Universität Münster

The Art of Cleaning Xenon: Technologies Behind Ultra-Low Backgrounds

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Bundesministerium für Bildung und Forschung

erc LowRad

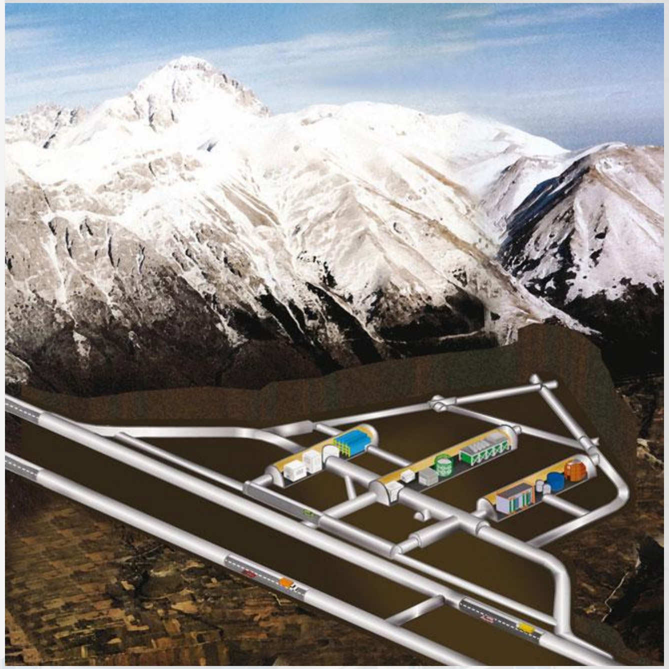
GRK 2149

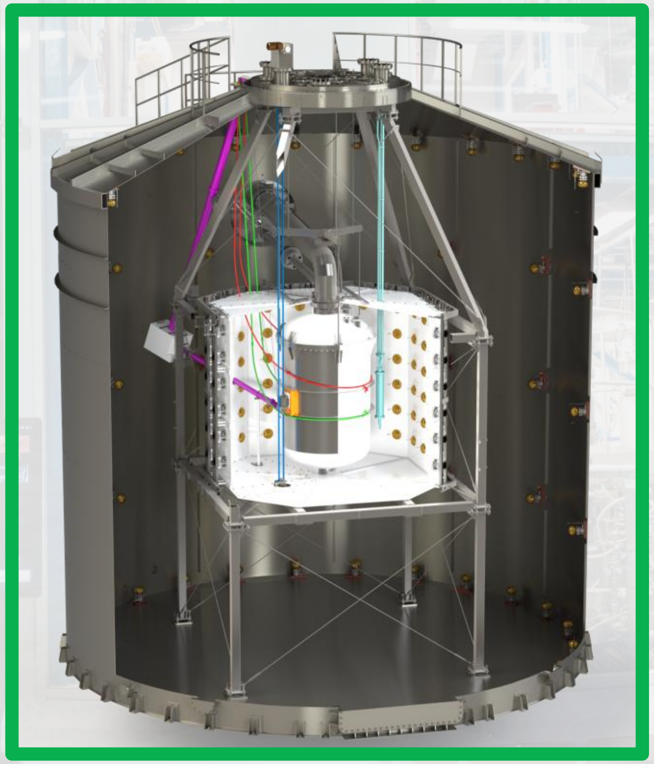
DFG

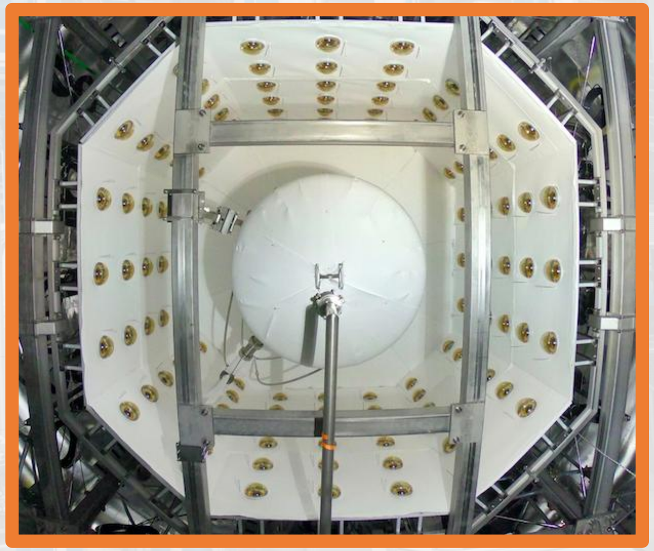
XENON

INFN LNGS

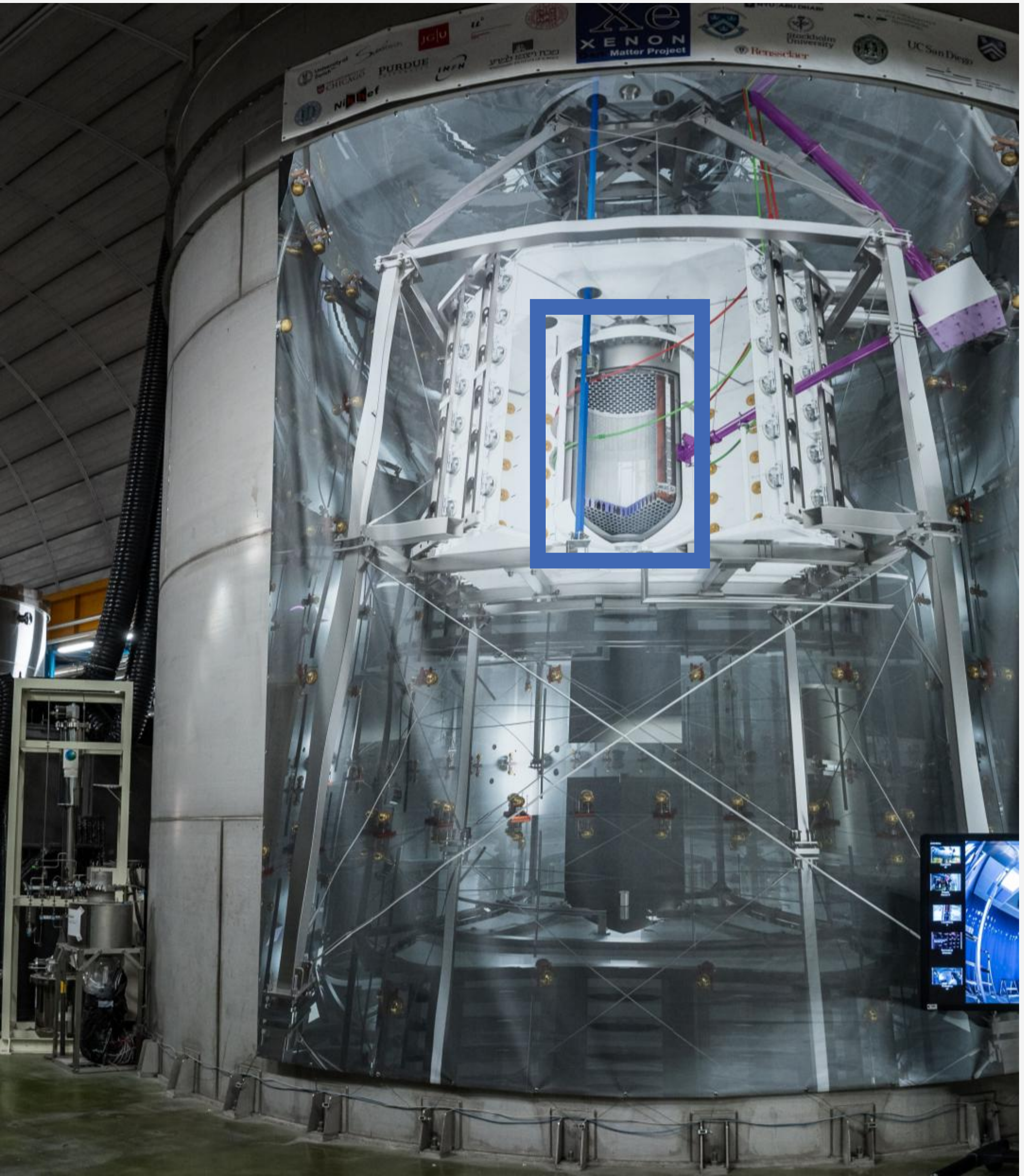
The XENONnT Experiment







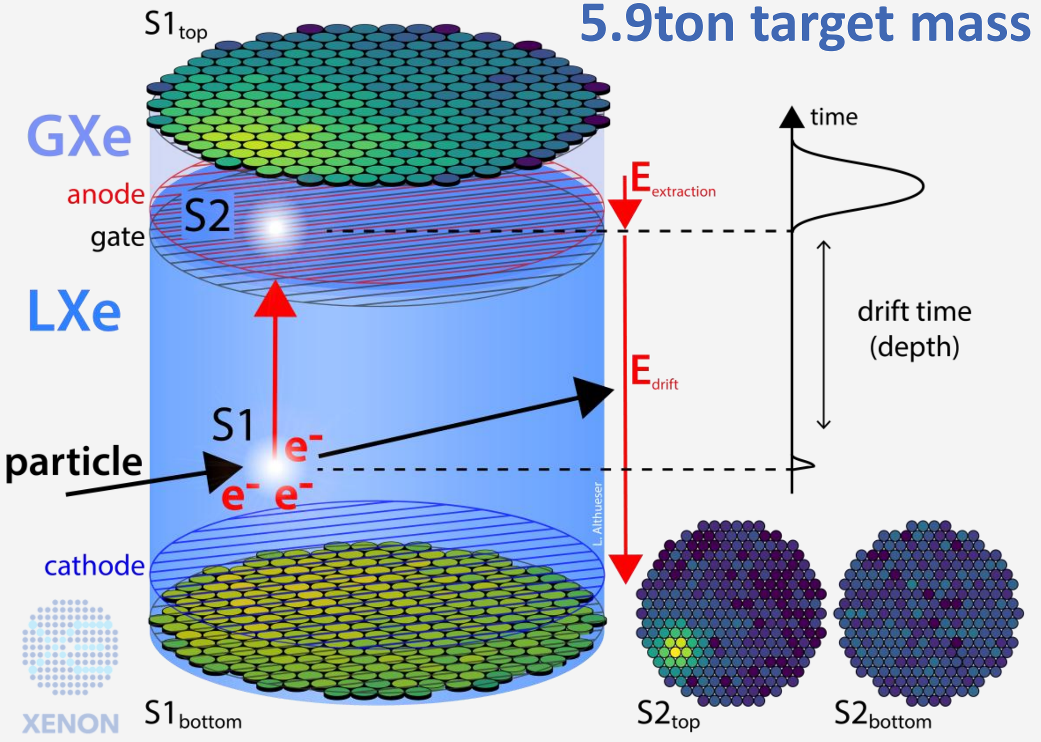
Dual-phase Time Projection Chamber (TPC)

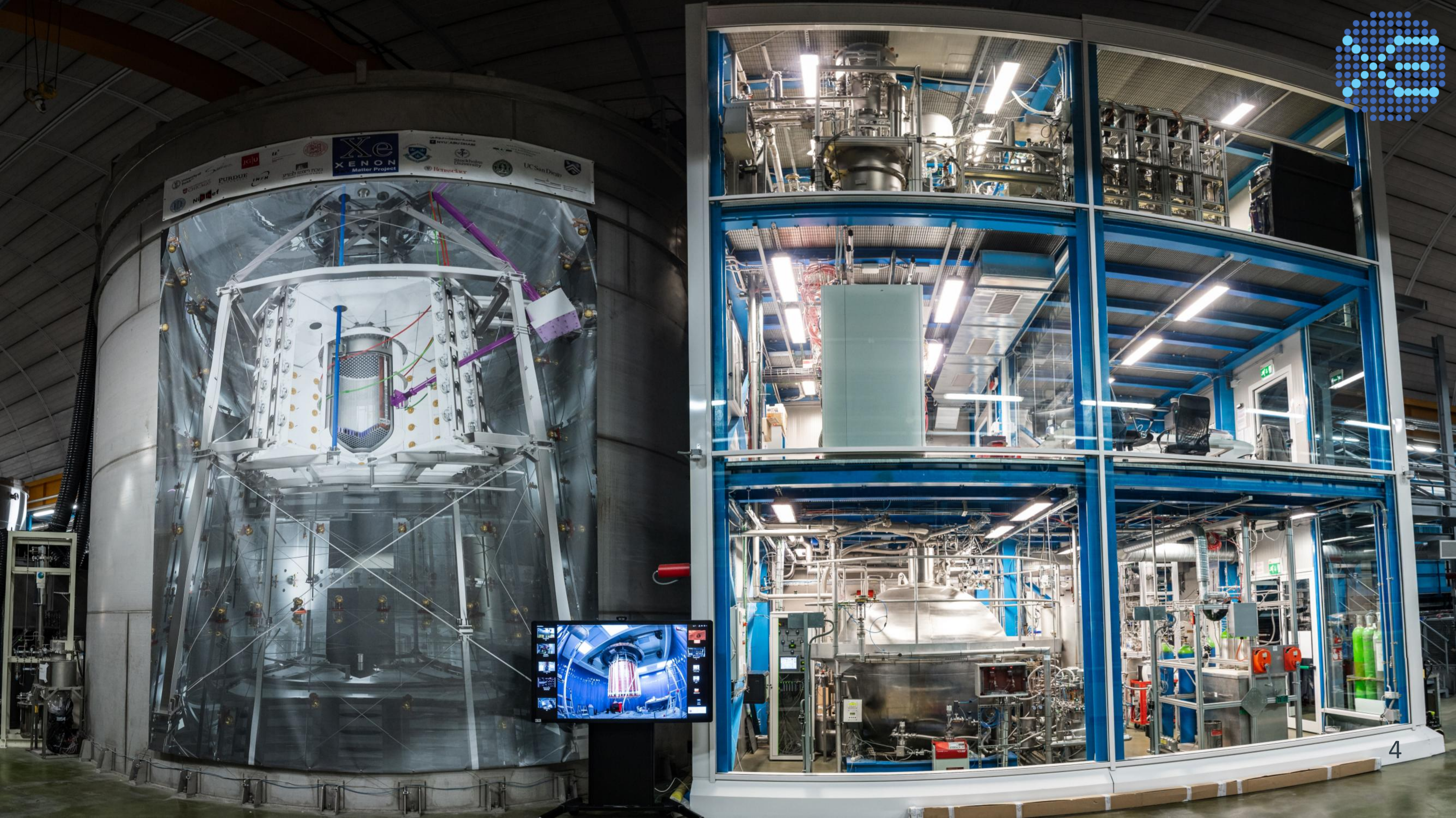


- Detector material selection: degreasing, etching, passivating, and screening to reduce radioactive emanation
  - *E. Aprile et al. (XENON Collab.), Eur. Phys. J. C. 82, 599 (2022)*

- **S1**: prompt scintillation, light signal
- **S2**: drift electrons, charge signal
- Accurate position reconstruction: fiducial volume selection

5.9ton target mass




Xe
XENON
Matter Project
NYU | ABU DHABI
Stockholm University
Rensselaer
UC San Diego
PURDUE
CHICAGO
INFN
JG|U

Electronegative Impurity in LXe

- H_2O: resides on metal surfaces
  - Light attenuation at scintillation wavelength
  - Uniform reduction of S1 signal

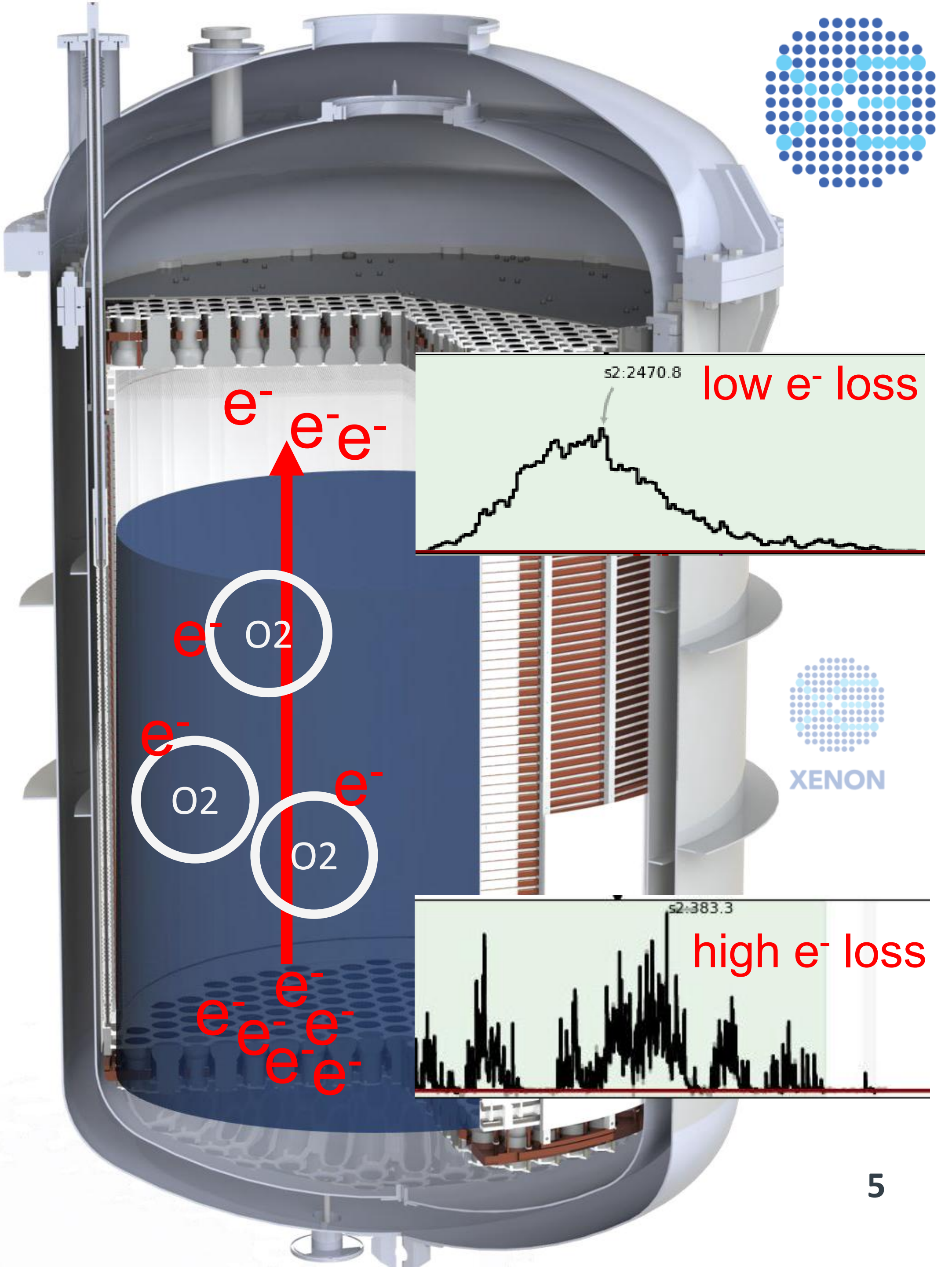
- O_2: resides within porous material such as PTFE
  - High electron attenuation; capturing drift electrons
  - Depth dependent loss of S2 signal
  - Quantified by **electron drift lifetime**:

$$\tau_e = \frac{1}{k_{O_2} C_{O_2}}$$

C_{O_2}: O_2 concentration, k_{O_2}: rate constant

  - Number of S2 electrons N_e lost at drift time t:

$$N_e(t) = N_e(0) e^{-\frac{t}{\tau_e}}$$



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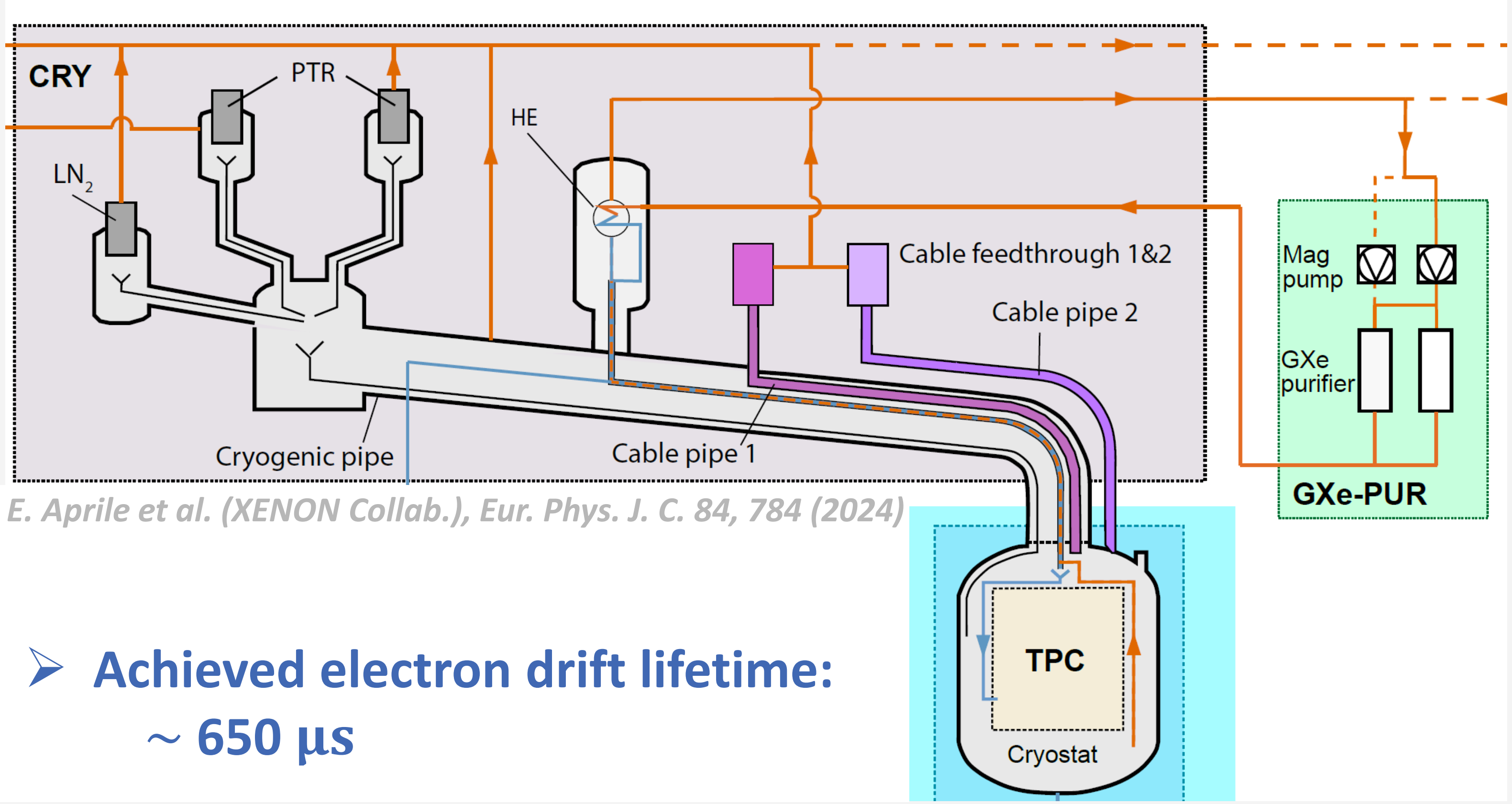
XENON1T/nT Gas Purification

