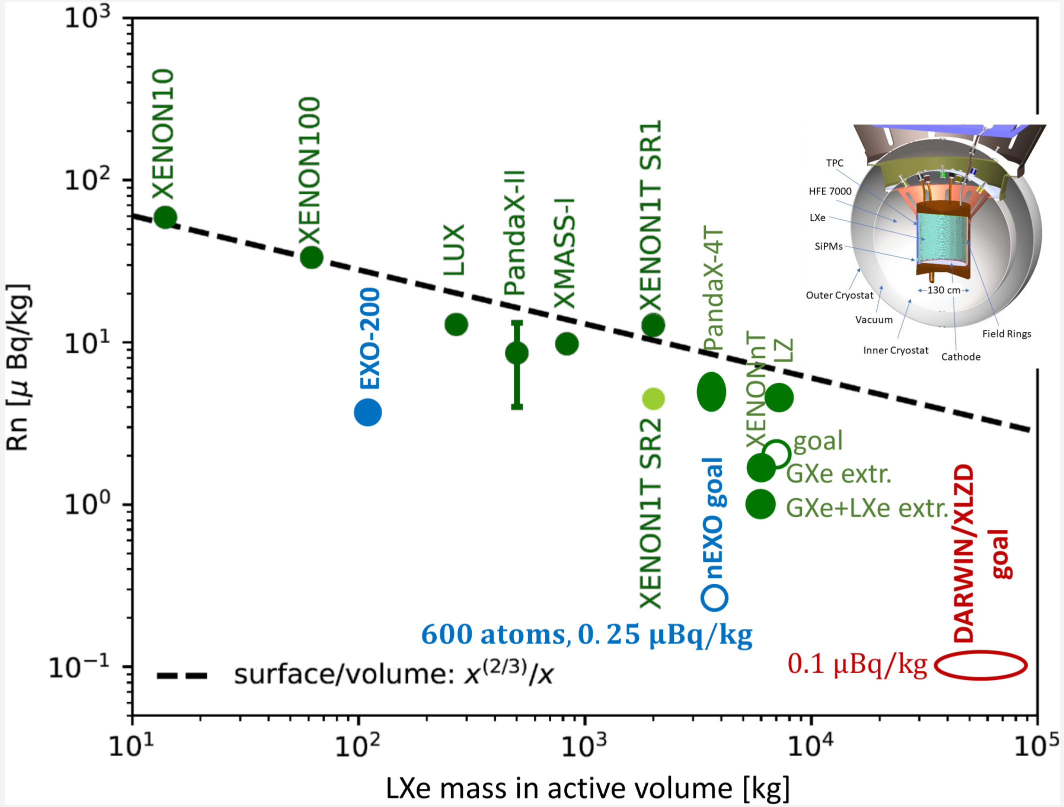
^{222}Rn: $t_{1/2} = 3.8$ d,

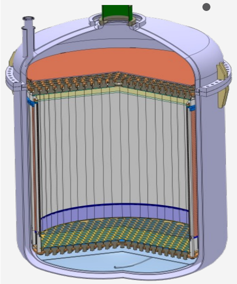
continuously emanating from detector materials

- 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

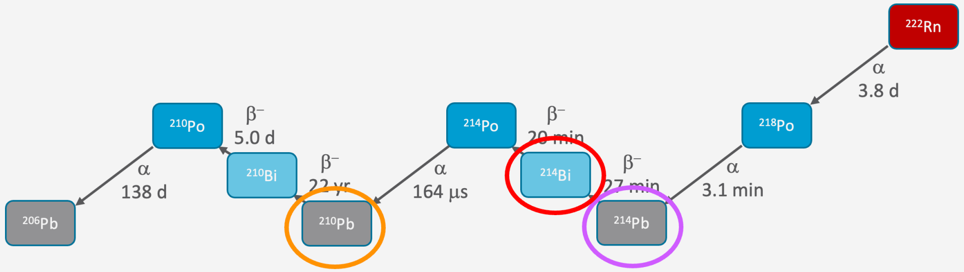




Yamashita-san plot

Rn requirements for xenon-based dark matter exp.

