Noble, but Troublesome: Radon in Dark Matter Experiments

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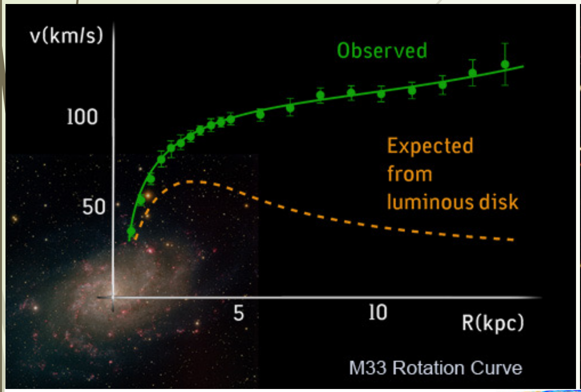
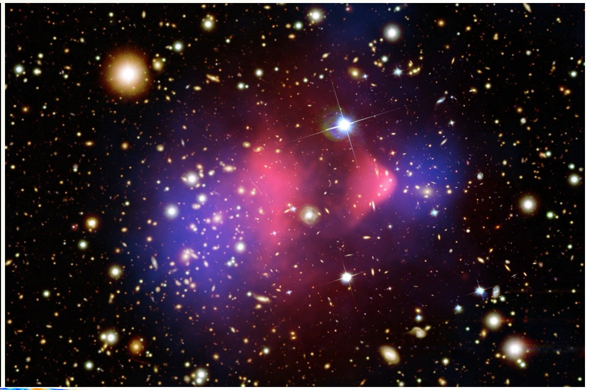
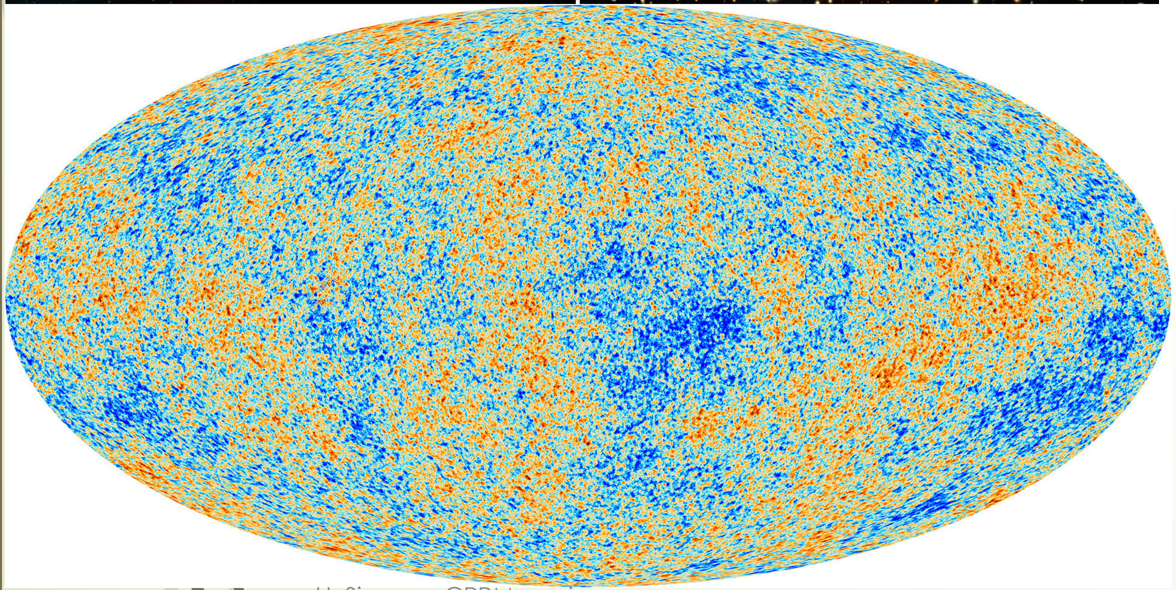
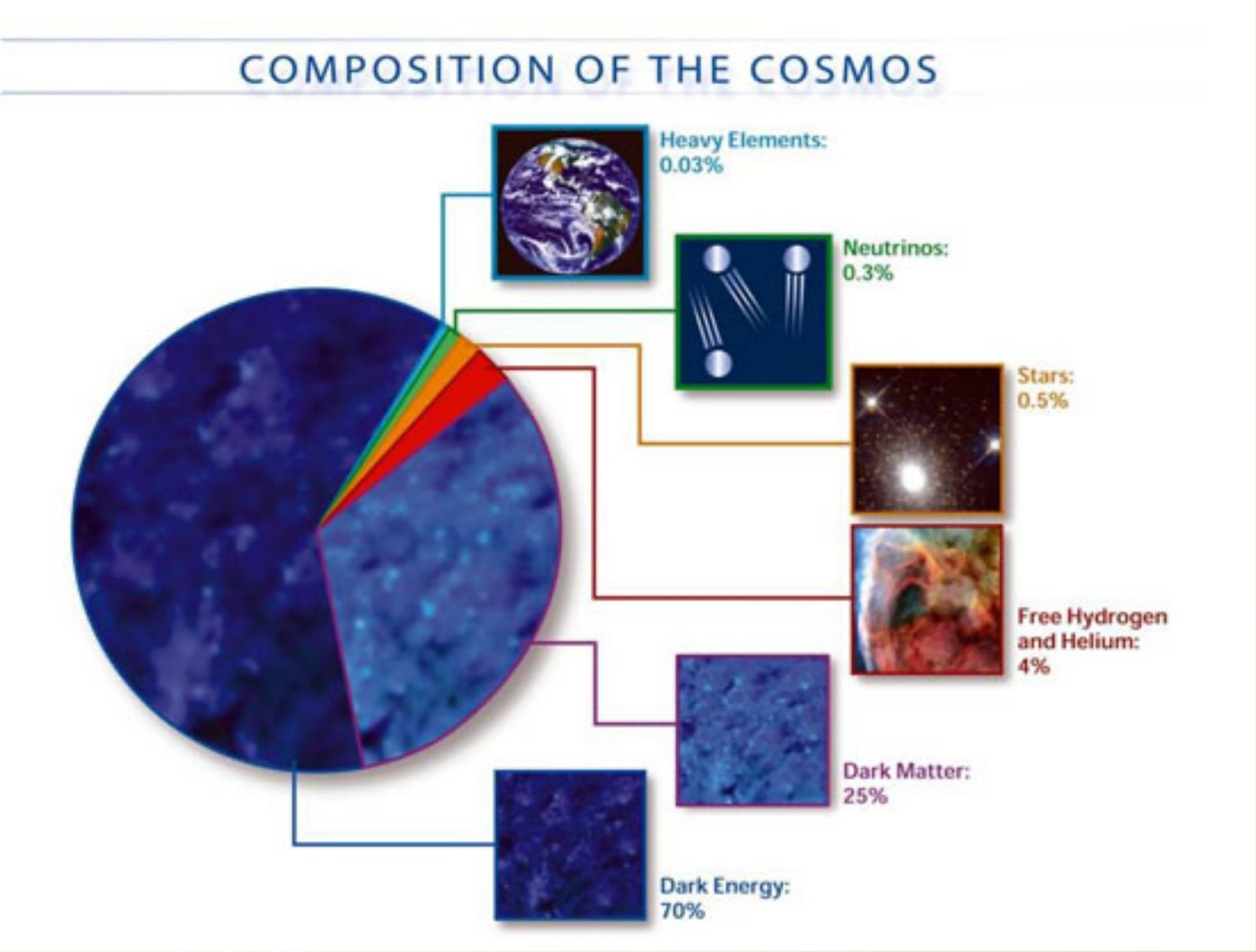
Dark Matter in the Cosmos

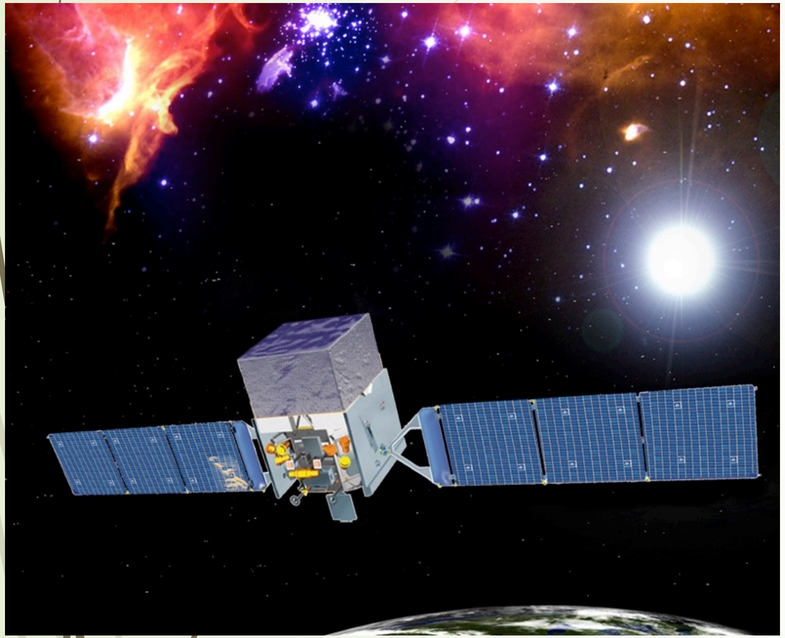
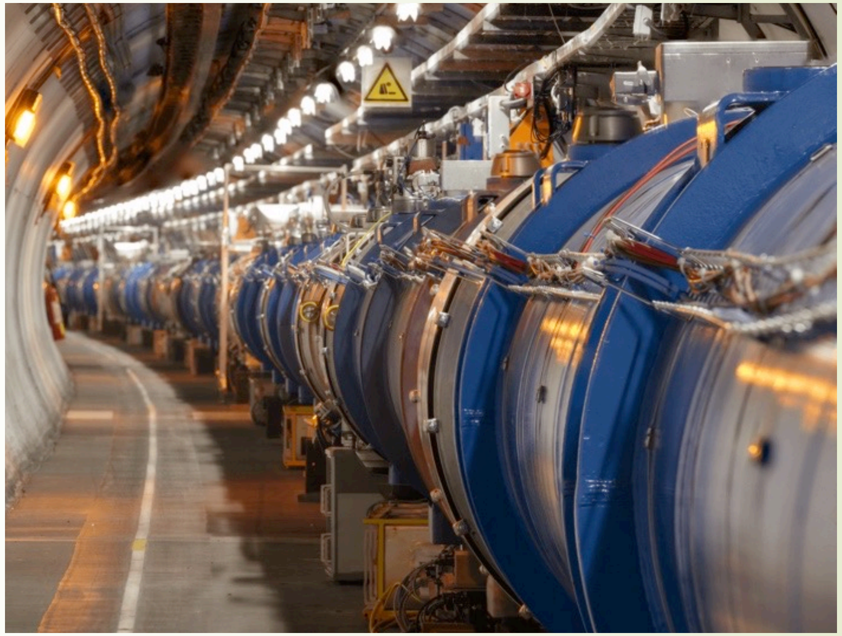






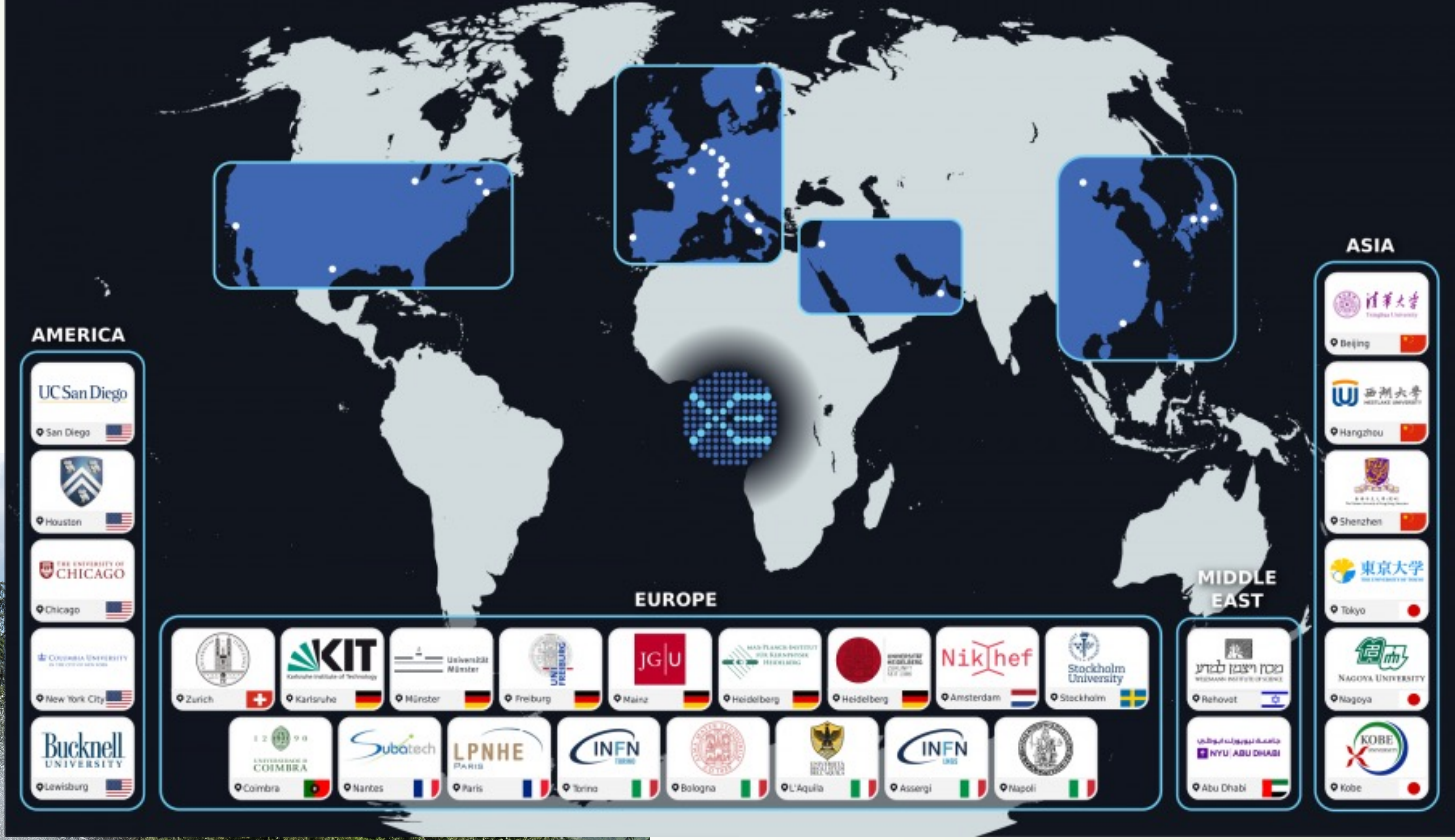


Hunting Dark Matter

Indirect detection	Direct detection	Production
		
$\chi + \chi \rightarrow f + \bar{f}$	$\chi + N \rightarrow \chi + N$	$p + p \rightarrow \chi + \ldots$

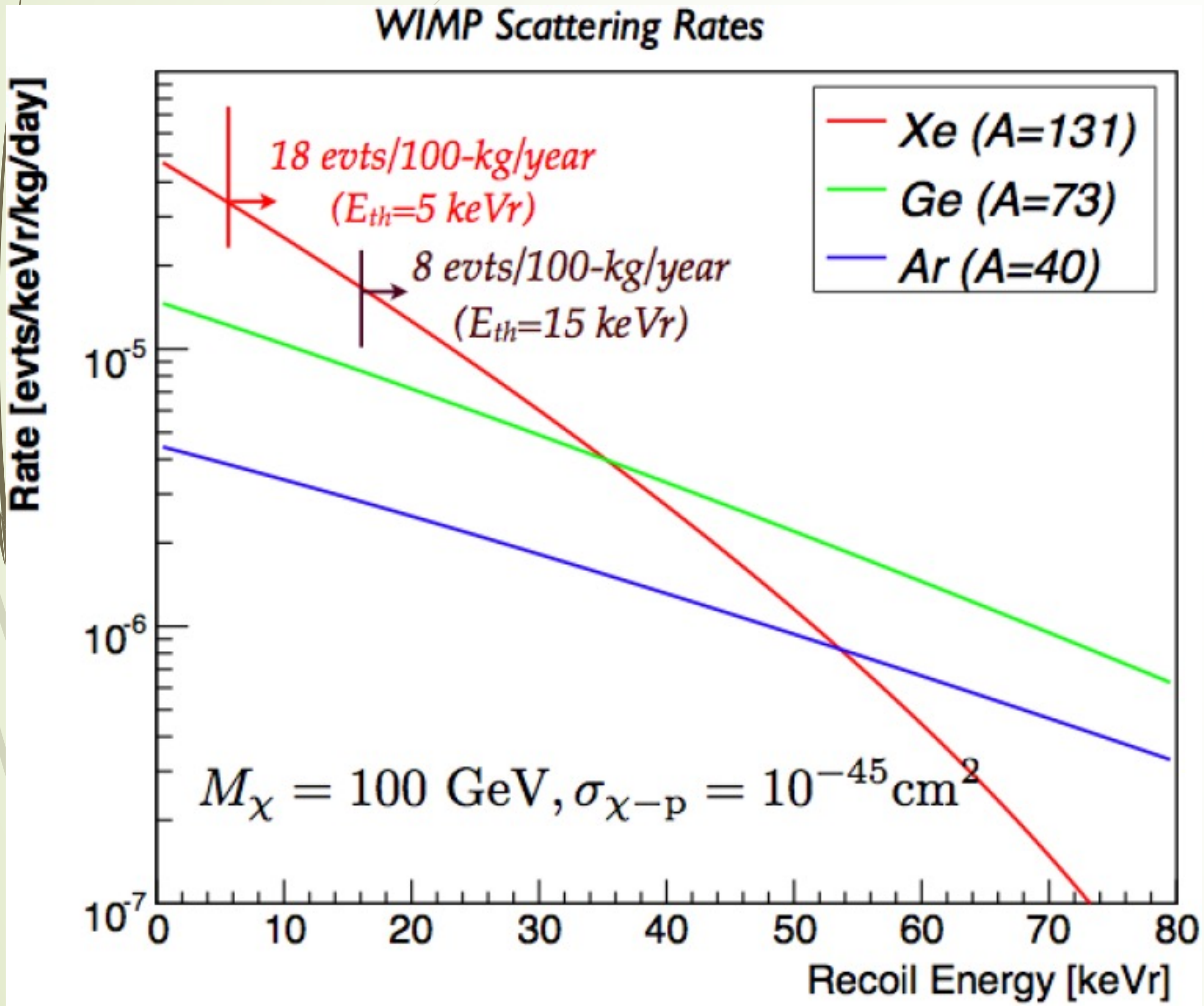
- 3 complementary channels
- very different techniques

XENON collaboration



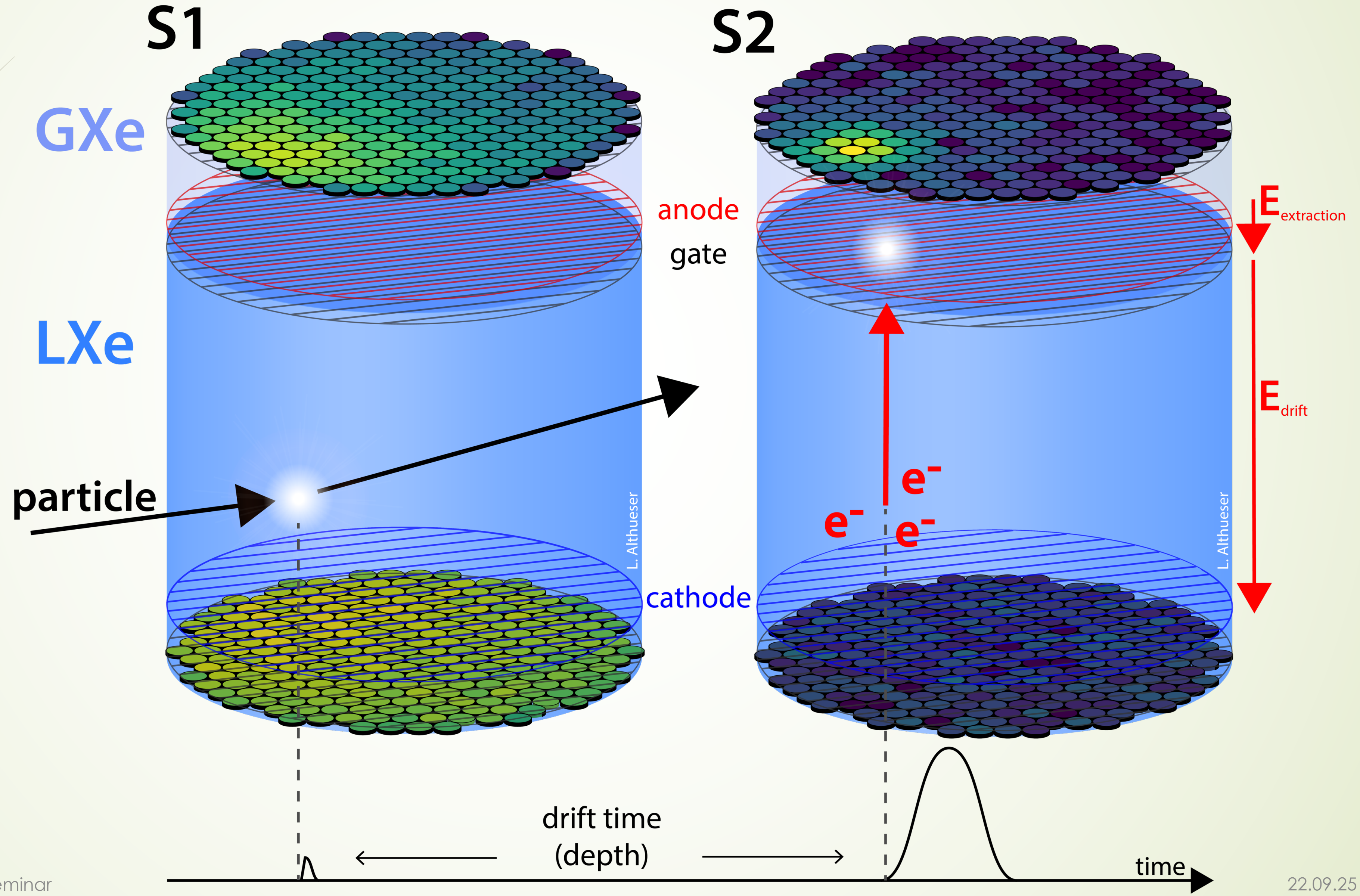
- 200+ scientists
- 30 institutes
- 12 countries

Why xenon?

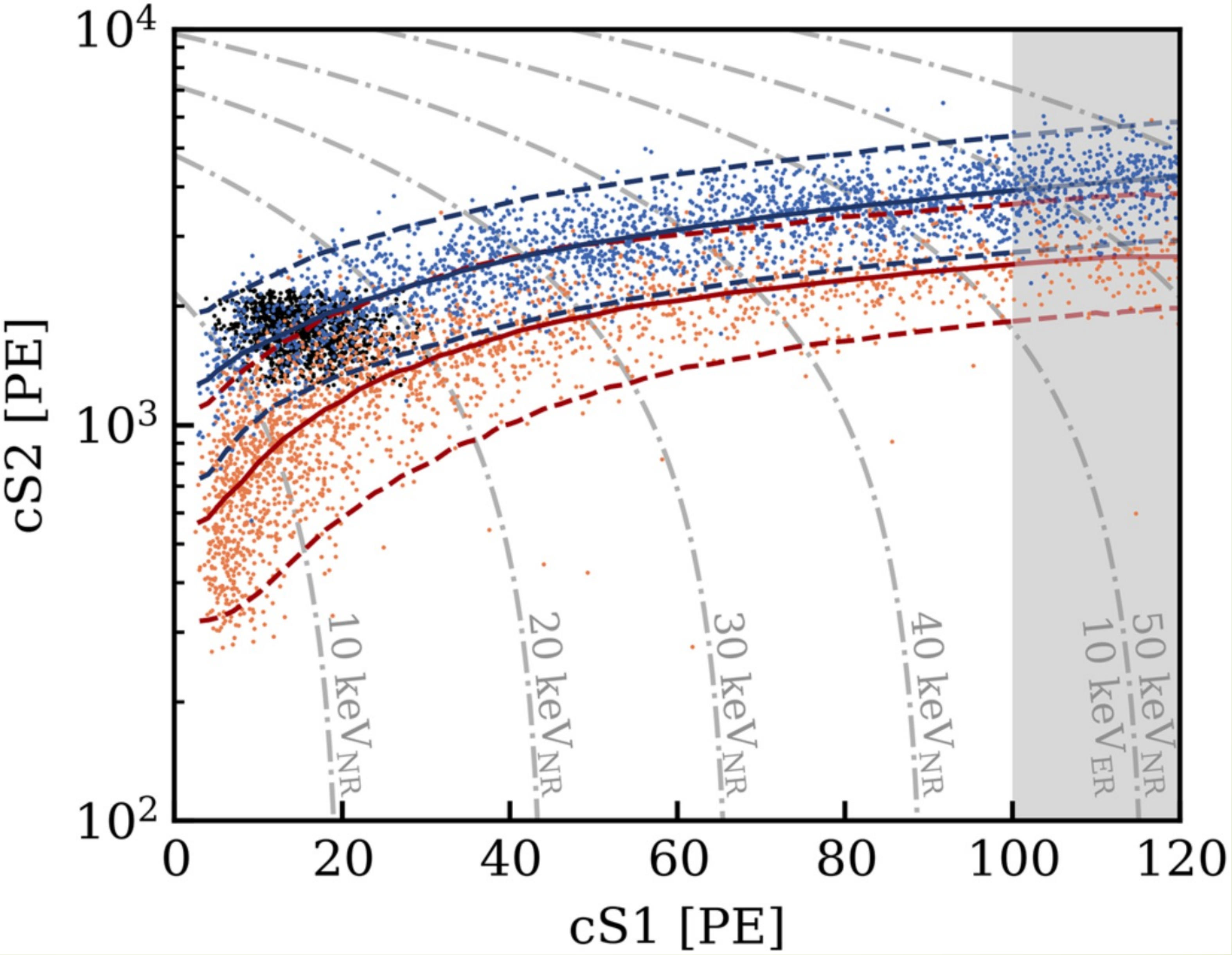


- High mass number (131) → relatively high rate
- LXe: Good self-shielding
- 178 nm scintillation photons: No wavelength shifter necessary
- No long-lived radioactive isotopes
- ^{129}Xe and ^{131}Xe → spin-dependent interactions

XENONnT working principle



Detector calibration

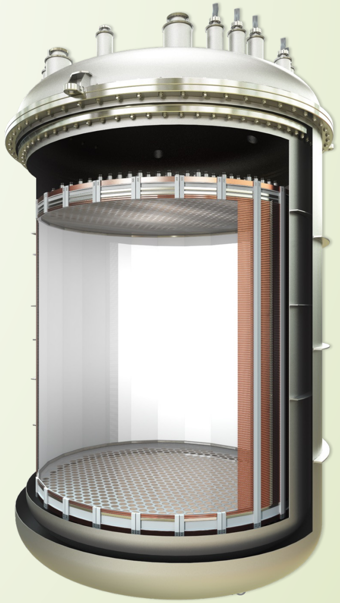


The XENON program

	XENON10	XENON100	XENON1T	XENONnT	XLZD
	2005-2007	2009-2016	2016-2018	2021-now	
Exposure:	0.87 kg*y	48 kg*y	1 t*y	20 t*y	300-600 t*y
Relative Background:	1	$5*10^{-3}$	$3*10^{-4}$	$3*10^{-5}$	