- General purification performance equation: $x_\infty = \frac{\Lambda \tau_p}{n\varepsilon}$

x_∞: impurity at equilibrium
Λ: total impurity source inflow
τ_p: flow turnaround time from TPC
ε: purifier efficiency
n: total LXe

- Hot getter purifiers
- Magnetic GXe pumps (mag-pumps): 22-36 kg/h ~ 60-100 slpm



E. Aprile et al. (XENON Collab.), Eur. Phys. J. C. 84, 784 (2024)

➢ **Achieved electron drift lifetime: ~ 650 µs**

Hot Getter

Mag-Pump

E. Brown et al., Eur. Phys. J. C. 78, 604 (2018)

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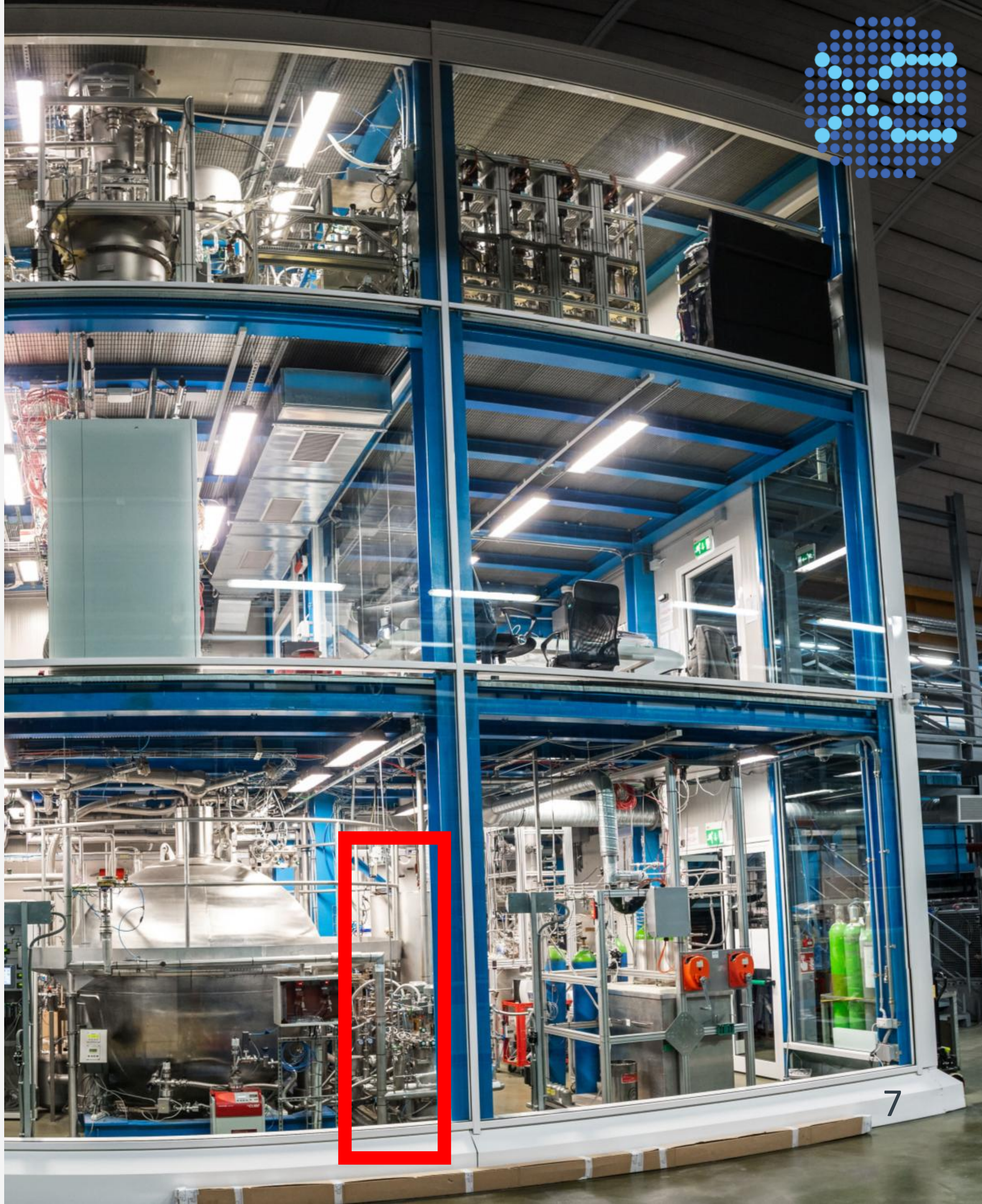
XENONnT Liquid Purification

- Magnetically coupled cryogenic rotor pumps:
  180-720 kg/h ~ 1-4 LPM
  Barber-Nichols

- Purifiers:
  - copper catalyst on high-surface-area alumina (Q5): **high ε, higher radon emanation**
  - sintered pellets of non-evaporable getter alloy (St707): **lower ε, low radon emanation**



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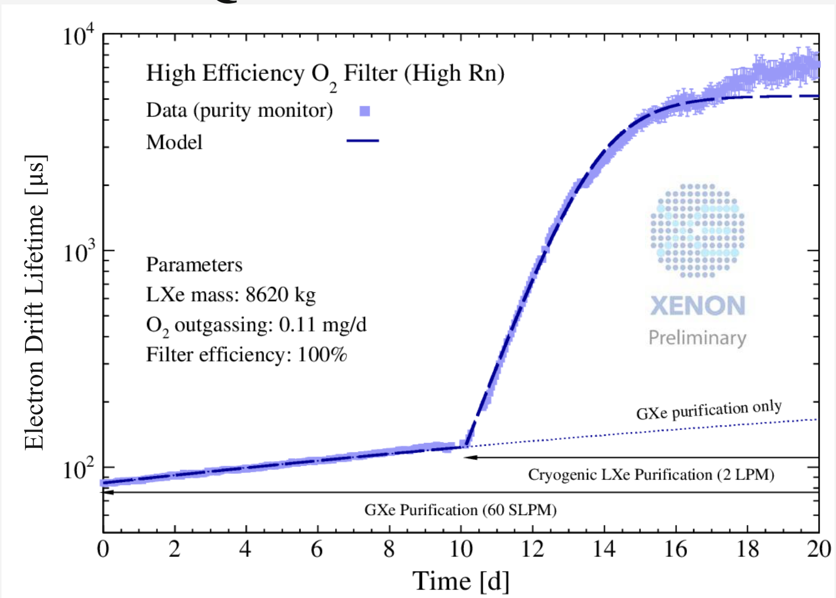
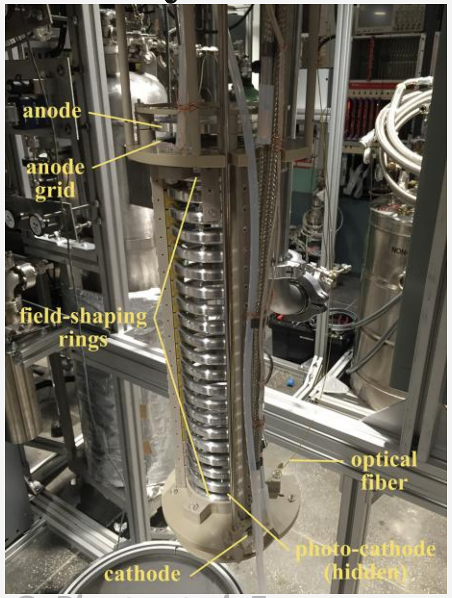
XENONnT Liquid Purification Performance

- With Q5, achieved 5 ms electron drift lifetime in 5 days
- In science run with St707, kept at 15 ms electron drift lifetime:
  ~90% full-drift electrons survive

Q5 Performance

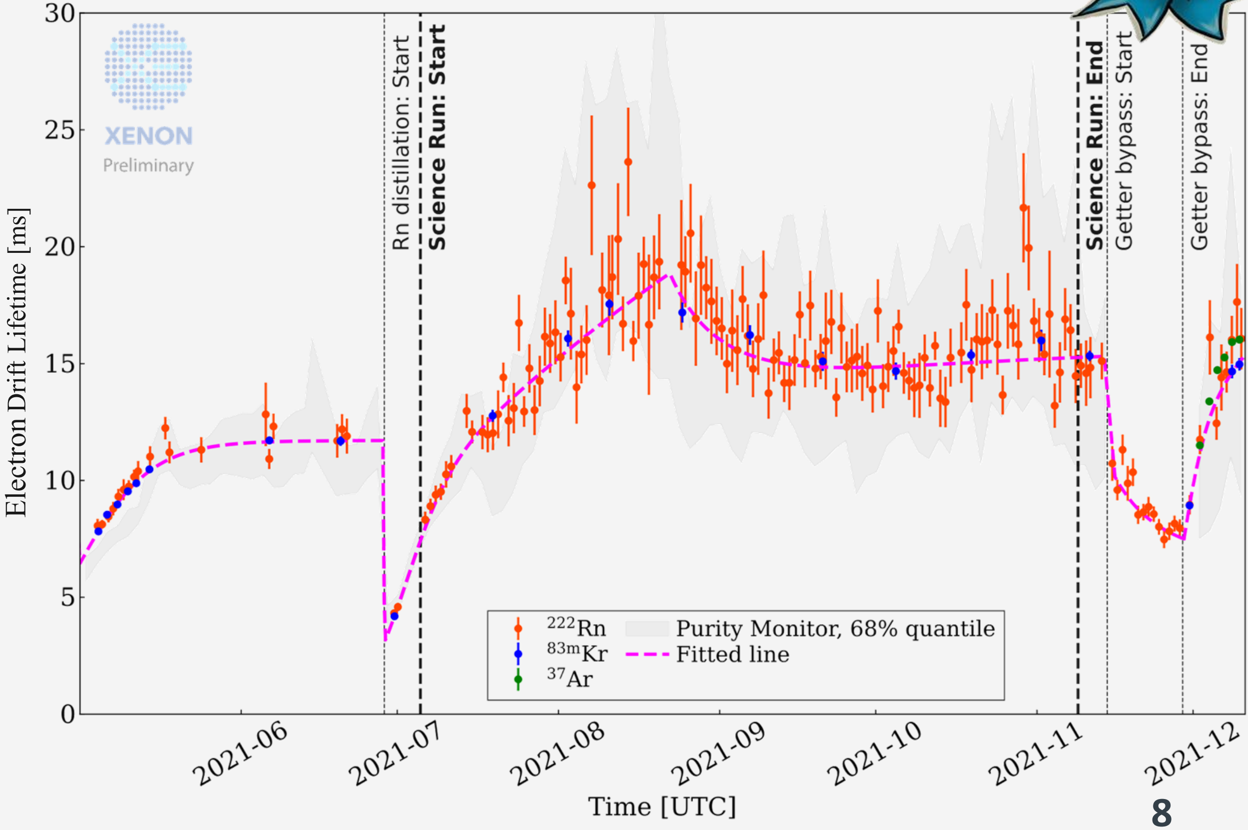


Xeclipse Purity Monitor



G. Plante et al, Eur. Phys. J. C 82, 860 (2022)

St707 Science Run Performance



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Nobel Gas Radioactive Contaminant in LXe

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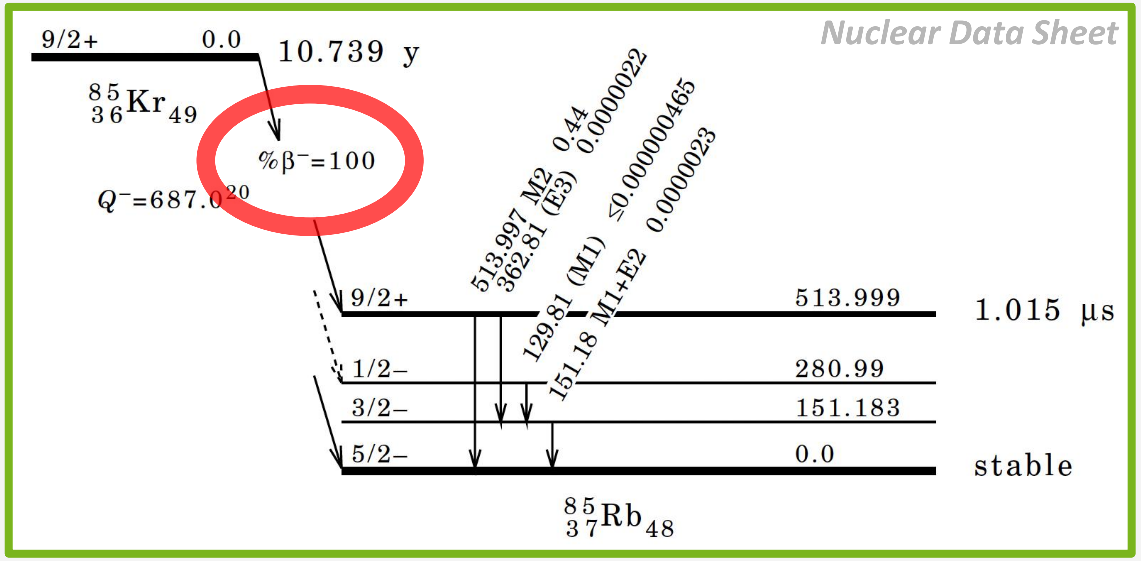
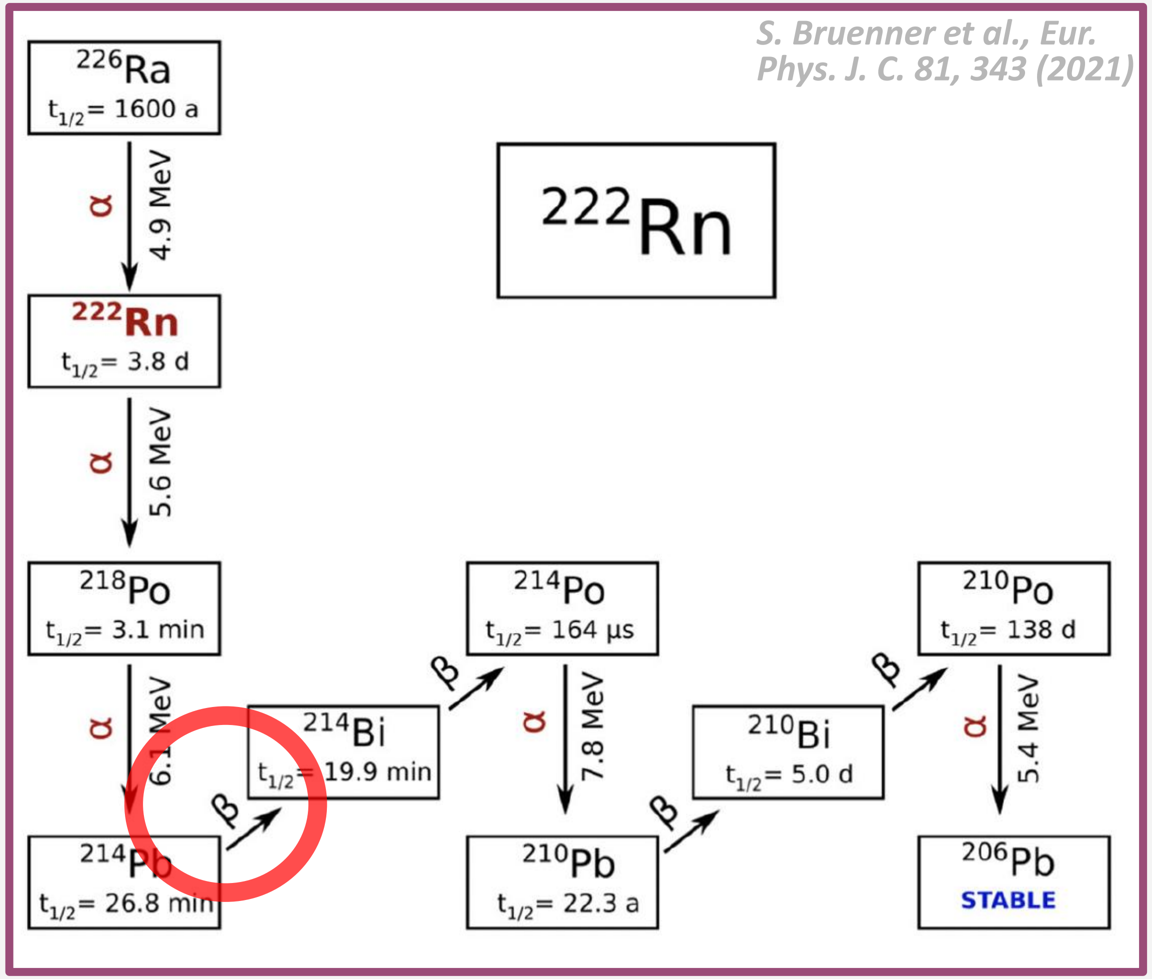
- Noble gas radioactive contaminants freely diffuse in LXe fiducial volume
- Beta decays from ^{85}Kr and ^{222}Rn daughter cover broad energy spectrum as background:
  - ^{85}Kr: introduced into the atmosphere via anthropogenic nuclear activities
  - ^{222}Rn: originates from trace ^{226}Ra in detector material





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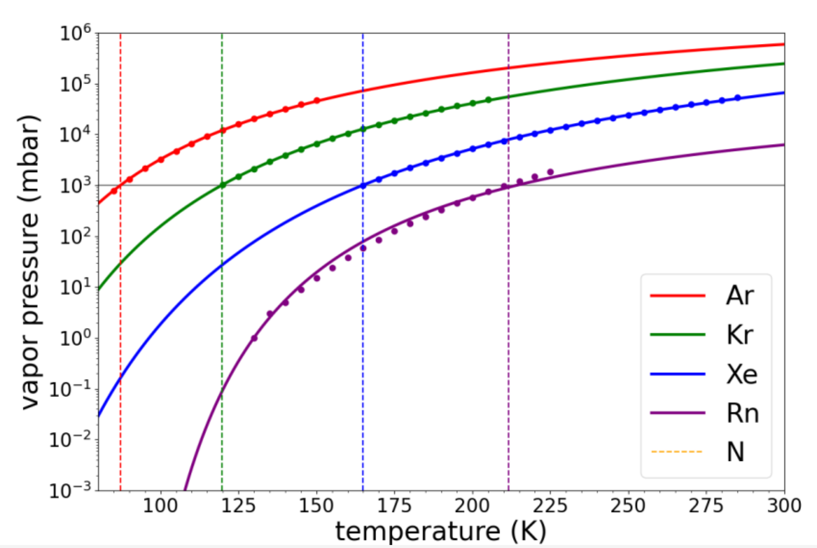
Nobel Gas Cryogenic Distillation

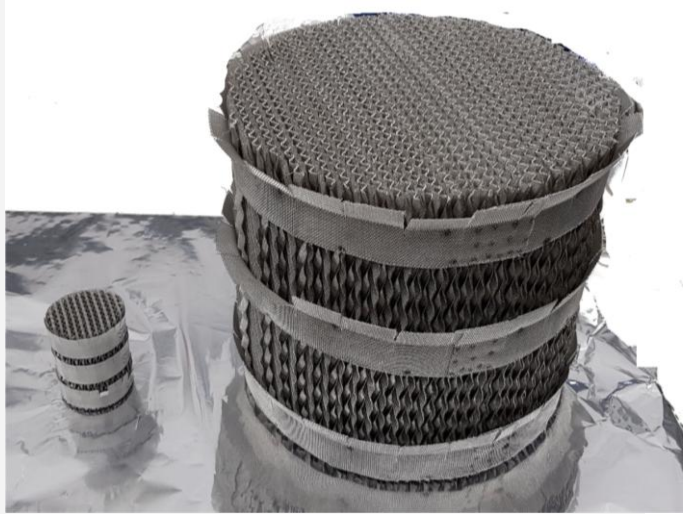
- Relative volatility as vapor pressure ratio:

$$\alpha_i \equiv \frac{p_i}{p_{Xe}}$$

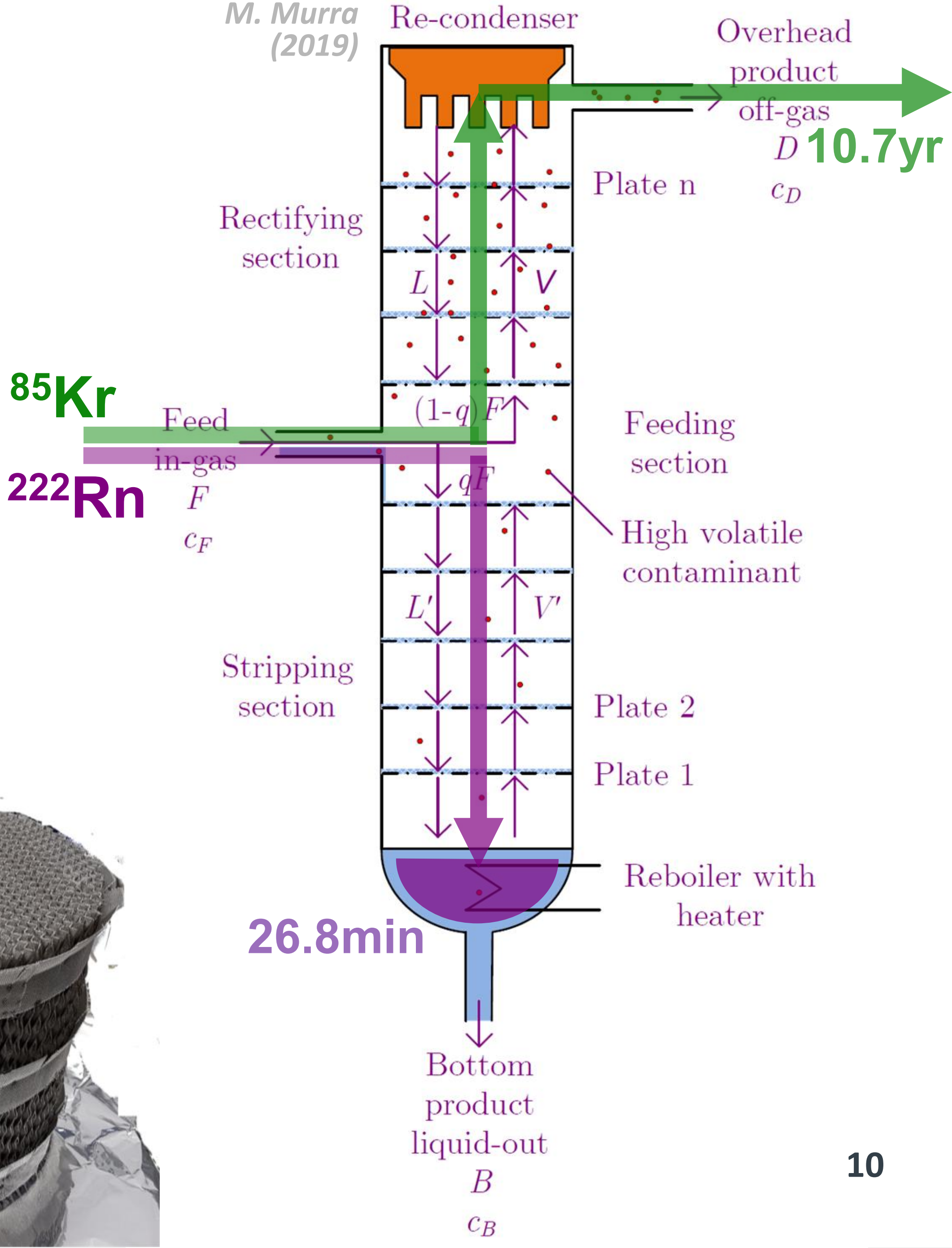
Data from CRC Handbook of Chemistry and Physics 95th Edition