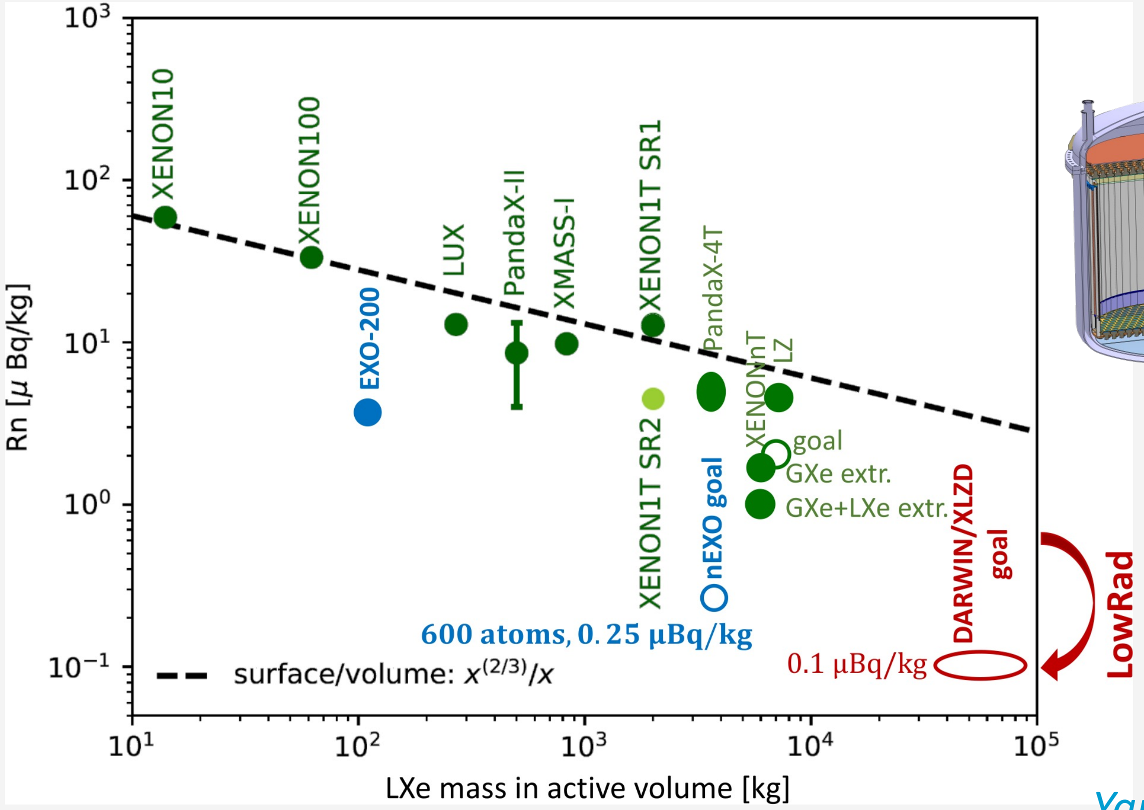
^{222}Rn: $t_{1/2} = 3.8$ d,
continuously emanating from detector materials

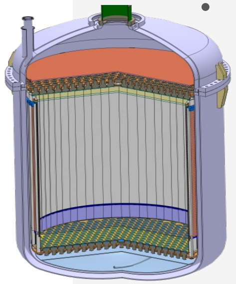


- Background from β-decay of ^{214}Pb which cannot be identified by accompanying α-decay
- Background from γ-decay of ^{214}Bi for 0νββ decay searches if not fully BiPo-tagged