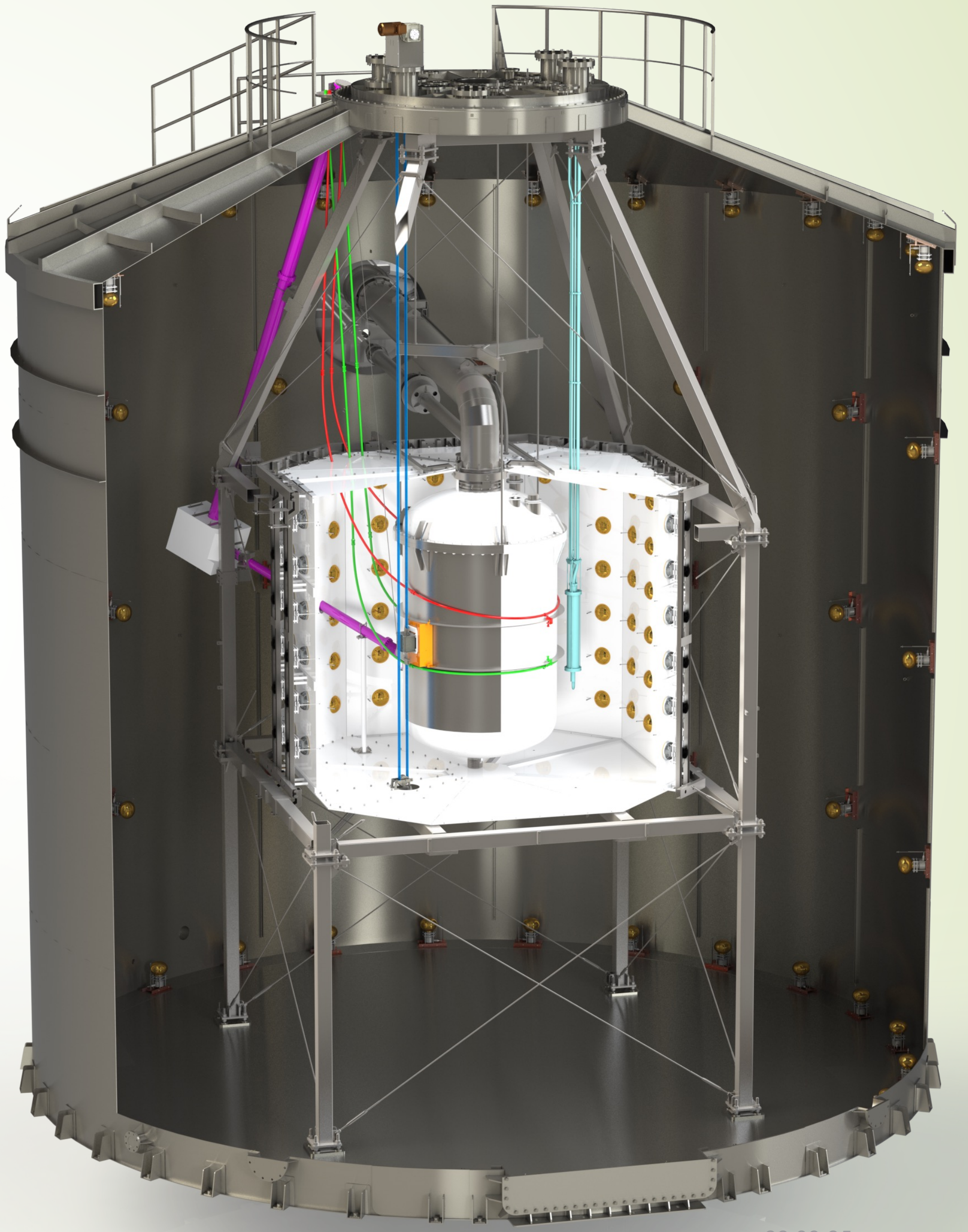




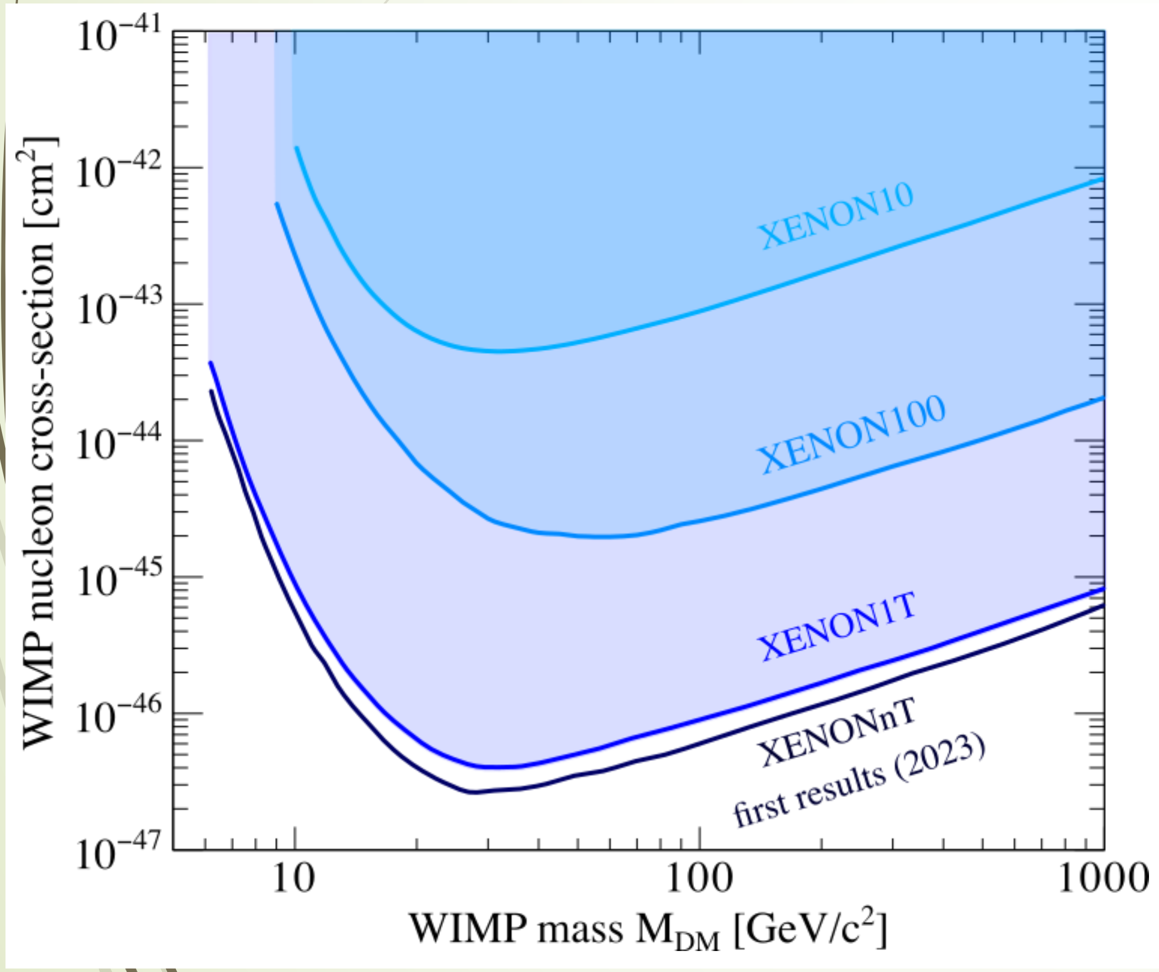


XENONnT

- 3 nested detectors
  - Water Cherenkov detector
  - Neutron veto system (Gd-loaded water)
  - Dual phase xenon TPC
- Many auxiliary systems
  - GXe purification system
  - LXe purification system
  - 2 xenon distillation columns
  - Cryogenic system
  - Calibration system
  - Xenon storage system
  - …



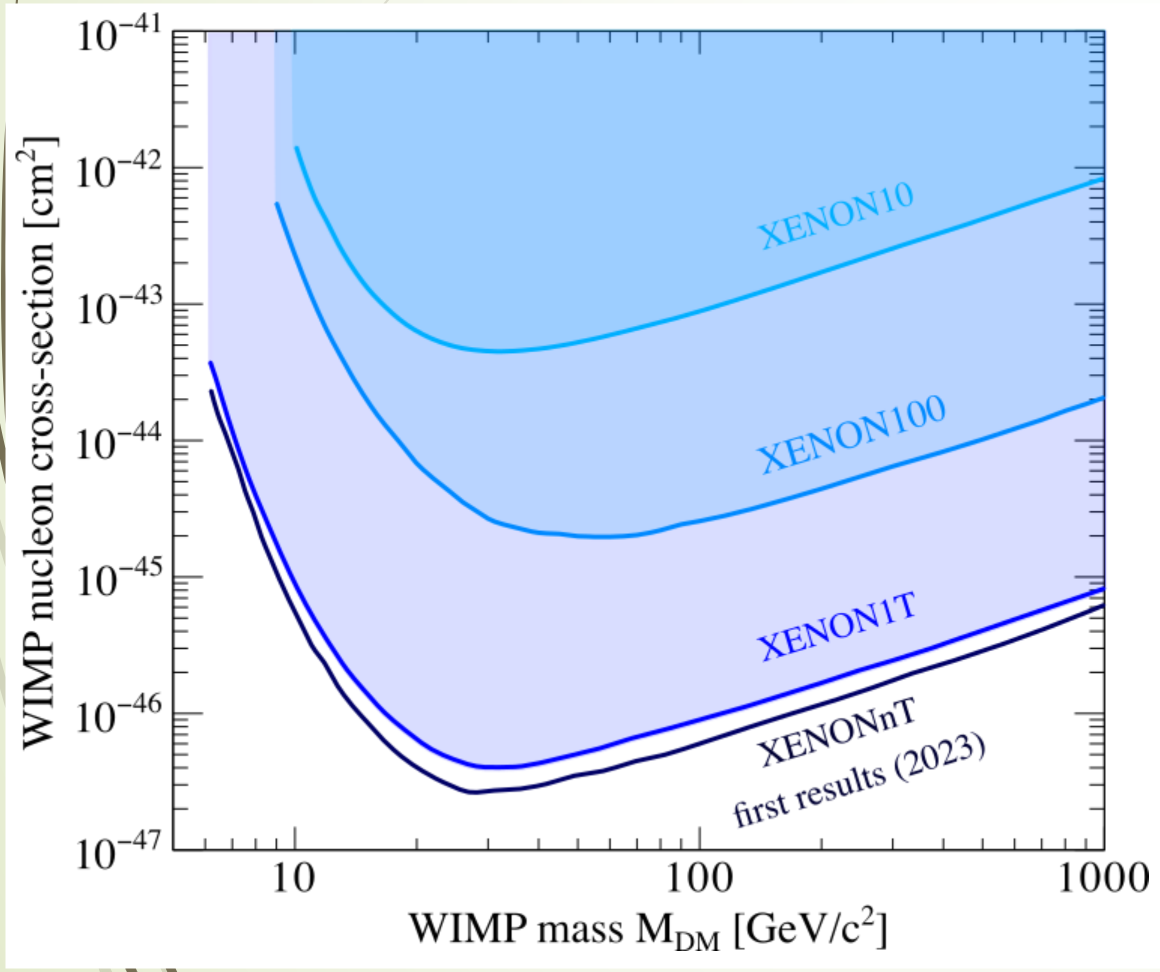
XENON experiments: WIMP results

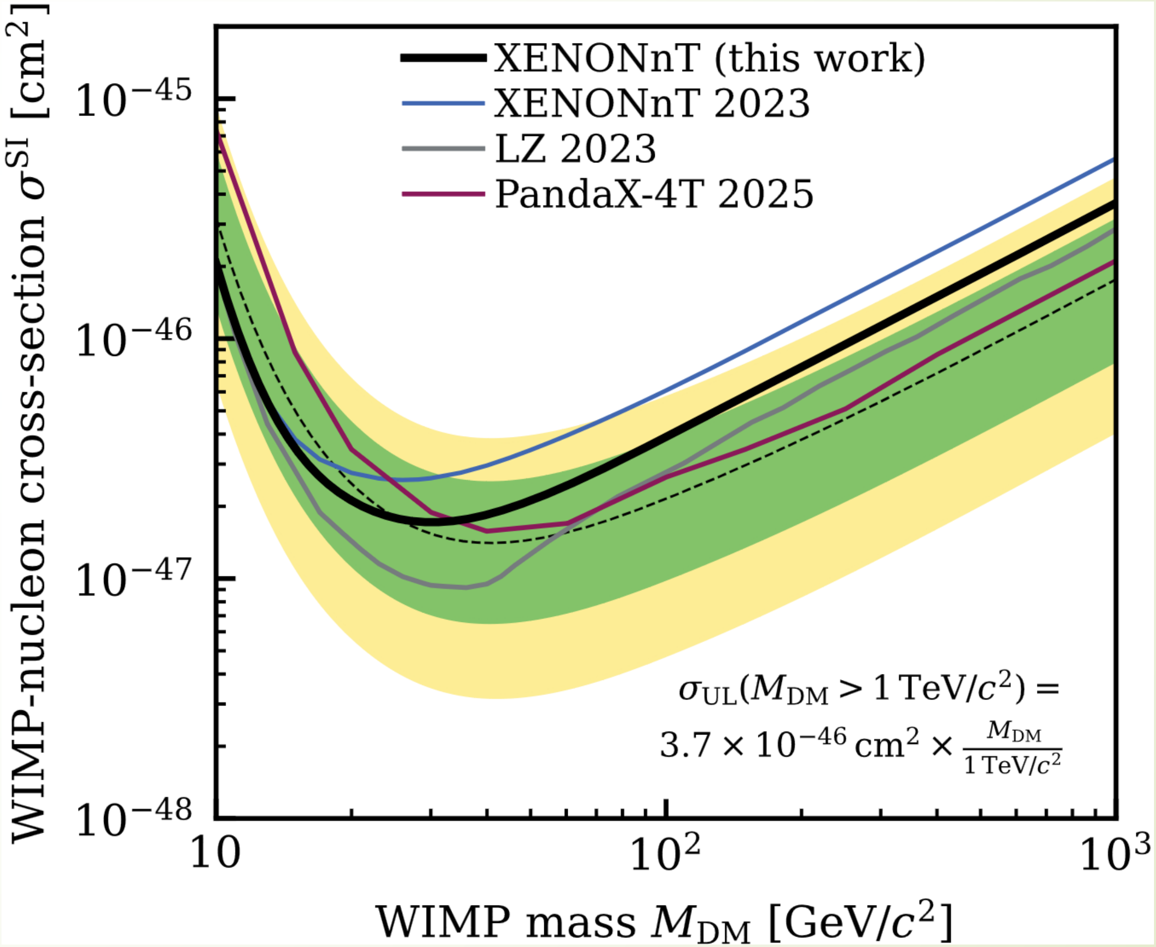


- Dual phase LXe TPCs have boosted direct dark matter search
- 4 orders of magnitude sensitivity improvement

XENON experiments: WIMP results

arXiv : 2502.18005



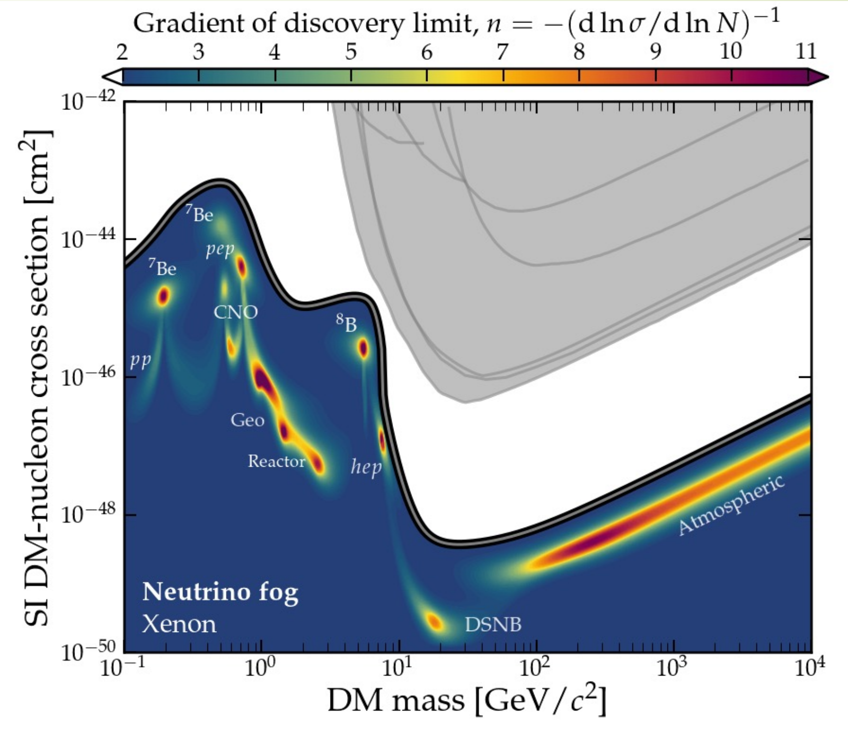


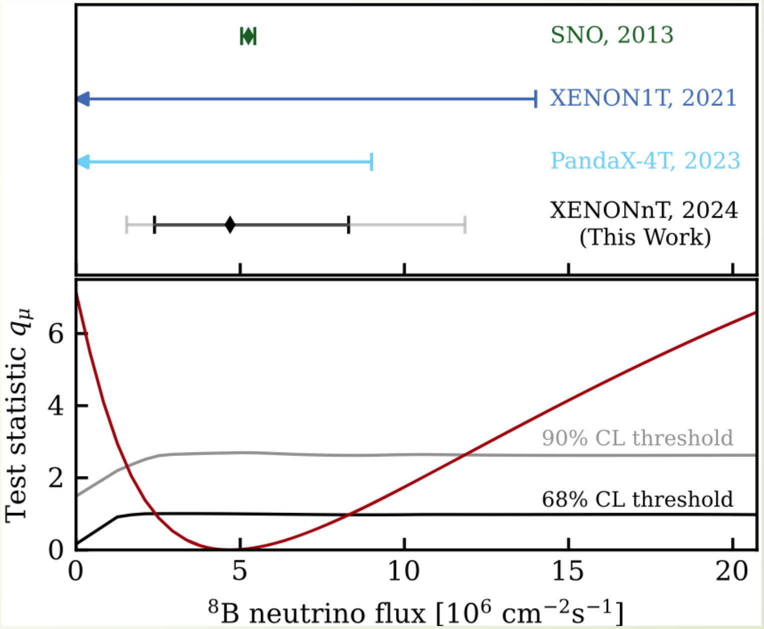
XENONnT: First signals from neutrinos

- DM sensitivity improved → neutrino signal within reach
- Special low-threshold analysis
- Very different background
- 2.7σ evidence for solar ^{8}B neutrinos via CEνNS

Component	Expectation	Best fit
AC (SR0)	7.5 ± 0.7	7.4 ± 0.7
AC (SR1)	17.8 ± 1.0	17.9 ± 1.0
ER	0.7 ± 0.7	$0.5^{+0.7}_{-0.6}$
Neutron	$0.5^{+0.2}_{-0.3}$	0.5 ± 0.3
Total background	$26.4^{+1.4}_{-1.3}$	26.3 ± 1.4
^{8}B	$11.9^{+4.5}_{-4.2}$	$10.7^{+3.7}_{-4.2}$
Observed	37	

PRL 133, 191002 (2024)





Electronic recoil background evolution

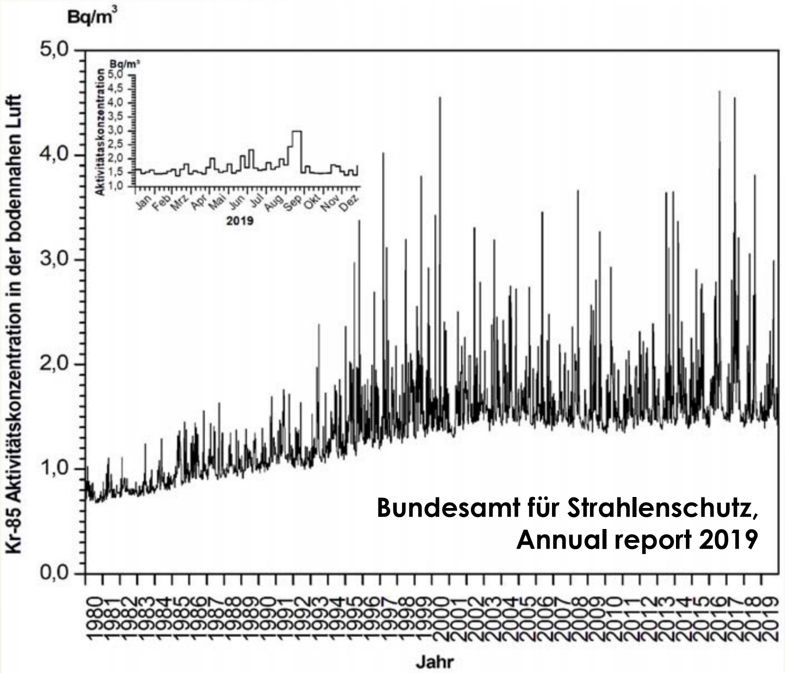
Background [events/t/y/keV]	**XENON100** [PRD 83, 082001] (2011)	**XENONnT** [PRL 129, 161805] (2022)
Detector materials	1160	1.7
^{85}Kr	860	0.6
^{222}Rn (^{214}Pb)	<140	5.9

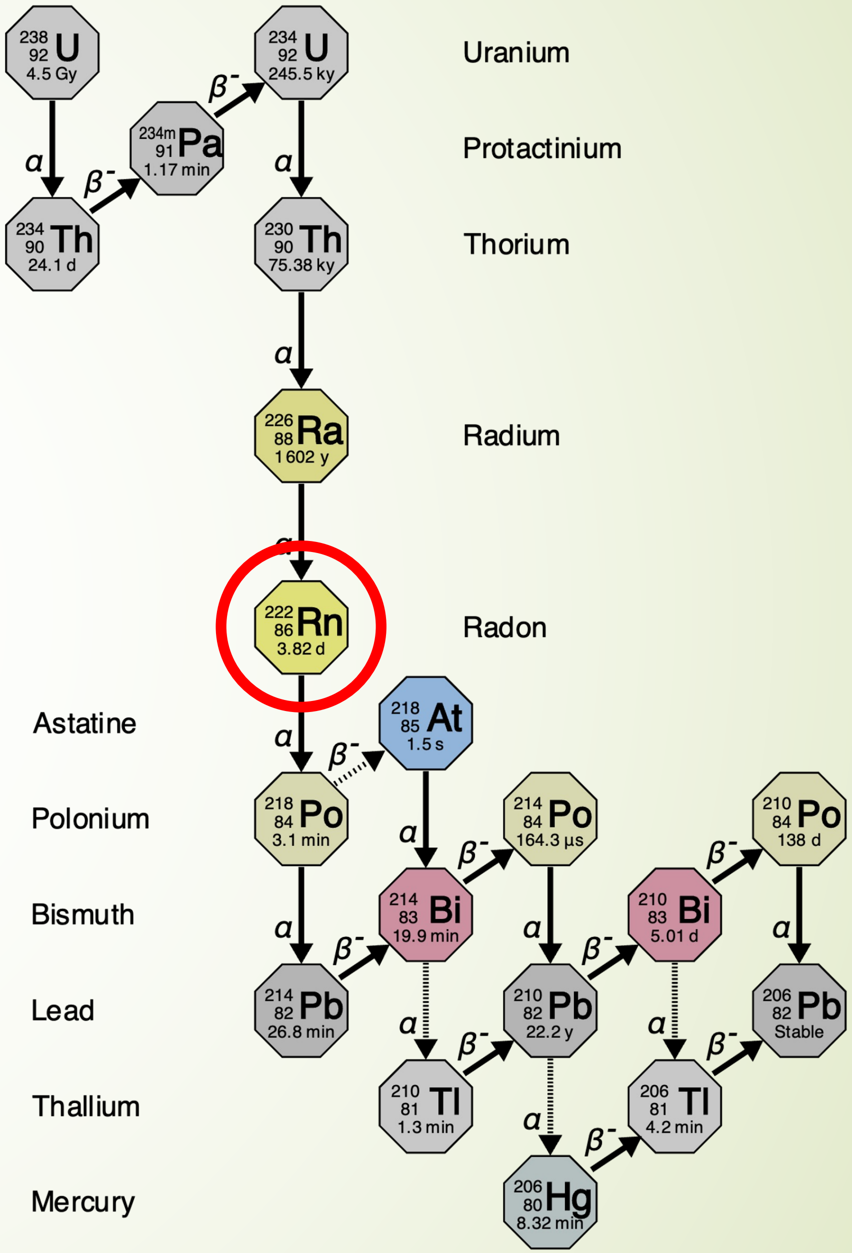
- XENON100: ^{222}Rn subdominant
  - Small detector → Material radioactivity dominant
  - Kr problem not yet solved
- XENONnT: ^{222}Rn dominant

^{222}Rn versus ^{58}Kr

	^{85}Kr	^{222}Rn
Half-life	10.4 years	3.8 days
Decay product	stable	Radioactive daughters
Origin	Man-made	Natural
Source	Nuclear fission	^{238}U chain

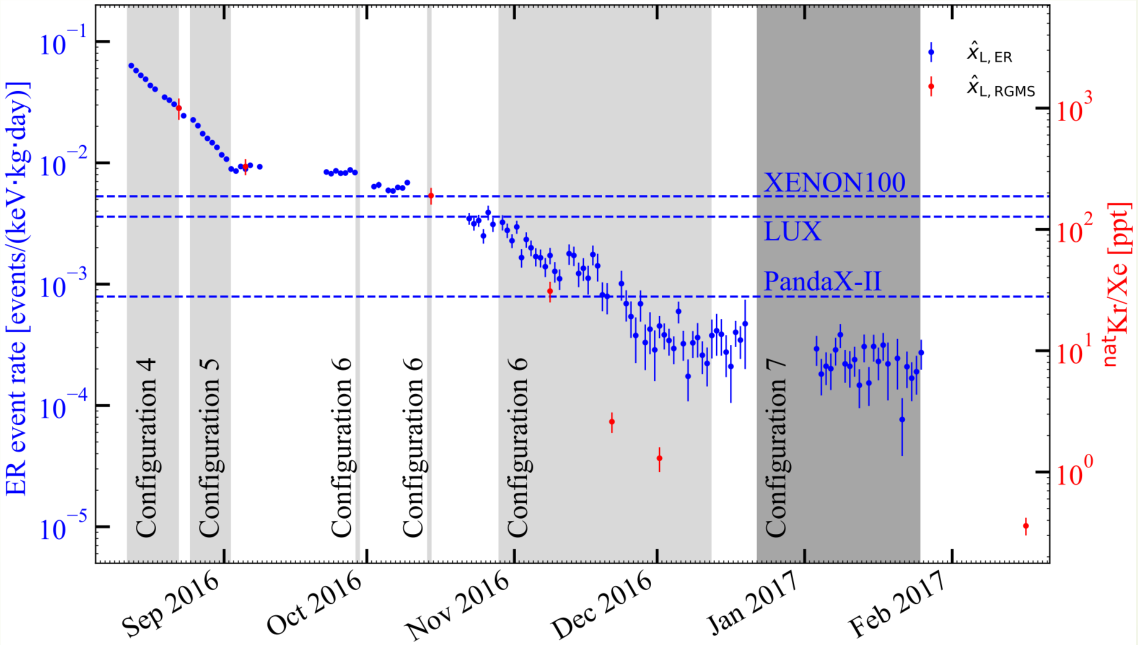
^{85}Kr in air (southern Germany)





Kr removal in XENON1T / XENONnT

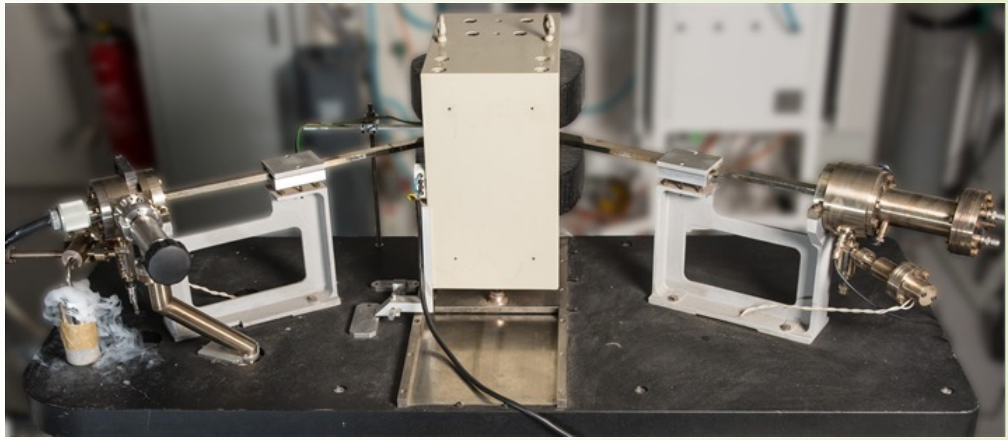
- Distillation column built for XENON1T
- Measured separation ~640.000 with 99% Xe recovery
- At least up to 6.5 kg/h throughput
- Lowest achieved concentration: 26 ppq
- Reliable Kr/Xe analytics with ppq-sensitivity required



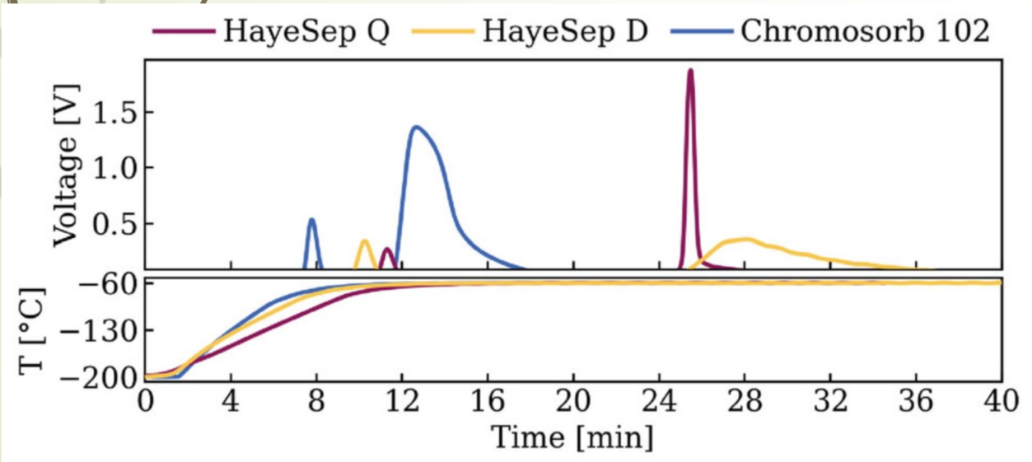
EPJC 77:275 (2017)

Rare Gas Mass Spectrometry (RGMS) at MPIK

EPJC 74:2746 (2014)