- ^{85}Kr: $\alpha = 10.5$ (-100 °C)
  - Enriched at the top
  - **Remove through off-gas**
- ^{222}Rn: $\alpha = 0.1$ (-100 °C)
  - Enriched at the bottom
  - **Trapped in reboiler to decay**



PhD thesis M. Murra (2019)



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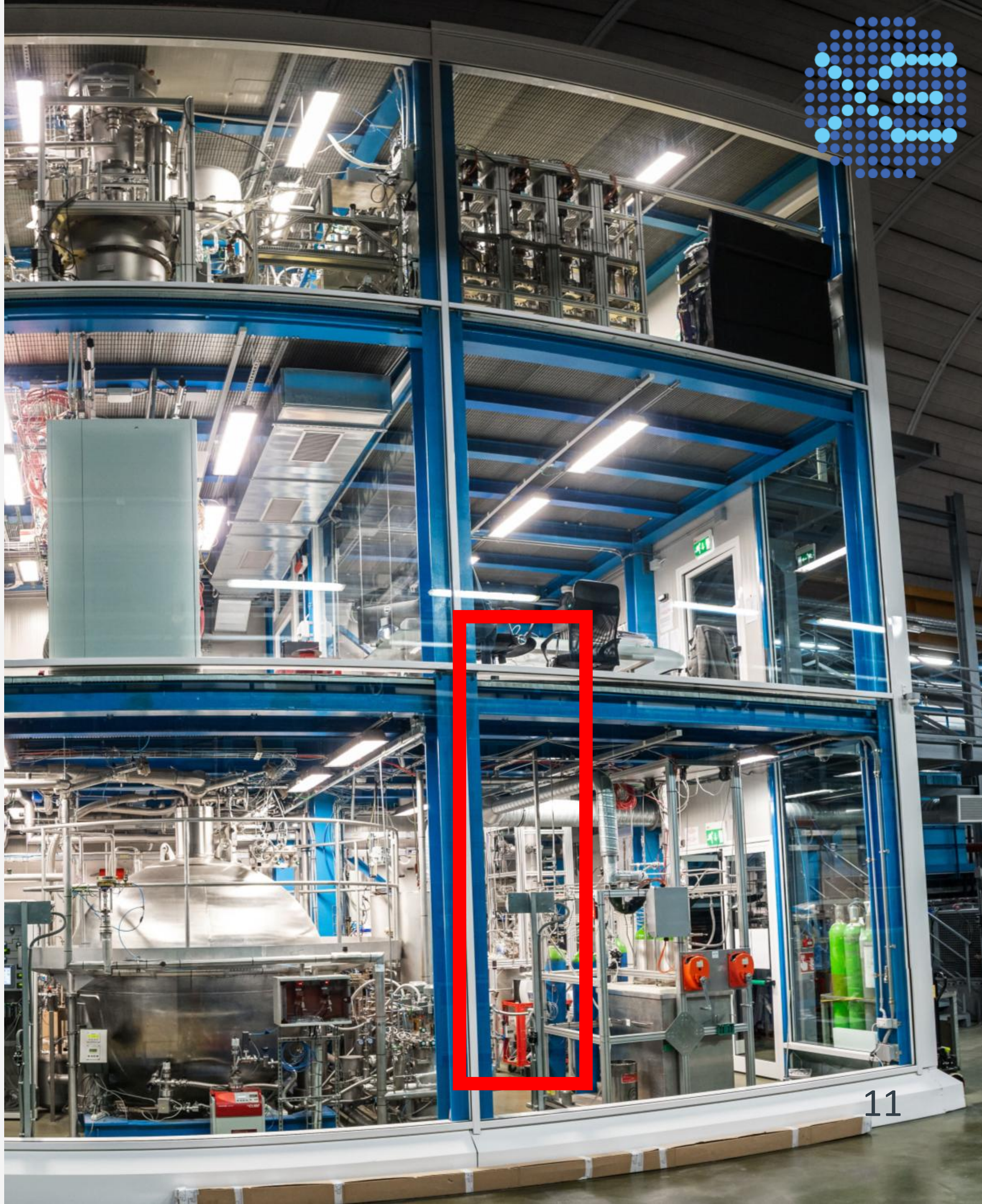
XENONnT Krypton Distillation

- Distillation mode:
  Offline and online
- Feeding flow:
  - 3 kg/h ~ 8.3 slpm
  - ➢ Achieved: 6.5 kg/h ~ 18 slpm
- Separation factor:
  - 10^4-10^5
  - ➢ Achieved: $6.4^{+1.9}_{-1.3} \times 10^5$
- Xe recovery:
  99%

5.5 m

E. Aprile et al. (XENON Collab.), Eur. Phys. J. C. 77, 275 (2017)



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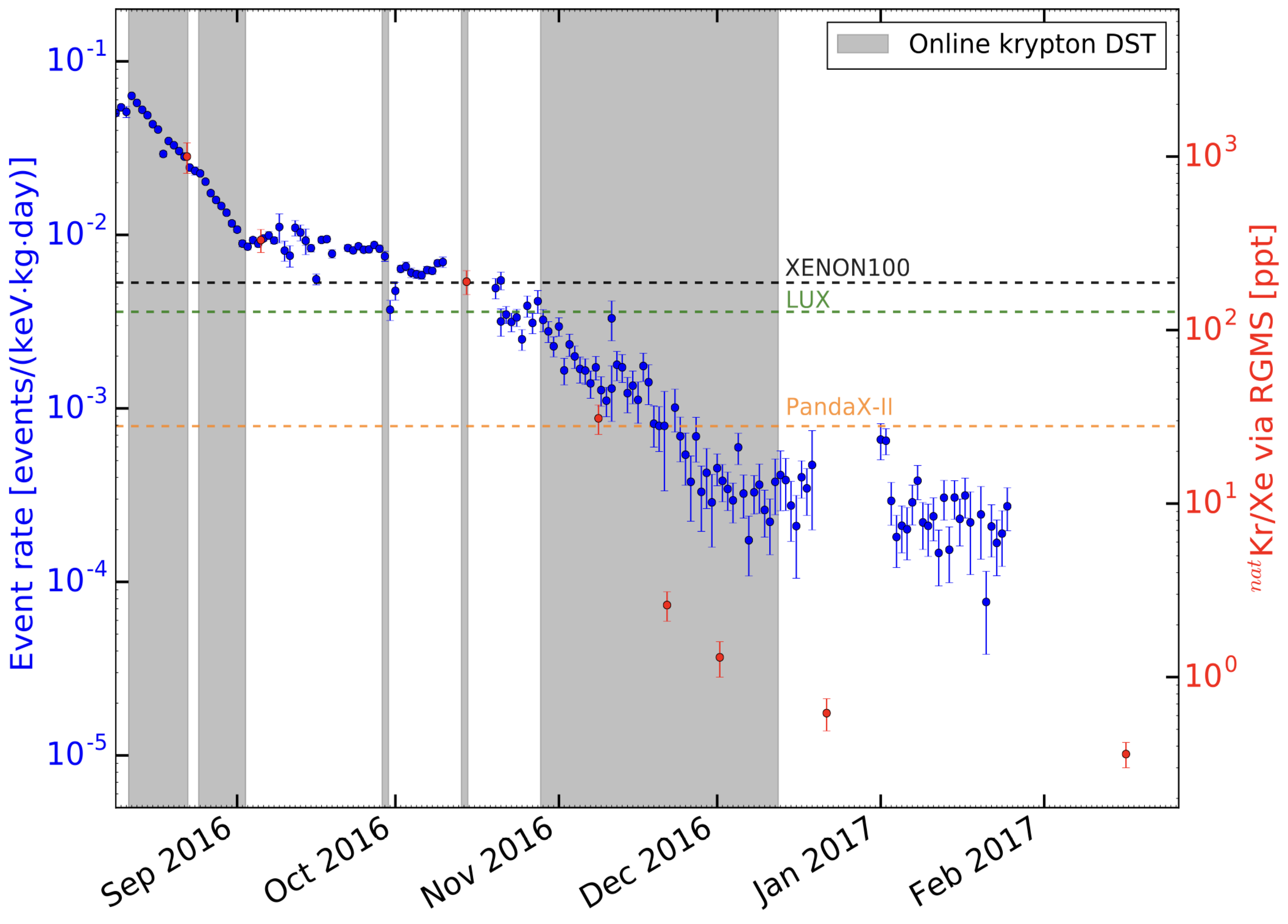
XENON1T/nT Krypton Distillation Performance

E. Aprile et al. (XENON Collab.), Prog. Theor. Exp. Phys., 053H01 (2022)



- Rare Gas Mass Spectrometer (RGMS)
  - Chromatography technique
  - Detection limit:

    8×10^{-15} (^{nat}Kr/Xe)
- *S.Lindemann and H. Simgen, Eur. Phys. J. C. 74, 2746 (2014)*
- *M. Guida, Y.-T. Lin, and H. Simgen, Eur. Phys. J. C. 85, 576 (2025)*
- XENONnT science run:

  $(56 \pm 36) \times 10^{-15}$ (^{nat}Kr/Xe)

WORLD RECORD

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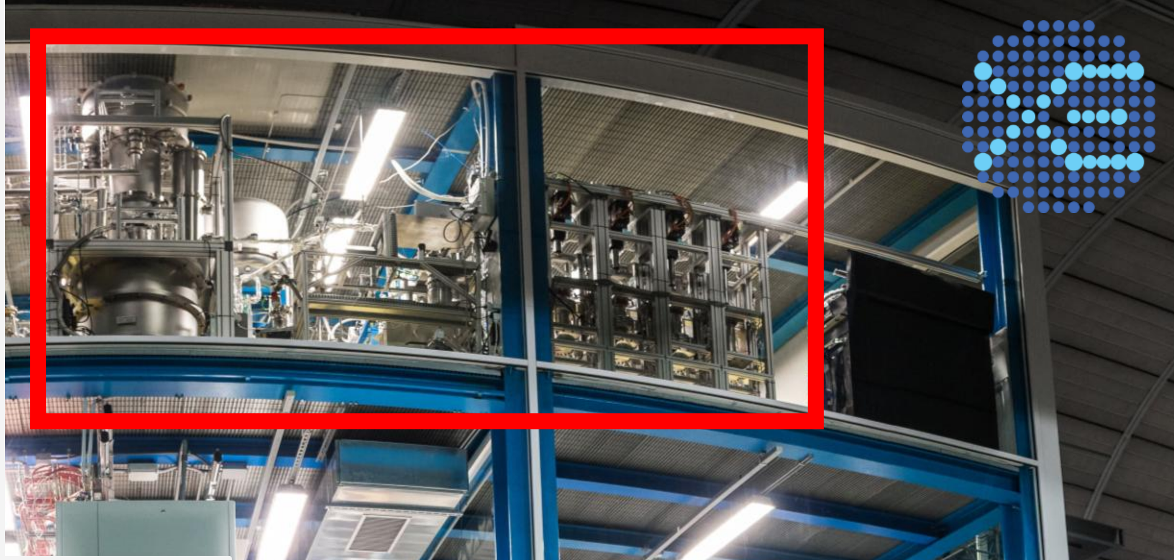
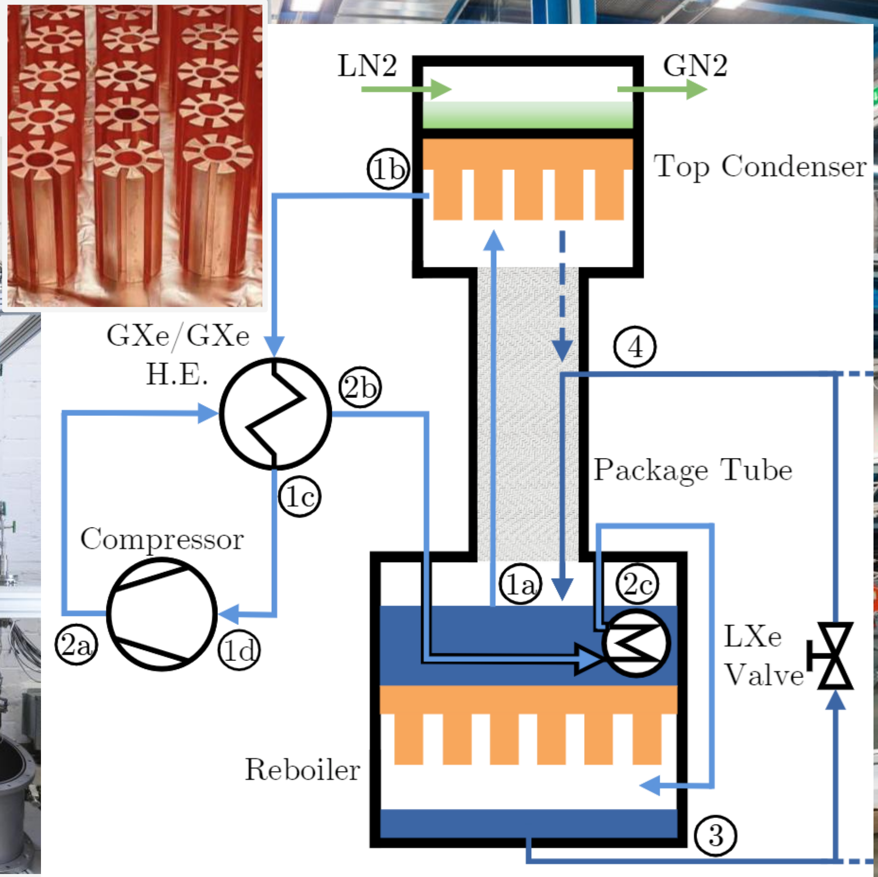
XENONnT Radon Removal

- Distillation mode:
  Continuous online
- Feeding flow (radon-free mag-pumps):
  targeting 72kg/h ~ 200 slpm (~15% of LXe flow)
- Separation factor:
  >156
- *XENON Collaboration, Phys. Rev. X 15, 031079 (2025)*
- Xe recovery:
  100%
- Reboiler heat exchanger (HE)
- Mag-pump compressor acts similar to a heat pump via another HE
- **Improve power consumption for cooling by a factor of 3!**

E. Aprile et al. (XENON Collab.), Eur. Phys. J. C. 82, 1108 (2022)





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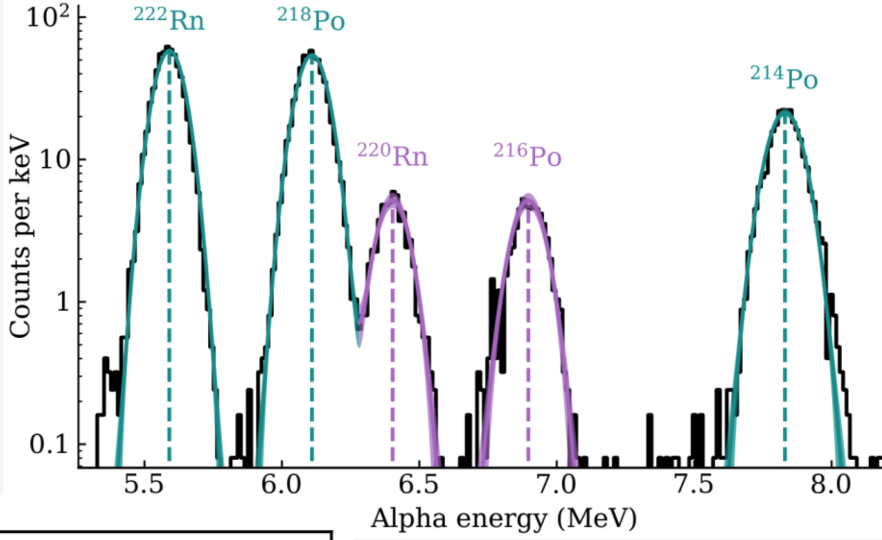
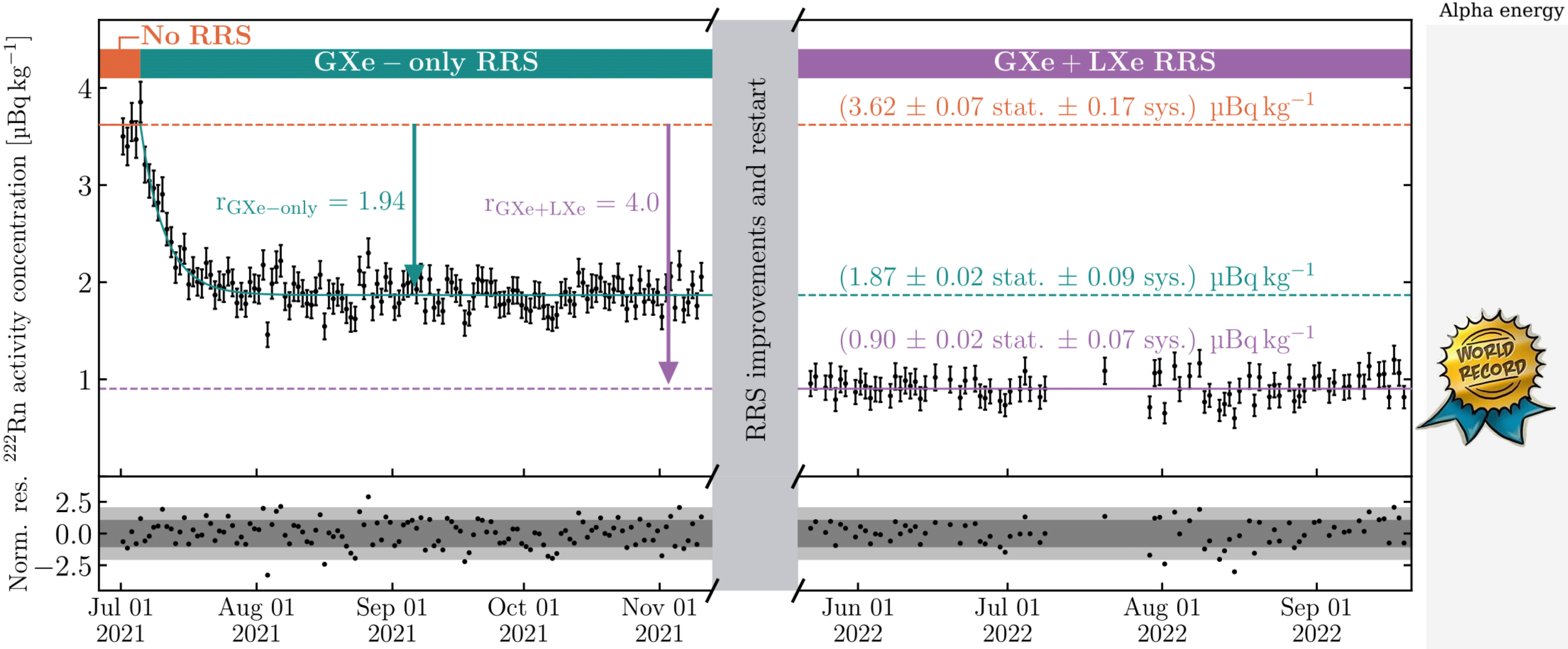
XENONnT Radon Removal Performance

- Radon Removal System (RRS) reduces the radon level down to level of the solar neutrinos, the irreducible external background

XENON Collaboration, Phys. Rev. X 15, 031079 (2025)