Additional backgrounds from plate-out of ^{210}Pb

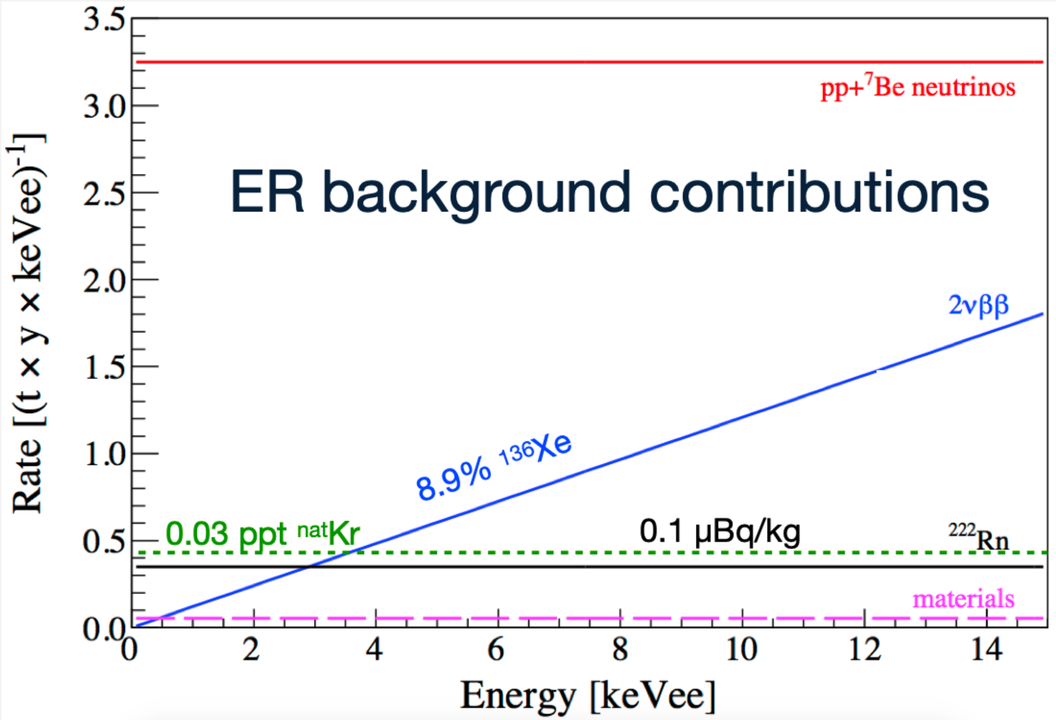
^{222}Rn concentrations achieved so far





Yamashita-san plot

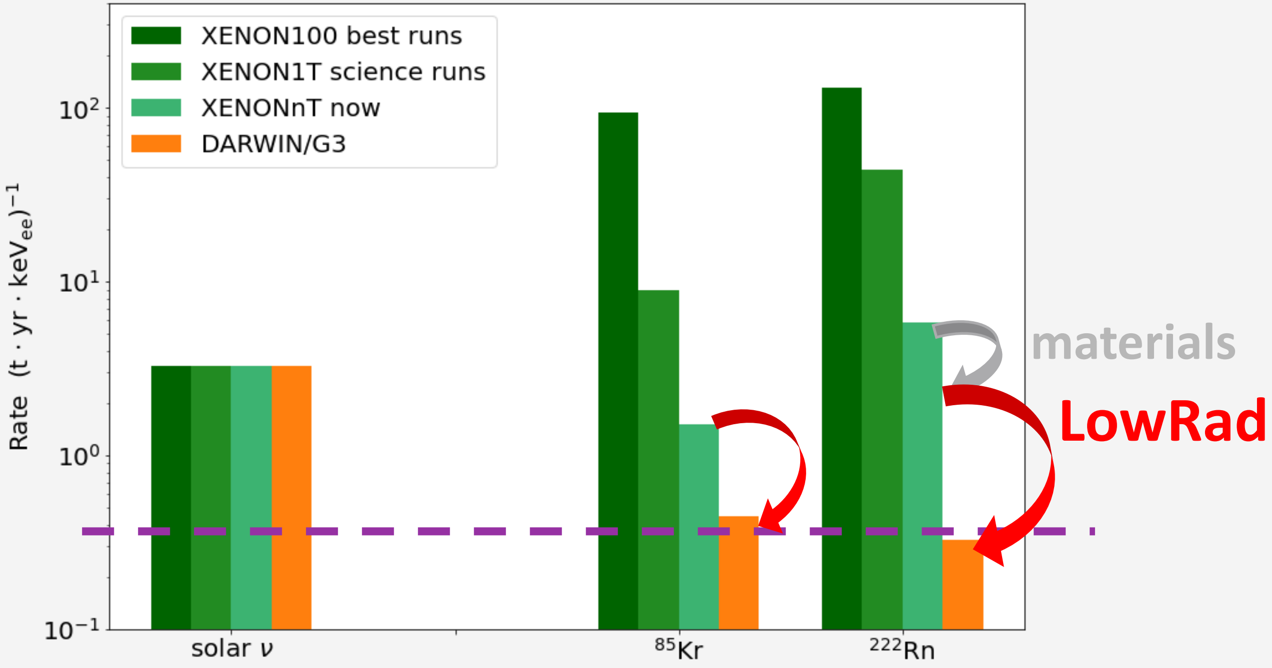
LowRad: Low radon and low internal radioactivity for dark matter and rare event xenon detectors



Goals:

- Develop technologies to reach another factor 10 lower 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"



LowRad: Low radon and low internal radioactivity for dark matter and rare event xenon detectors