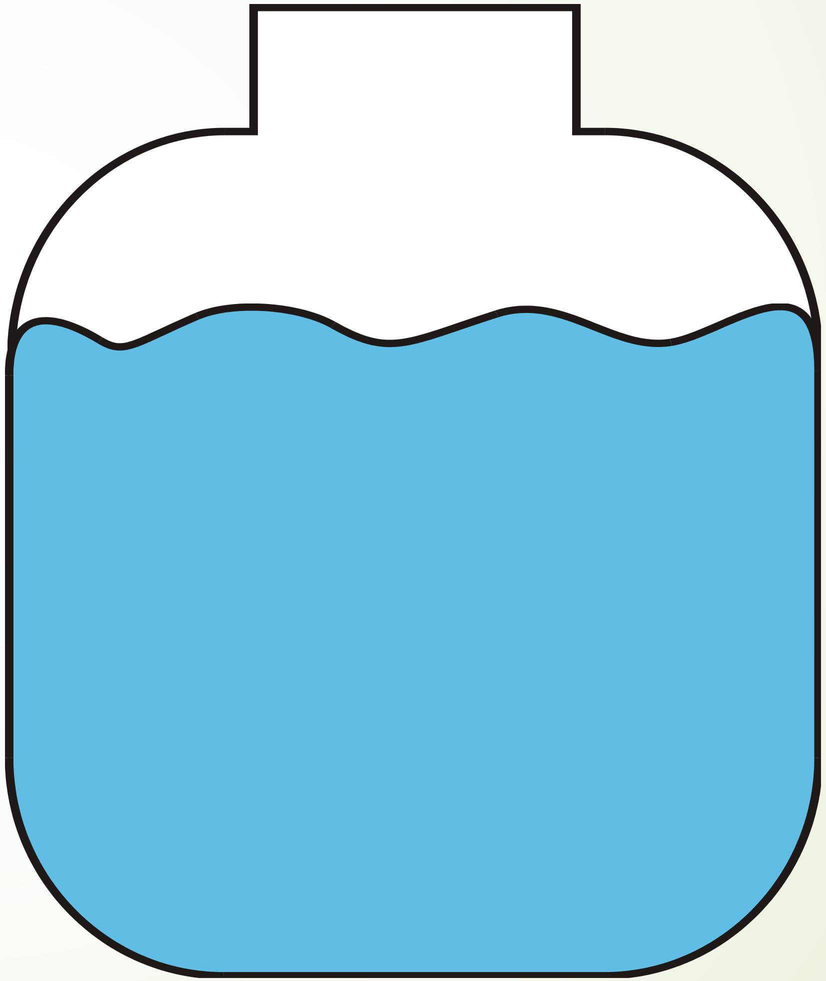


- Requires efficient removal of Xe → gas chromatography.
  - Homemade UHV-qualified system
  - Low mass packed columns
- 8 ppq detection limit
- Future: Automated RGMS (Auto-RGMS)
  - Fully automated operation (Improved repeatability)
  - Improved separation columns



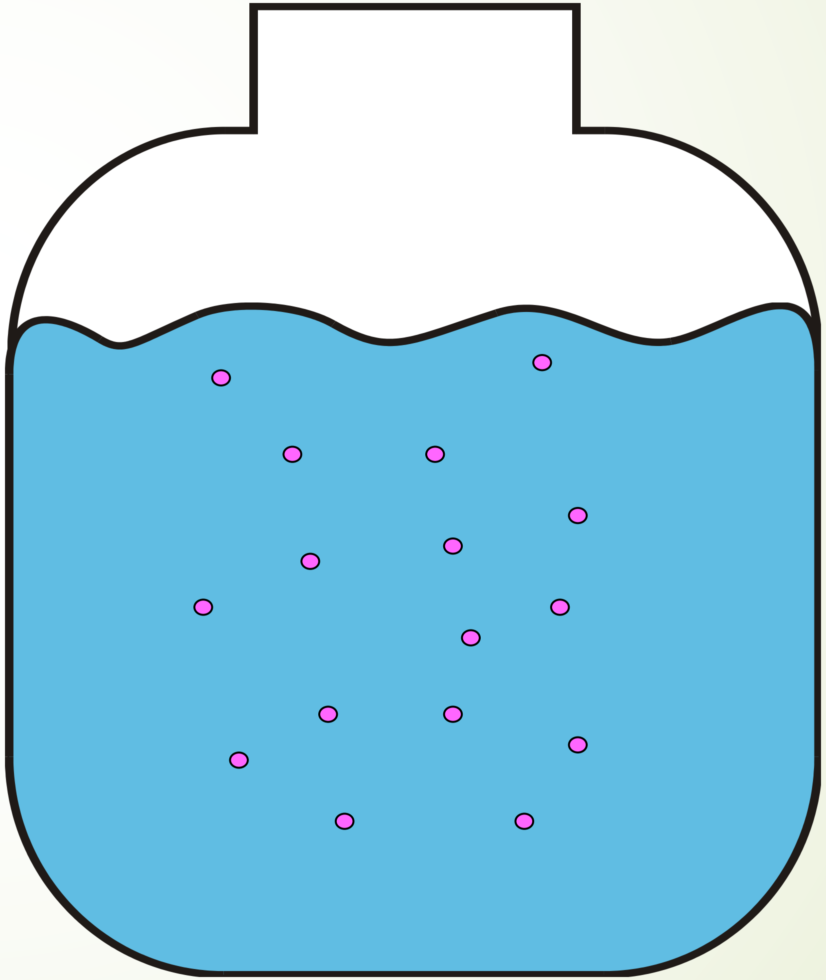
EPJC 85:576 (2025)

Radon sources in a generic experiment



Radon sources in a generic experiment

- Intrinsic radium (uranium/thorium) contamination



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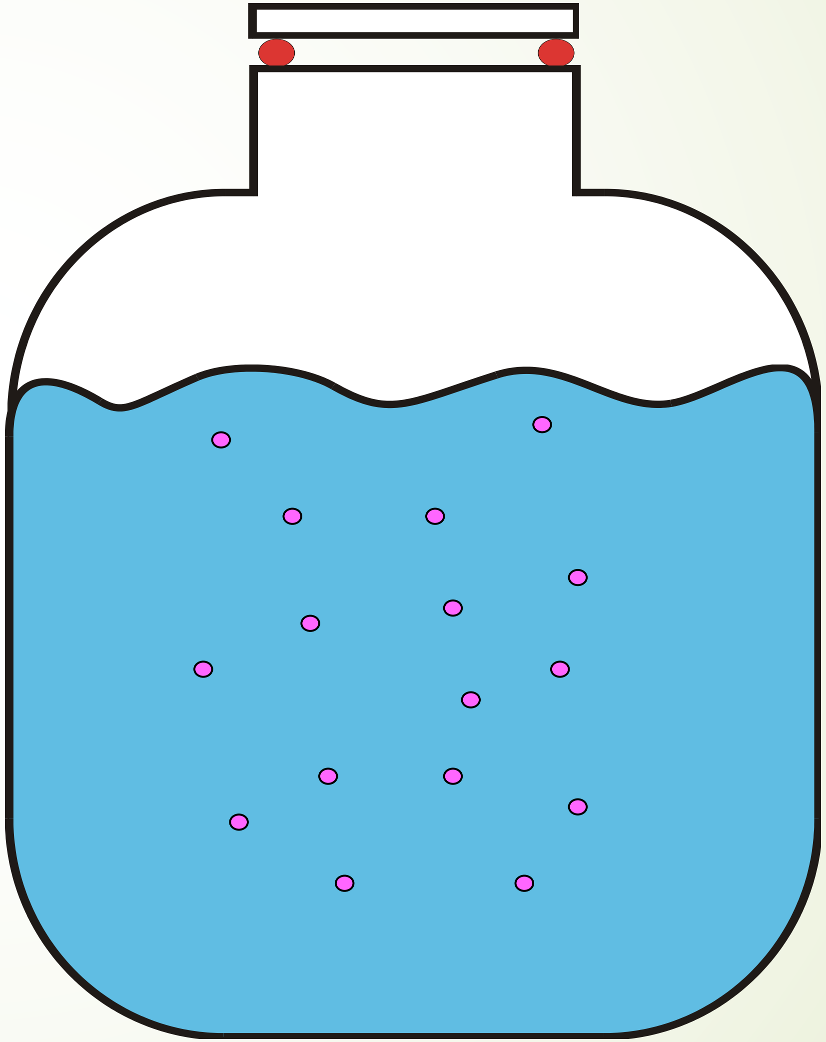

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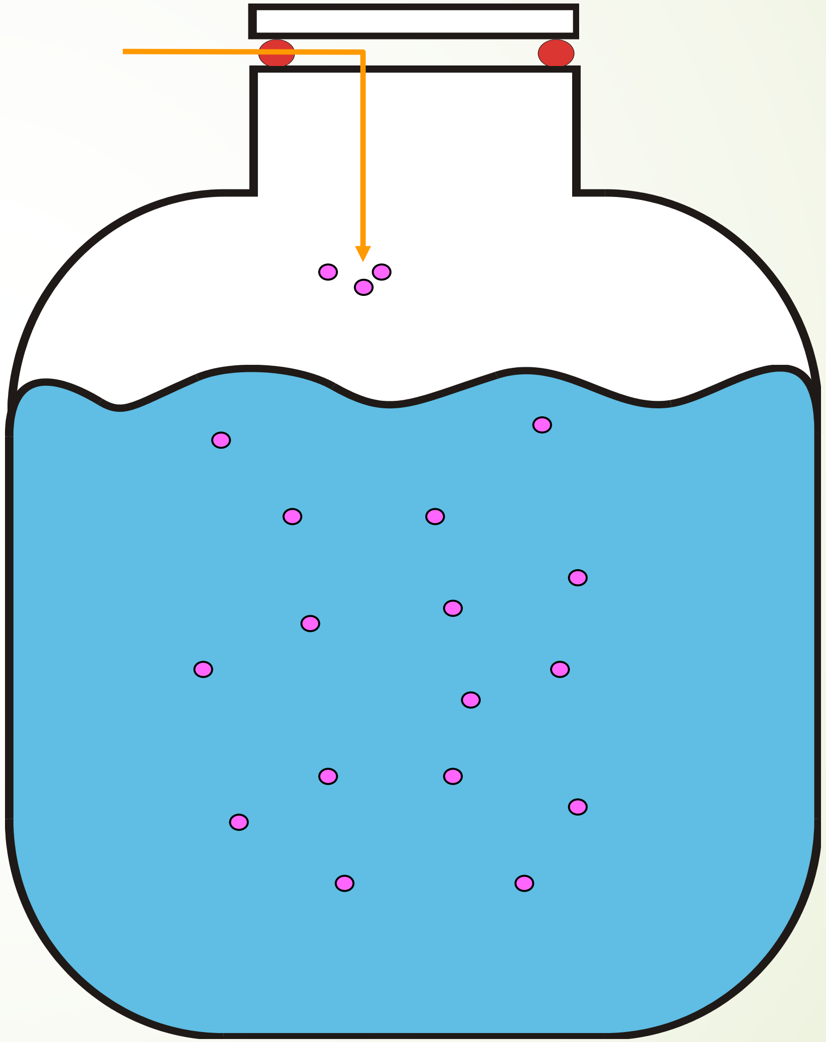
- Intrinsic radium (uranium/thorium) contamination
- Diffusion through seals



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- Intrinsic radium (uranium /thorium) contamination
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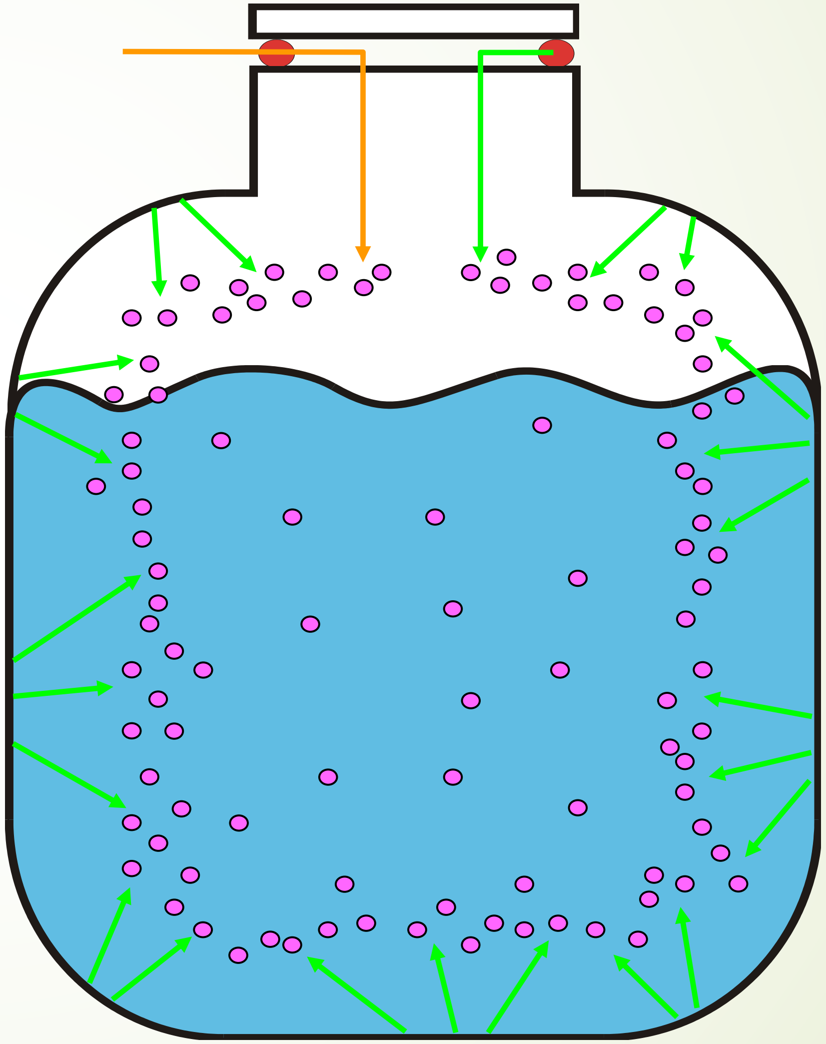
- Emanation from vessel and instrumentation



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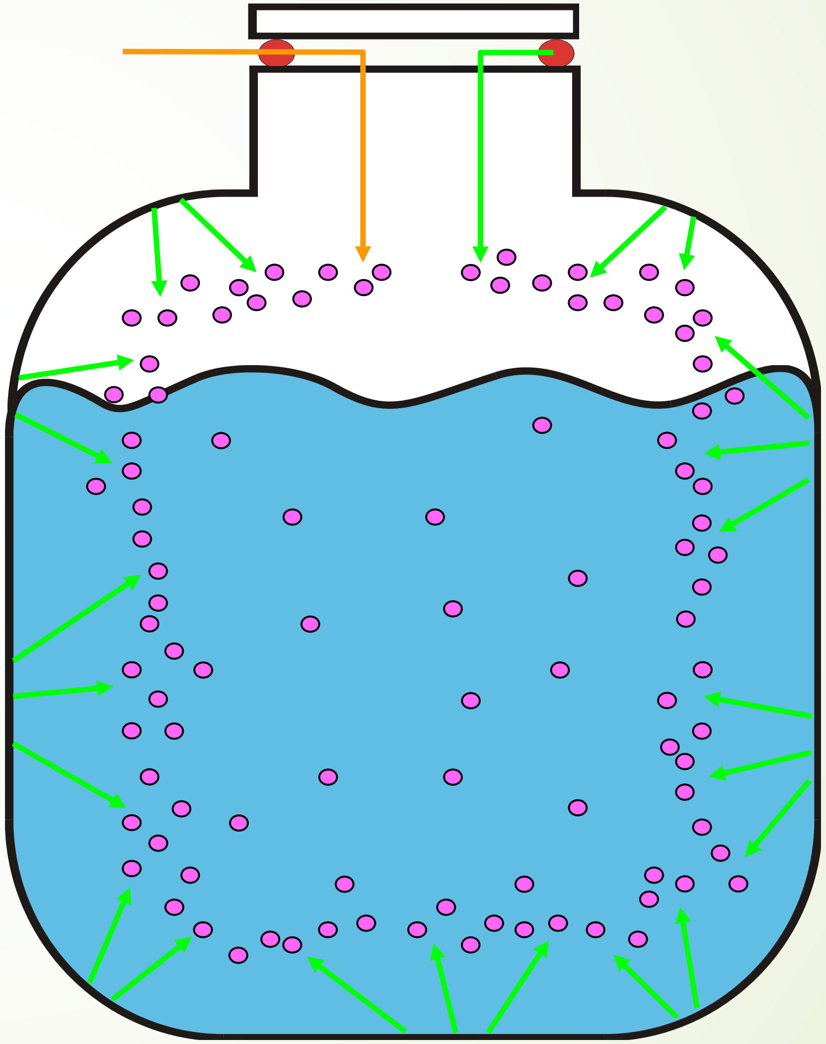
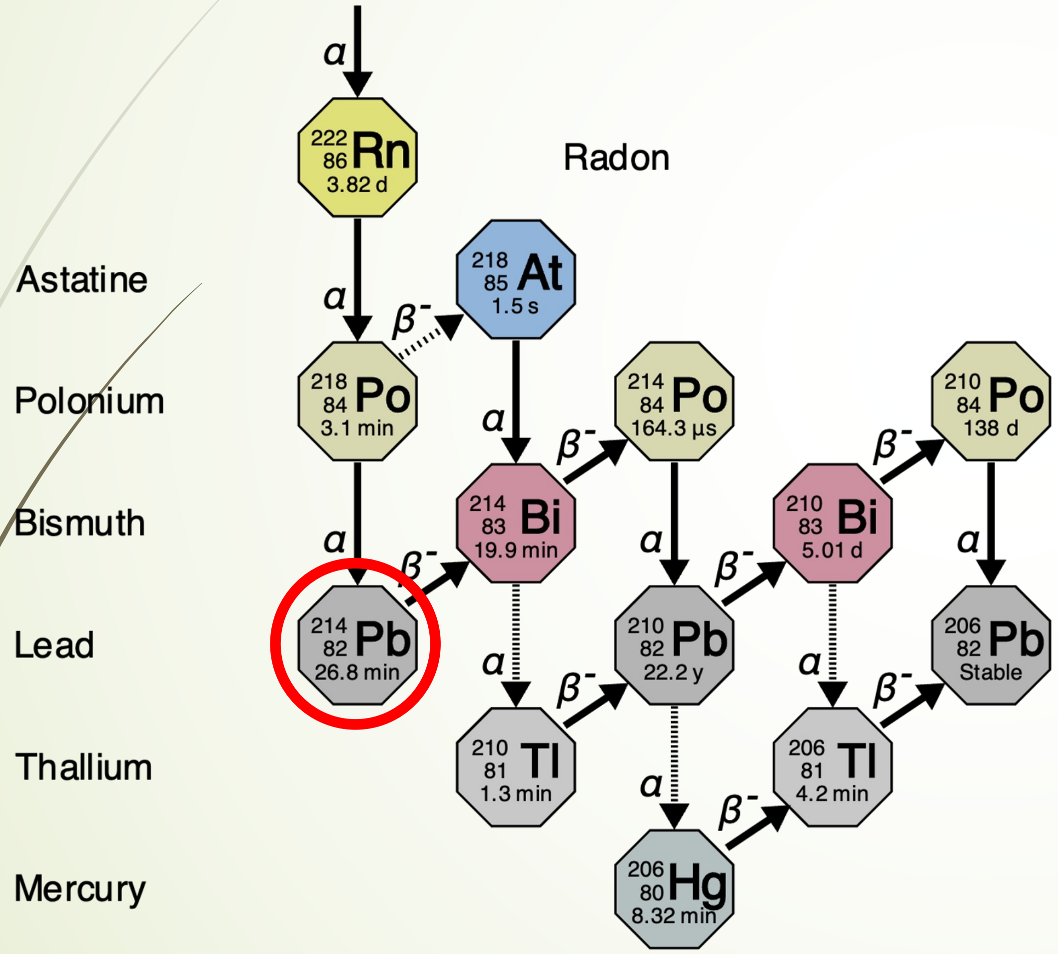
- Emanation from vessel and instrumentation

- A successful radon mitigation strategies must address all radon sources!



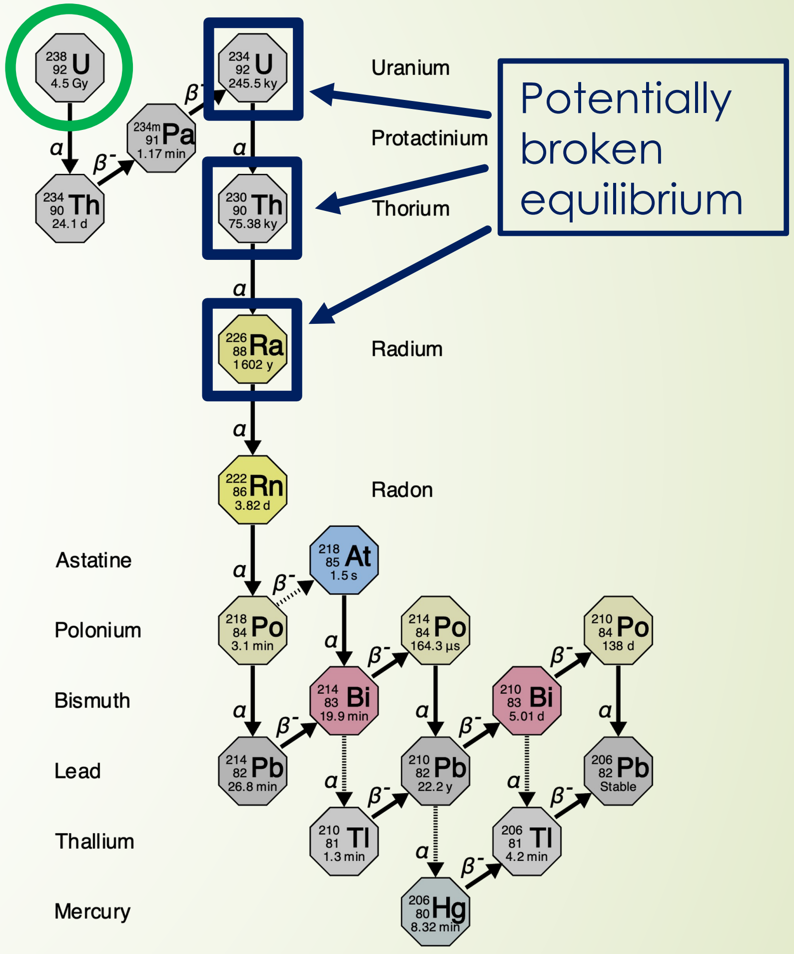
^{222}Rn in the XENON experiments



- Dark Matter signal is low-energetic (<10 keV)
- Alpha emitter ^{222}Rn, ^{218}Po, ^{214}Po: High energy events (MeV)
- Long-lived daughters out of equilibrium
- ^{214}Bi-^{214}Po coincidence
- Background only due to ^{214}Pb: Isolated beta emitter

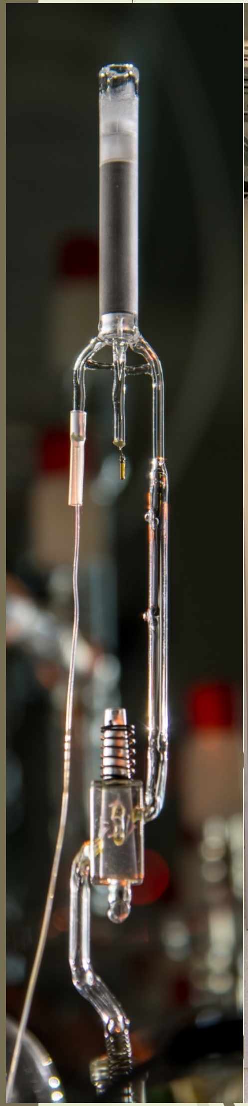
Radon detection (at low level)

- All radon detection by measurement of radioactivity (Alpha decays)
- Low-level → Requires radon collection
  - By cryo-trapping
  - By electrostatic collection of charged daughters
- Low-level → Clean materials and vacuum
- Warning: ICP-MS / NAA has fantastic sensitivity for U/Th. But radioactive may be broken, so no information about Rn!

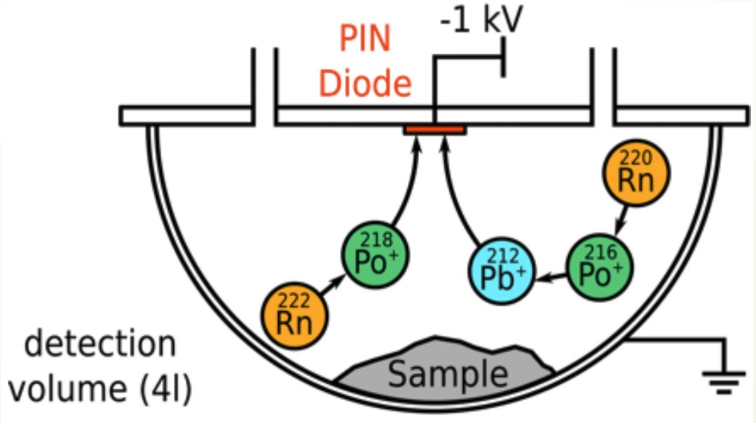


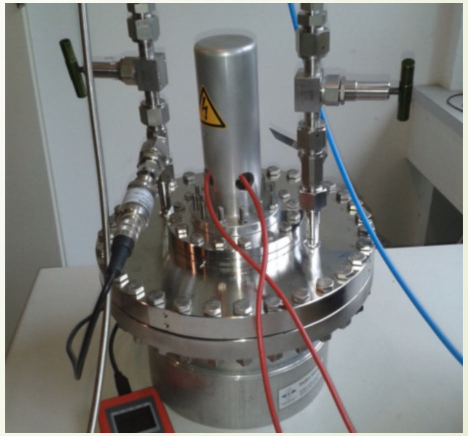
By http://commons.wikimedia.org/wiki/User:BatesIsBack

Material screening by ^{222}Rn emanation



- ^{222}Rn-emanation rate provides complementary information
- MPIK ^{222}Rn infrastructure:
  - >20 ultralow background miniaturized proportional counters
    - Sensitivity: ~10 atoms.
    - 8 parallel counting lines
  - Fully automated ^{222}Rn concentration system (AutoEma).
  - ~15 sample vessels (0.1 – 80 lit.)
  - 3 electro-static ^{222}Rn monitors





The radon emanation process

- *Thermochimica Acta 192,1 (1991)*

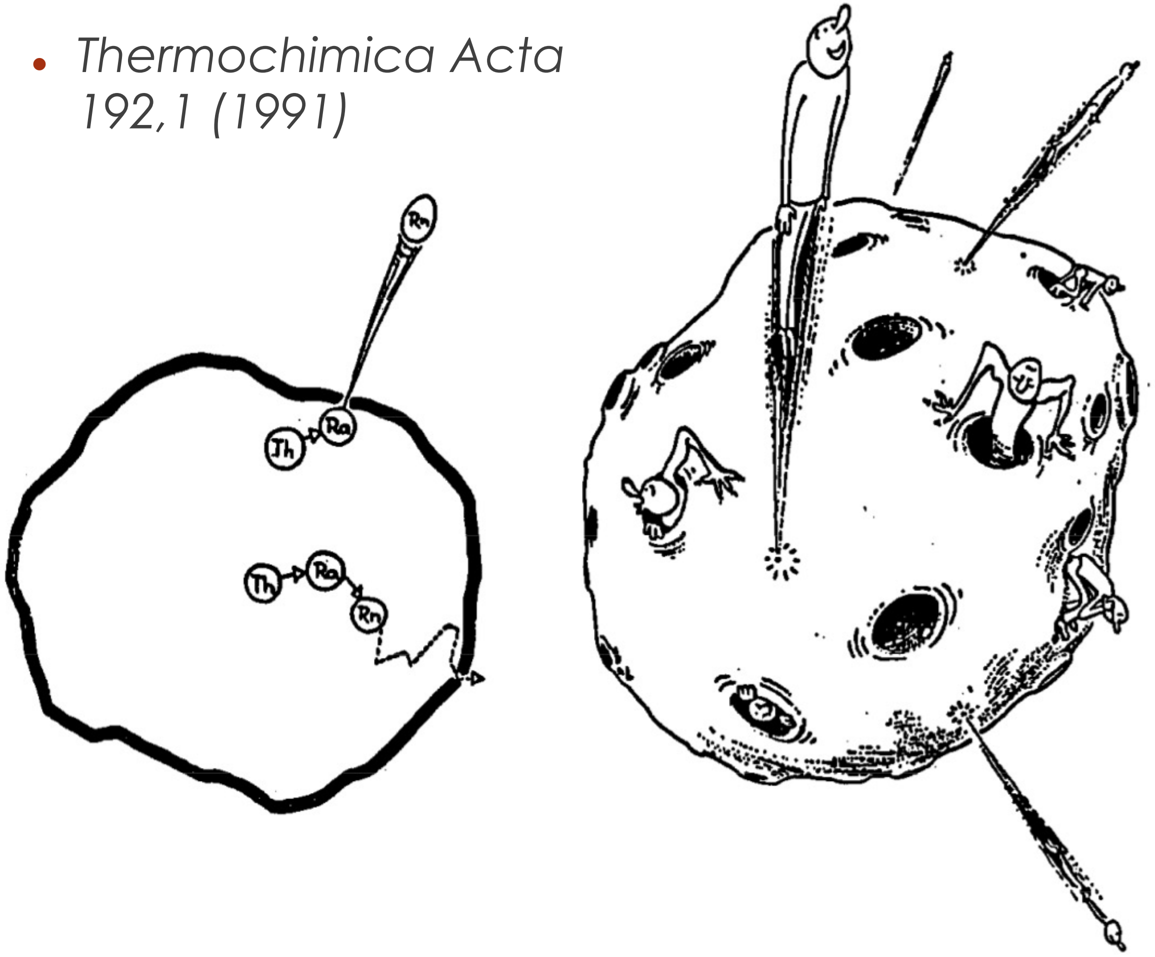


Fig. 2. Scheme of the release of radon from the sample by recoil and diffusion mechanisms.