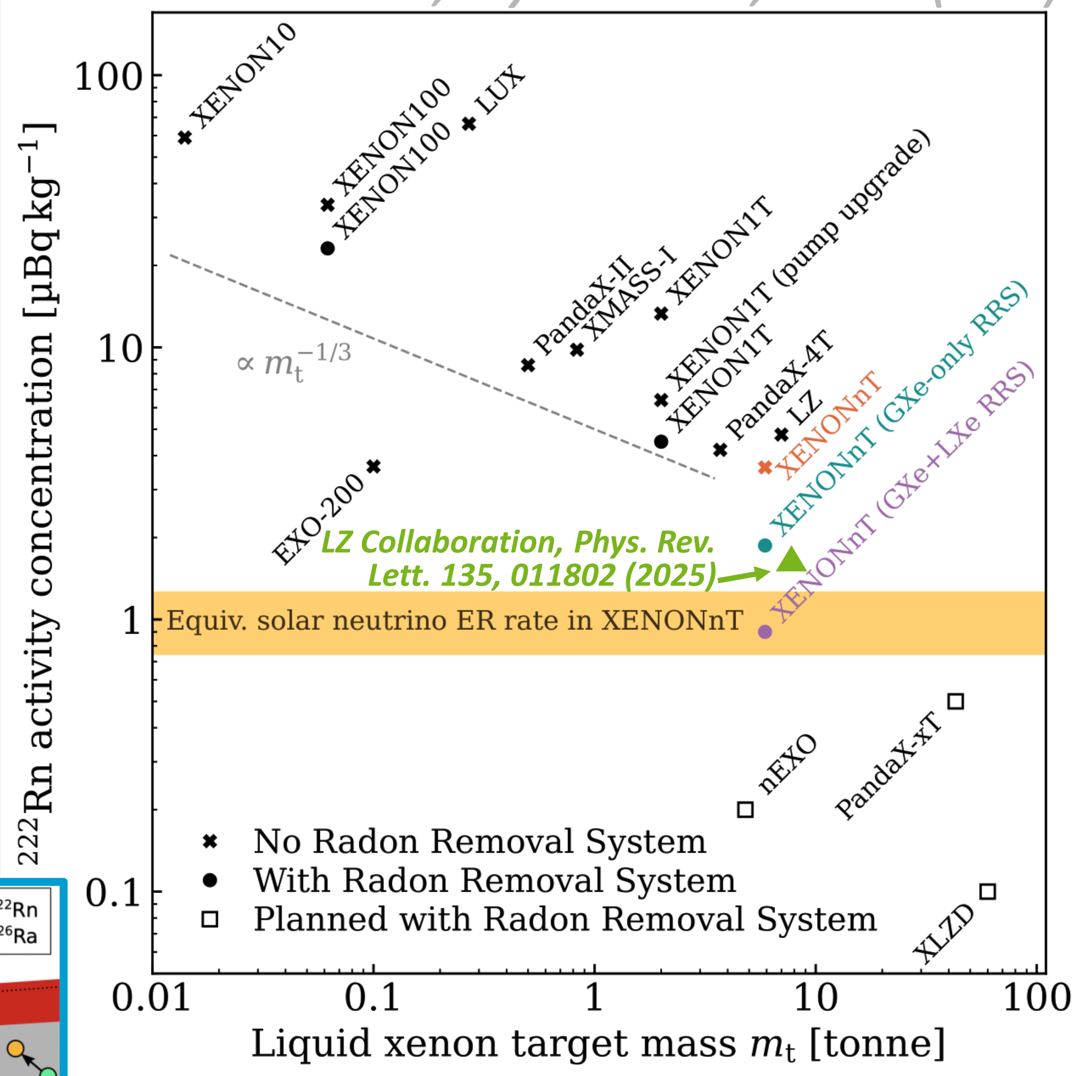


XLZD The Ultimate Xenon Detector

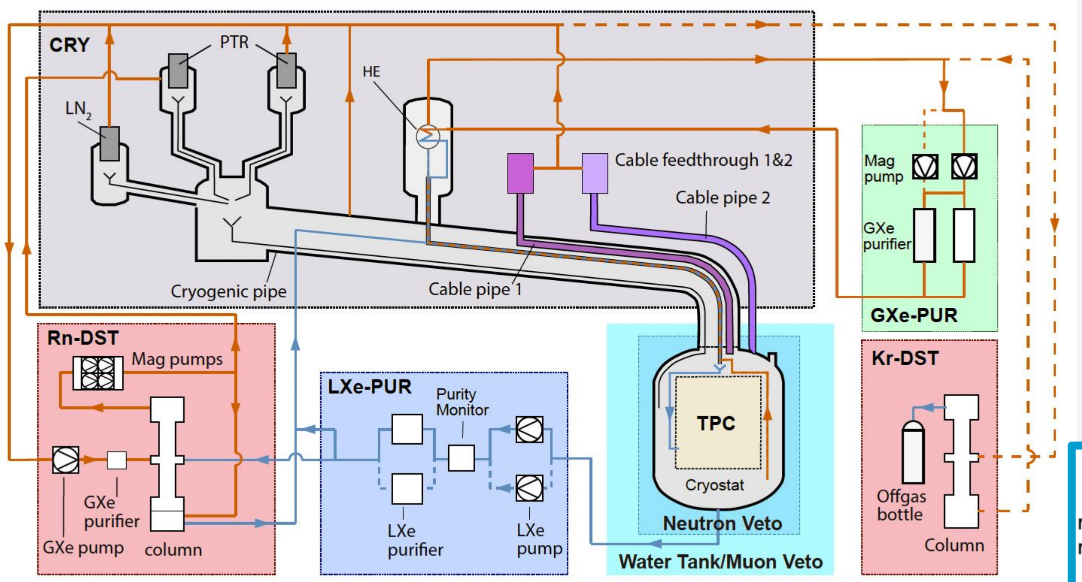
- With >60 tons of xenon target mass, aiming to reach neutrino fog for WIMP dark matter search
- *XLZD Collab., The XLZD Design Book, arXiv:2410.17137 (2024)*

- Coating method to reduce surface radon emanation
- Radon tagging analysis method from LZ
- Purification/distillation integration from XENONnT

XENON Collaboration, Phys. Rev. X 15, 031079 (2025)

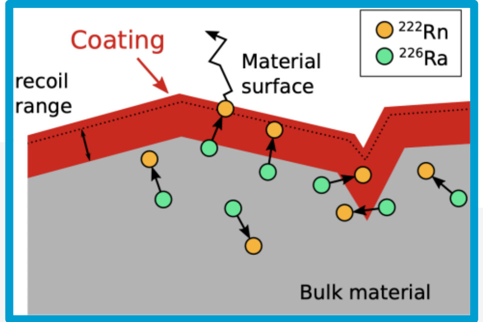


LZ Collaboration, Phys. Rev. Lett. 135, 011802 (2025)



E. Aprile et al. (XENON Collab.), Eur. Phys. J. C. 84, 784 (2024)

PhD thesis, F. Jörg (2022)



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LowRAD Project Goals

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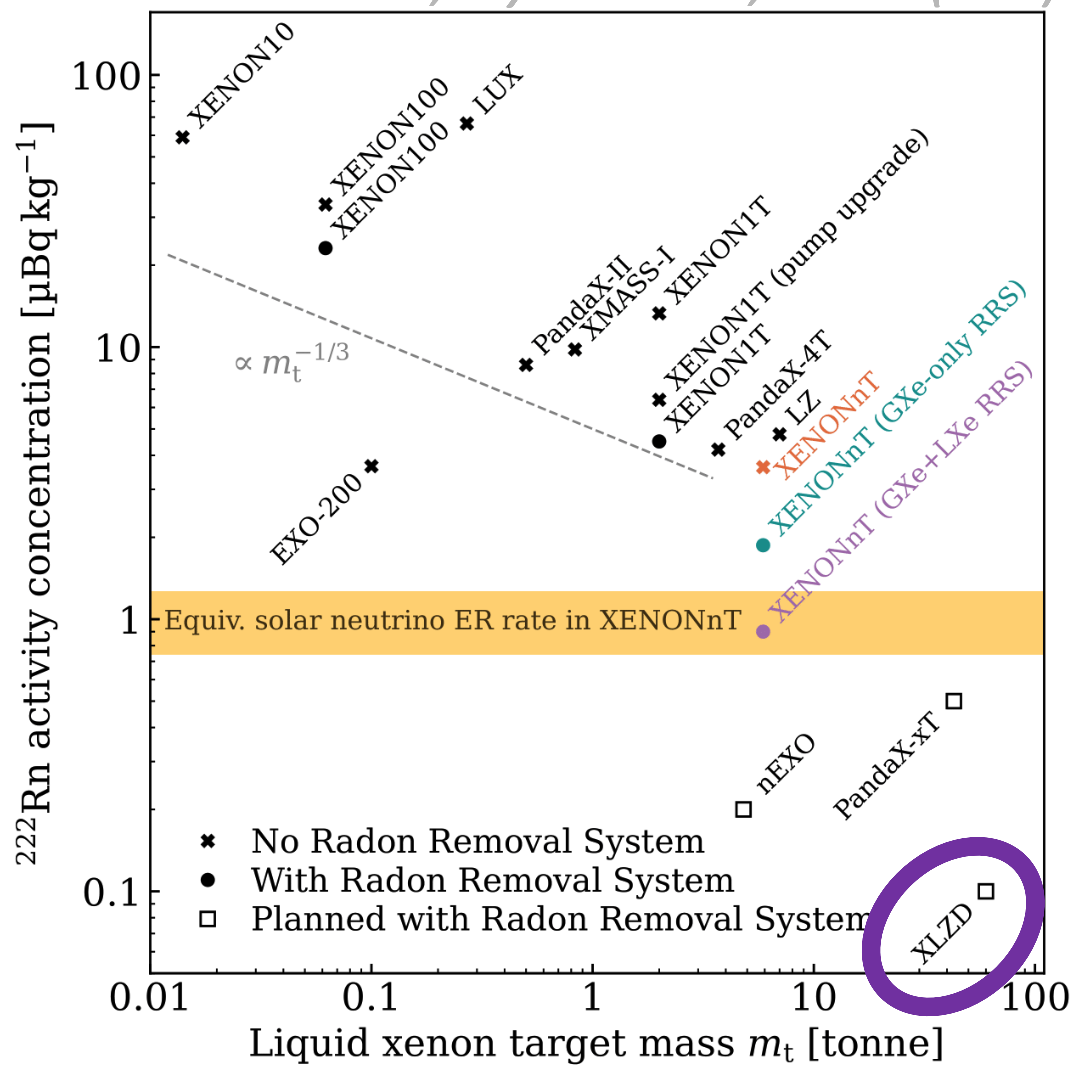
- **Low Rad**on and **Low** Internal **Radi**oactivity (LowRad) ERC Advanced Grant

erc LowRad

- **High flow radon** removal with factor of 10 combined improvement in radon reduction to:
  0.1 µBq/kg of xenon
- **Lossless** online **krypton** removal at:
  30 x 10^{-15} (^{nat}Kr/Xe)
- **All-in-one** purification & distillation system
- R&D for novel purification methods
- Advancing analysis method for physics search

XENON Collaboration, Phys. Rev. X 15, 031079 (2025)



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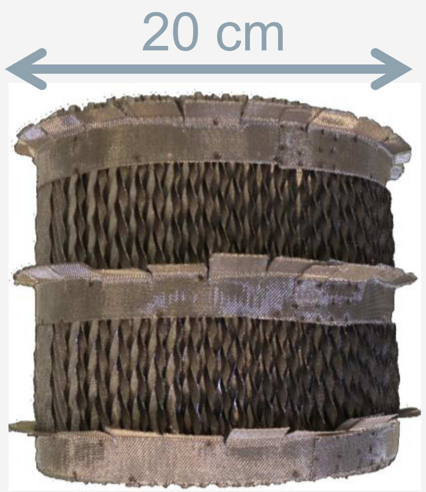
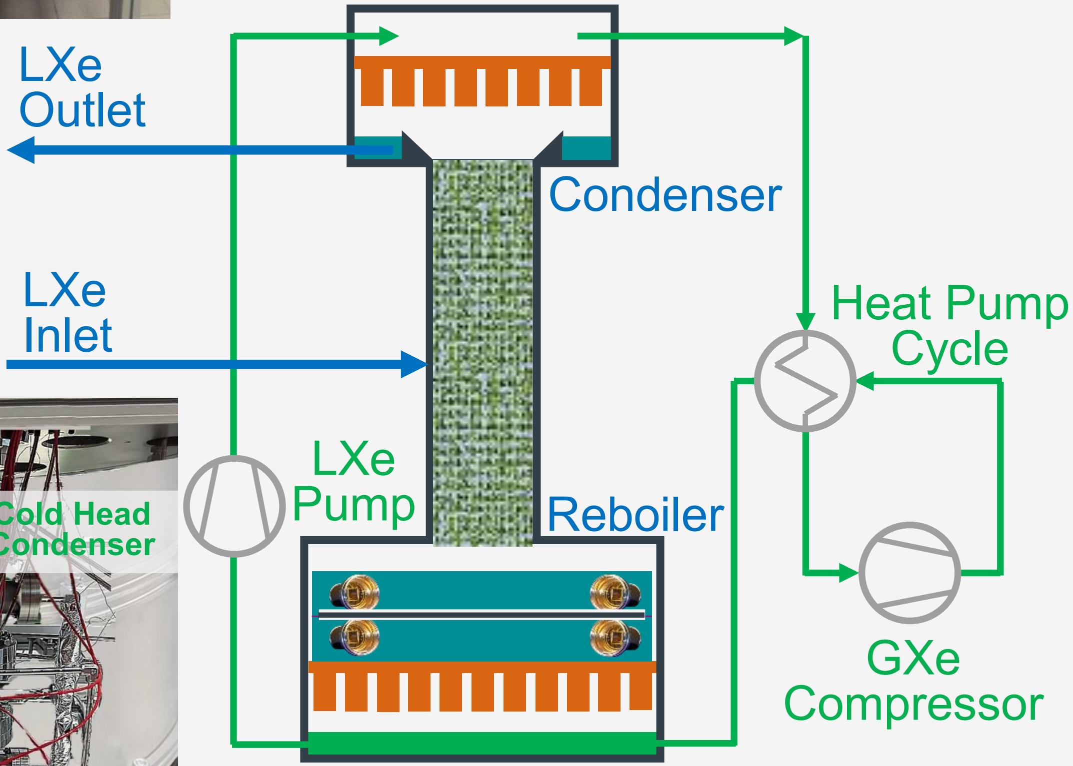
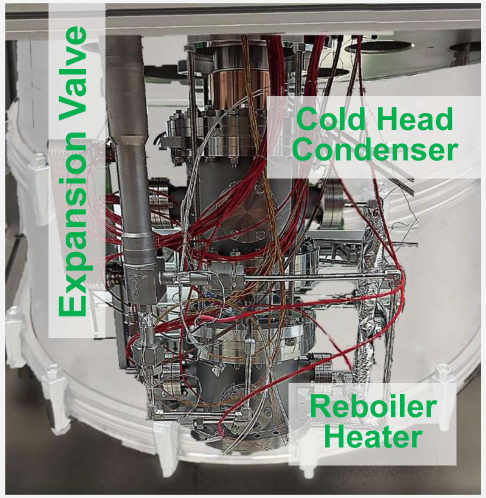
LowRAD Radon Removal

- **High feeding flow** in LXe:
  - ➢ 75 kg/h (demonstrator)
  - ➢ 1600 kg/h (final multi-column system)
- Enormous cooling power required:
  - Applying reverse Clausius-Rankine cycle
  - ➢ Dedicated hermetically sealed external xenon-based **heat pump** developed
- **In-system radon monitor:**
  - ➢ PMTs at the radon-enriched reboiler
- Status:
  - ➢ Heat pump test demonstrator built: achieved planned 125 W cooling power
  - ➢ Heat pump paper to be published
  - ➢ Radon column fully planned







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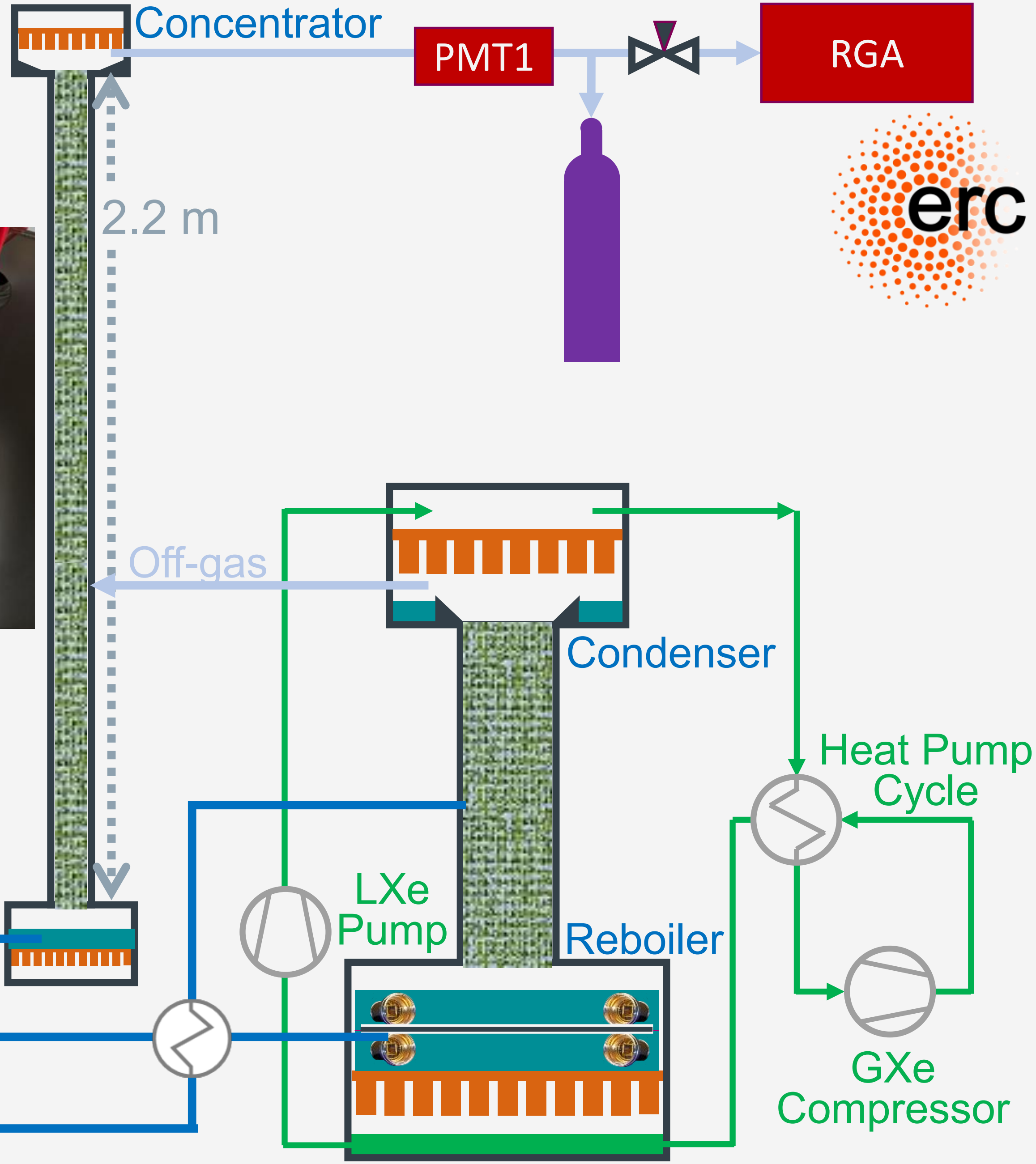
LowRAD Krypton Distillation

- To improve the xenon recovery rate:
  - McCabe-Thiele: 9 stages
  - ➢ Additional **krypton concentrator column** at off-gas to improve recovery **by 1000 (lossless)**

- **In-system krypton monitor:**
  - ➢ Residual gas analyzer (RGA) at the condenser of the concentrator
    - *A. Dobi et al., Nucl. Instrum. Methods Phys. Res. A, Vol. 665, 11, pg1-6 (2011)*
    - *E. Brown et al., JINST Vol. 8, P02011 (2013)*
  - ➢ In-system Auto-RGMS (outside LowRAD)
    - *M. Guida, Y.-T. Lin, and H. Simgen, Eur. Phys. J. C. 85, 576 (2025)*
- Status:
  - ➢ Concentrator built, being characterized
  - ➢ Showing promising initial results (PMTs+^{83m}Kr)



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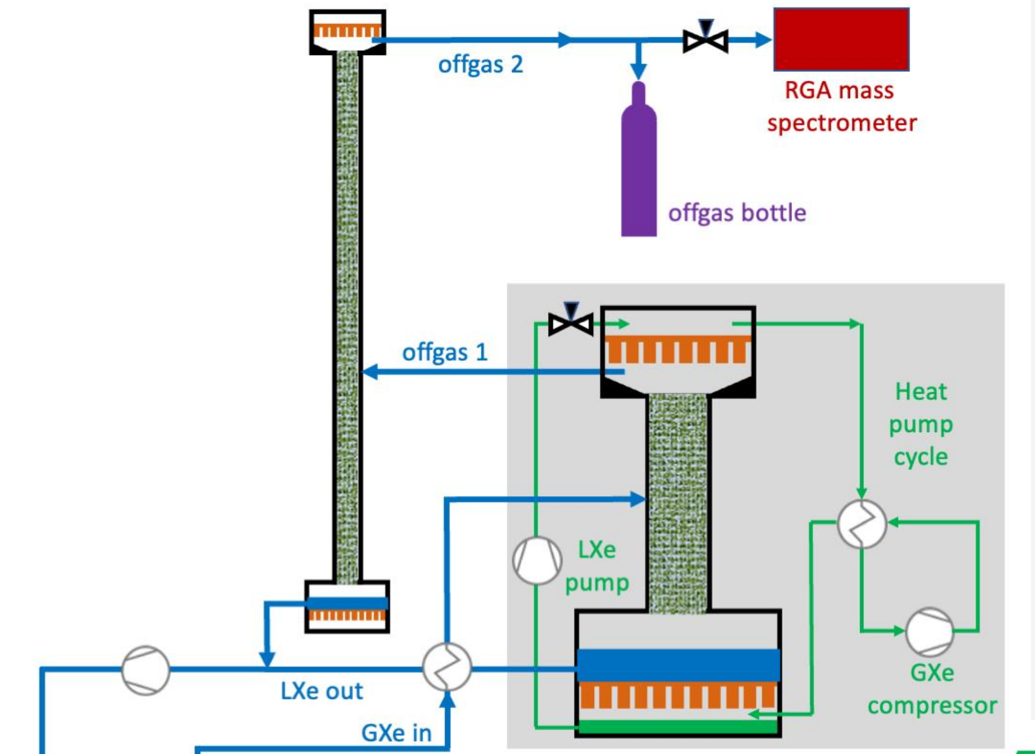
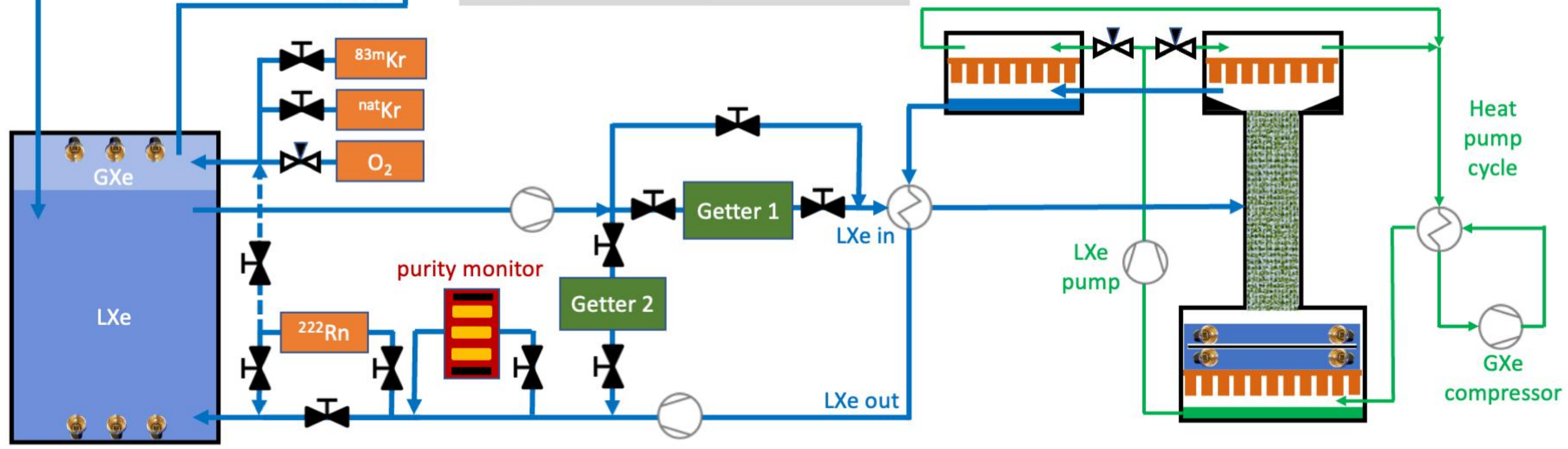
LowRAD All-in-One System