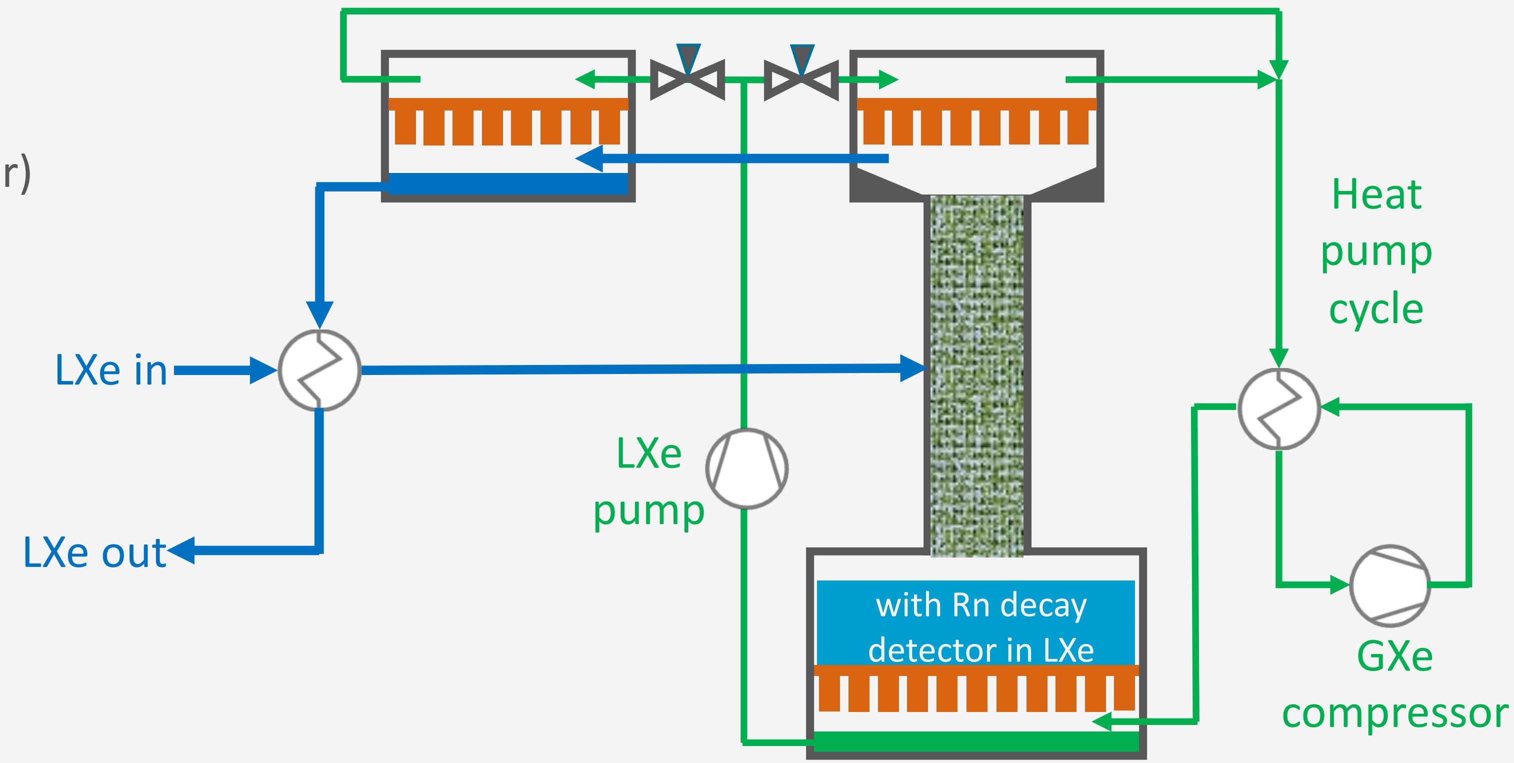
Challenges/tasks:

- Prepare for continuous/often online Kr removal:
  → develop quasi lossless method (much less off gas)
- Develop Rn removal technology with very high throughput O(1 t/h)
  → need efficient use of cooling power: cryogenic heat pump
- Make use of the fact, that cryogenic distillation depletes on one output, but concentrates on the other output
  → integrate very sensitive diagnostics
- High flow cryogenic distillation and purification from electronegative impurities
  → integrate system in one together with radioactive noble gas calibration and diagnostics

Cryogenic distillation system for DARWIN/XLZD

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
  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

- 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
- Cryogenic distillation is a robust and efficient method yielding ultralow concentrations at XENONnT:
  ^{85}Kr (≈100 ppq ^{nat}Kr) and ^{222}Rn (≈1 µBq/kg)
  Should be the default method for DARWIN/XLZD (and nEXO)
  after all primary mitigation strategies have been explored:
  - ^{85}Kr: removal at beginning, absolute leak tightness
  - ^{222}Rn: material screening and emanation tests as well as selection, coating, apparatus design
- LowRad kickoff meeting at Münster "Low radon in dark matter and neutrino experiments", June 28-30, 2023

This research at U Münster is funded by