- Recoil-driven emanation:
  - O(5 MeV) α-decay creates O(100 keV) nuclear recoil
  - Recoild range 10 – 100nm, depending on material
  - Independent of temperature
- Diffusion-driven emanation
  - Strongly depends on temperature
  - Diffusion coefficient varies a lot between materials

Radon emanation from charcoal

- Many charcoals screened at MPIK:
  - 30 years ago: Discovery of “CaroAct”
  - 15 years ago: Discovery of “Saratech”

NIM A 903, 267 (2018)

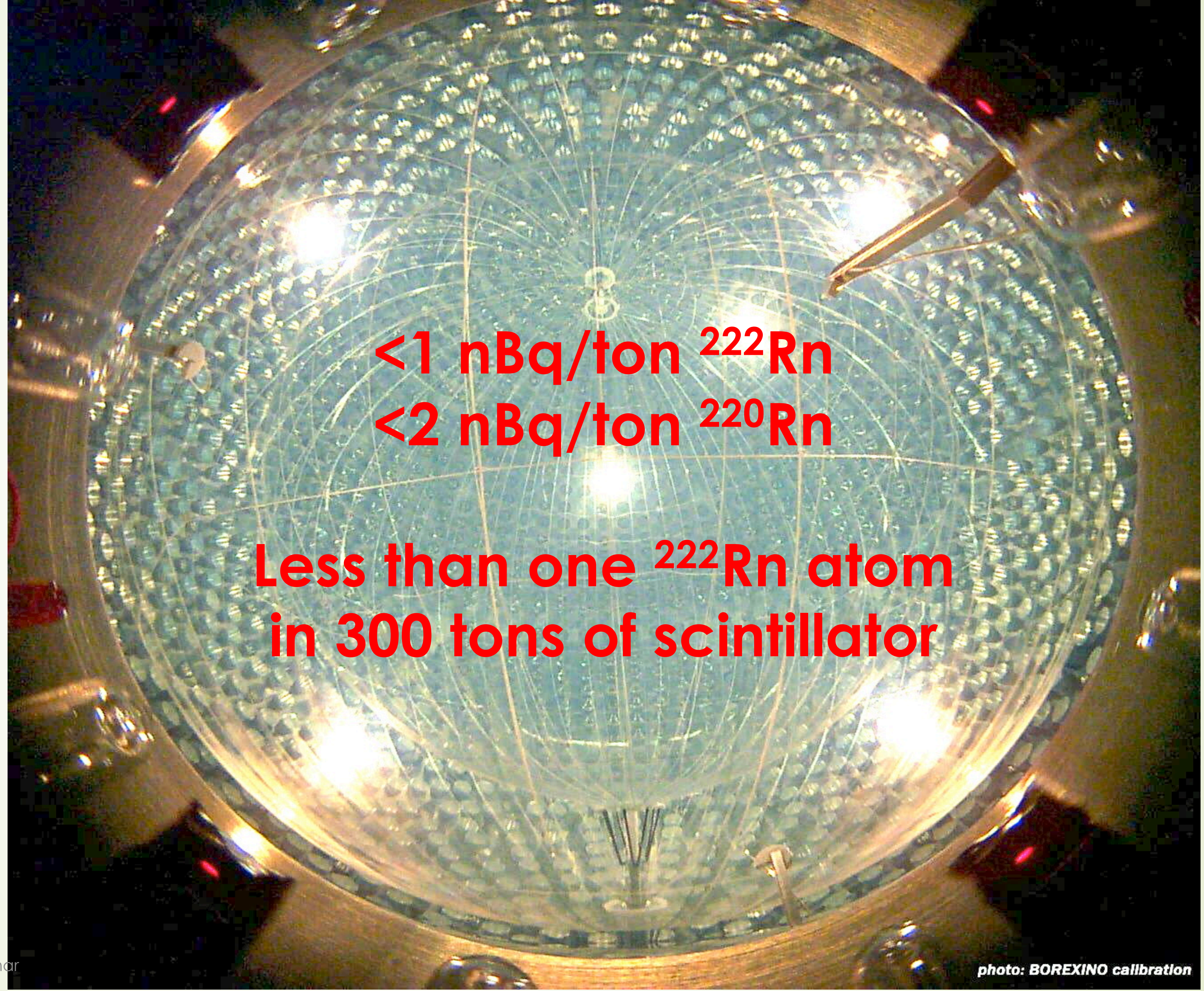
Charcoal	Specific activity (mBq/kg)	Price (USD/kg)	References
Calgon OVC 4 × 8	53.6 ± 1.3	6	This work
Shirasagi G2 × 4/6–1	101.0 ± 8.0	27	This work
Saratech	1.71 ± 0.20	35	This work
HNO_3 etched Saratech	0.51 ± 0.09	135	This work
Carboact	0.23 ± 0.19	15,000	This work
Carboact	0.33 ± 0.05	15,000	[28]

^{222}Rn emanation from Saratech charcoal

- ^{222}Rn release rate strongly depends on extraction parameters
- ^{226}Ra activity (HPGe spectroscopy): (7 ± 1) mBq/kg
- Gamma-ray measurement of HNO_3-cleaned charcoal ongoing.
- ^{222}Rn emanation into xenon?

Charcoal	Extraction conditions	^{222}Rn emanation rate [mBq/kg]
Saratech	Room temperature	<0.3
Saratech	200 °C and prolonged extraction	3.5 ± 0.2
HNO_3-cleaned Saratech	200 °C and prolonged extraction	1.0 ± 0.1

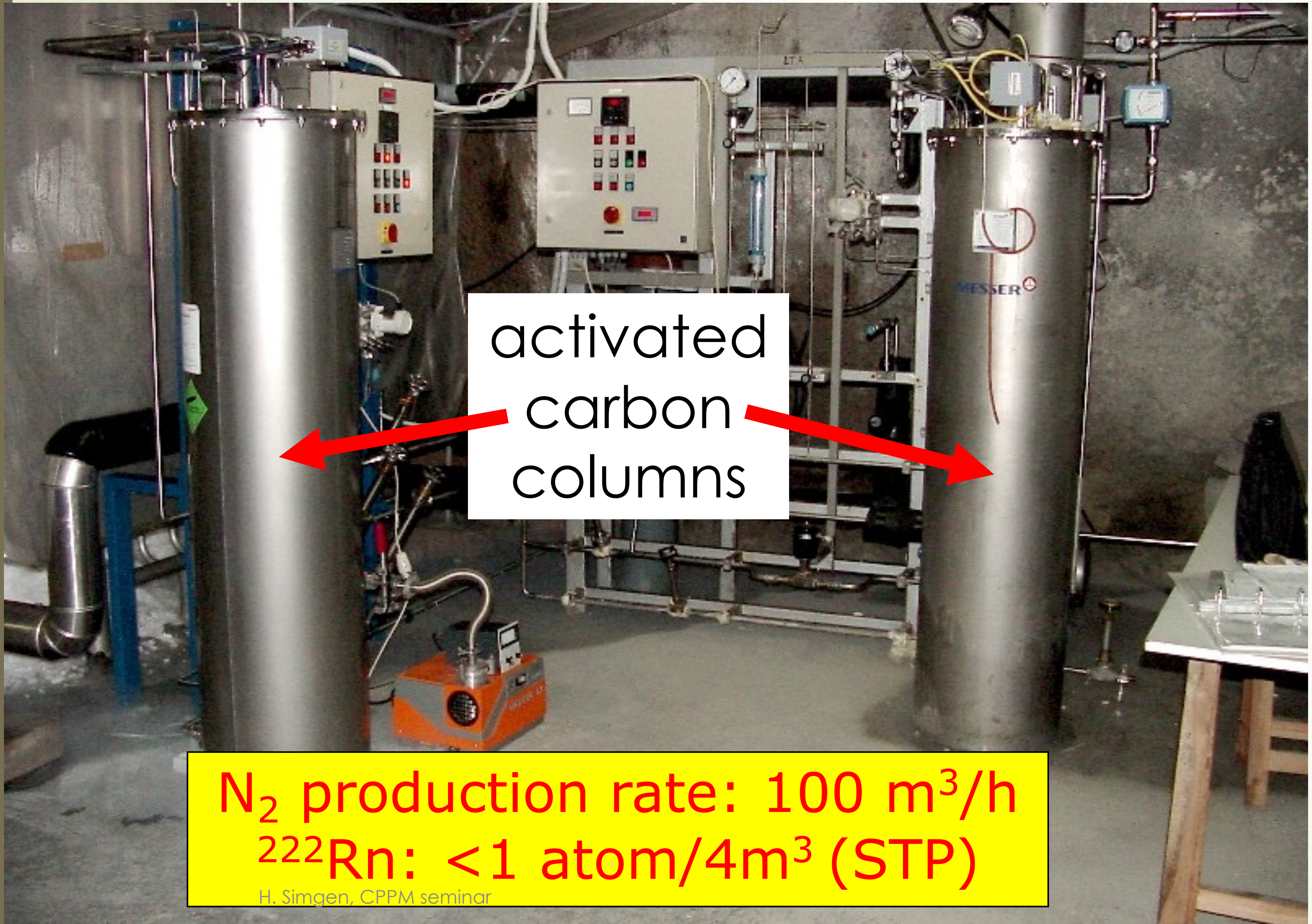
BOREXINO



<1 nBq/ton ^{222}Rn
<2 nBq/ton ^{220}Rn

Less than one ^{222}Rn atom in 300 tons of scintillator

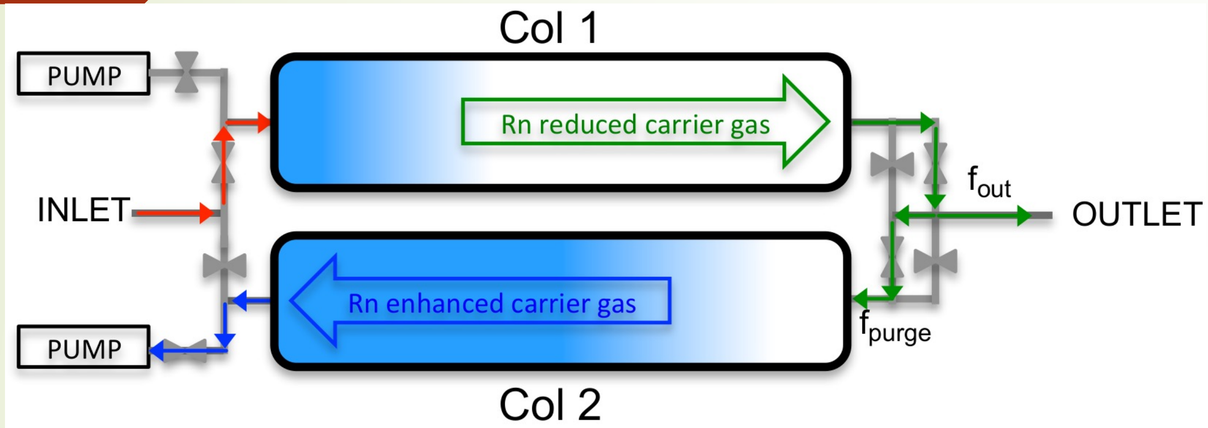
High Purity nitrogen for BOREXINO



- Radon-free nitrogen for scintillator sparging
- Large flow-rate (100 m^3/h)
- Simple concept withlittle maintenance needed
- Lqiuid nitrogen cooled columns
- Purifications of liquid nitrogen (less efficient, but high throughput)
- Key: Low ^{222}Rn emanating activated carbon

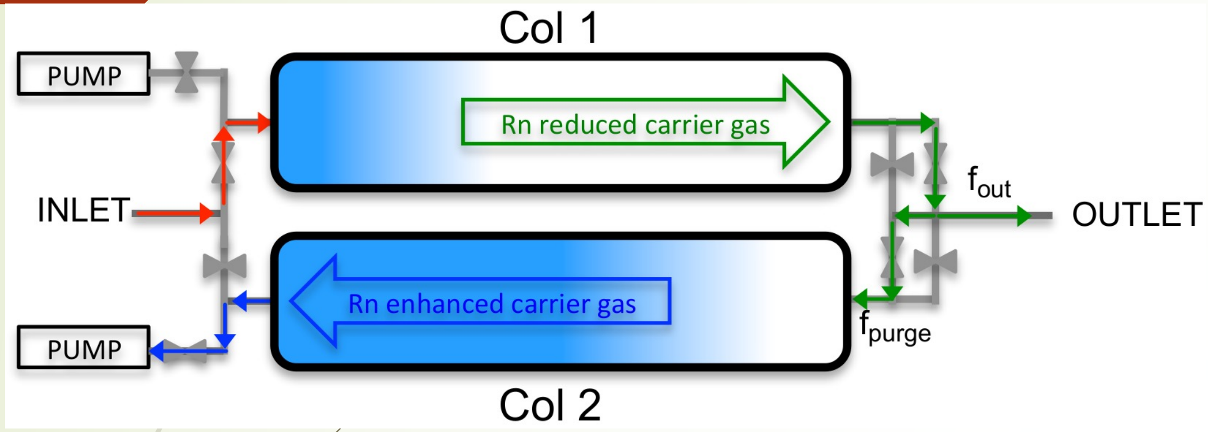
Appl. Rad. Isot. 52 (2000) 691

Improving adsorption gas purification



- Improving performance by doubling columns and avoiding equilibrium
- Vacuum swing adsorption technique can reduce amount of adsorbens
- Gain in radiopurity → purer gas
  - *JINST 16 P07047 (2021)*

Improving adsorption gas purification



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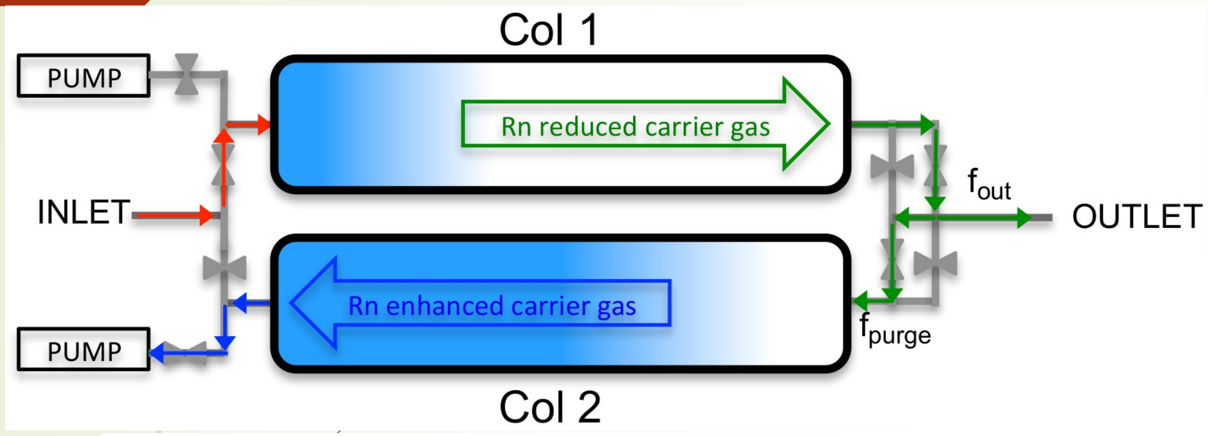
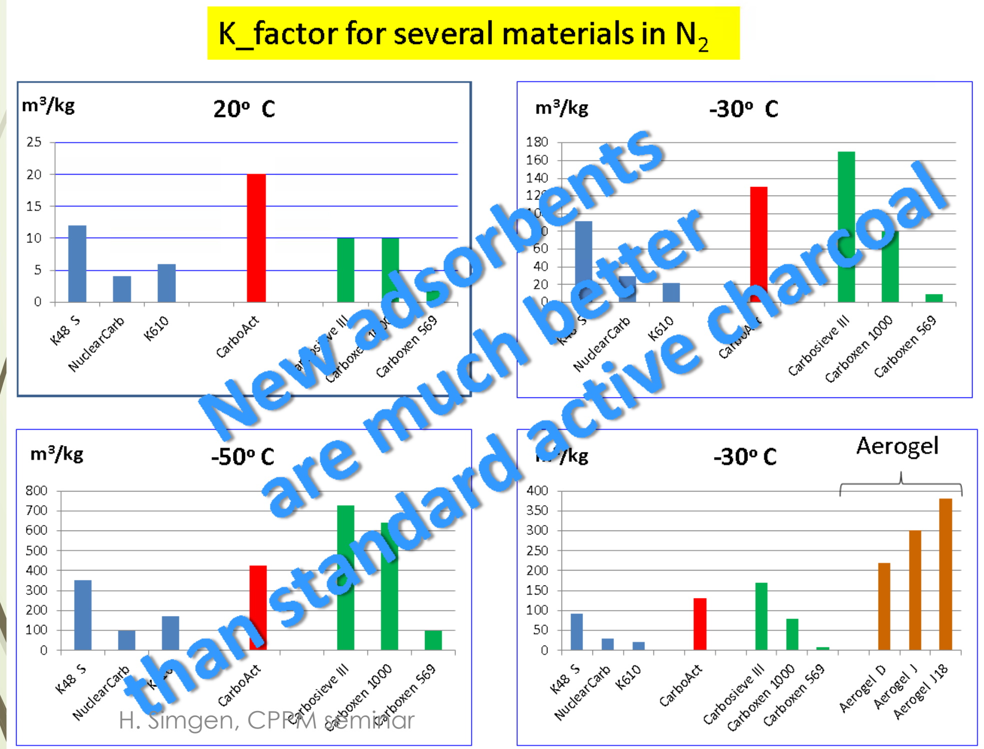
- New adsorber materials → José Busto
  - Carbon molecular sieves
  - metal organic frameworks
  - molecular cages
  - carbon aerogel
  - …

Improving adsorption gas purification





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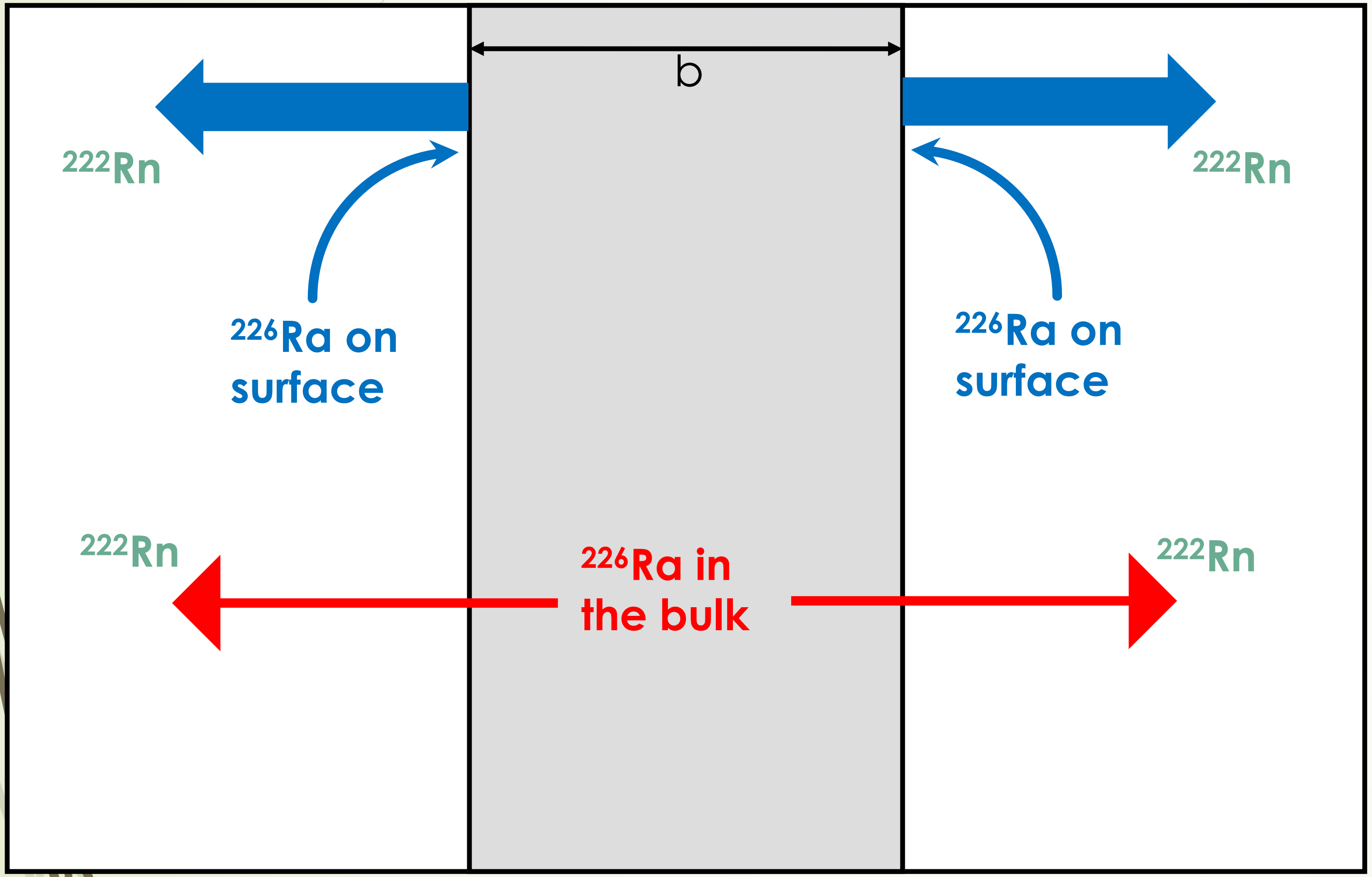
J. Busto,
GDR Nov. 22

^{222}Rn emanation rate of some stainless steel vessels

Vessel	Size	^{222}Rn emanation rate [mBq]
BX storage tank HT2	2.1 m^3	1.2 ± 0.4
BX storage tank D330	1.6 m^3	7.1 ± 1.2
GERDA cryostat	64 m^3	13.7 ± 1.9
XENON1T cryostat	~2 m^3	1.8 ± 0.3
XENONnT cryostat	~4.5 m^3	1.9 ± 0.2
Borexino water extraction column	0.6 m^3, 608 m^2 (SS packings)	4.8 ± 0.7 → 8 μBq/m^2

Nylon film during measurement @ MPIK

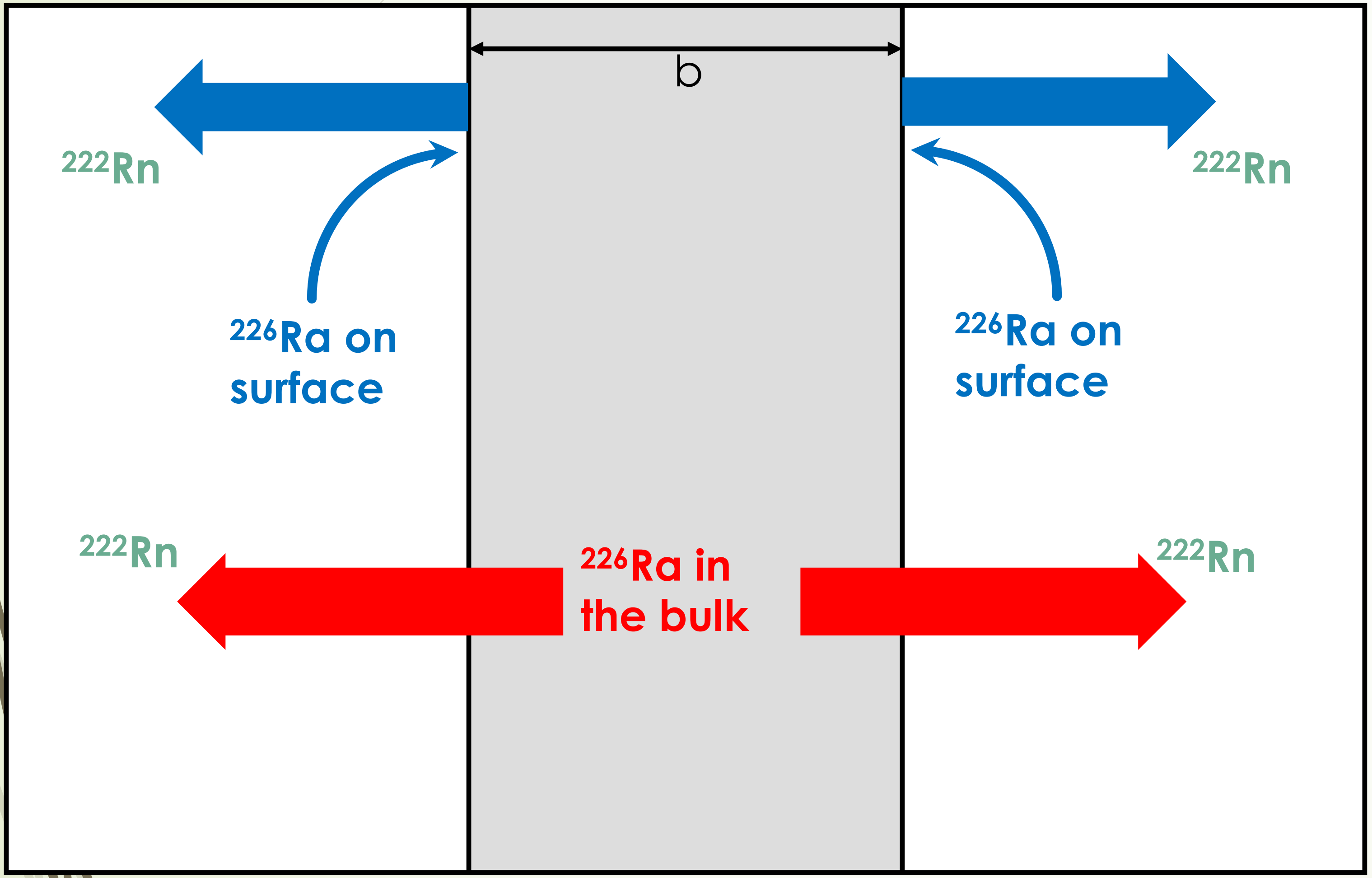
Radon in the BOREXINO nylon vessel



- Radon measurement from thin nylon foild yields
  - Contribution from surface

    plus
  - Unknown fraction of bulk contamination
- For ^{222}Rn mitigation it is crucial to know its origin.
- Nylon can absorb a lot of water (10% of its weight)
  - „widening“ of polymers
  - much faster radon diffusion

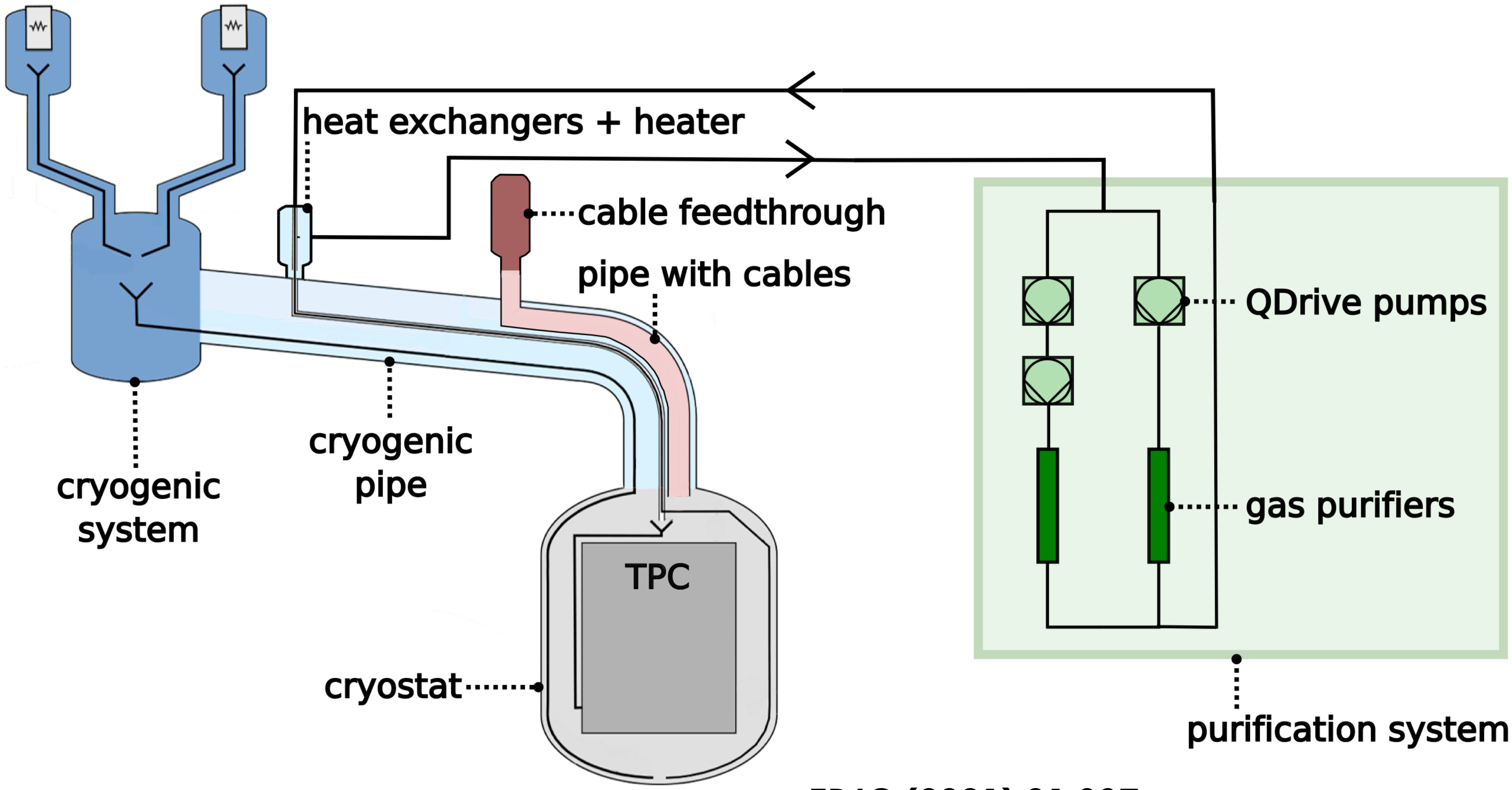
Radon in the BOREXINO nylon vessel



- d_{dry} = (270 ± 30) µm
- d_{humid}= (7 ± 1) µm = 40 x d_{dry}
  (*NIM A 449 (2000) 158-171*)
- 1-dimensional, stationary model of diffusion:
  - $A_{dry} = A_{surf} + 0.144 \times A_{bulk}$
  - $A_{humid} = A_{surf} + 0.988 \times A_{bulk}$
- Disentanglement of bulk and surface contribution
- Finally upper limits for both:
  - A_{bulk} <15 µBq/kg
  - A_{surf} <0.9 µBq/m^2