- Combined radon and krypton removal system
- Integrating purification systems for electro-negative impurity:
  - ➢ **Gas purification**: theoretically achievable via distillation from the krypton column
  - ➢ **Liquid purification**: full LXe flow through both purifier and radon column
- Integrating a shielding to the LXe line to prevent activation



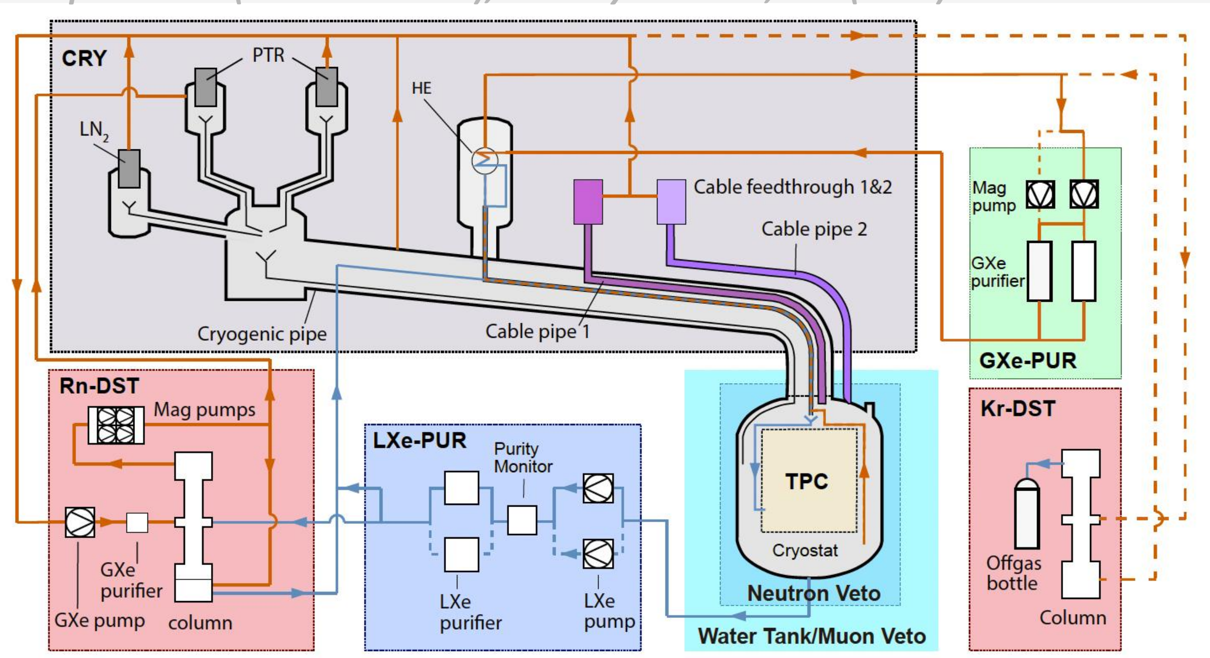
- **Continuous online design:**
  - ➢ **Long-term operation**
  - ➢ **Consistently low background level**
- **Multiple parallel systems:**
  - ➢ **Scalability**

Summary: Art of Producing Ultra-Pure Xenon

LXe detector experiments (XENON, LZ, PandaX, XMASS, EXO): demonstrated viable systems and provided clues to optimization

1. **Background Prevention**
   - Shielding and active vetoes
   - Meticulous detector material selection
   - Coating R&D to prevent surface radon emanation
   - Leak tightness with bakeout
2. **Active Removal**
   - Liquid purification (high flow):
     - ➢ Electron drift lifetime > 15ms
   - Krypton Removal (online):
     - Current: $^{nat}Kr/Xe = (56 \pm 36) \times 10^{-15}$
     - ➢ Target: $^{nat}Kr/Xe = 30 \times 10^{-15}$ (lossless design)
   - Radon Removal (high flow):
     - Current: ^{222}Rn activity = 0.90±0.07 μBq/kg
     - ➢ Target : ^{222}Rn activity = 0.1 μBq/kg
   - Radon tagging via analysis
   - Heat pump concept for cooling power efficiency
3. **Online Diagnosis**
   - Slow control: LXe liquid level, pressure, temperature
   - Dedicated detections: purity monitor, RGMS
   - Online Analysis: alpha rate monitor

E. Aprile et al. (XENON Collab.), Eur. Phys. J. C. 84, 784 (2024)



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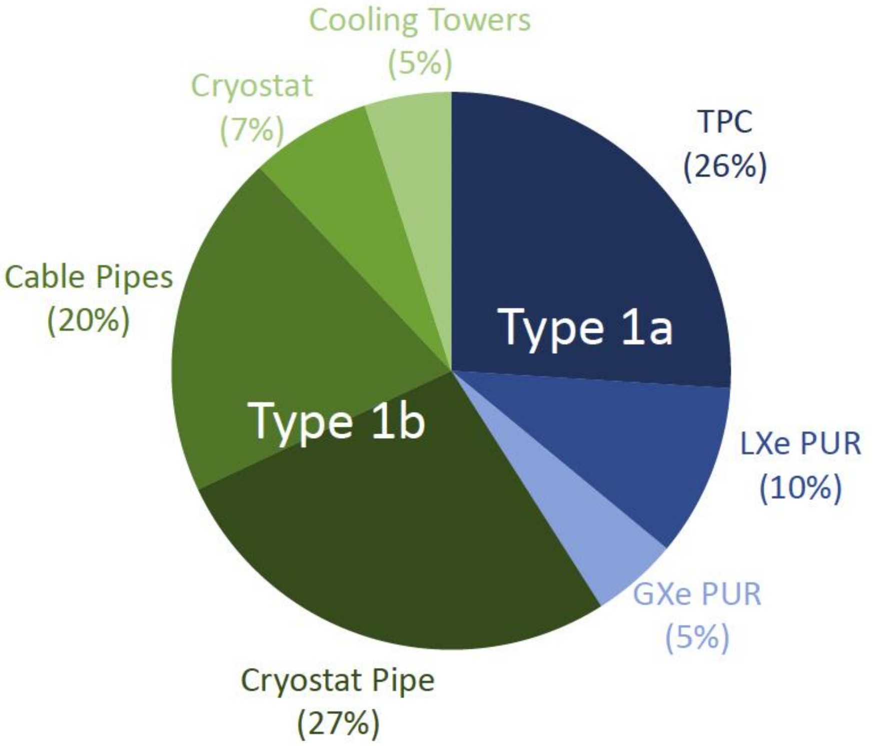
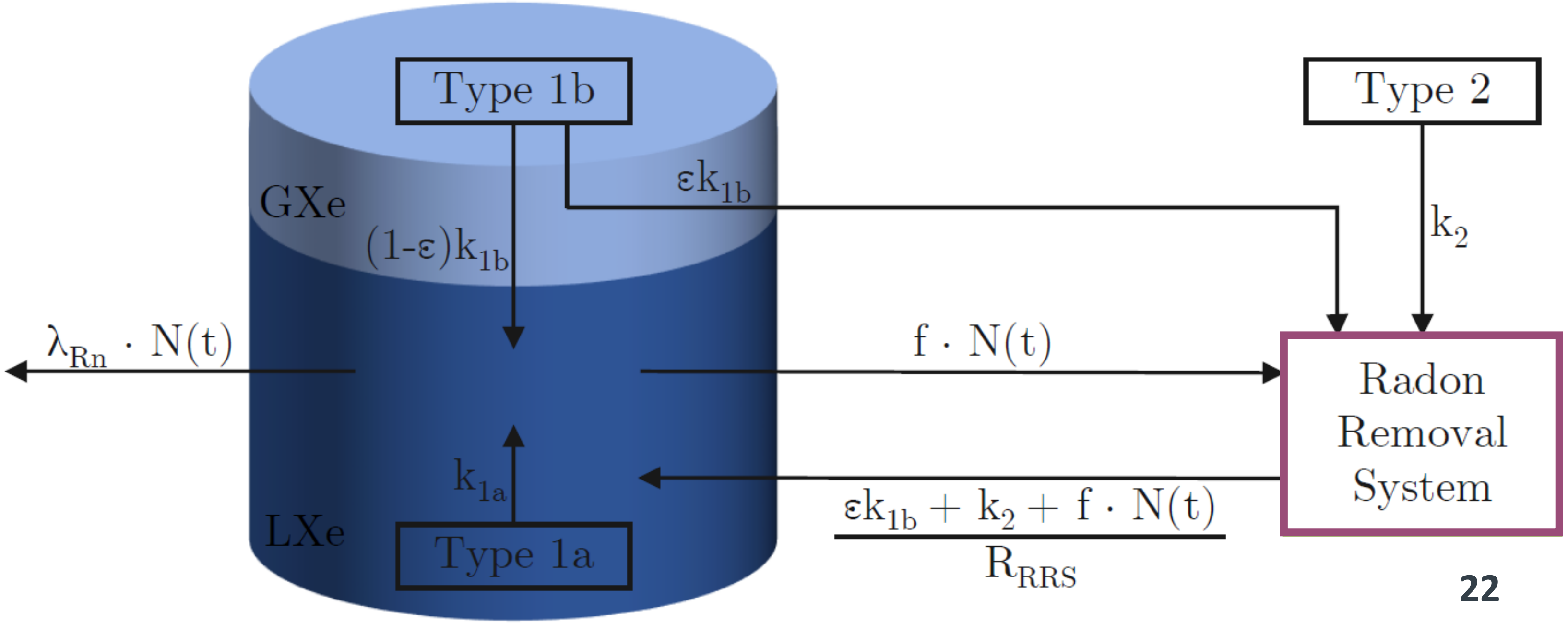
Backup Slides

XENONnT Radon Budget

- **Type 1**: source entering the detector before the radon removal system (RRS)
  - **Type 1a**: source inside LXe
    - ➢ Removed only vias fast circulation
  - **Type 1b**: source inside GXe
    - ➢ Convert to type 2 by GXe extraction
- **Type 2**: source entering RRS before the detector:
  - ➢ Enters RRS with GXe and decays away at the reboiler

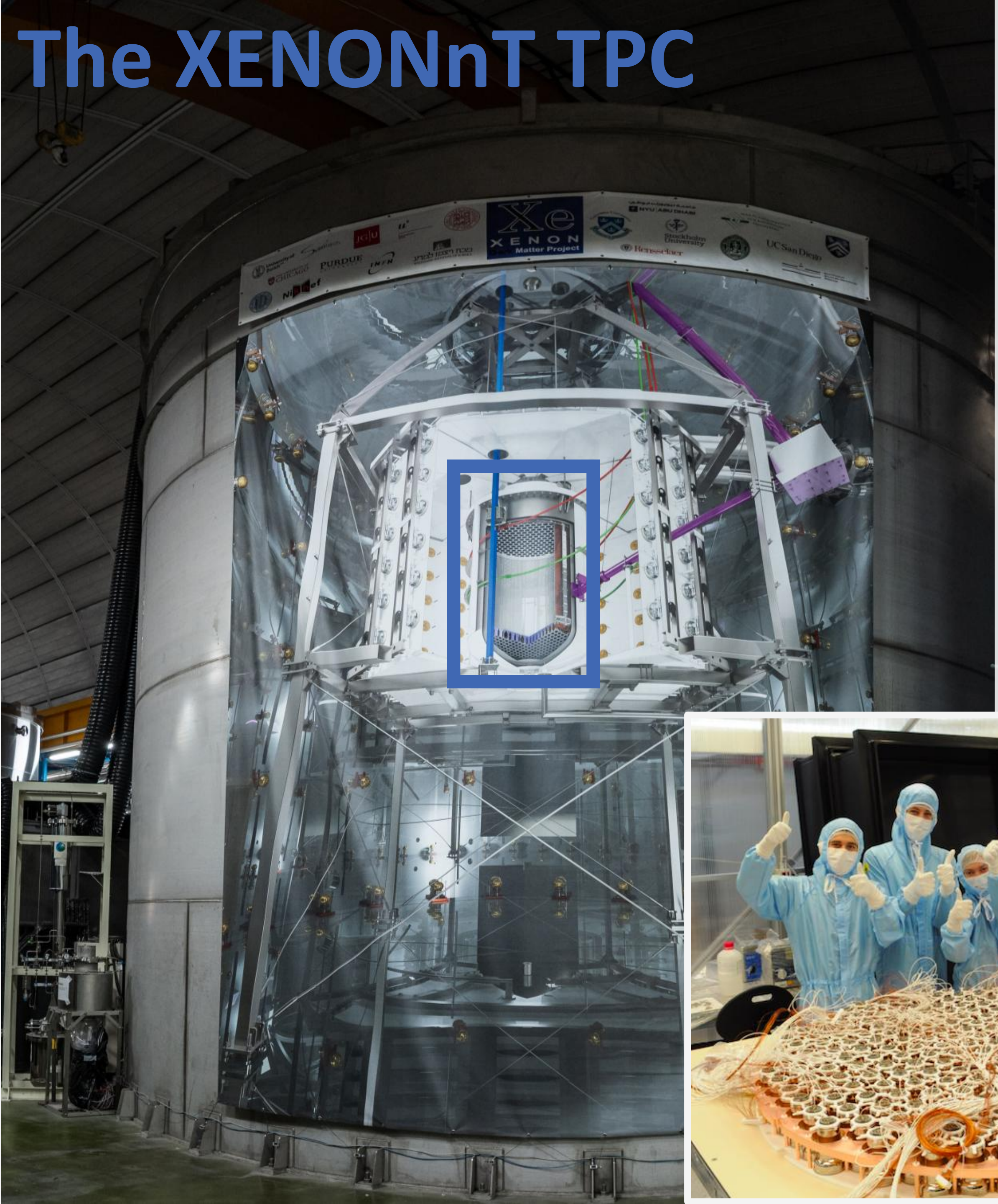
N: total ^{222}Rn count in TPC LXe
k: ^{222}Rn source
λ_{Rn}: ^{222}Rn decay constant
f: flow turnaround rate from TPC LXe to RRS
ε: type-1b/type-1 ratio

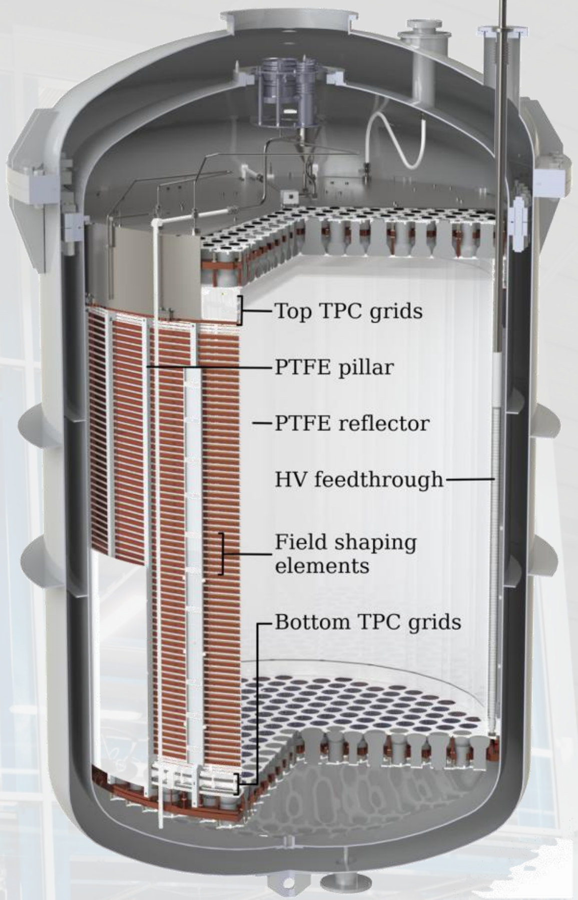




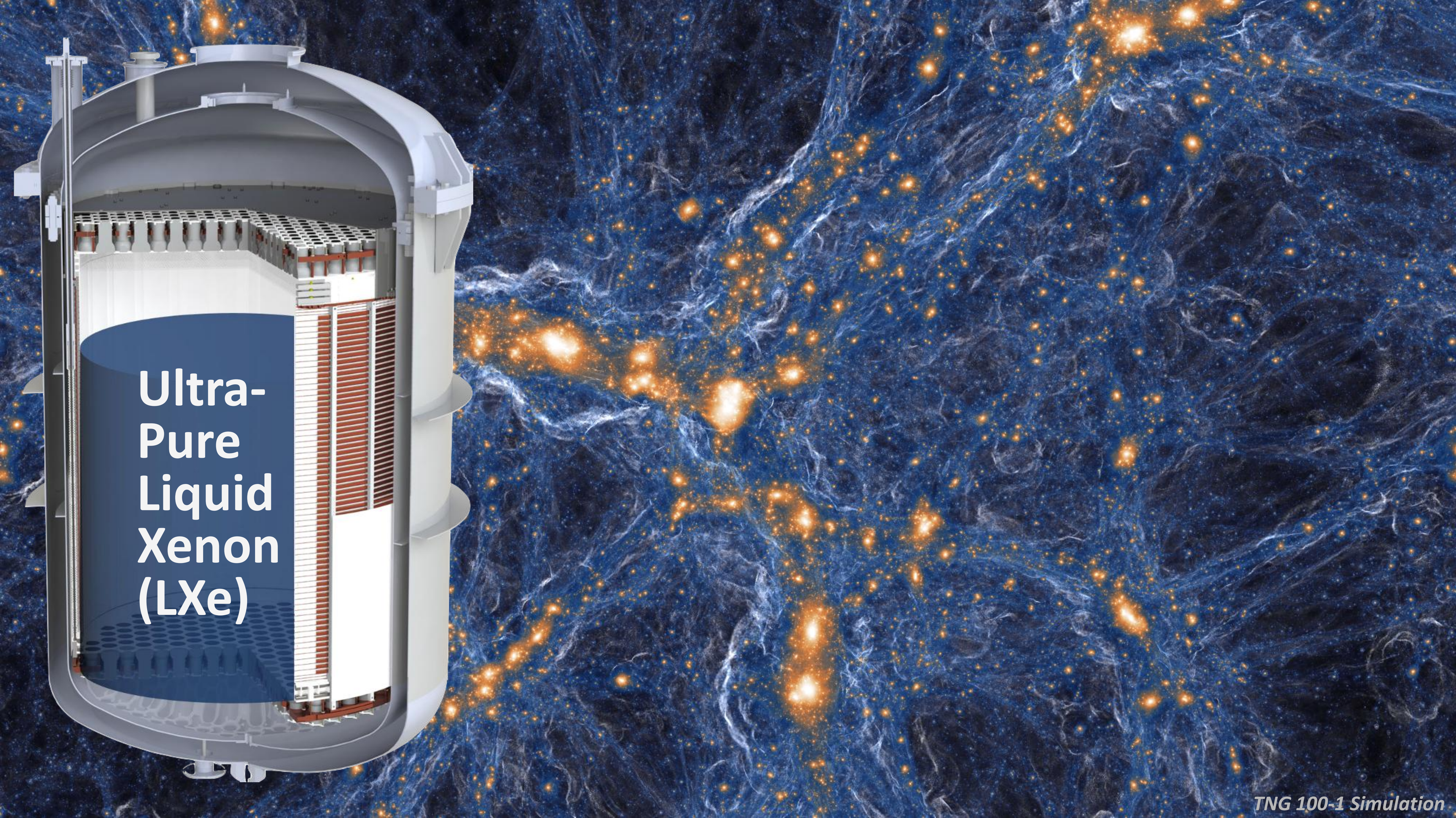
Murra et al, Eur. Phys. J. C. 82, 1104 (2022)