Understanding ^{222}Rn source distributions

Example: XENON1T setup



EPJC (2021) 81:337

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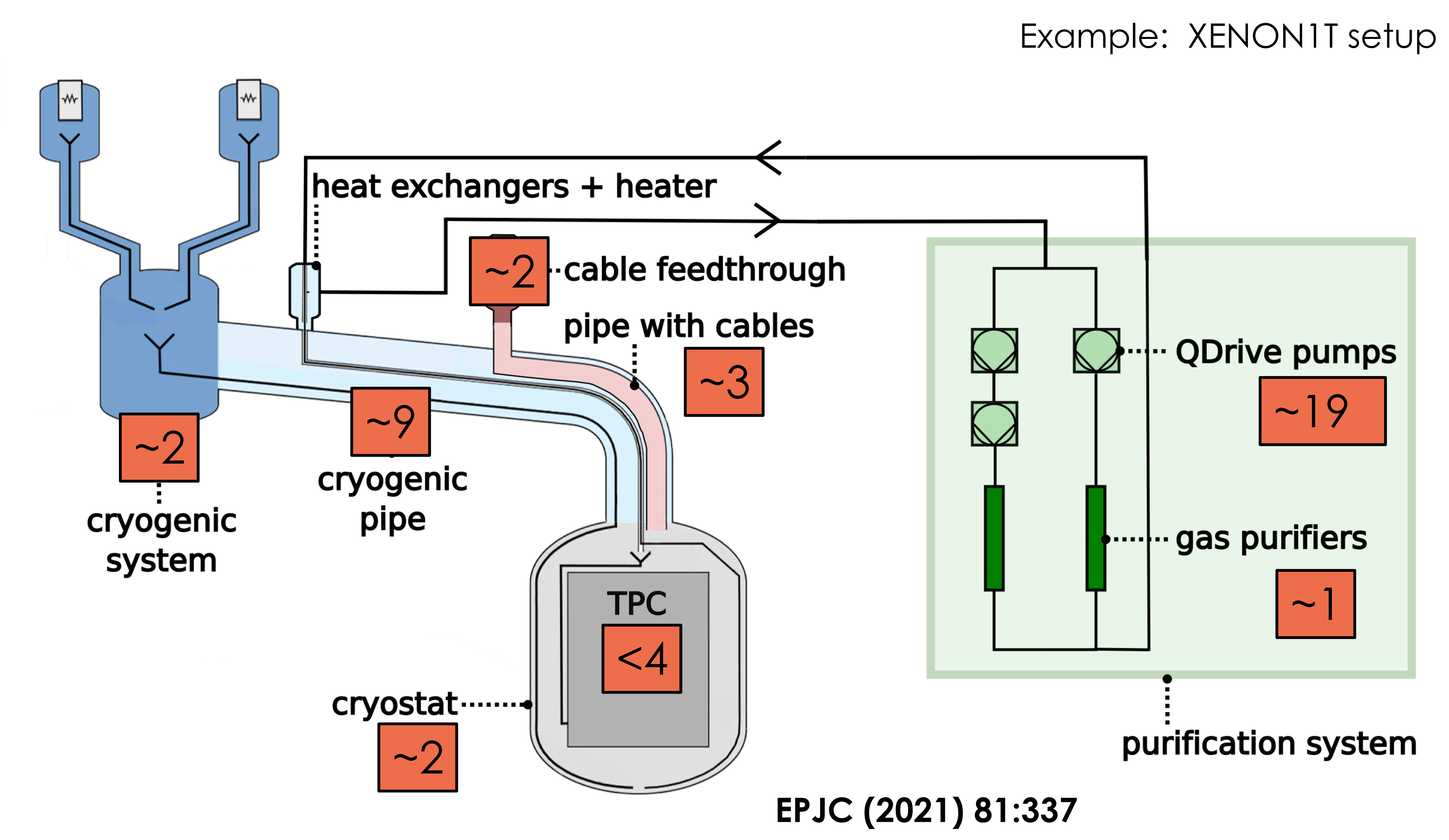
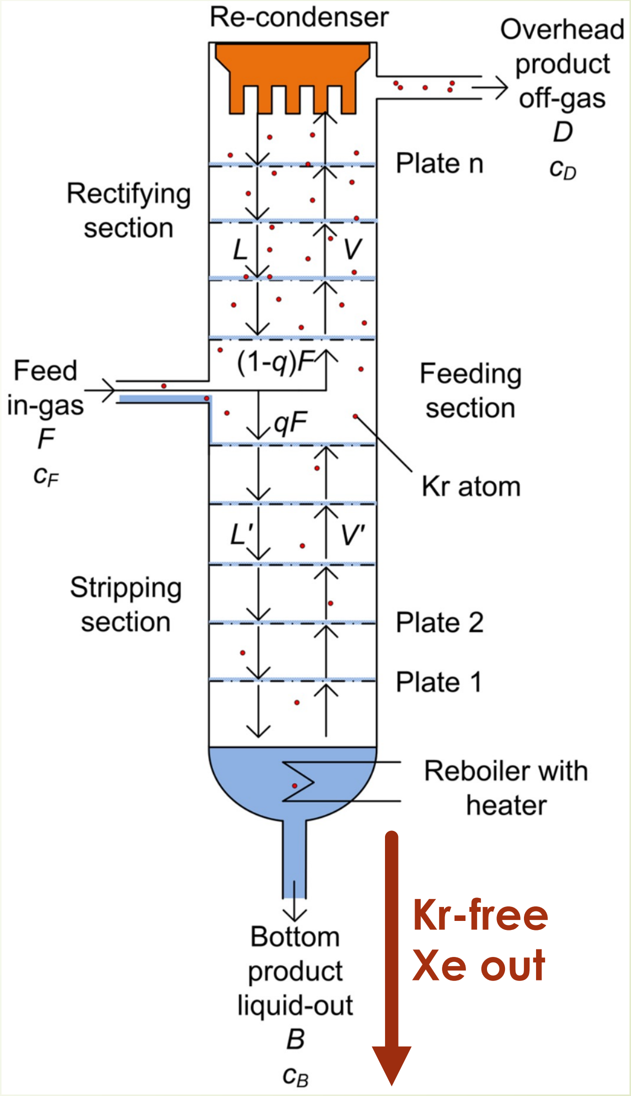


Radon removal by xenon distillation

- Radon is less volatile than xenon → reverse operation mode w.r.t. Kr removal
- Feasibility demonstrated in Xenon100: EPJC (2017) 77:358
- Applied in XENON1T: 4.5 μBq/kg achieved: EPJC (2021)81:337
- High flow radon removal system developed for XENONnT: arXiv: 2205.11492
- **0.8 μBq/kg achieved**

- **Future: Further upscaling?**
  - Need to process entire budget in O(^{222}Rn half-life)
  - Processing speed for XLZD must be >=10 tons/day
  - Efficiency in power consumption and xenon holdup versus radon reduction is crucial



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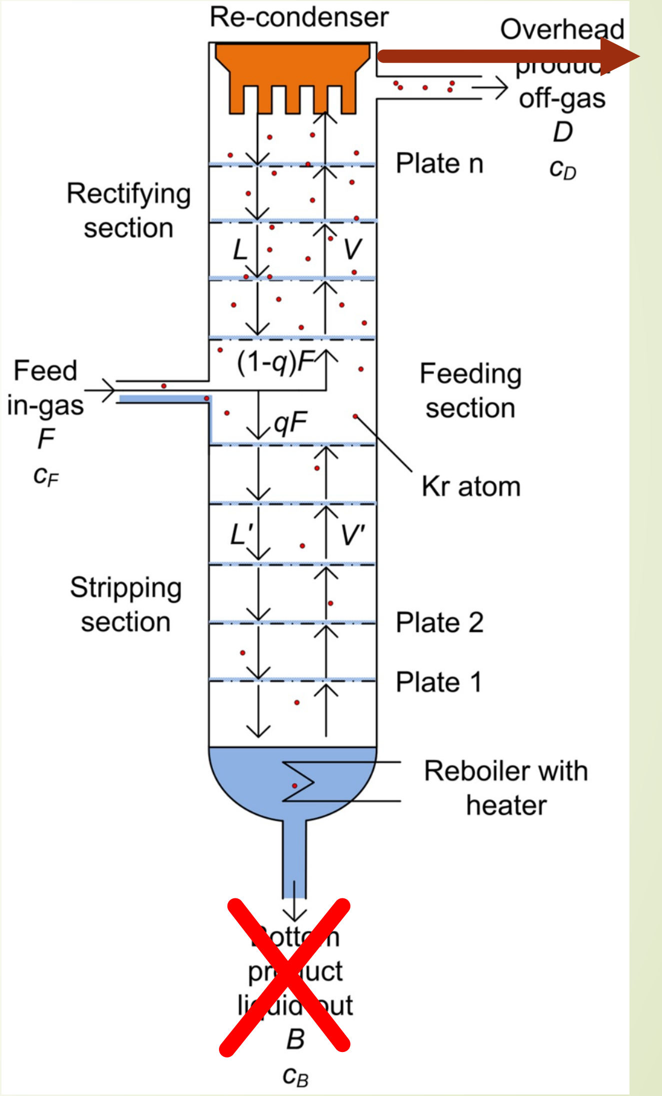
- Feasibility demonstrated in Xenon100: EPJC (2017) 77:358
- Applied in XENON1T: 4.5 μBq/kg achieved: EPJC (2021)81:337
- High flow radon removal system developed for XENONnT: arXiv: 2205.11492
- **0.8 μBq/kg achieved**
- **Future: Further upscaling?**
  - Need to process entire budget in O(^{222}Rn half-life)
  - Processing speed for XLZD must be >=10 tons/day
  - Efficiency in power consumption and xenon holdup versus radon reduction is crucial

Rn-free Xe out



PandaX talk at LRT 2024 workshop

Surface Treatments to Boost the Sensitivity

Different types of polishing methods were tested on the same chamber to lower the radon background.

	7.4 SS detector	7.4 SS detector	7.4 SS detector
Polishing	Electrochemical	Mirror	Mirror + electrochemical
Roughness [um]	3.00 ± 0.44	0.12 ± 0.04	0.13 ± 0.03
Blank [mBq/m^2]	9.08 ± 0.71	0.48 ± 0.14	0.33 ± 0.10
Bulk* [mBq/kg]		10.15±0.68	

*ICP-MS ^{238}U-early chain measurement

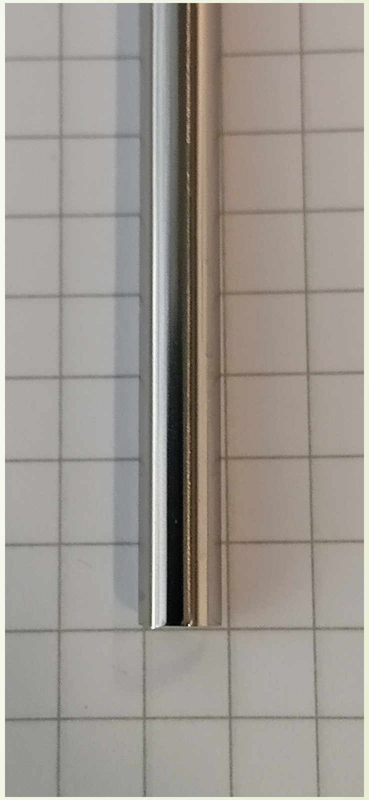
Radon mitigation by surface polishing

- ^{222}Rn emanation often due to surface impurities
- 2 effects of polishing
  - Removing material
  - Smoothening
- Tests with 4% thoriated tungsten → smoothening is the dominant effect
- Metallic samples → Rn diffusion negligible → ^{222}Rn emanation only due to surface impurities

Untreated

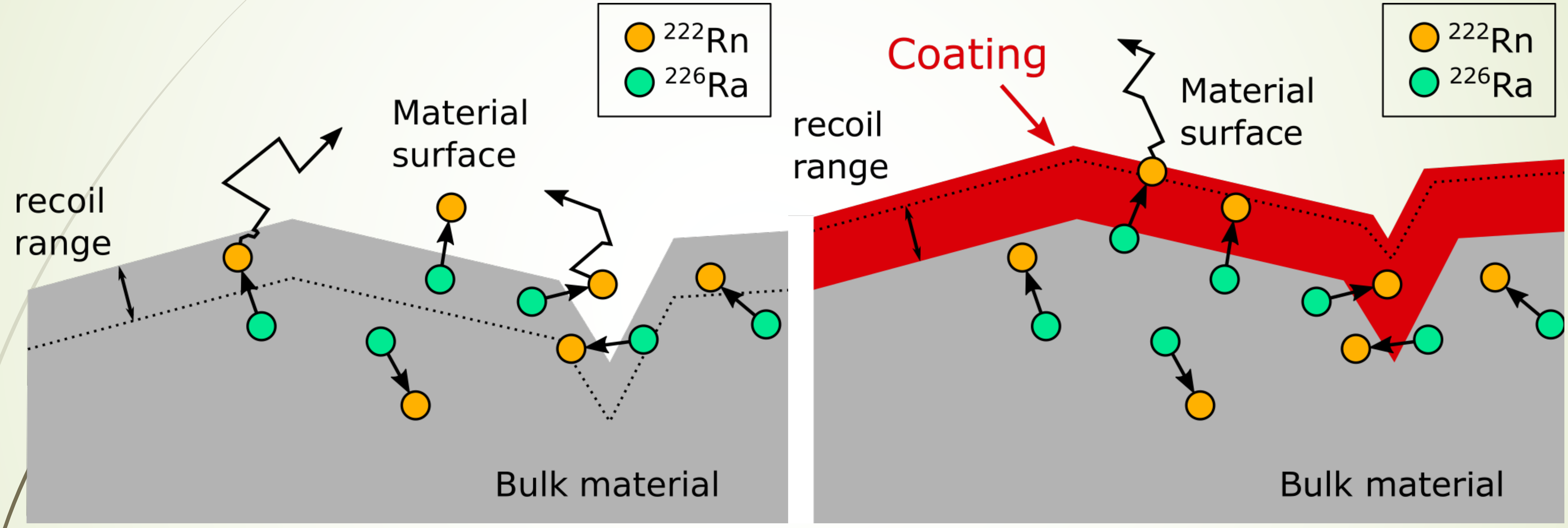
Roughness 2.5 micron

Mirror polished



Roughness 1.5 micron

Radon mitigation by surface coating



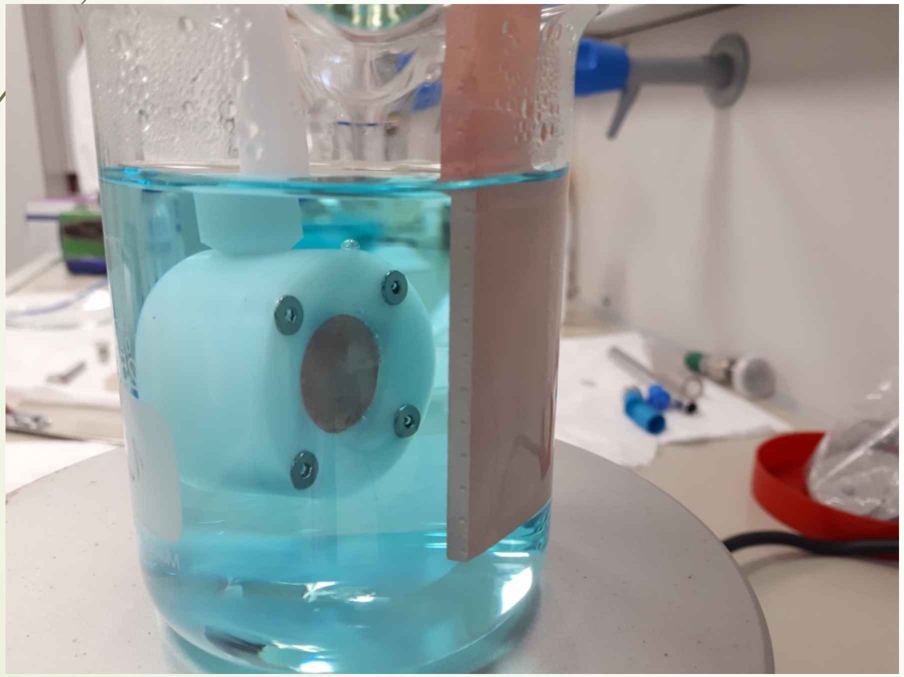
- Idea: A Rn-tight, clean (Ra-free) surface coating blocks Rn-emanation
- Should work for recoil-driven (86 keV) AND diffusion-driven emanation

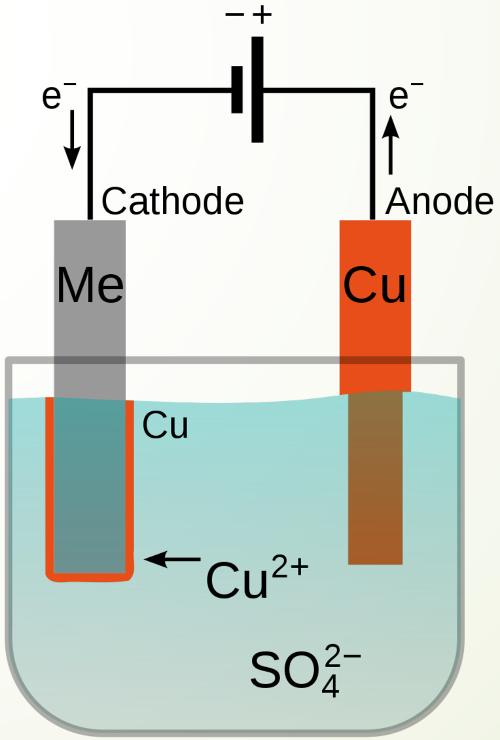
Radon mitigation by surface coating

- Countless different coating techniques exist: Where to start?
- Required properties: Tight, homogeneous, stable (also at low temperature)
- Coating cleanliness may be ultimate limitations → start with the cleanest!
  - Vacuum processes
    - Physical Vapor Deposition (PVD)
    - Chemical Vapor Deposition (CVD)
  - In-house electro-deposition
    - Experience from electro-formed Cu
- Samples: Metallic (ideally stainless steel) with high radon emanation rate
- Initially 4% thoriated tungsten welding rods
  - Wrong substrate tungsten
  - Wrong isotope ^{220}Rn: Much shorter half-life than ^{222}Rn

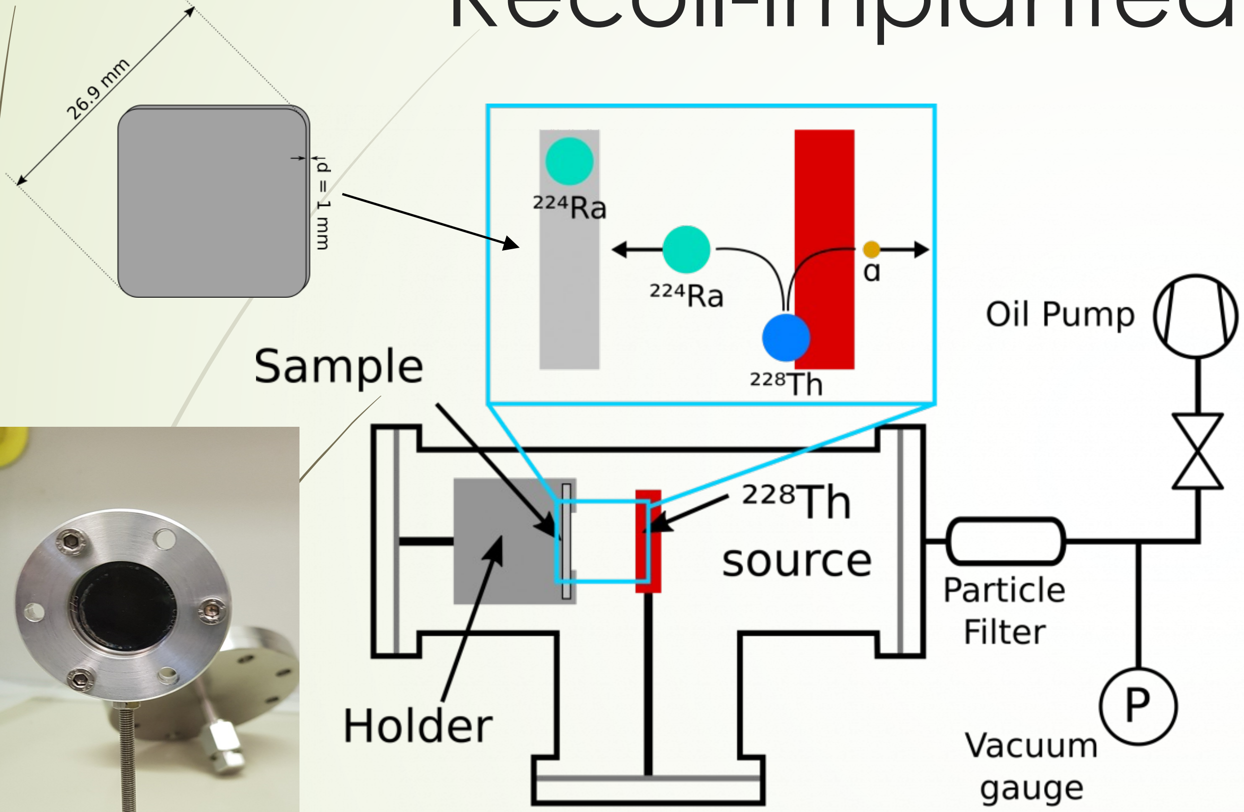
Copper electro-deposition

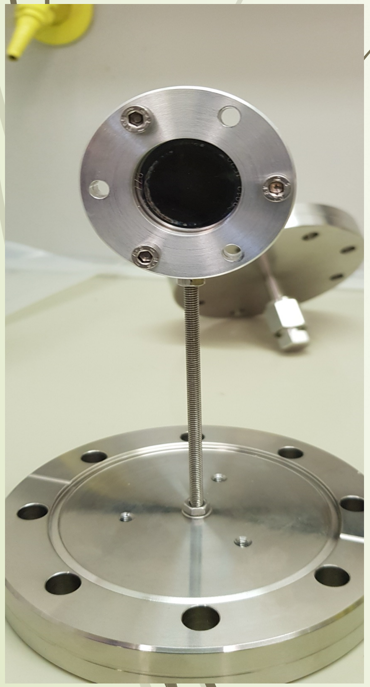
- Motivated by experience with electro-formed copper (clean!)
- In-house development at MPIK: 5 µm thick Cu layer
- Anode made from copper
- Good mechanical stability on tungsten
- Efficient blocking of ^{224}Ra alpha-decay
- ^{220}Rn reduction factor up to 100 observed!

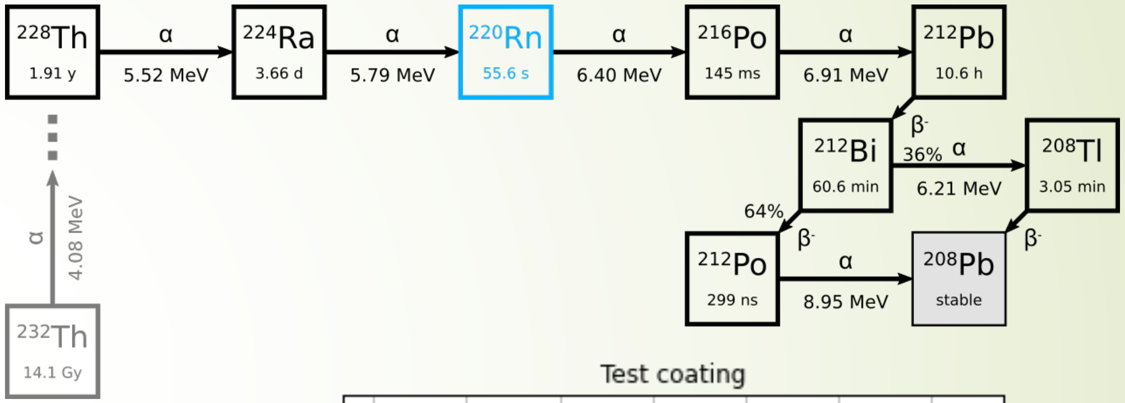




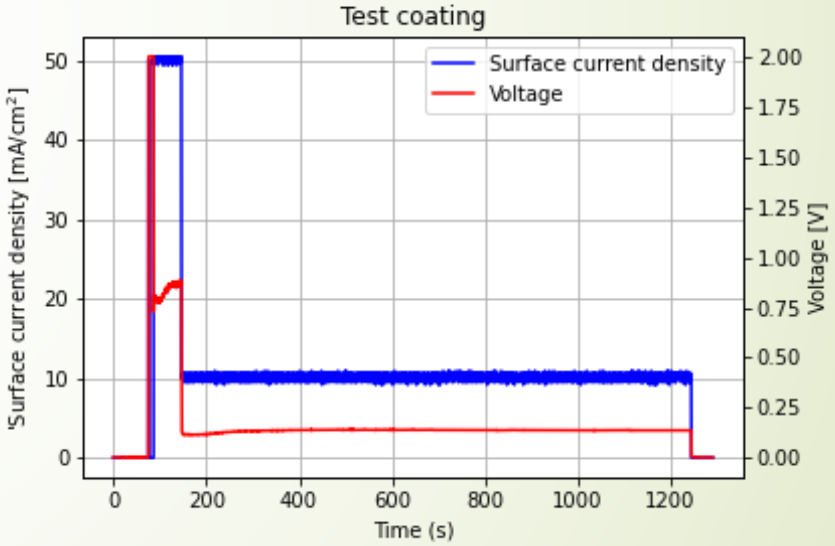
From tungsten to stainless steel: Recoil-implanted ^{224}Ra





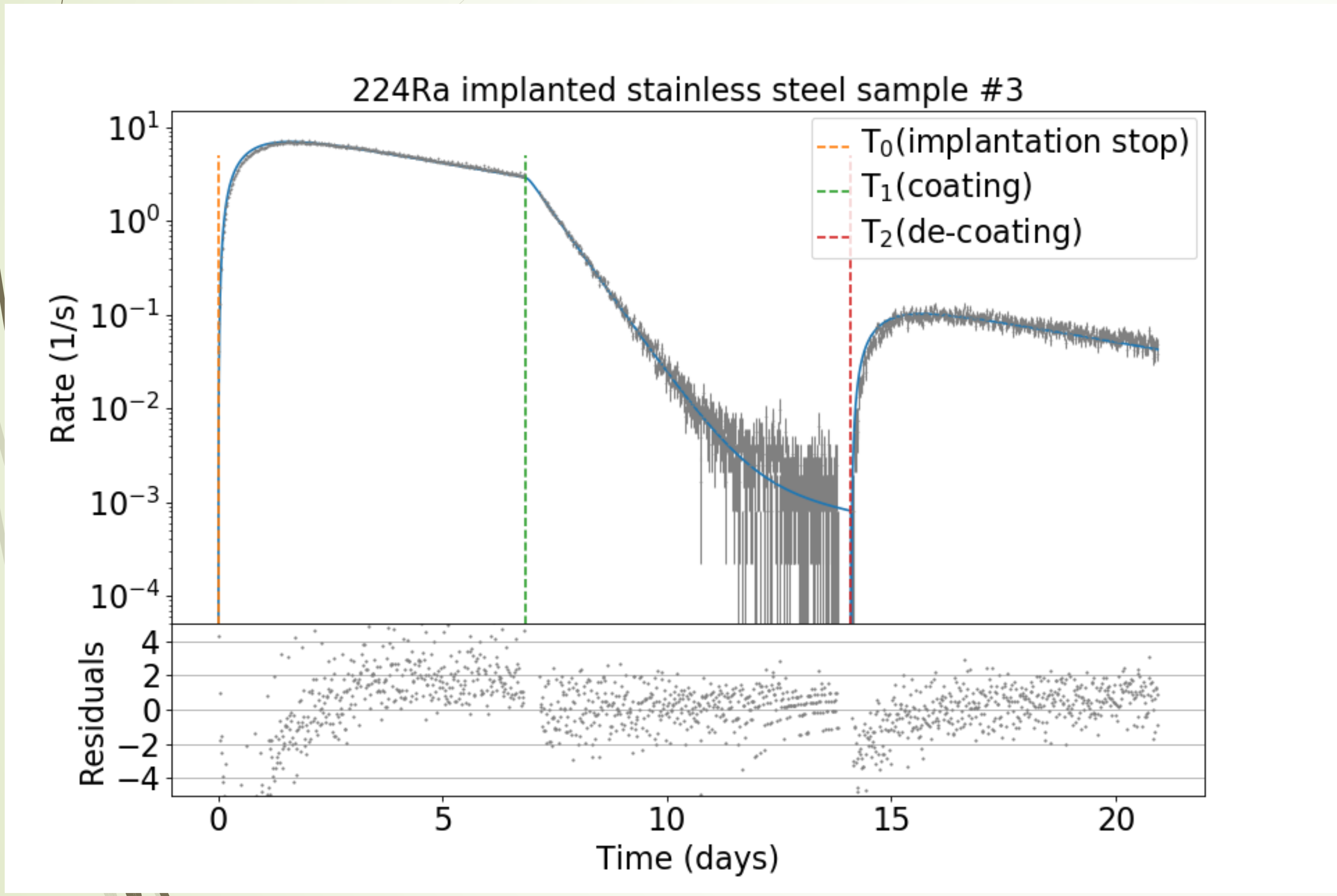


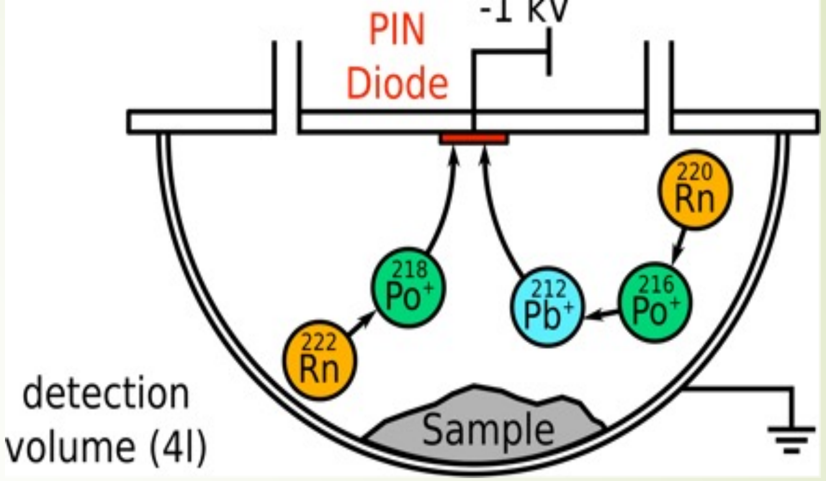
- ^{228}Th source recoild ^{224}Ra into SS disc
- Short-lived (t_H=3.7 days) ^{220}Rn-emanating SS disc
- Easy to produce, relatively high activity



Procedure modification : Adhesion layer (~1 μm) for mechanical stability

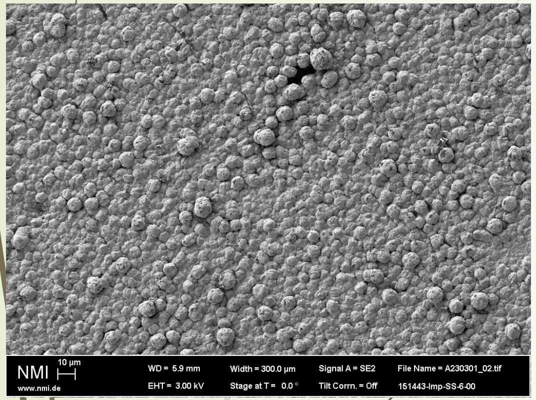
Coating (and de-coating) of ^{224}Ra-implanted SS disc

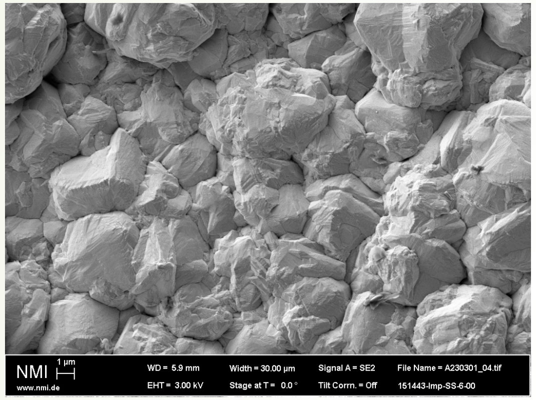


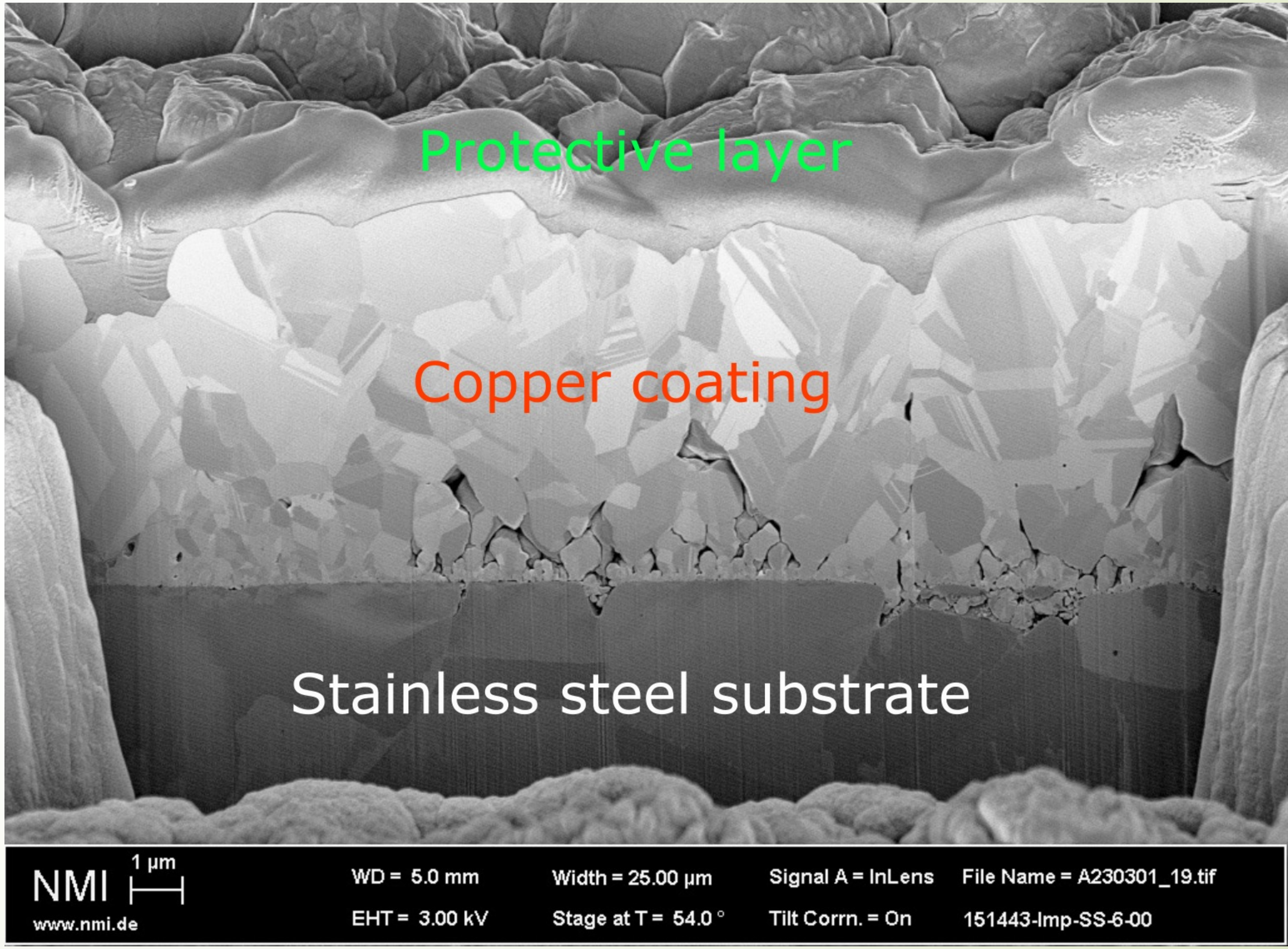


- ^{224}Ra decays on SS disc
- ^{220}Rn is emanated and decays in electrostatic radon monitor
- Charged ^{212}Pb (^{220}Rn-daughter) is collected on PIN diode
- Counting of ^{212}Po a-decays
- Possible issue: Activity wash-off in electrolyte
- Procedure: Implantation → coating → de-coating
- Upper limit from coating, lower limit from de-coating
- Results for reduction factor R: **20 < R < 1000**

Secondary Electron Microscopy (SEM) investigation of our coating

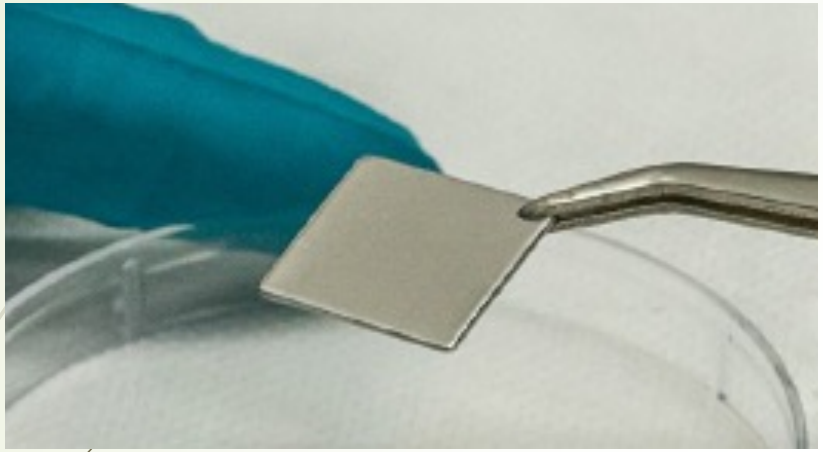


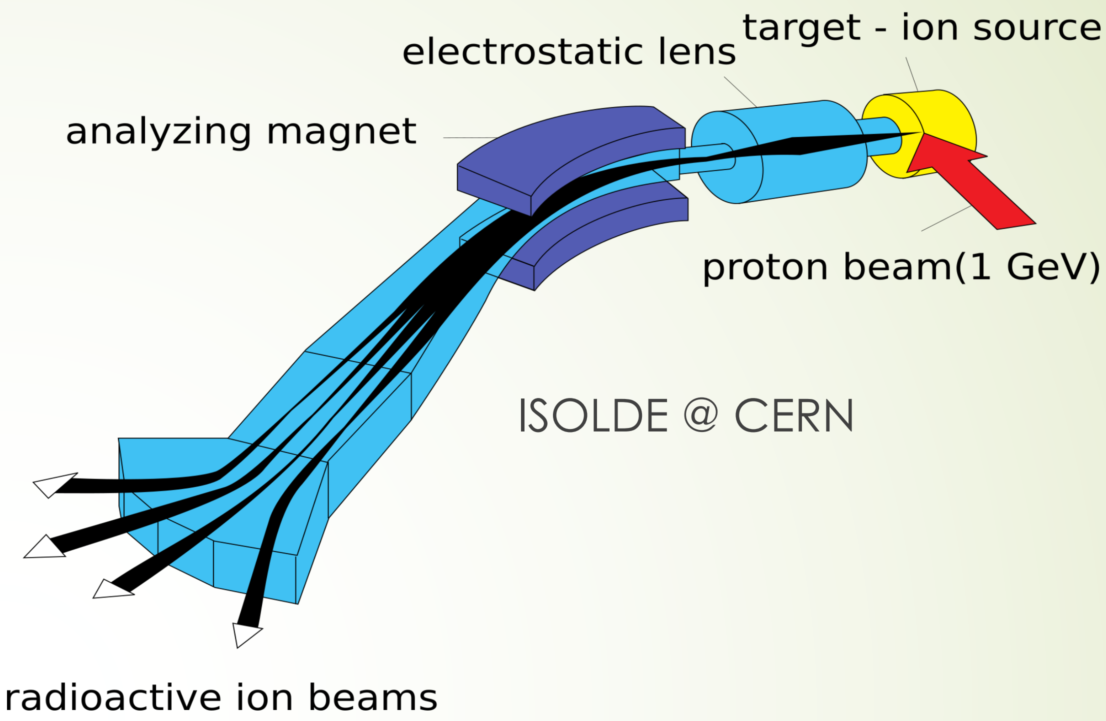


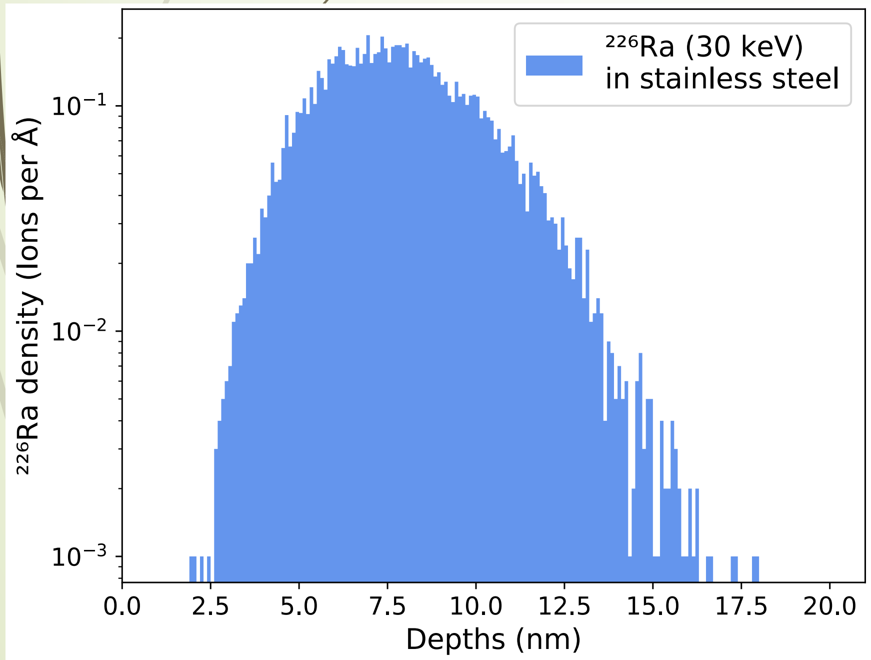


- Rough surface texture with spherical structures.
- Unhomogeneous adhesive layer with small grain size and holes.
- Tight cover layer with larger grains.

Finally: ^{222}Rn on SS

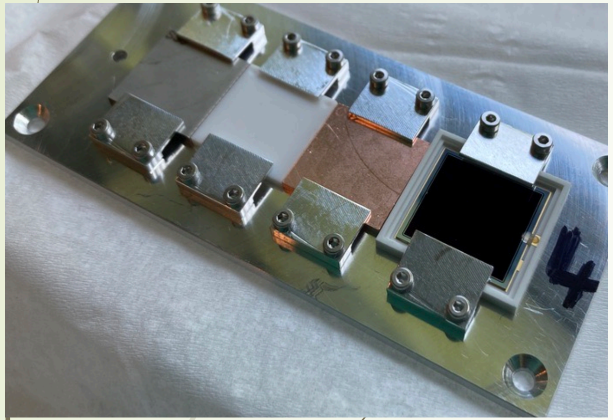




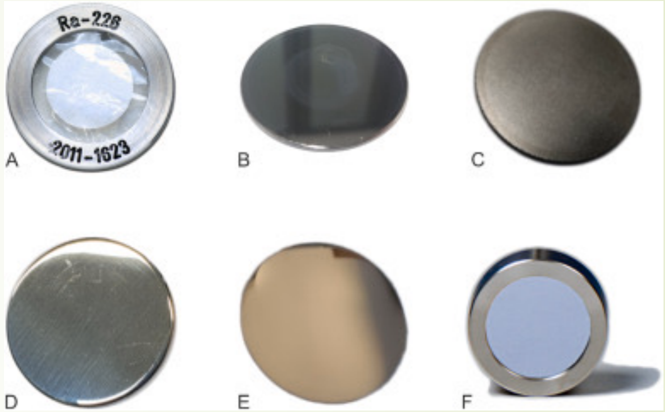


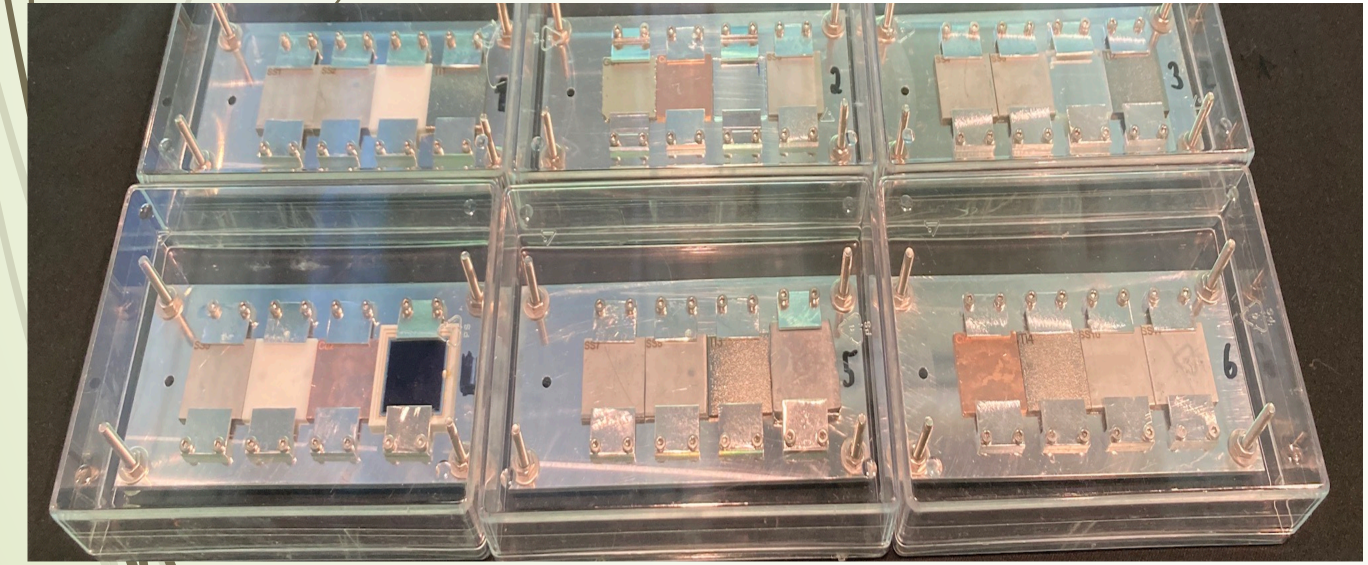
- ^{226}Ra-implanted stainless steel discs (2cm x 2cm)
- Produced at ISOLDE facility (CERN)
- 30 keV implantation energy
- Ion range distribution simulation in SS (SRIM):
  - $\mu = 7.9$nm, $\sigma = 2.3$nm
- 2 test samples produced in 2017
- Summer beam time for 20 new samples approved

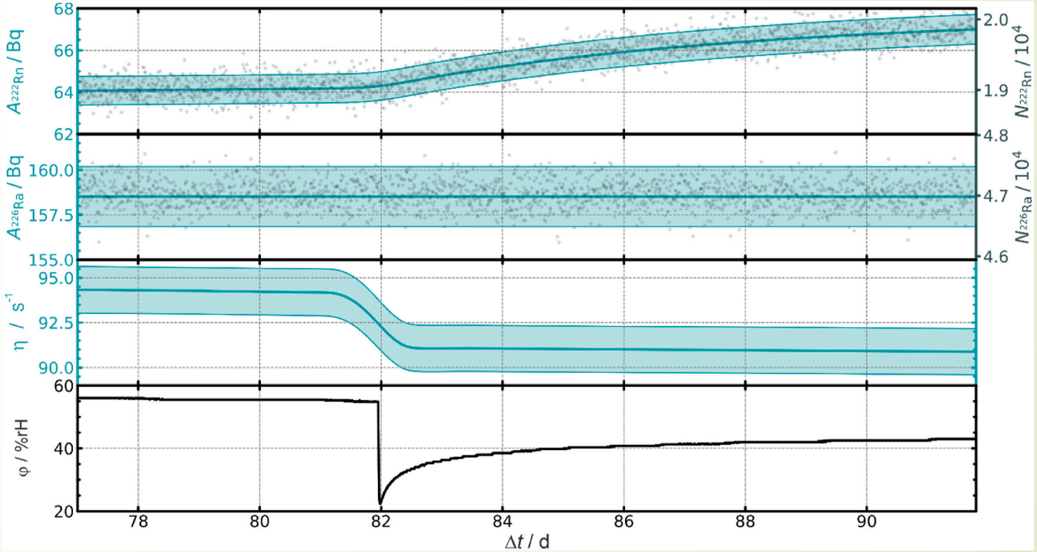
Novel ^{222}Rn sources



- ^{226}Ra implantation in SS, Cu, Ti, Pb, Ge, Si, PTFE, SiO_2, acrylic.
- >30 samples.
- Similar development at PTB (Braunschweig): Traceable ^{222}Rn sources.
- Deposition on an active Si detector allows online emanation rate monitoring.







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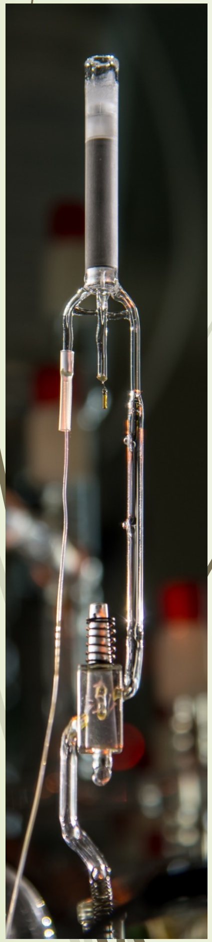
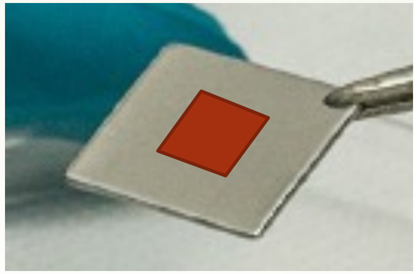
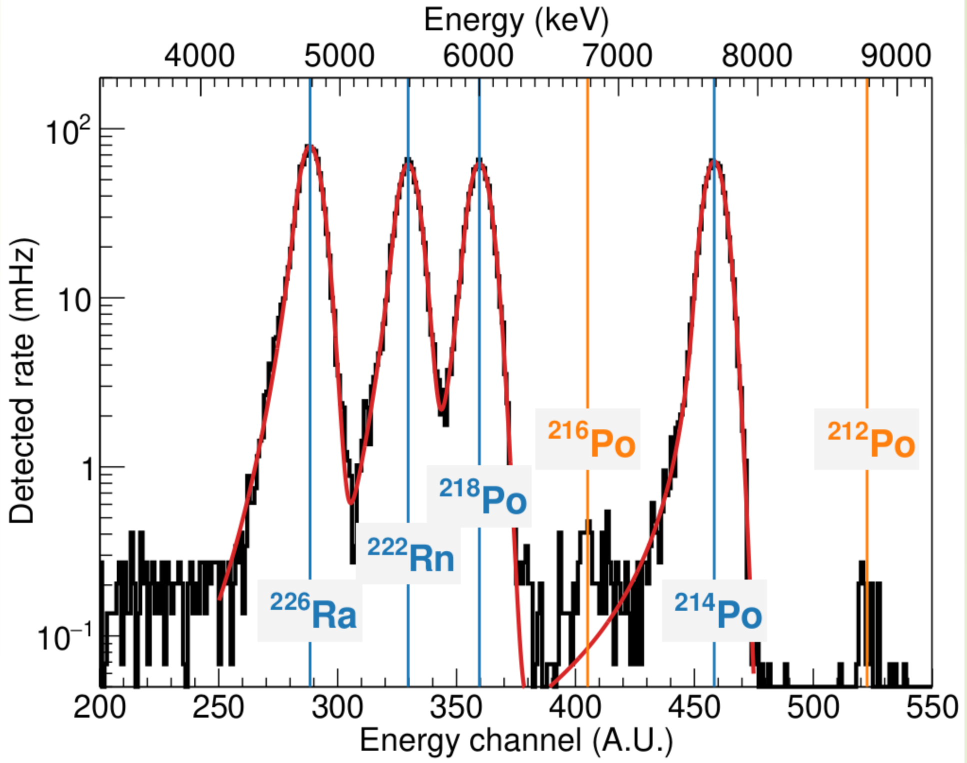
ISOLDE sample characterization







- Alpha measurement:
  - Short-lived contaminants (from ^{235}U chain)
  - ~8.5 Bq ^{226}Ra activity
  - Central deposition confirmed
- Gamma measurement confirms alpha measurement
  - Unexpected ^{139}Ce discovered (t_H = 137.6 d)
- Direct ^{222}Rn emanation test with proportional count
  - Sample a: (2.00 ± 0.05) Bq
  - Sample b: (2.07 ± 0.05) Bq
- Wipe test: Less than 1% of activity removed

Measurement		Result (Bq)
^{222}Rn emanation	a	2.07 ± 0.03 (stat) ± 0.04 (syst)
	b	2.00 ± 0.03 (stat) ± 0.04 (syst)
γ-spectrometry	a	7.4 ± 0.1 (stat) ± 0.9 (syst)
	b	8.4 ± 0.3 (stat) ± 1.0 (syst)
α-spectrometry	a	8.7 ± 0.1 (stat) $^{+2.0}_{-1.8}$ (syst)
	b	9.1 ± 0.1 (stat) $^{+0.7}_{-0.4}$ (syst)

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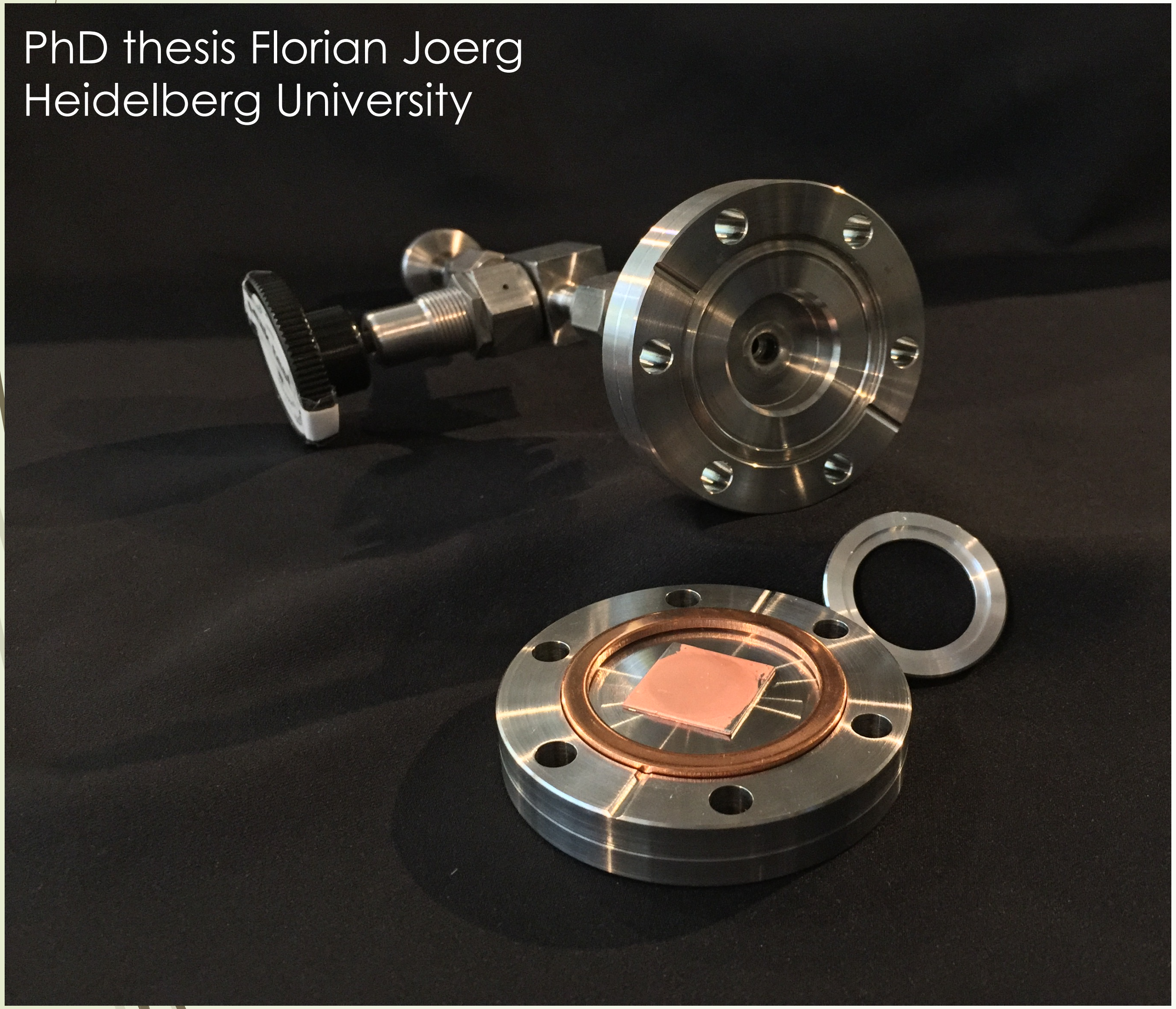
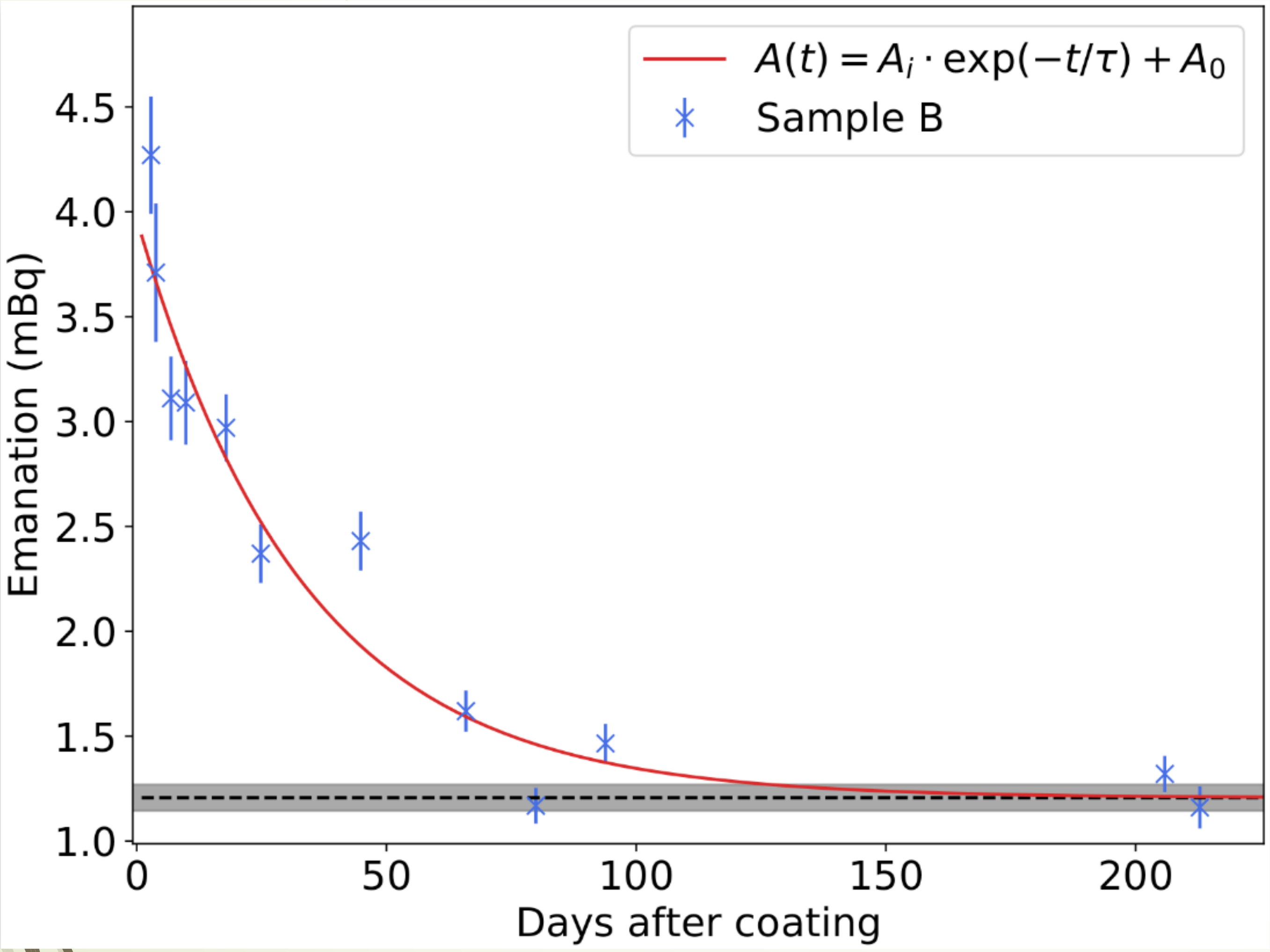
Coating of the 1st ISOLDE sample