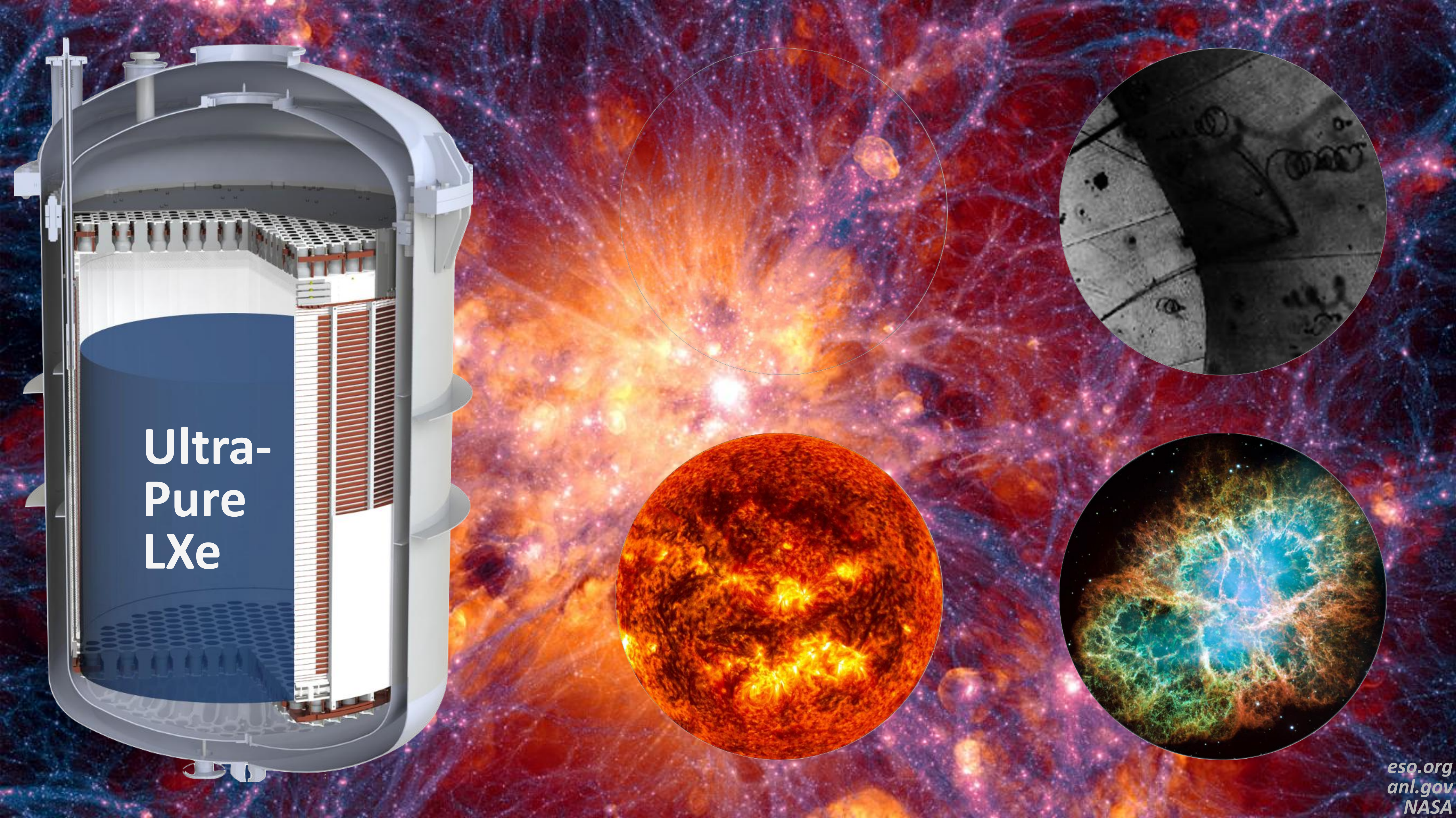
The XENONnT TPC





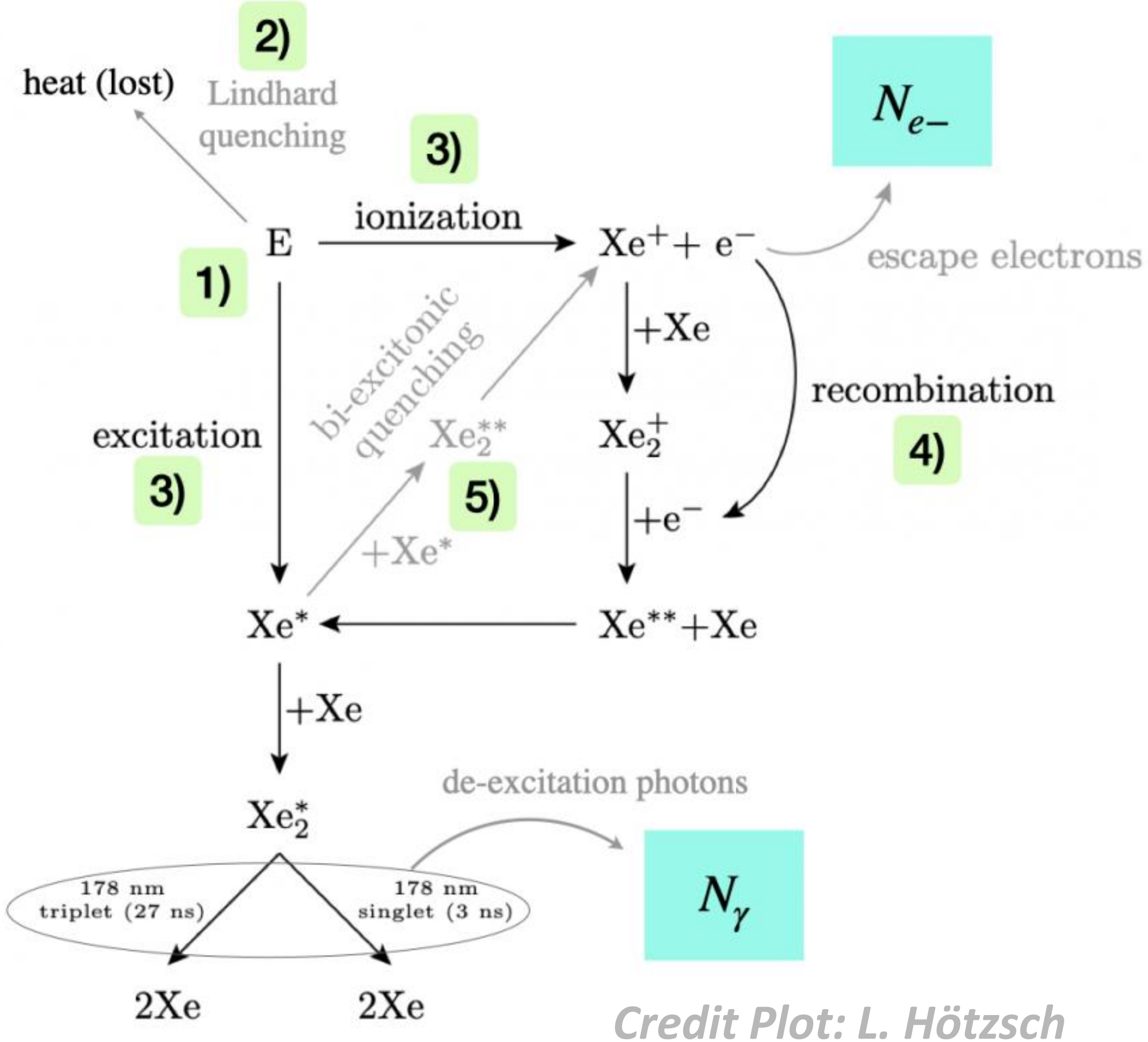
- Dual-phase Time Projection Chamber (TPC)
- Photosensors: 494 PMTs
- Polytetrafluoroethylene (PTFE) reflective panels to enhance photon gain


Ultra-Pure Liquid Xenon (LXe)
TNG 100-1 Simulation


Ultra-
Pure
LXe
eso.org
anl.gov
NASA

Liquid Xenon Target

- scintillation yield ≃ 46 γ/keV$_{ee}$
- ionization yield ≃ 64 e$^-$/keV$_{ee}$

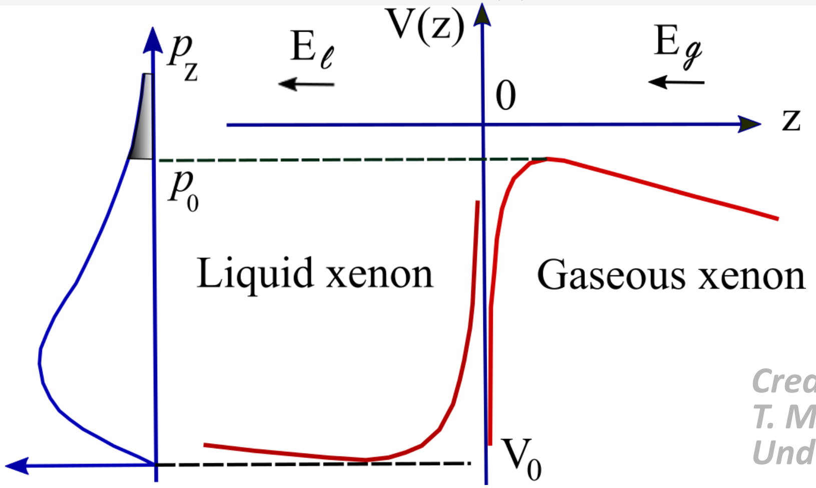


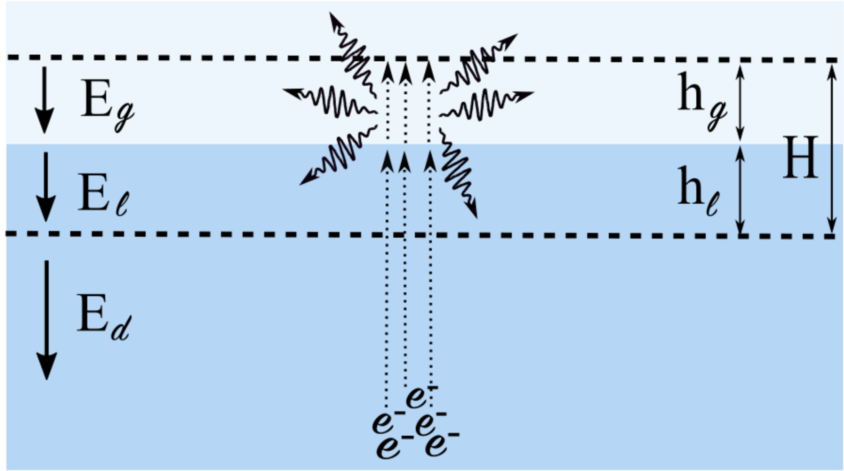
Credit Plot: L. Hötzsch

Isotope	Abundance	Decay mode and half-life
^{124}Xe	0.09 %	double-electron capture, 1.8×10^{22} y
^{125}Xe	synthetic	electron capture, 16.9 h
^{126}Xe	0.09 %	stable *
^{127}Xe	synthetic	electron capture, 36.35 d
^{128}Xe	1.92 %	stable
^{129}Xe	26.44 %	stable
^{130}Xe	4.08 %	stable
^{131}Xe	21.18 %	stable
^{132}Xe	26.89 %	stable
^{133}Xe	synthetic	beta decay β^-, 5.25 h
^{134}Xe	10.44 %	stable *
^{135}Xe	synthetic	beta decay β^-, 9.14 h
^{136}Xe	8.86 %	double-beta decay, 2.23×10^{21} y

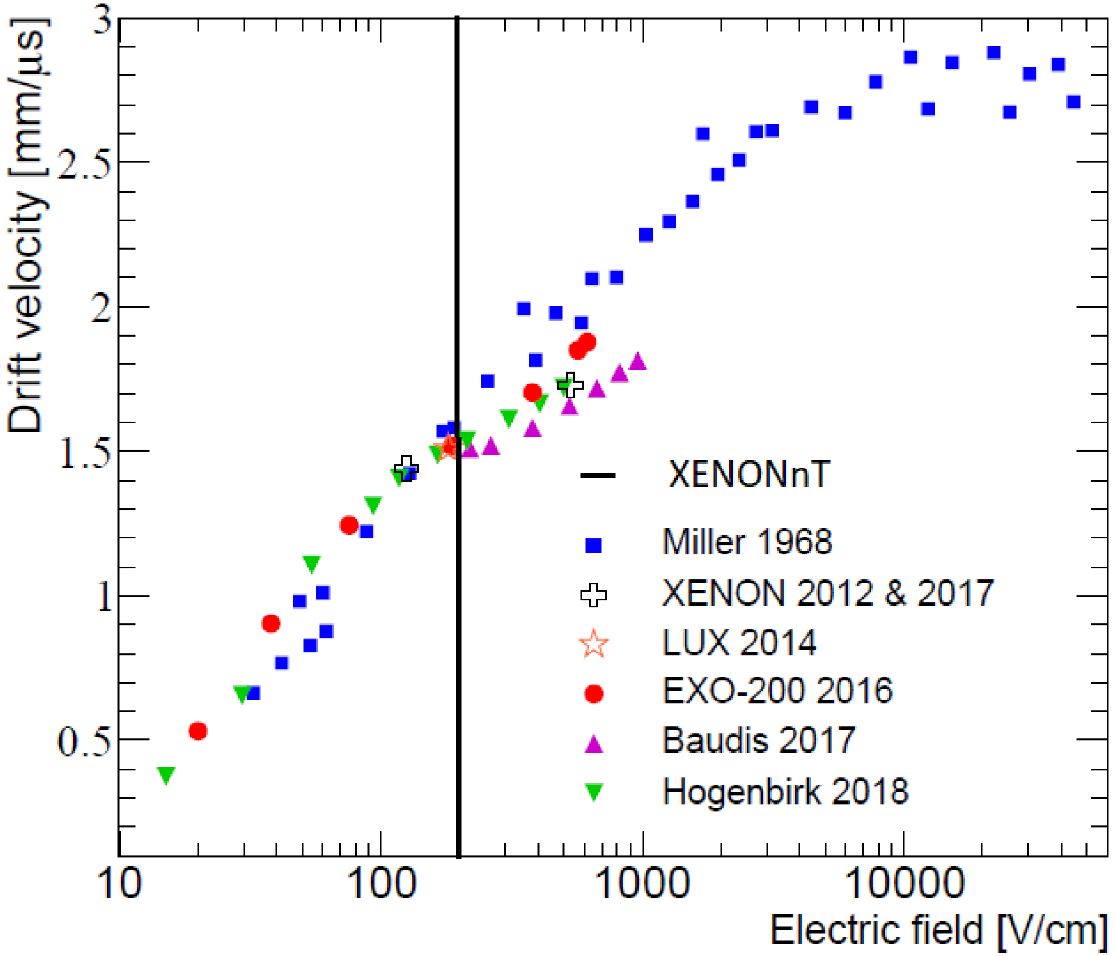
*Candidate for double-beta decay

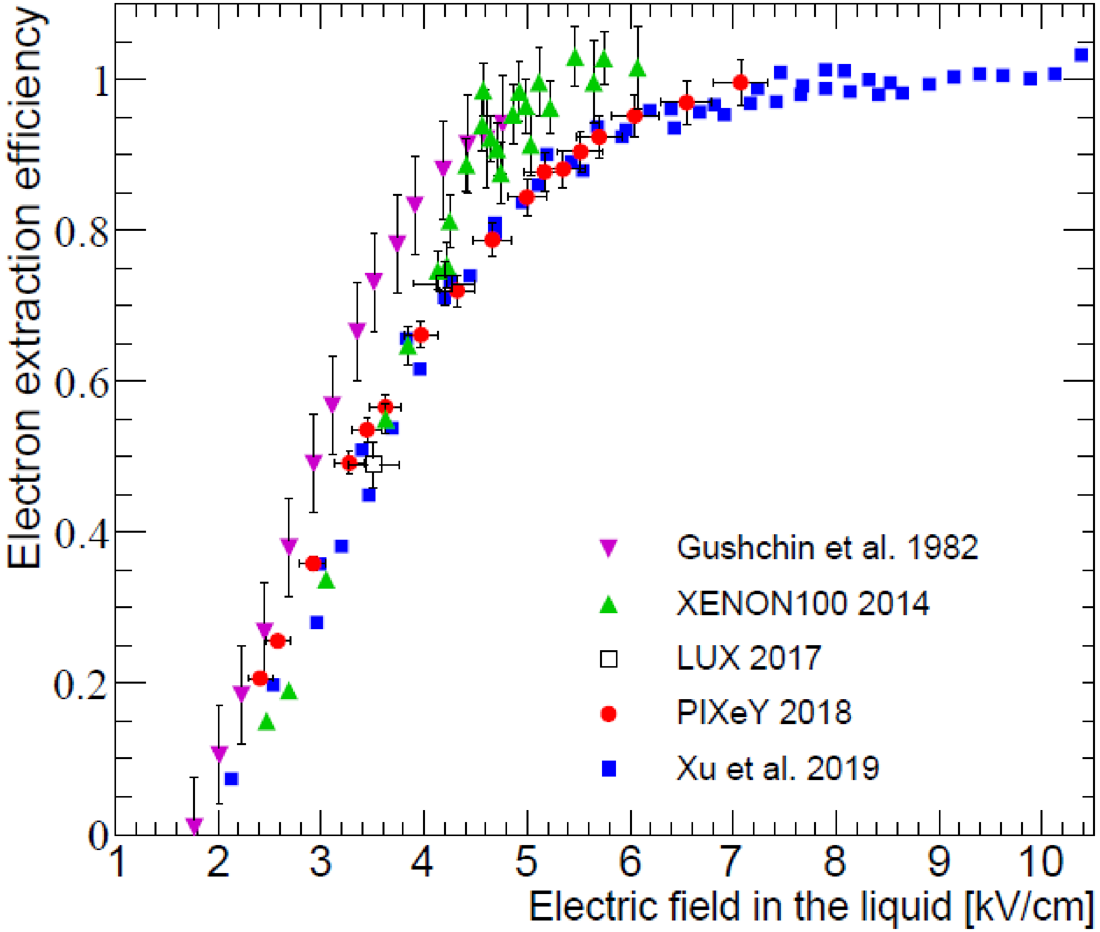
Electron Drift and Extraction





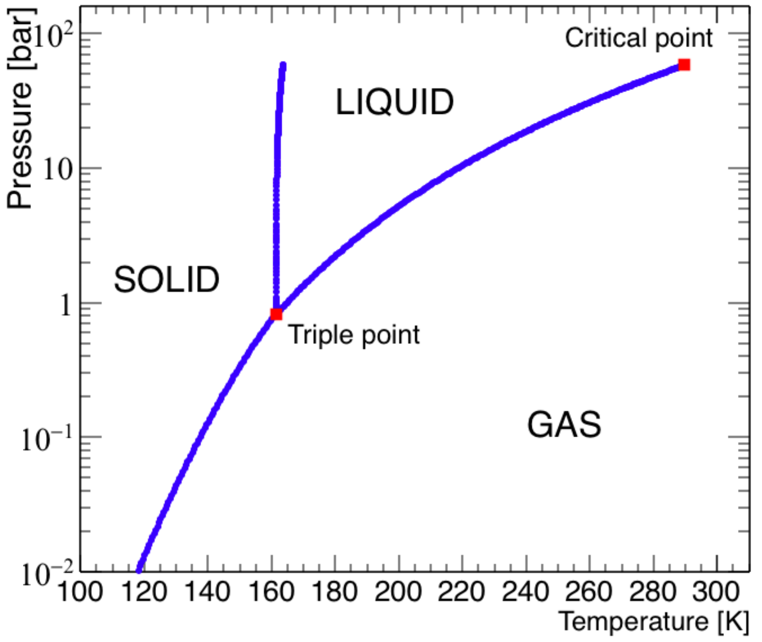
Credit Plot: T. Marrodán Undagoitia



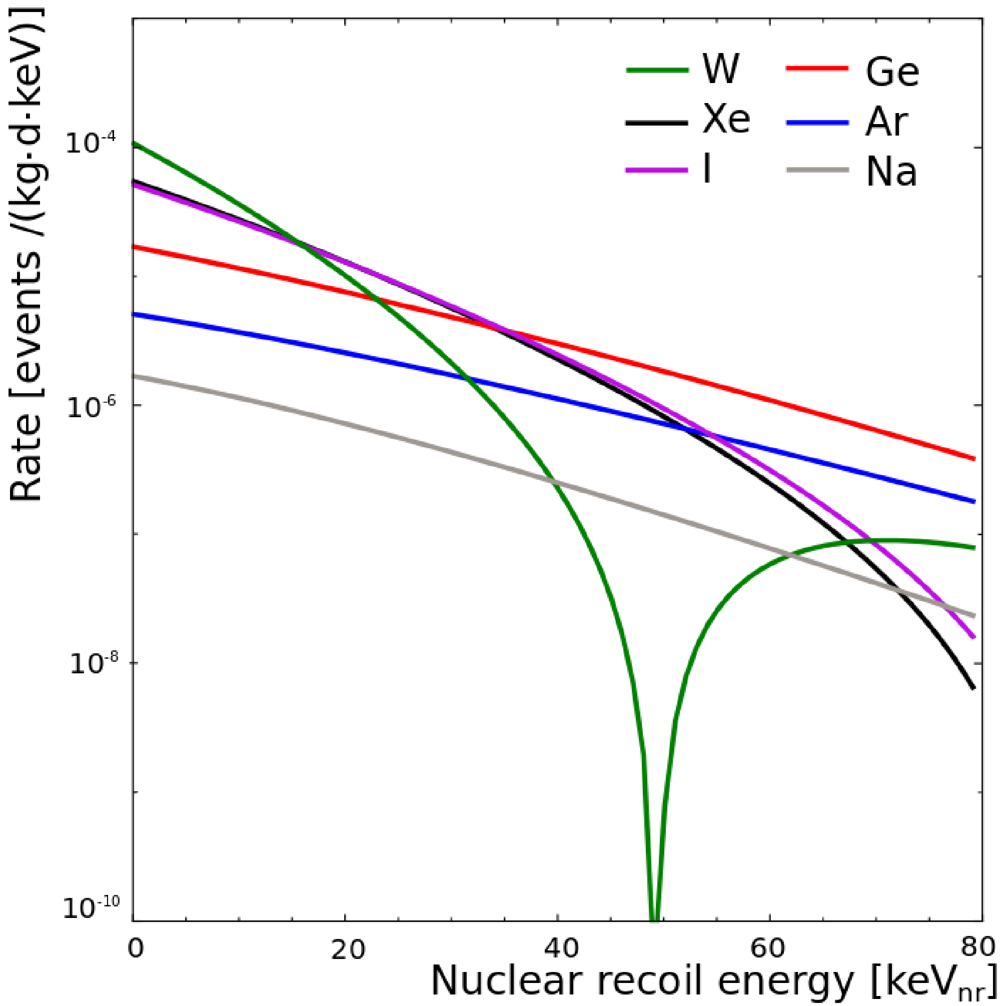


Liquid Xenon (LXe) Rare Event Detection

- High mass number: high density (3 g/cm^3), high nuclear interaction cross-section
- Homogeneity: liquid target under cryogenic temperature
- Noble gas: can achieve high purity
- Low intrinsic background
- Vacuum Ultra-violet (VUV) scintillation: high light/charge yield
- Time projection chamber (TPC) allow 3D position reconstruction