- Standard MPIK electrochemical Cu-on-SS coating recipe applied
- ^{222}Rn emanation rate
  - Before coating: (2.00 ± 0.05) Bq
  - After coating: (4.3 ± 0.3) mBq
- Unexpected large ^{222}Rn reduction factor: ~465
- Gamma spectroscopy results:

Activity [Bq]	^{226}Ra (186 keV)	^{222}Rn daughters
ISOLDE sample before coating	8.4 ± 1.0	6.0 ± 0.3
ISOLDE sample after coating	7.7 ± 1.0	7.2 ± 0.4
Electrolyte after coating	---	0.34 ± 0.02

1st coated ISOLDE sample: Temporal development of ^{222}Rn emanation rate



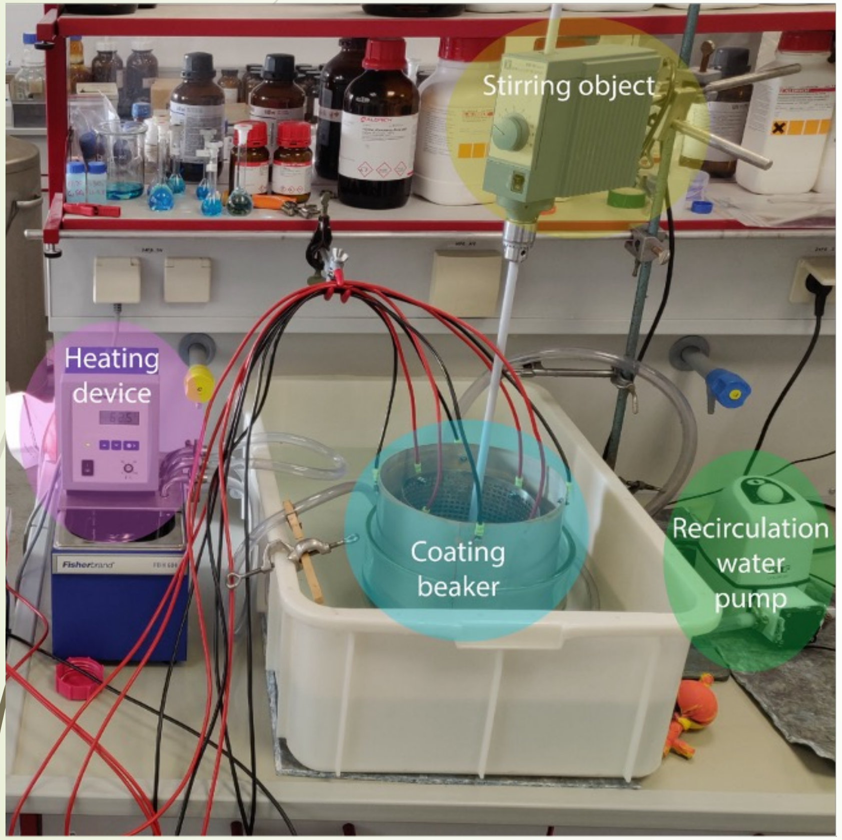
- ^{222}Rn emanation rate was found to decrease
- Coating is getting "tighter"
- Oxidation?
  - But storage under protective atmosphere
- Re-crystallisation?
- **Final ^{222}Rn reduction factor: ~1700**
- Currently: Temperature dependency studies ongoing

Upscaling

- All samples so far were few cm^2 - size
- Applicability to XLZD requires (much) larger coated surfaces.
  - Larger coating vessels
  - Higher-current power supply
  - New copper electrode
  - Better temperature control
  - Improved mixing
- New samples:
  - Stainless steel cylinders
    - ~20cm height
    - ~20cm diameter
    - 1250 cm^2 surface

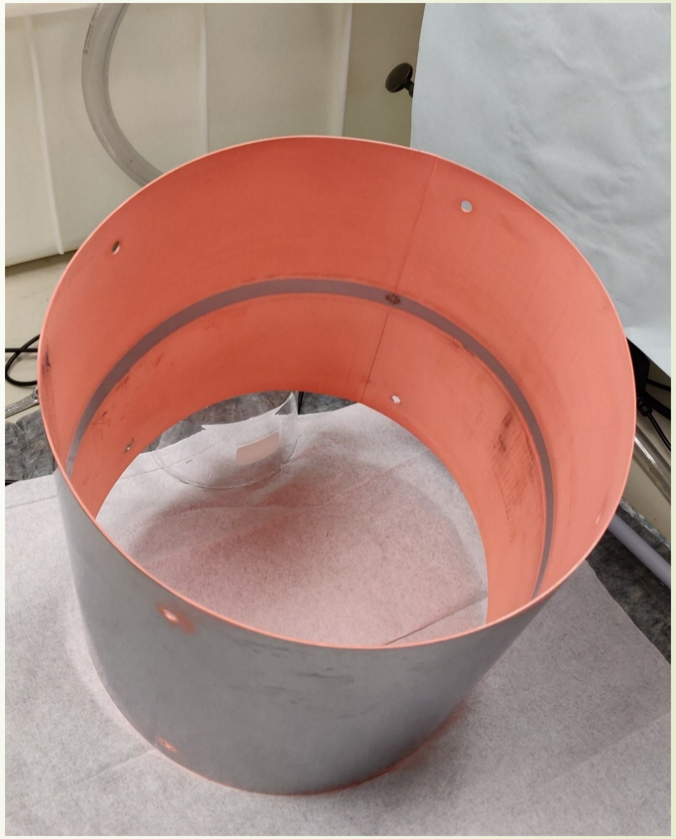
Upscaling

First tests with temporary setup

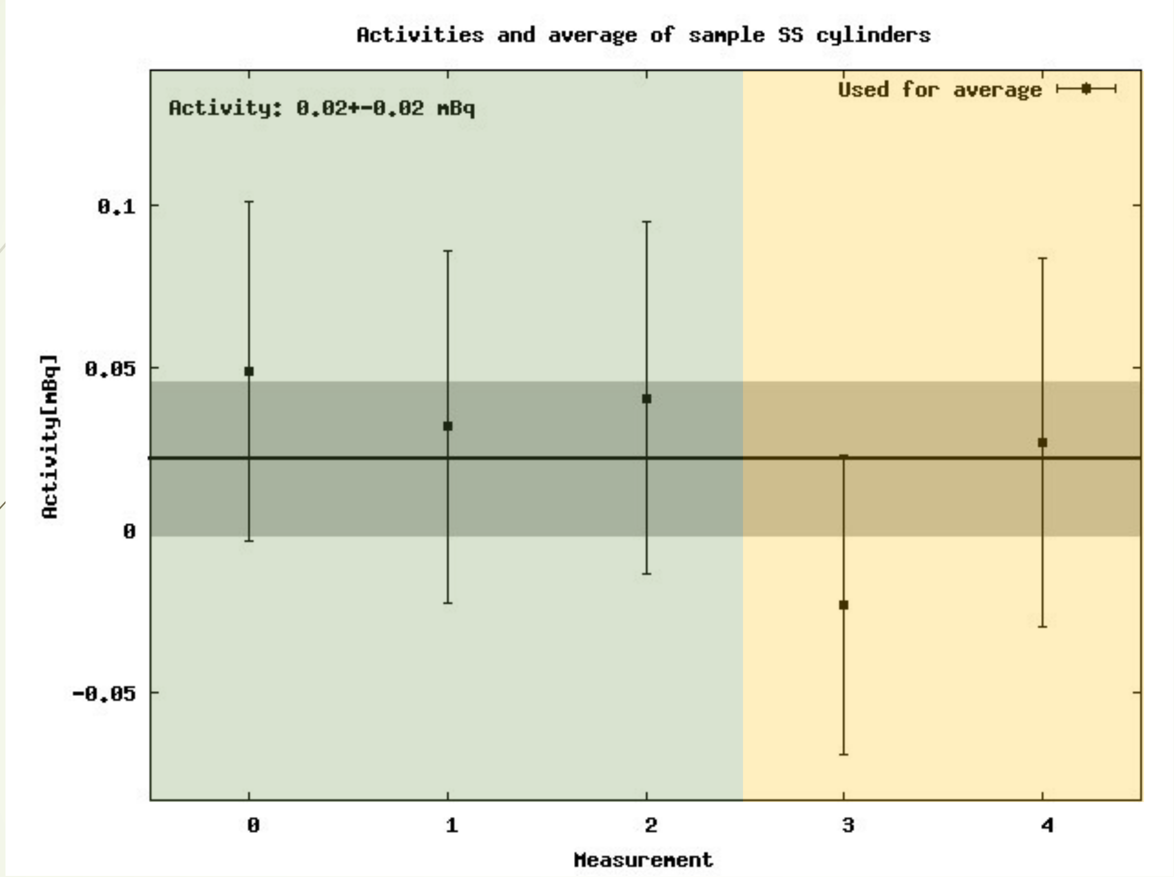


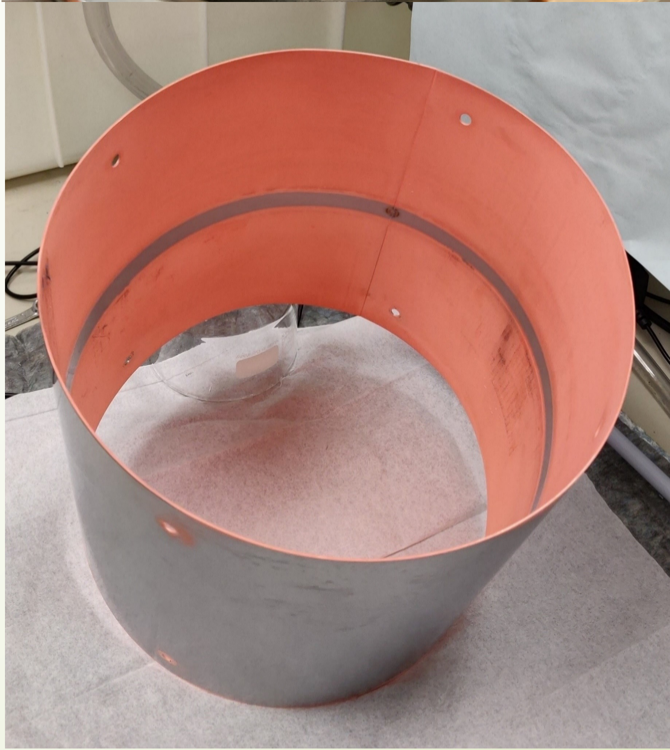
New copper electrode

First “large surface” coating



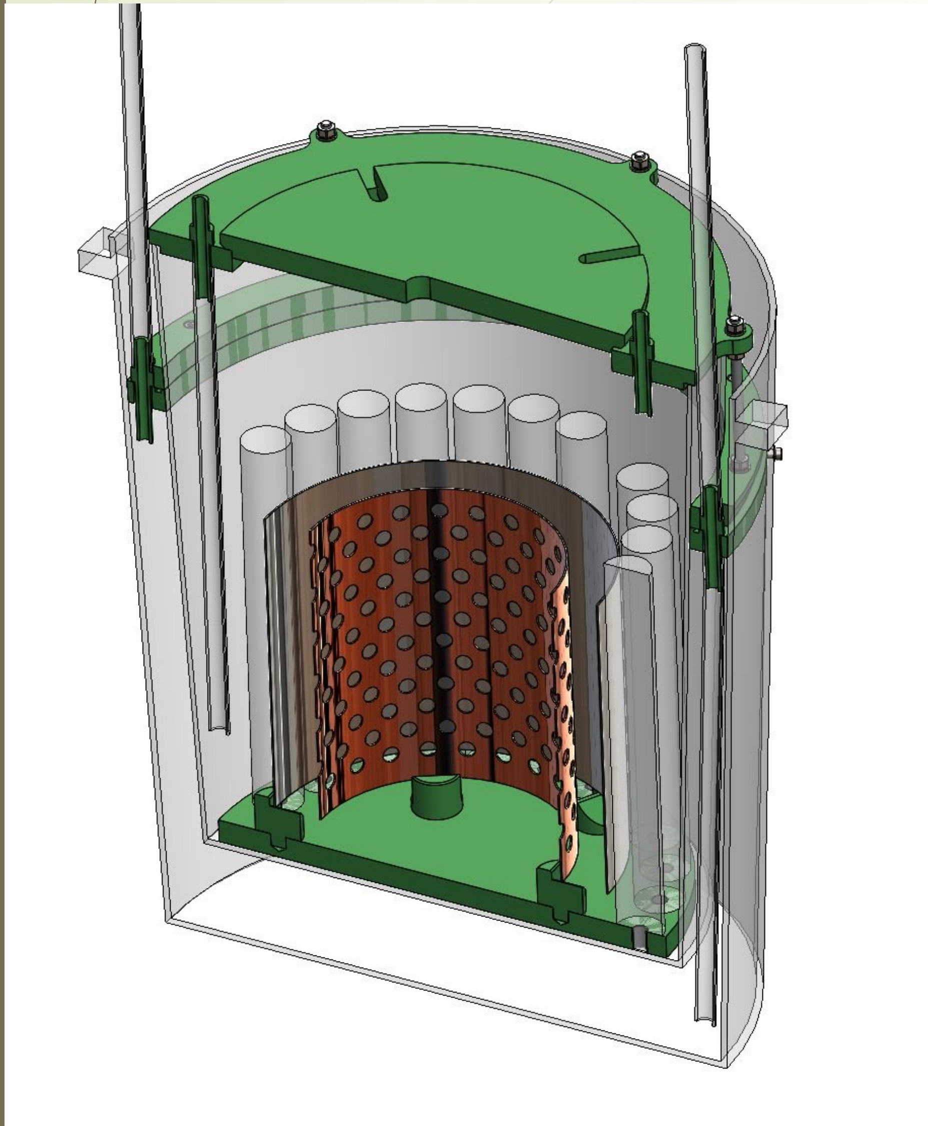
First radiopurity tests

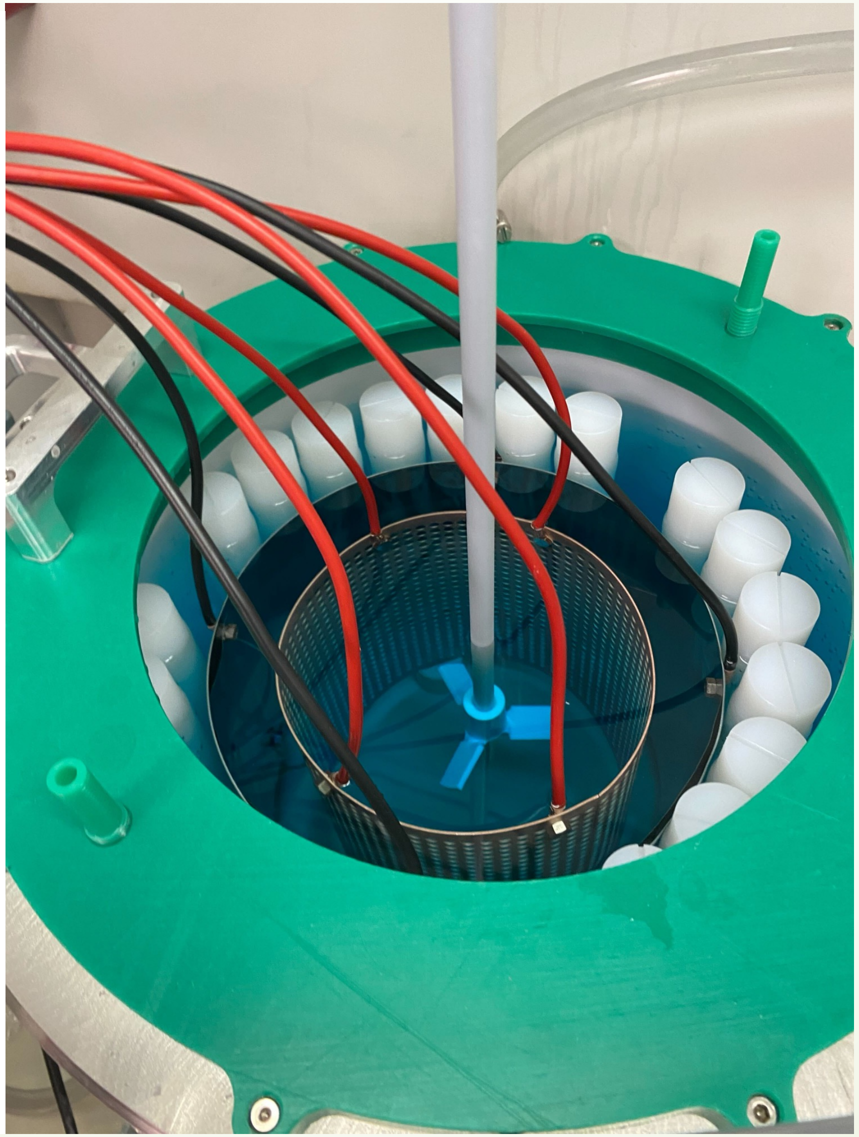




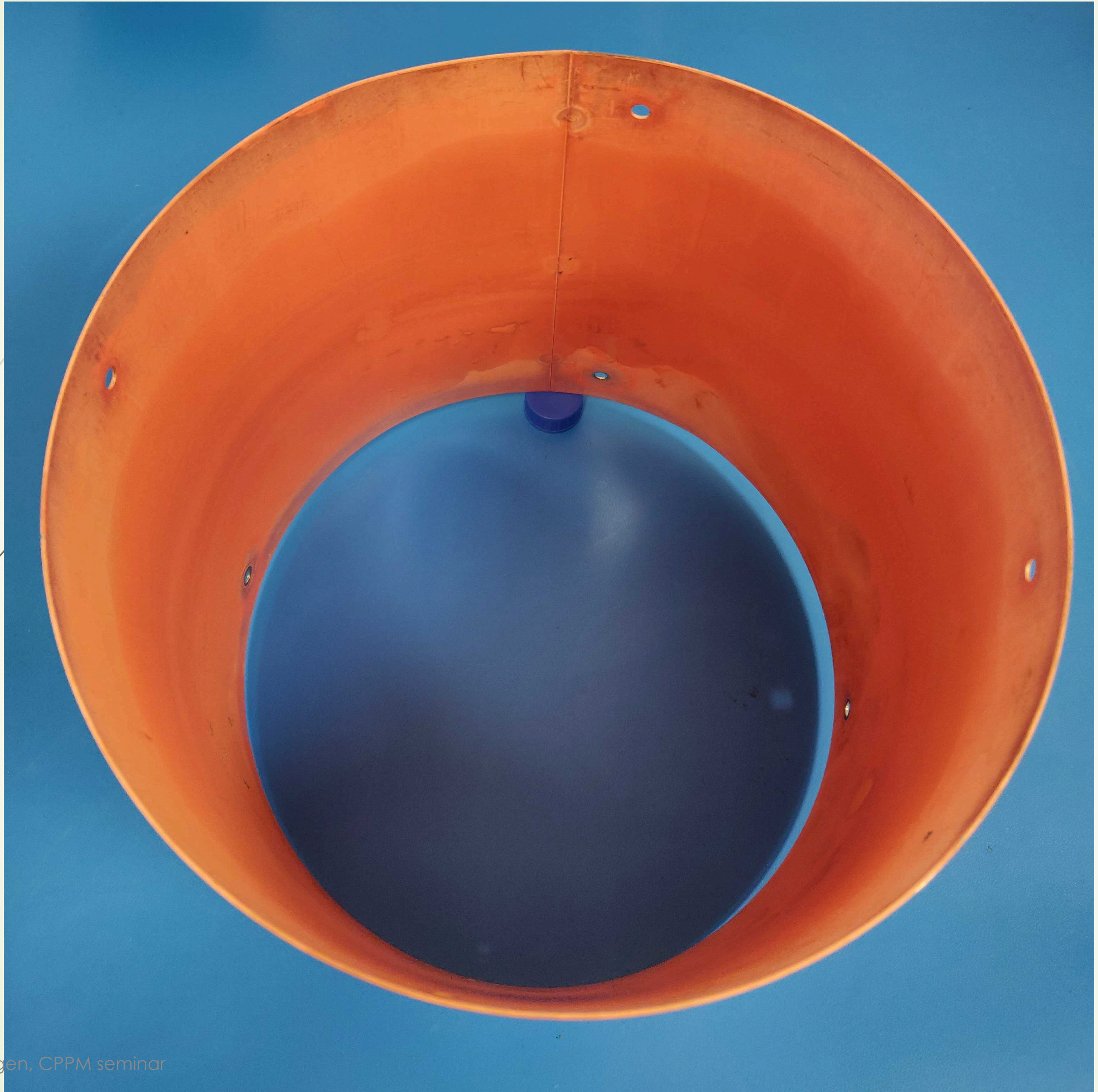
- ^{222}Rn emanation rate from five stainless steel cylinders measured before and after coating.
- No increase observed: Extra ^{226}Ra introduced <80 μBq/m^2.

New dedicated coating vessel

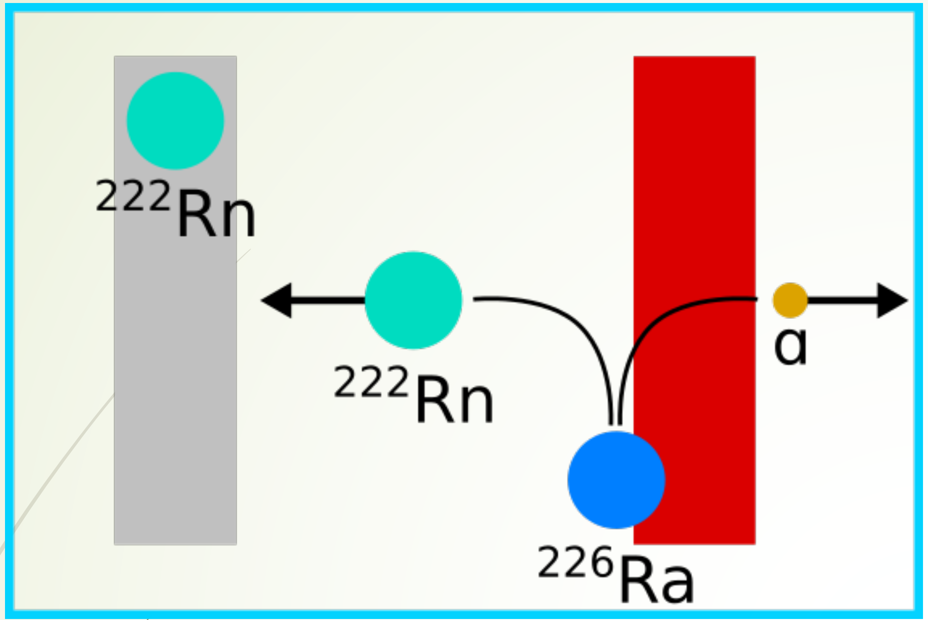


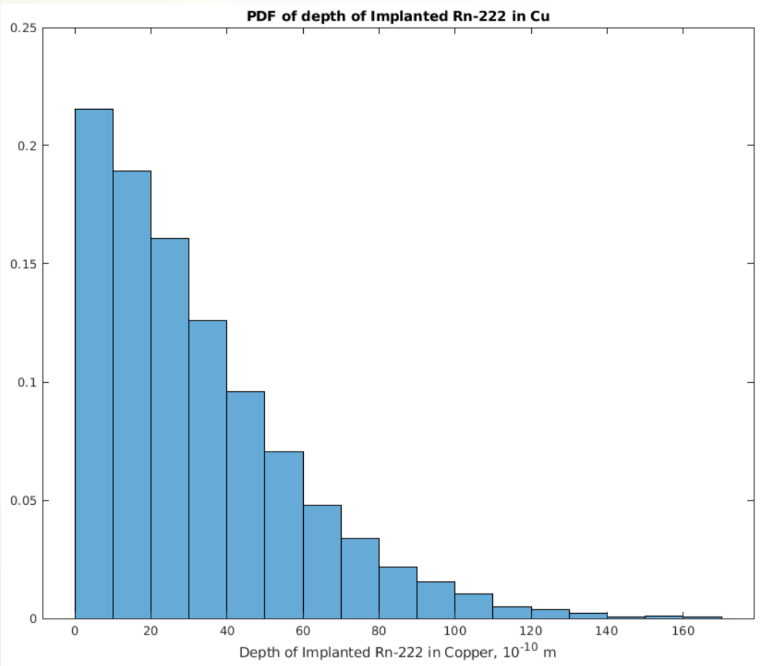


- Newly designed HDPE vessel.
- Sufficiently high.
- Stronger power supply unit.
- Electrolyte immersed in thermally controlled water bath.



- Fully coated inner cylindrical mantle.
  - ~20 cm height
  - ~20 cm diameter
  - ~1250 cm^2 surface
- Coating is stable and homogenous.
- Meanwhile >10 cylinder mantles successfully coated.





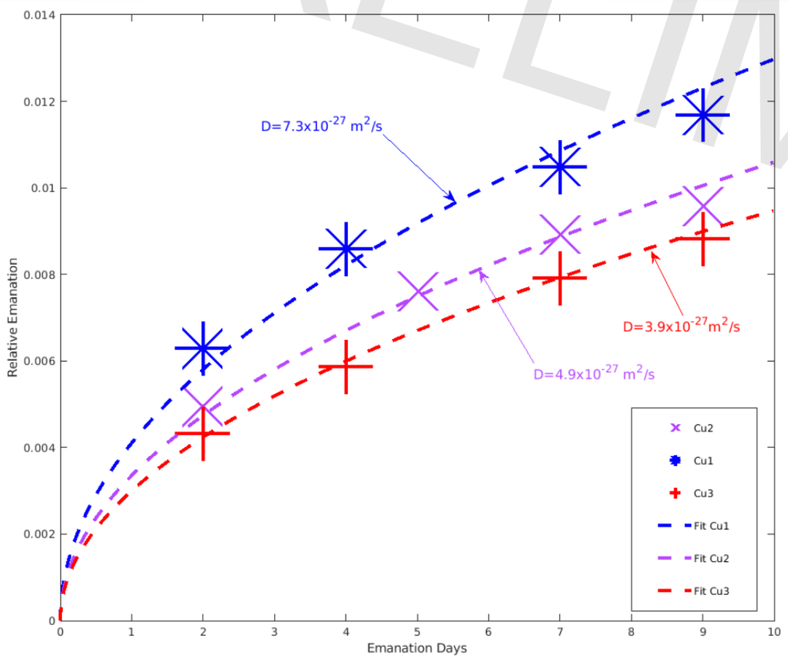
Radon diffusion studies

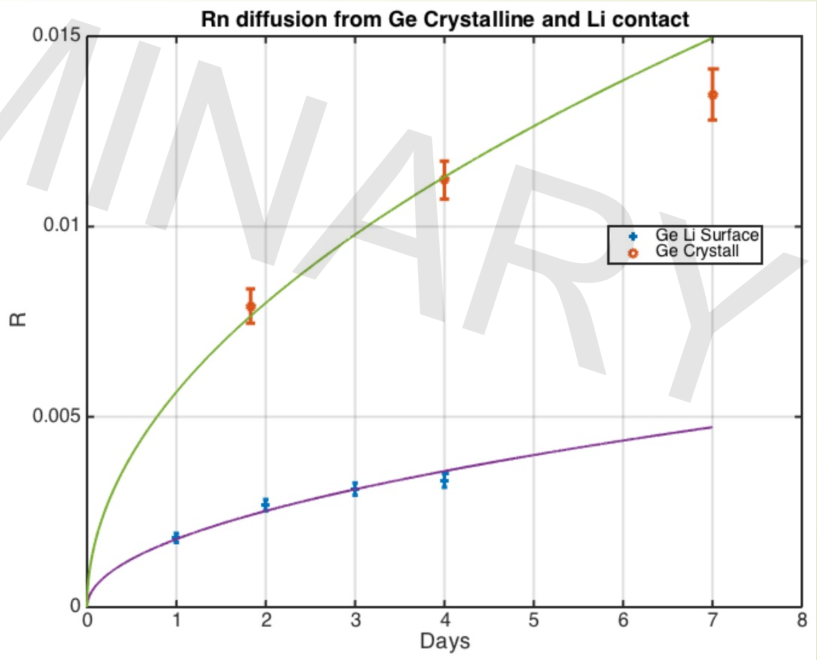
- ^{226}Ra source: How to measure only ^{222}Rn emanation by diffusion (no recoil)?
- Need ^{222}Rn source without ^{226}Ra
- Recoil-implant ^{222}Rn in substrate and measure ^{222}Rn emanation
- Diffusion in metals is low → only ^{222}Rn close to surface relevant.
- Alpha counter → Total activity
- Proportional counter → Emanation fraction
- Simple diffusion model predicts emanated radon fraction:

$$R = \frac{Emanation(t)}{Activity(t)}$$
$$\sim \sqrt{D \cdot t}$$

PRELIMINARY results

Material	Radon diffusion constant
Copper	$(5 \pm 2) \times 10^{-23}$ cm²/s
HP Germanium	$\sim 2 \times 10^{-23}$ cm²/s
HP Germanium (Li-doped)	$\sim 2 \times 10^{-22}$ cm²/s
Stainless steel	$\sim 1 \times 10^{-22}$ cm²/s
Quarz glass (amorphous)	$(4 \pm 2) \times 10^{-24}$ cm²/s
Quarz crystal	$(3 \pm 1) \times 10^{-22}$ cm²/s



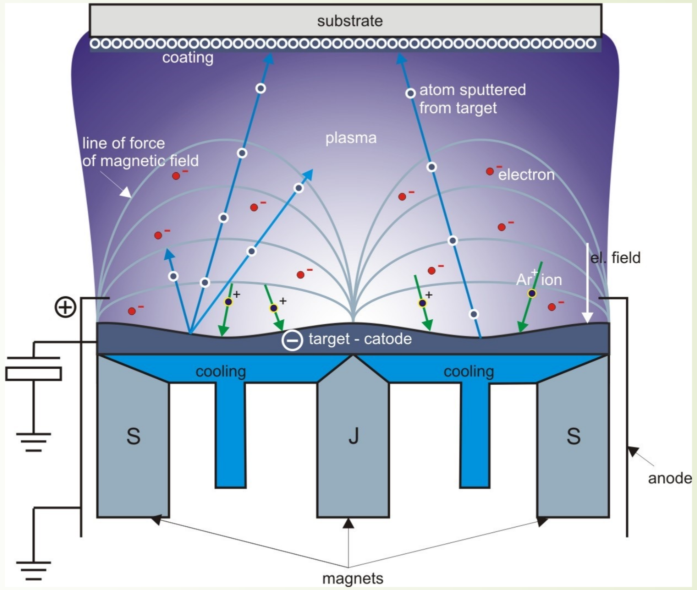


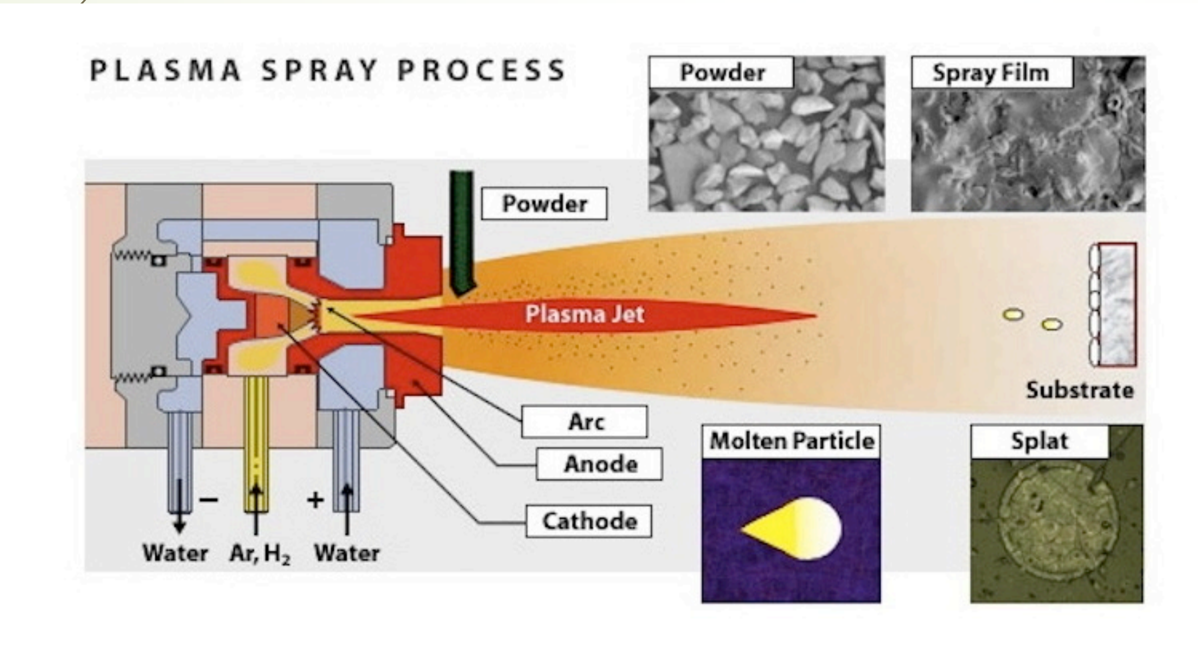
$$R = \frac{Emanation(t)}{Activity(t)} \sim \sqrt{D \cdot t}$$

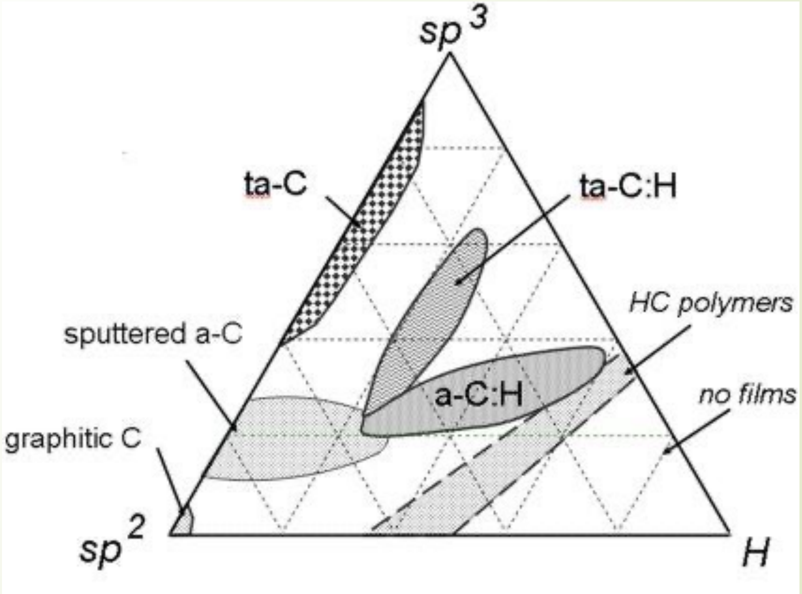
Backup

Investigated vacuum coating techniques

- Physical vapor deposition (PVD)
  - Titanium sputtering
- Chemical vapor deposition (CVD):
  - Amorphous hydrogenated carbon coating (a-C:H)
- Copper plasma deposition







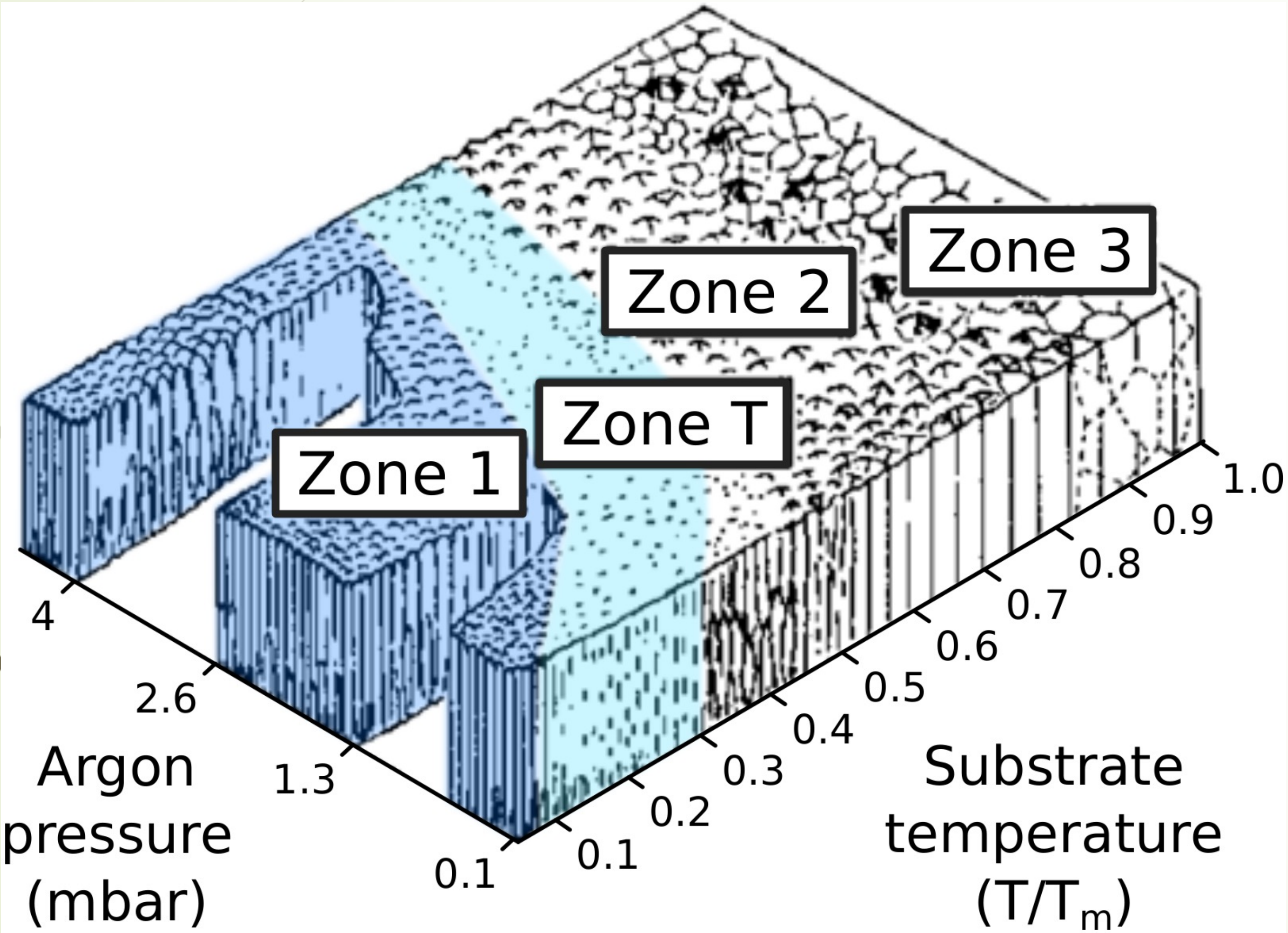
J. Robertson, Materials Science and Engineering, 2002

Results: ^{222}Rn emanation reduction factors

Method	Coated material	Company	^{220}Rn reduction	^{222}Rn reduction
Physical vapor deposition (sputtering)	Ti	Europcoating	1 – 5	~1
Plasma deposition	Cu	Dr. Laure	2 – 20	---
Chemical vapor deposition	C-H	Innovative Coating Solutions	~3	~1,5

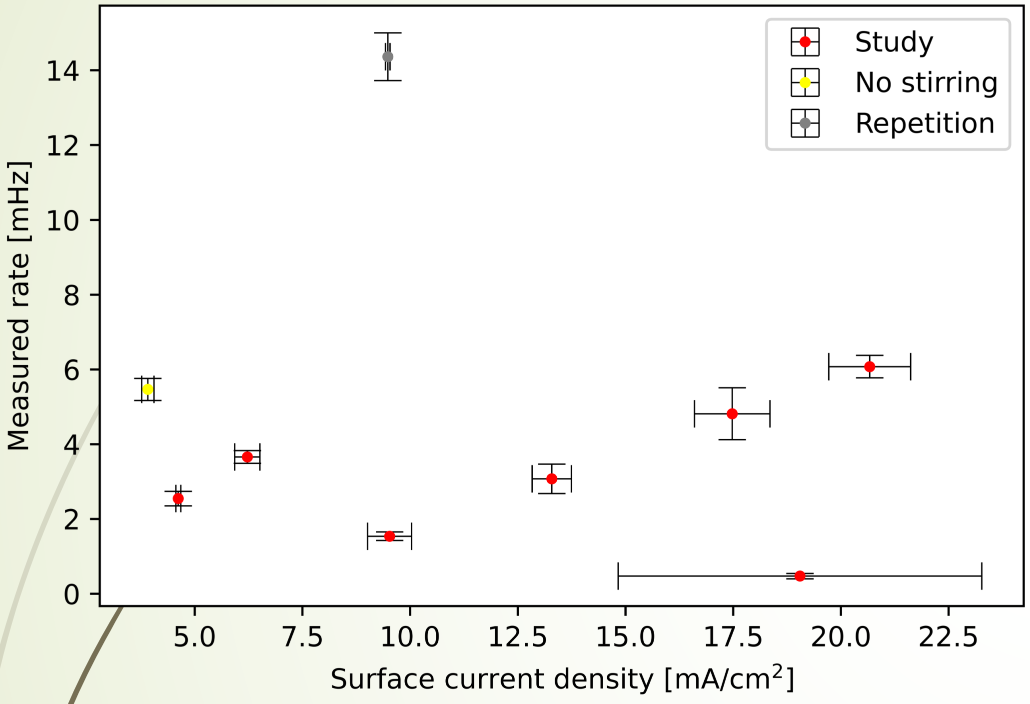
- Little ^{220}Rn reduction and essentially no ^{222}Rn reduction
- Best result for „hot“ plasma depsoition, but re-evaporation due to hot substrate

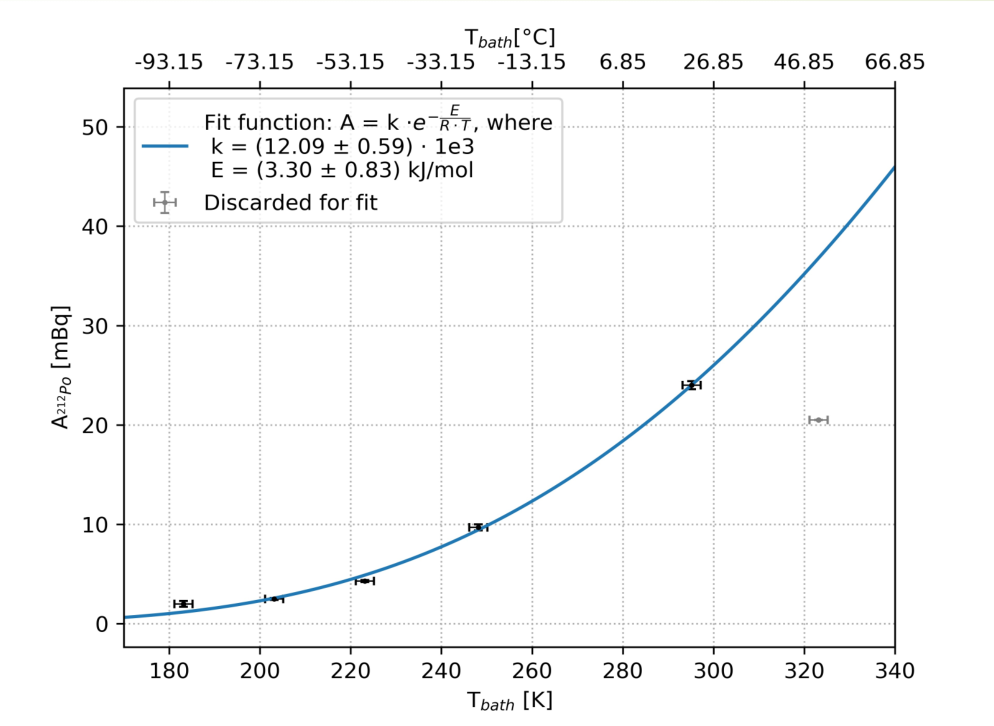
Thornton structure zone model:



- Sputtering is low temperature process
- Growth of vertically aligned grain boundaries
- May block reactive gases (corrosion protection), but „diffusion highway“ for noble gases.
- Focus on high temperature applications (plasma coating) or non vacuum-growth technique.
- But what about CVD?

Optimization of Cu coating procedure and ^{220}Rn reduction results

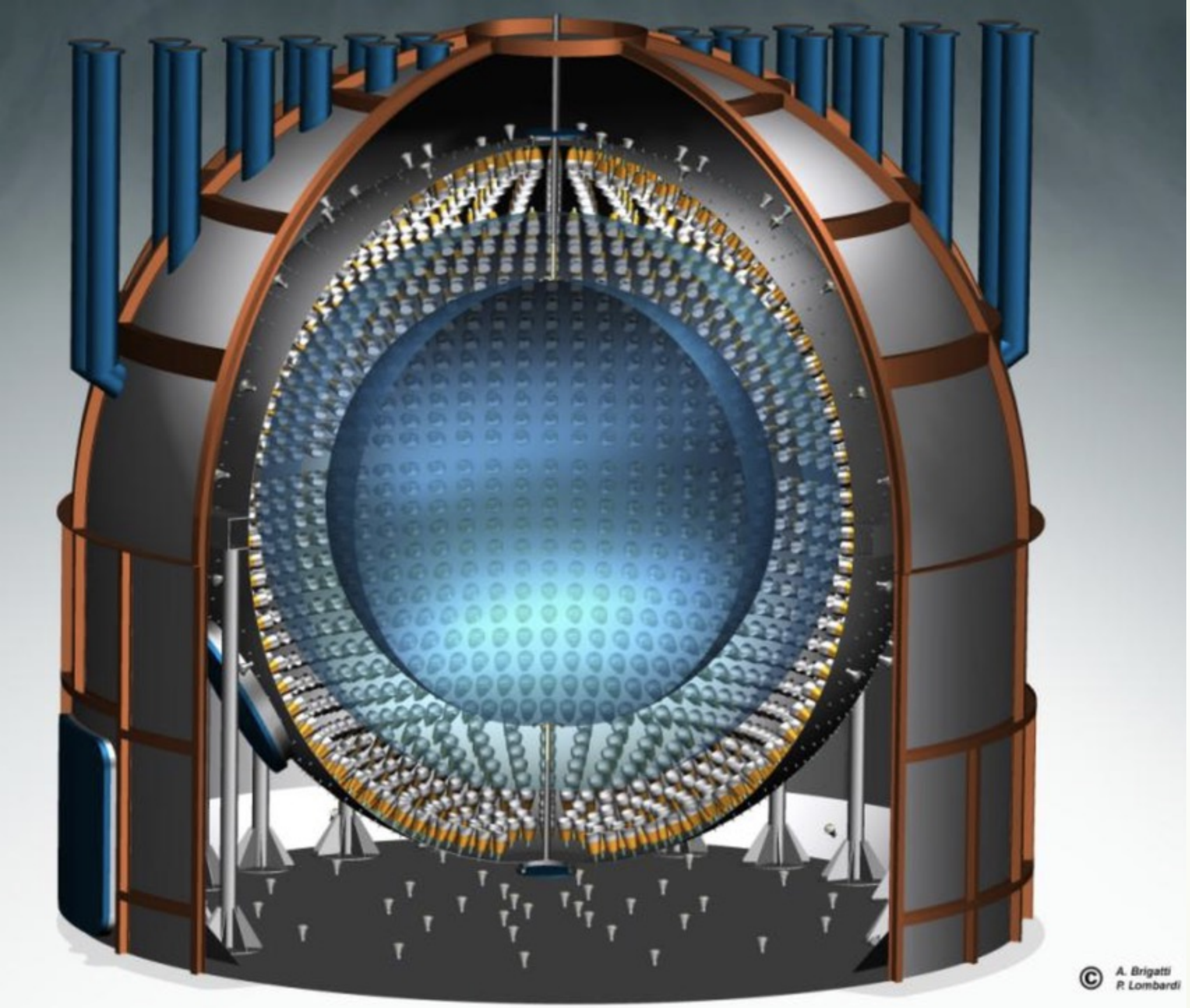




- Optimum surface current density identified.
- Avoid whisker growing by careful parameter control.
- Diffusion-driven emanation confirmed by tests at different temperatures.
- Even hints for slight ^{222}Rn reduction.

Radon – Some properties

- Noble gas.
- Heaviest existing gas → not **so** noble.
- No stable isotopes → All radon is radioactive.
- Part of natural (primordial) radioactivity.
- Short-lived: ^{222}Rn (3.82 days) by far the longest living, rest much shorter
- Followed by a chain of radioactive heavy metals (α-, β- and γ-emitters)

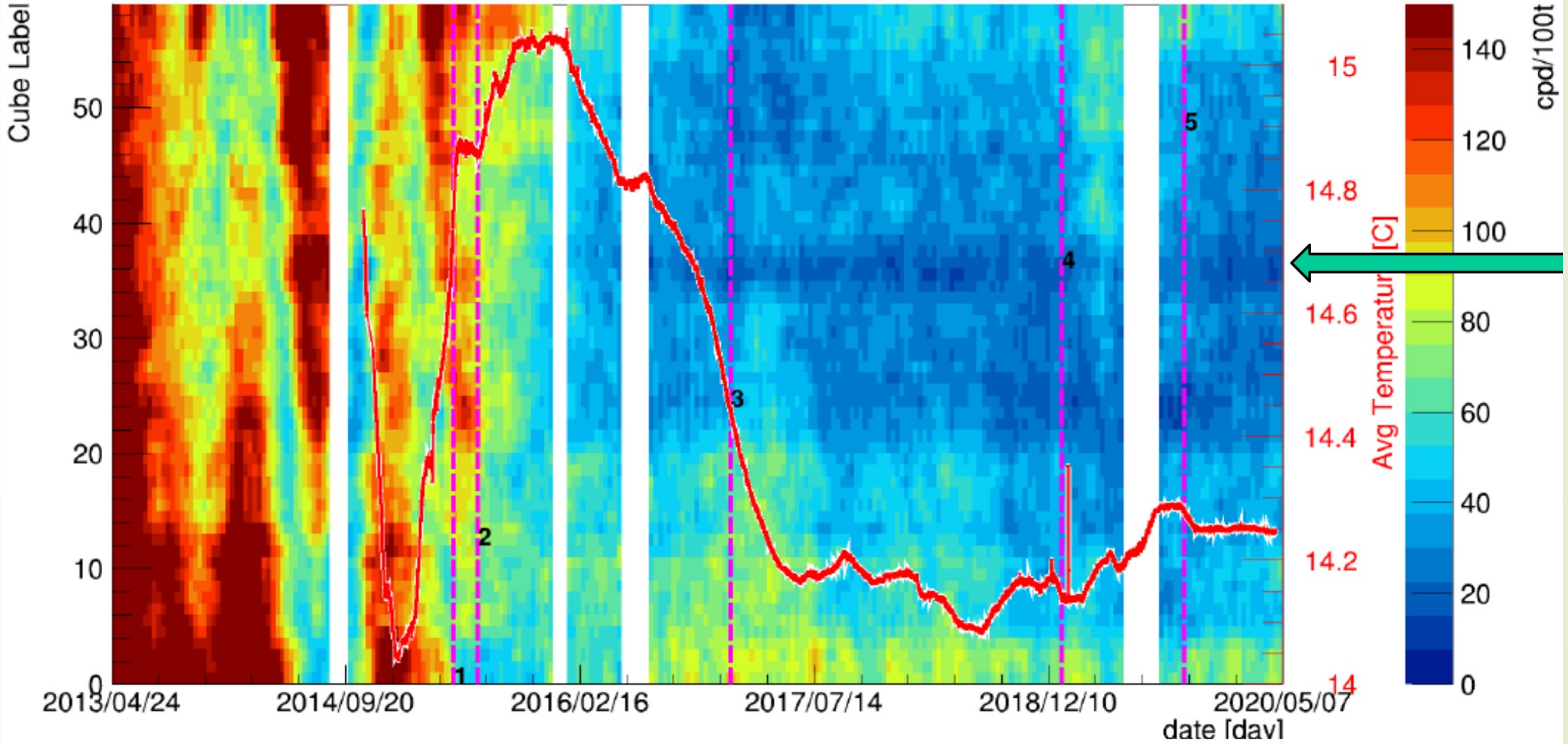


BOREXINO

- Liquid target
  - „easy“ to purify
  - Repeated purification possible
- Minimization of vessel material (nylon balloons)
- Minimization of seals
- Thorough ^{222}Rn screening campaign (complementing bulk impurity screening program)
- Thermal stability → No convection → Inner „fiducial“ volume remains clean!

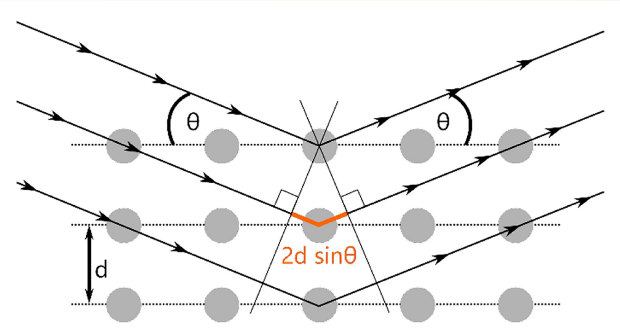
BOREXINO: Thermal stabilization

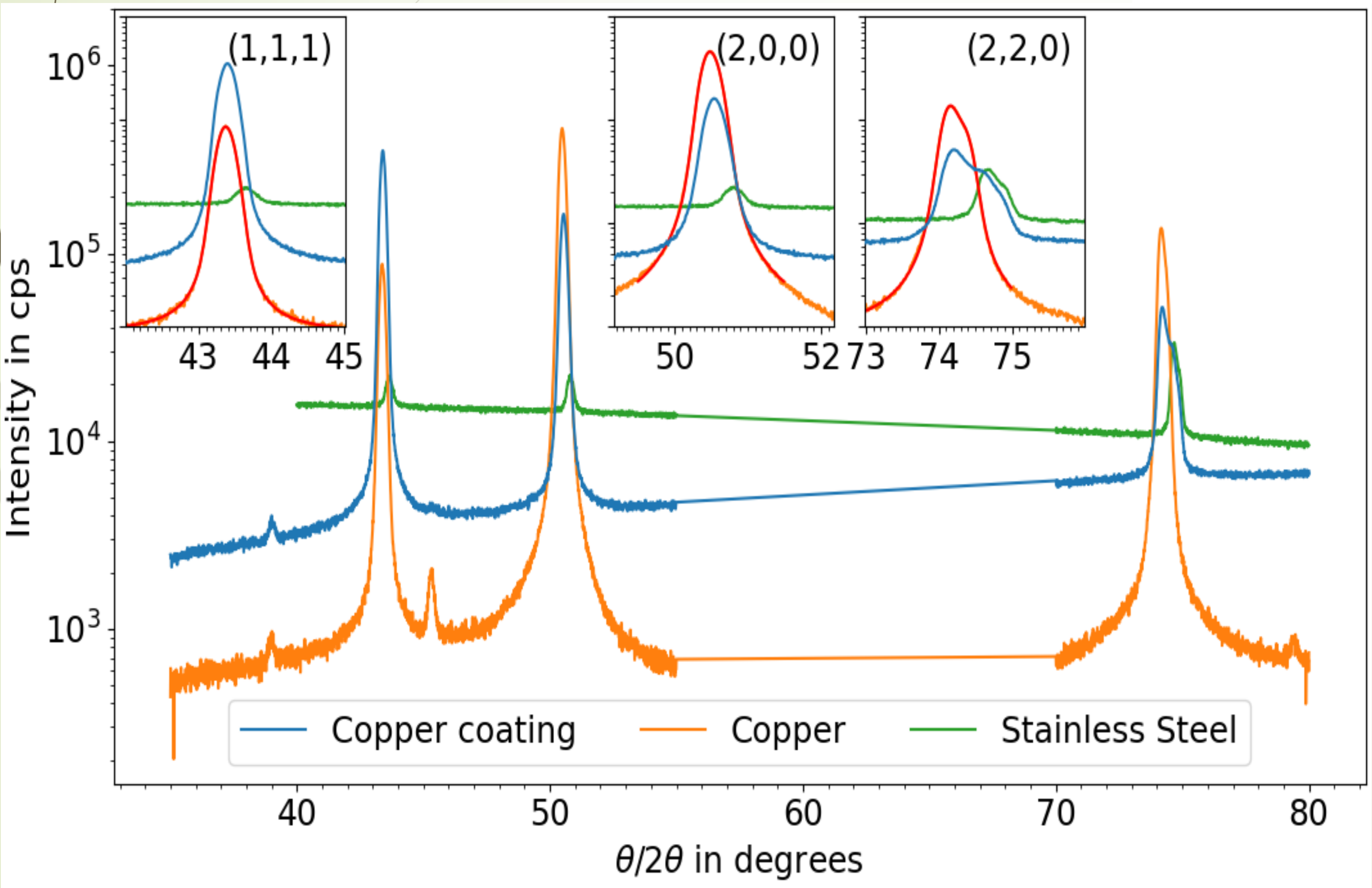
G. Ranucci, Neutrino 2020



- Switch off convection to achieve ultimate purity!

X-ray diffraction





- Very preliminary study
- Done at Heidelberg University (IMSEAM: Institute for molecular systems engineering and advanced materials)
- Basic features as expected, but some unexplained effects:
  - Amplitude ratios doesn't always match expectation (directionality in lattice?)
  - Peak positions slightly shifted (material stress?)
  - Not understood low intensity peaks