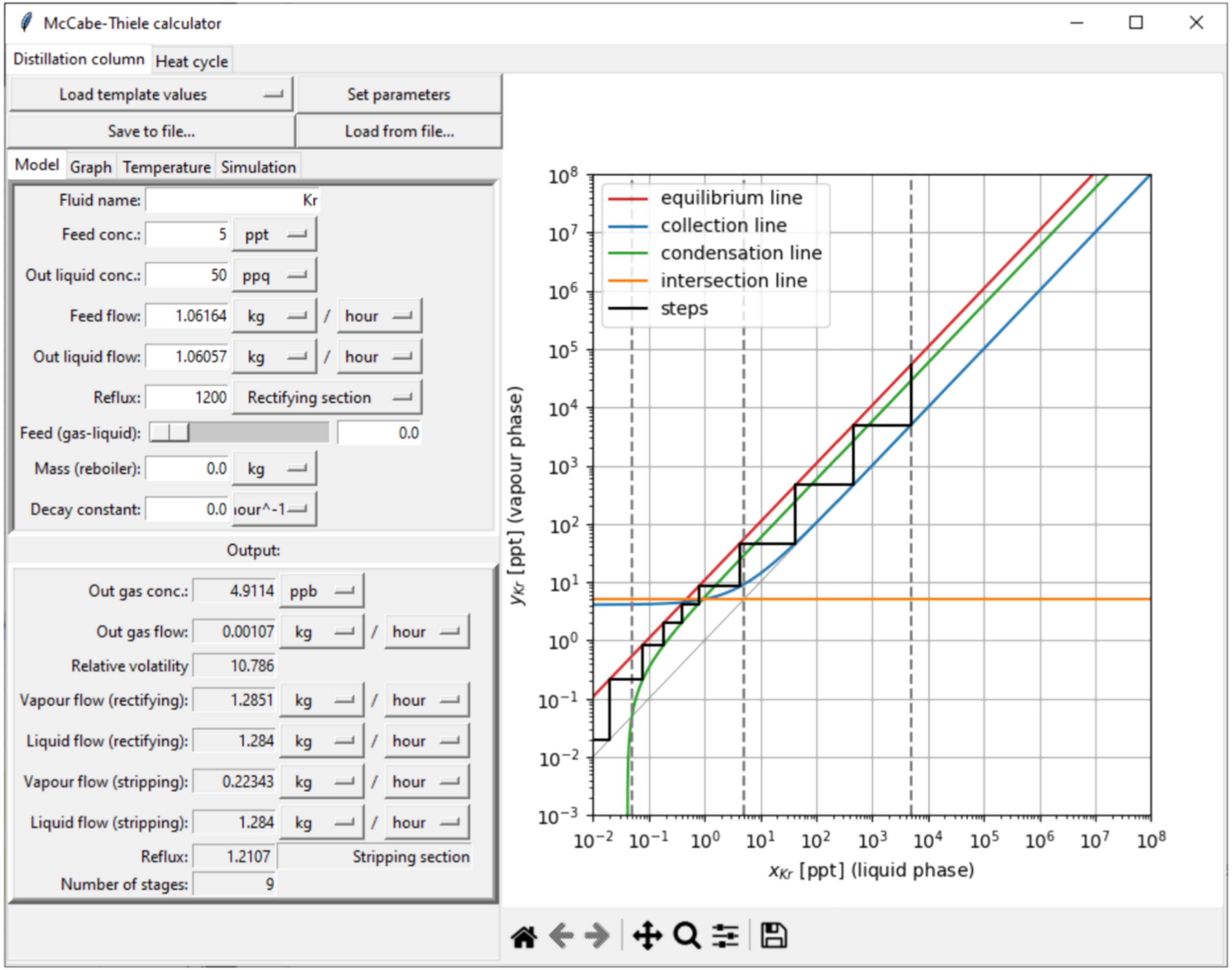


Data from Air Liquide Encyclopedia



T. Marrodán Undagoitia, L. Rauch, J. Phys. G: Nucl. Part. Phys. 43 013001 (2016)

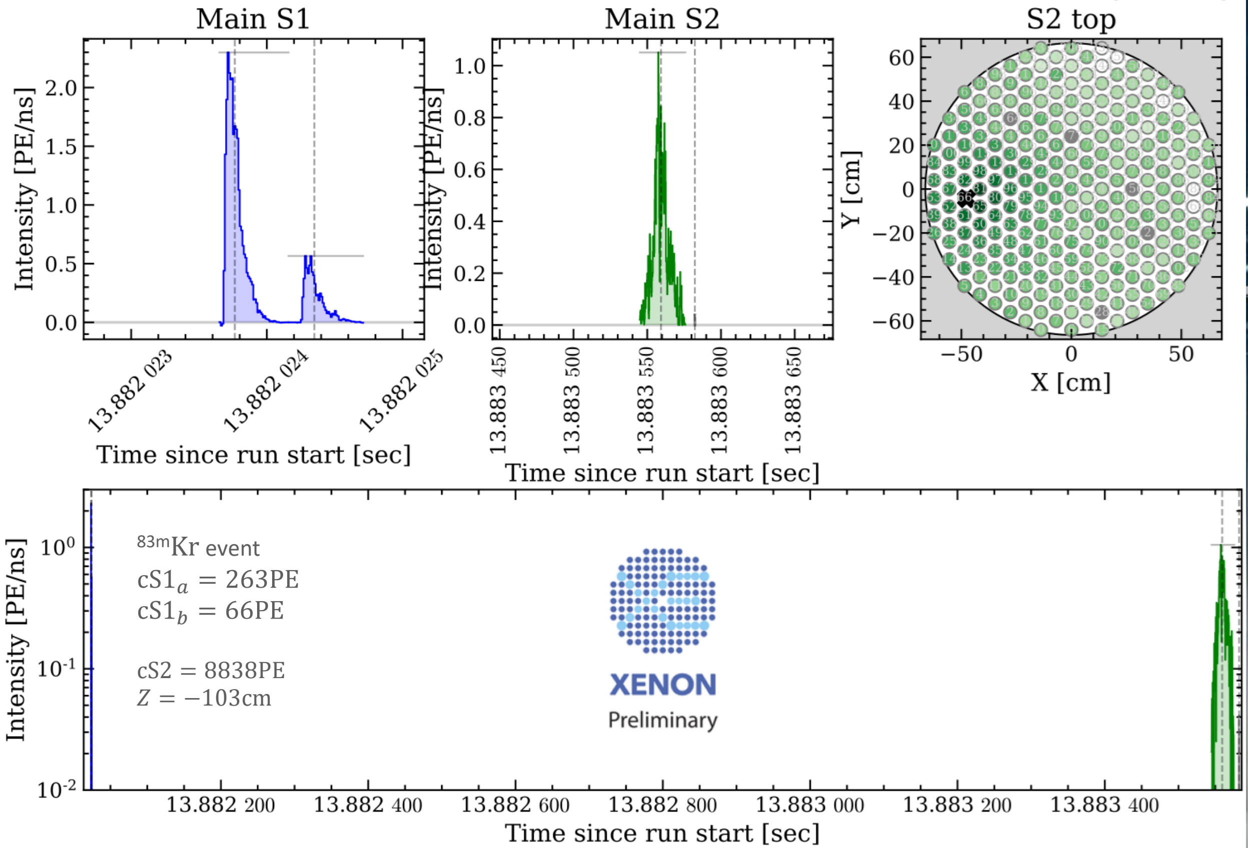
Summary: How to Produce Ultra-Pure Xenon



Data-Acquisition

- **Triggerless**: all data above per channel threshold stored long term
- Fully live processing
- Open source software

JINST 18 P07054 (2023)

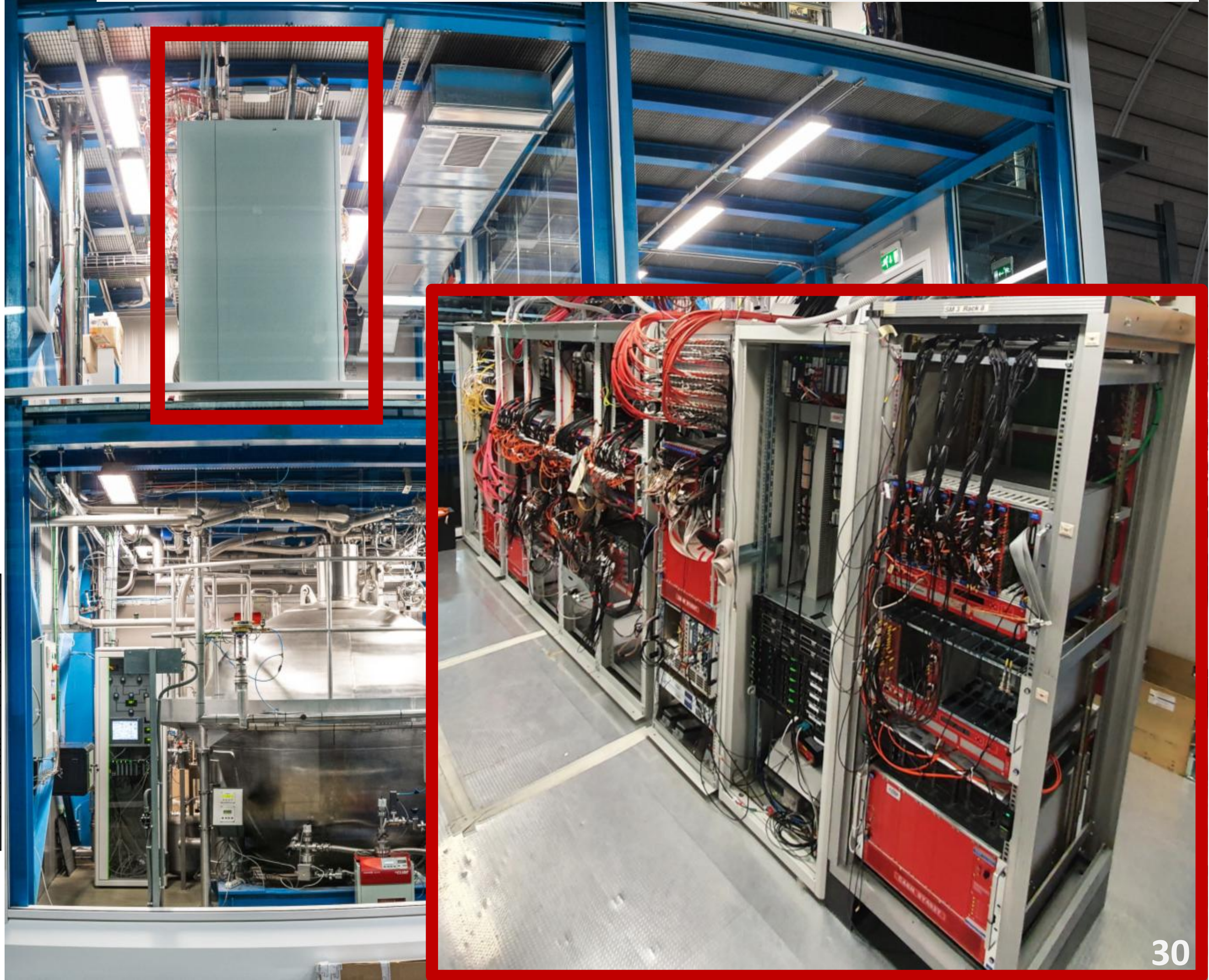


strax
Streaming analysis for xenon experiments
github.com/AxFoundation/strax

straxen
Streaming analysis for XENON(nT)
github.com/XENONnT/straxen

XeDocs
XENON metadata management tool
github.com/XENONnT/xedocs
zenodo.org/record/7945375

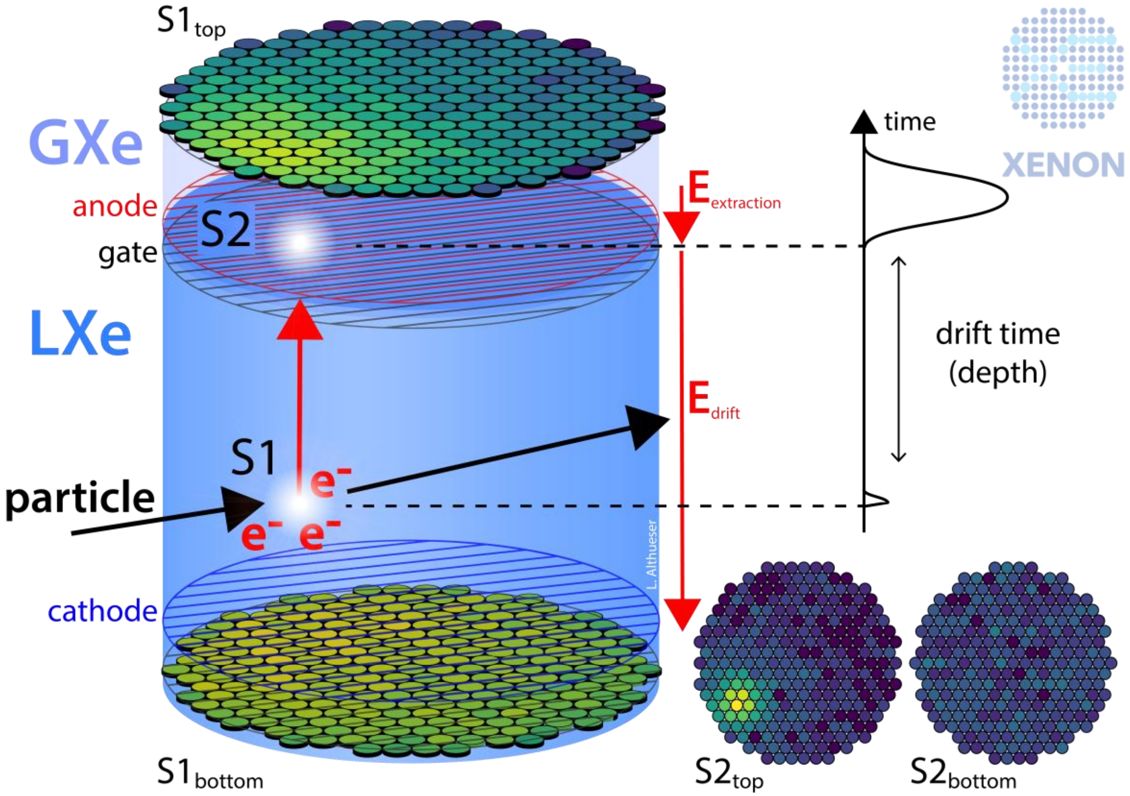
WFSim/fuse
The XENON waveform simulator
github.com/XENONnT/wfsim

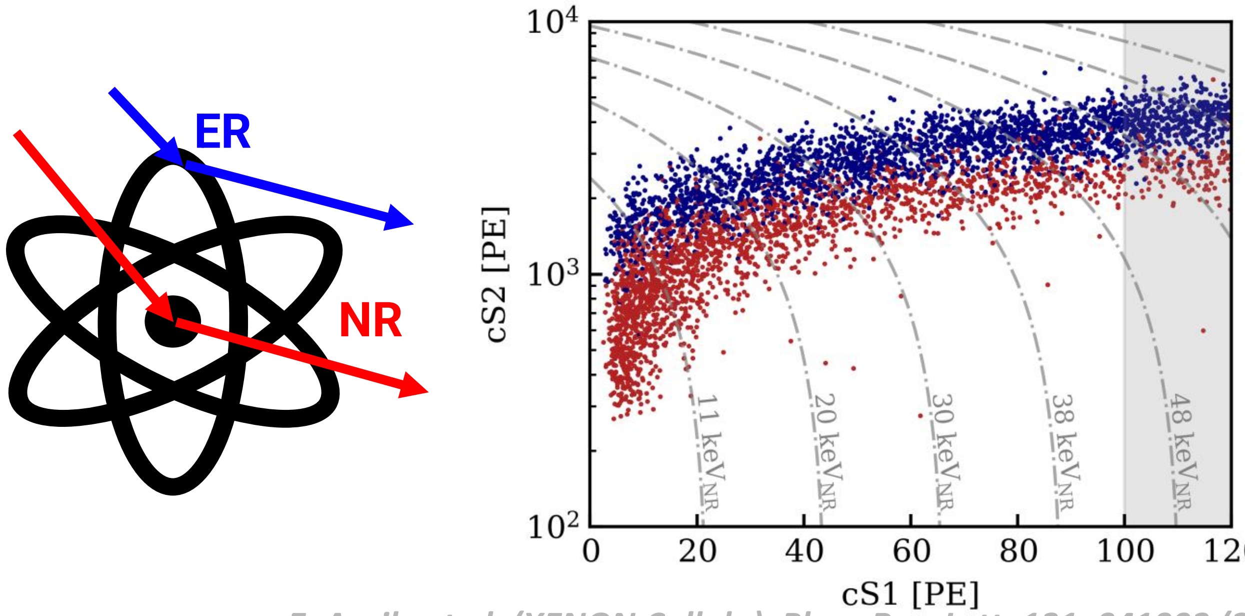


Dual-phase Time Projection Chamber (TPC)

- **S1**: prompt scintillation signal
- **S2**: electrons drift toward LXe surface, producing electroluminescence signal proportional to charge

➢ Position reconstruction using S1&S2 => accurate fiducial volume selection





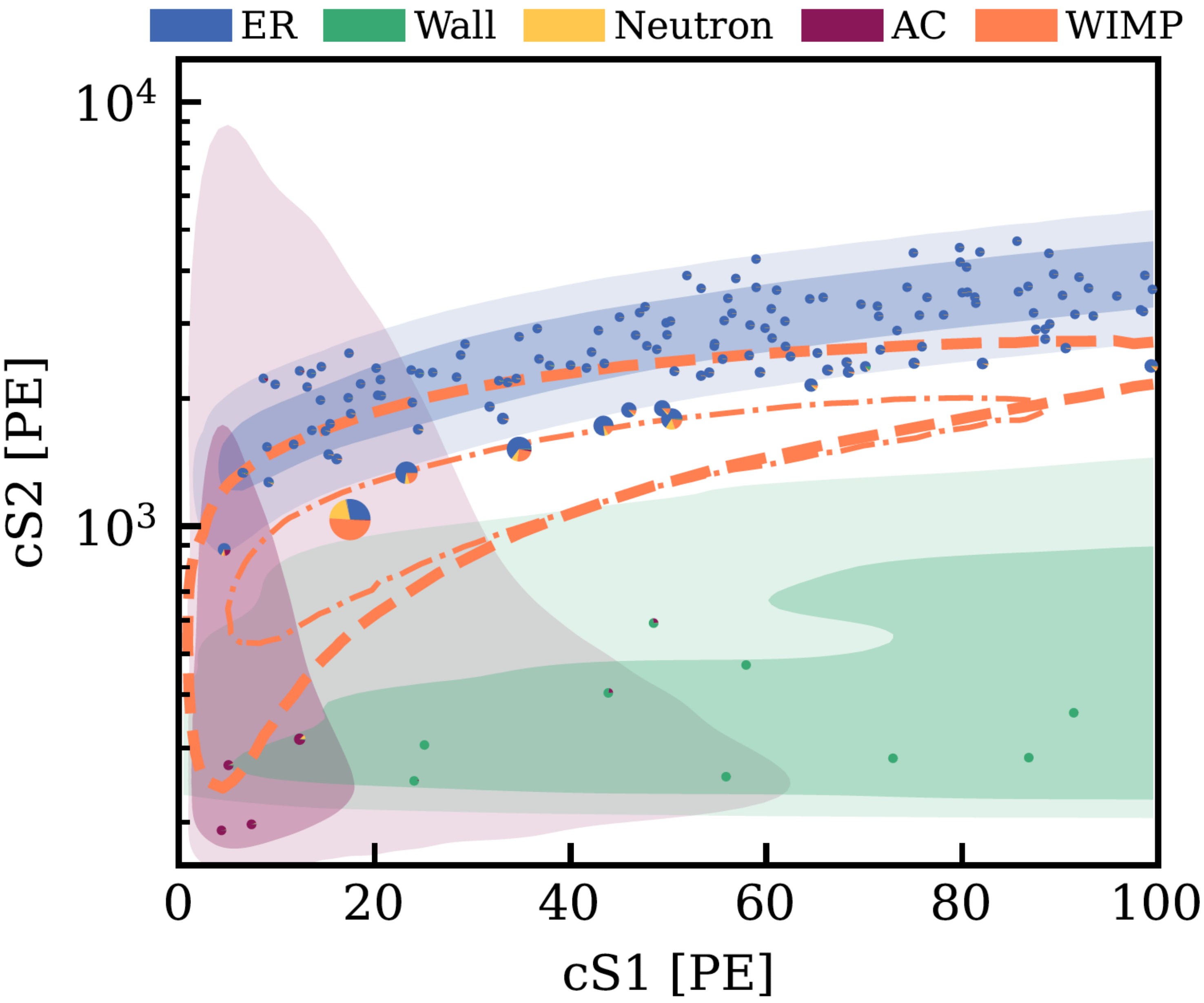
E. Aprile et al. (XENON Collab.), Phys. Rev. Lett. 131, 041003 (2023)

➢ S2/S1 ratio => event discrimination

ER (Electronic Recoils): electron, photon, neutrino, (axions…)

NR (Nuclear Recoils): neutron, CEvNS, (WIMPs…)

WIMP Blind Analysis: Science Run 0 (SR0) WIMP Result



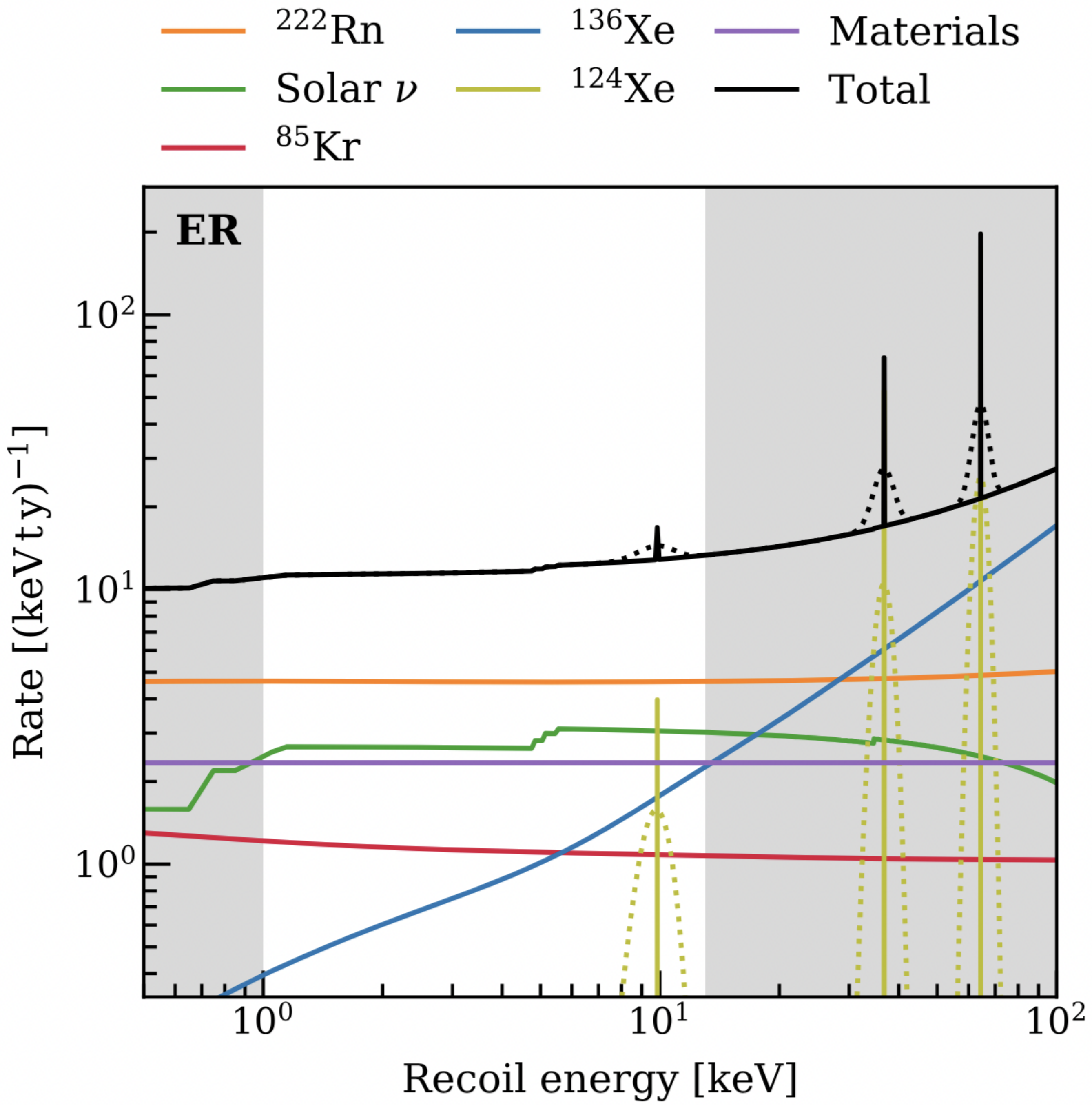
- ER: electron recoil
- Neutron: radiogenic neutrons
- Surface/Wall: plate-out ^{210}Pb on the PTFE panels
- AC: accidental coincidence; randomly paired S1-S2 signal
- WIMP: 200 GeV/c^2 in this case; dashed-dotted enclosure indicates 50% of WIMP signal

	Nominal	Best fit	
	ROI		Signal-like
ER	134	135^{+12}_{-11}	0.92 ± 0.08
Neutrons	$1.1^{+0.6}_{-0.5}$	1.1 ± 0.4	0.42 ± 0.16
CEνNS	0.23 ± 0.06	0.23 ± 0.06	0.022 ± 0.006
AC	4.3 ± 0.9	$4.4^{+0.9}_{-0.8}$	0.32 ± 0.06
Surface	14 ± 3	12 ± 2	0.35 ± 0.07
Total background	154	152 ± 12	$2.03^{+0.17}_{-0.15}$
WIMP	...	2.6	1.3
Observed	...	152	3

Phys. Rev. Lett. 131, 041003 (2023)

ER Region Backgrounds

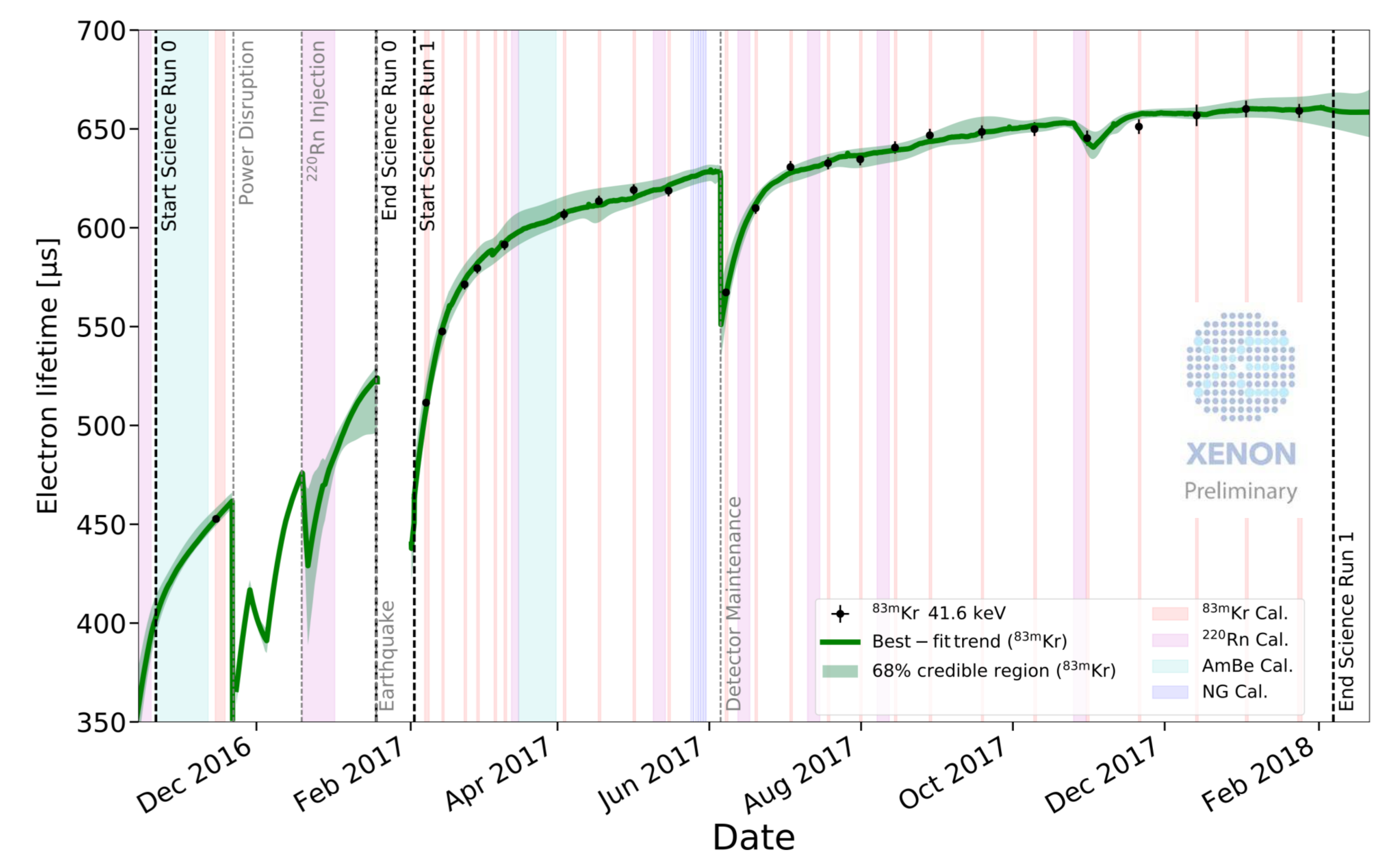
- External Backgrounds:
  - Material: gamma and neutrons from the surrounding instruments
- Internal Backgrounds:
  - ^{136}Xe: two-neutrino double-beta ($2\nu\beta\beta$) decay, half-life of 2.3×10^{21} years
  - ^{124}Xe: two-neutrino double-electron capture (2νECEC), half-life of 1.8×10^{22} years
  - ^{85}Kr: from ^{nat}Kr in Xe in the xenon inventory
  - ^{222}Rn: decay daughter of the material; dominant ER background
- Neutrinos:
  - Solar neutrino: via elastic neutrino-electron scattering



E. Aprile et al JCAP 11, 031 (2020)

Universität Münster

XENON1T/nT Gas Purification Performance

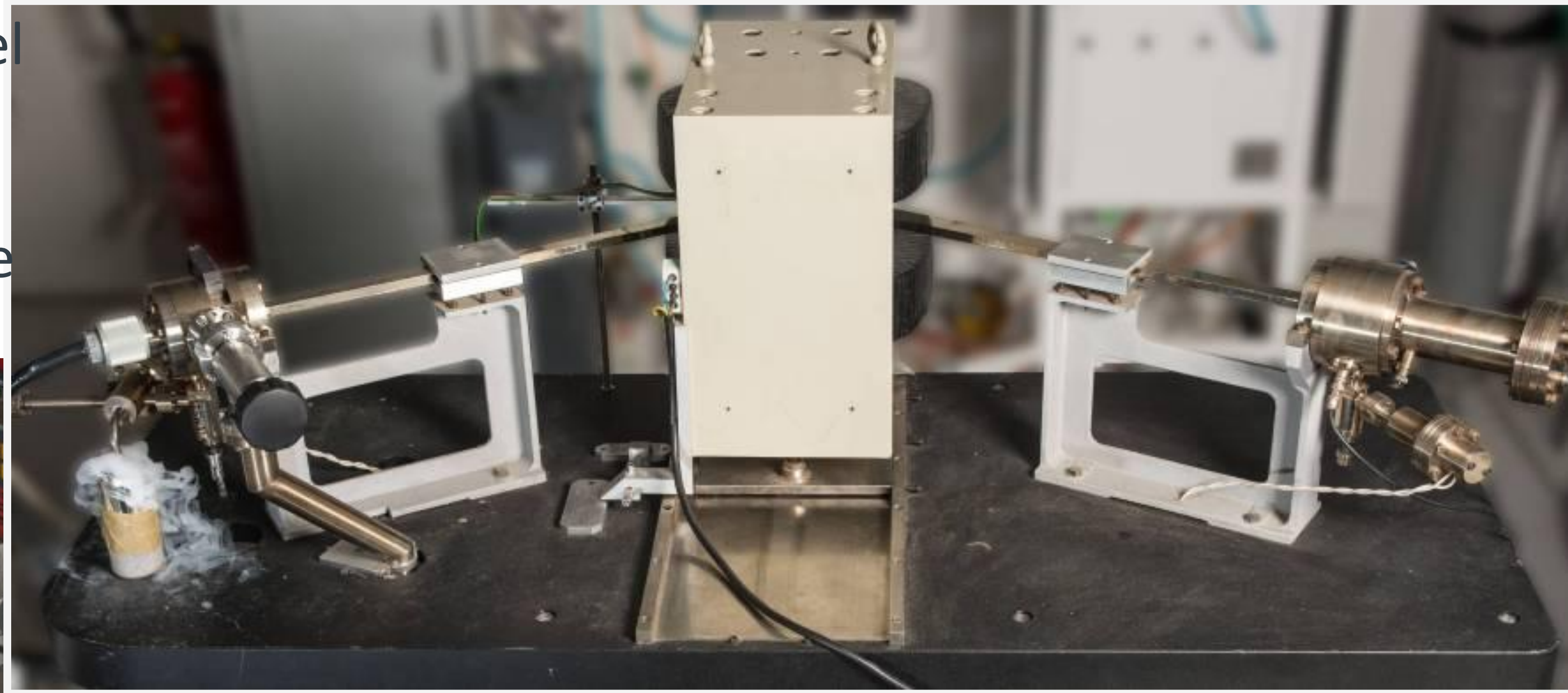


Ying-Ting Lin, ylin3@uni-muenster.de

RGMS: Rare Gas Mass Spectrometer

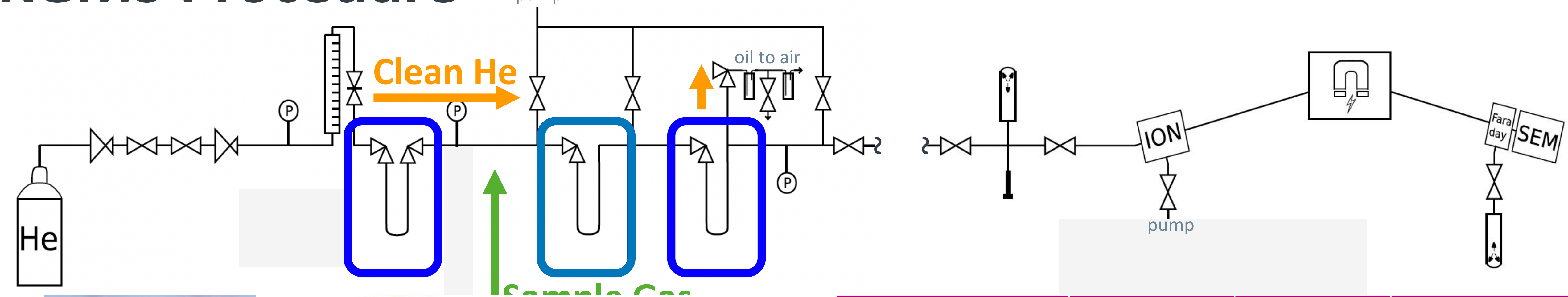
Measuring Kr in Xe at such a low level is challenging

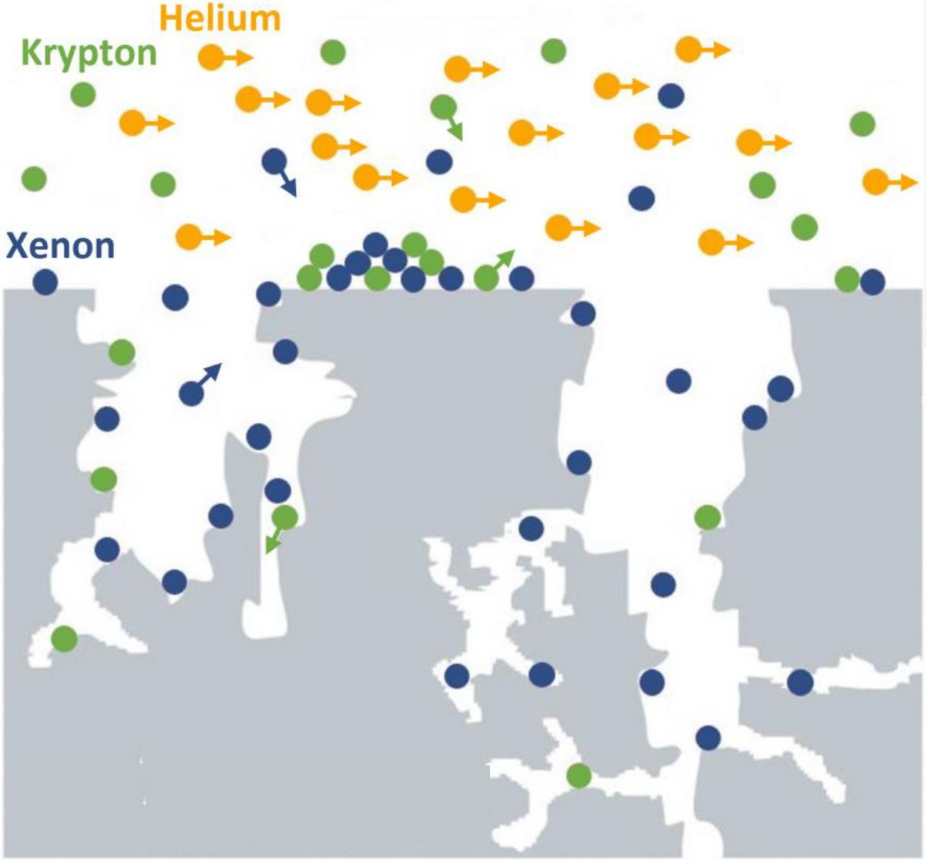
The Rare Gas Mass Spectrometer (RGMS) measures the content of rare gas such as Kr in a sample gas



- At the first stage, Kr is separated from the bulk of Xe using a cryogenic gas chromatographic system
- At the second stage, the amount of krypton is measured via a mass spectrometer
- RGMS has demonstrated a detection limit of **8ppq** [Eur. Phys. J. C. (2014) 74:2746]
- RGMS measured a ^{nat}Kr/Xe level of **65±40 ppq** for XENONTnT [Phys. Rev. Lett. 129, 161805]

RGMS Procedure

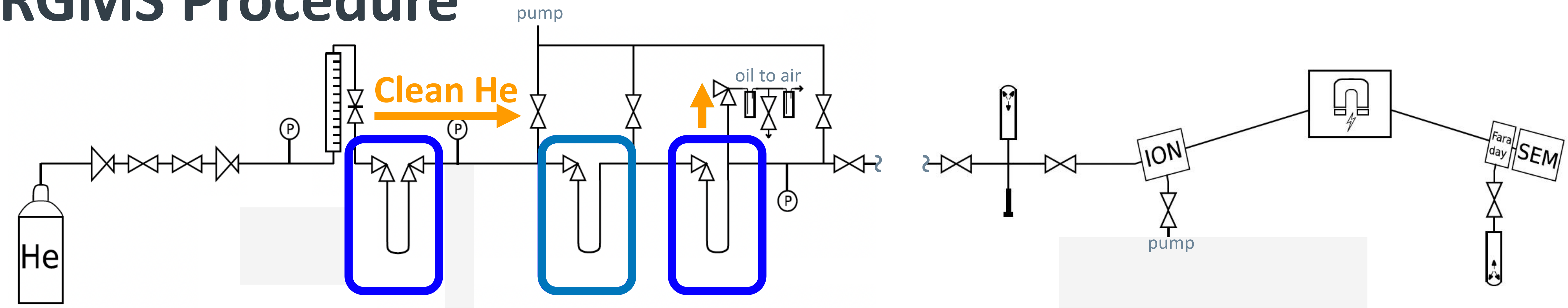


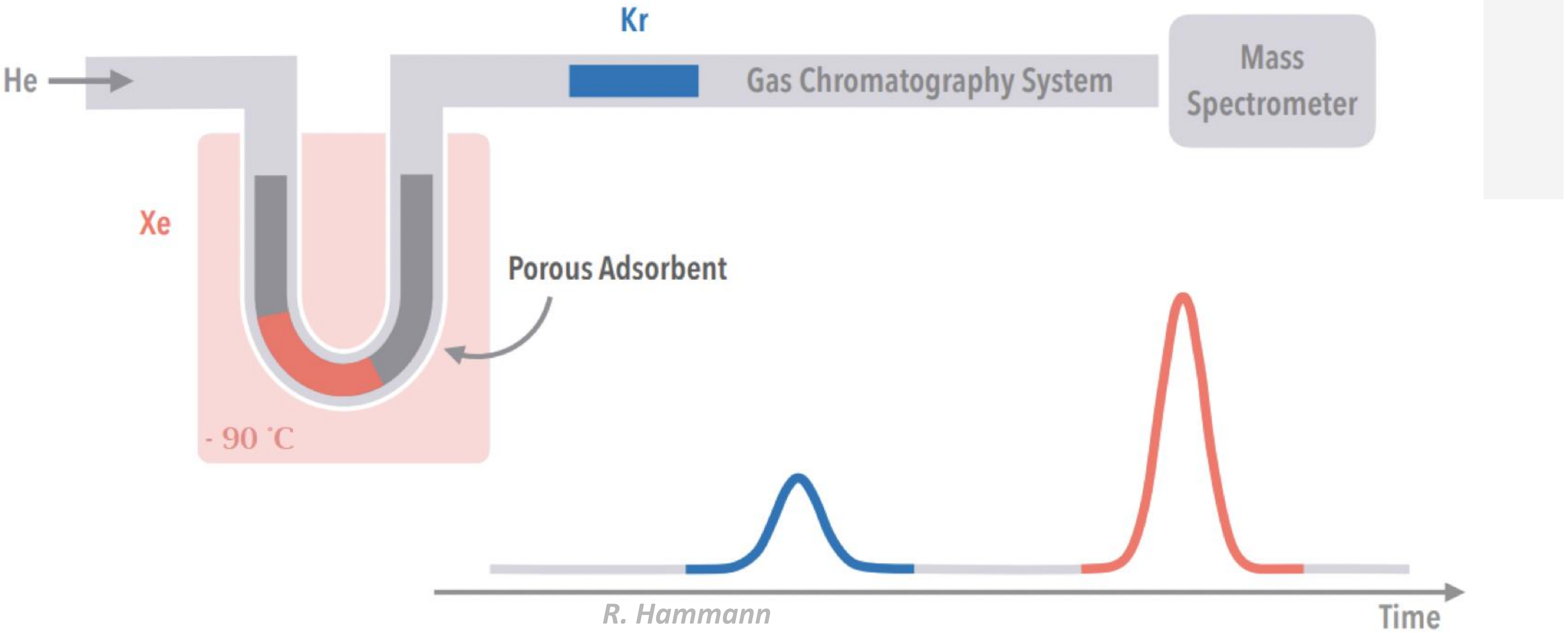


	Hayesep Q	Hayesep D	Chromosorb
Surface area [m²/g]	582	795	350
Bake-out Temperature [ºC]	250	220	230

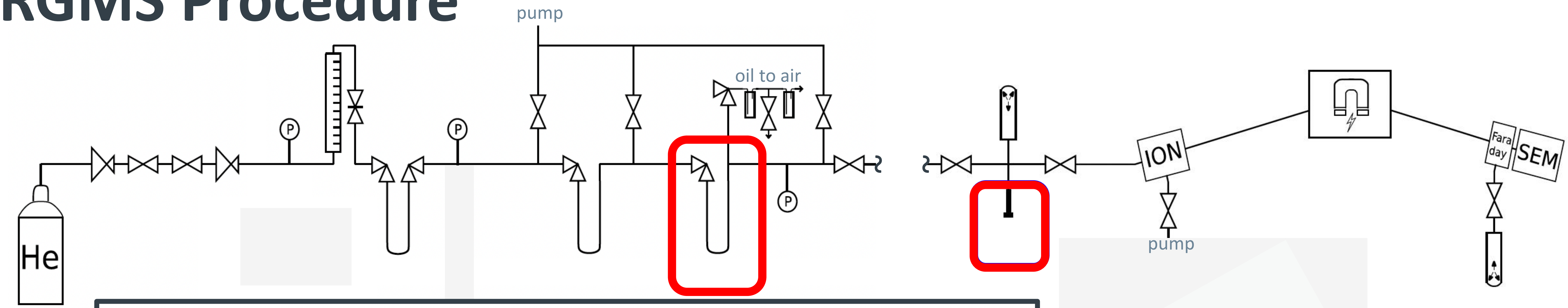
Currently being studied by M. Guida (Matteo's talk was on Wednesday, T 66.6)

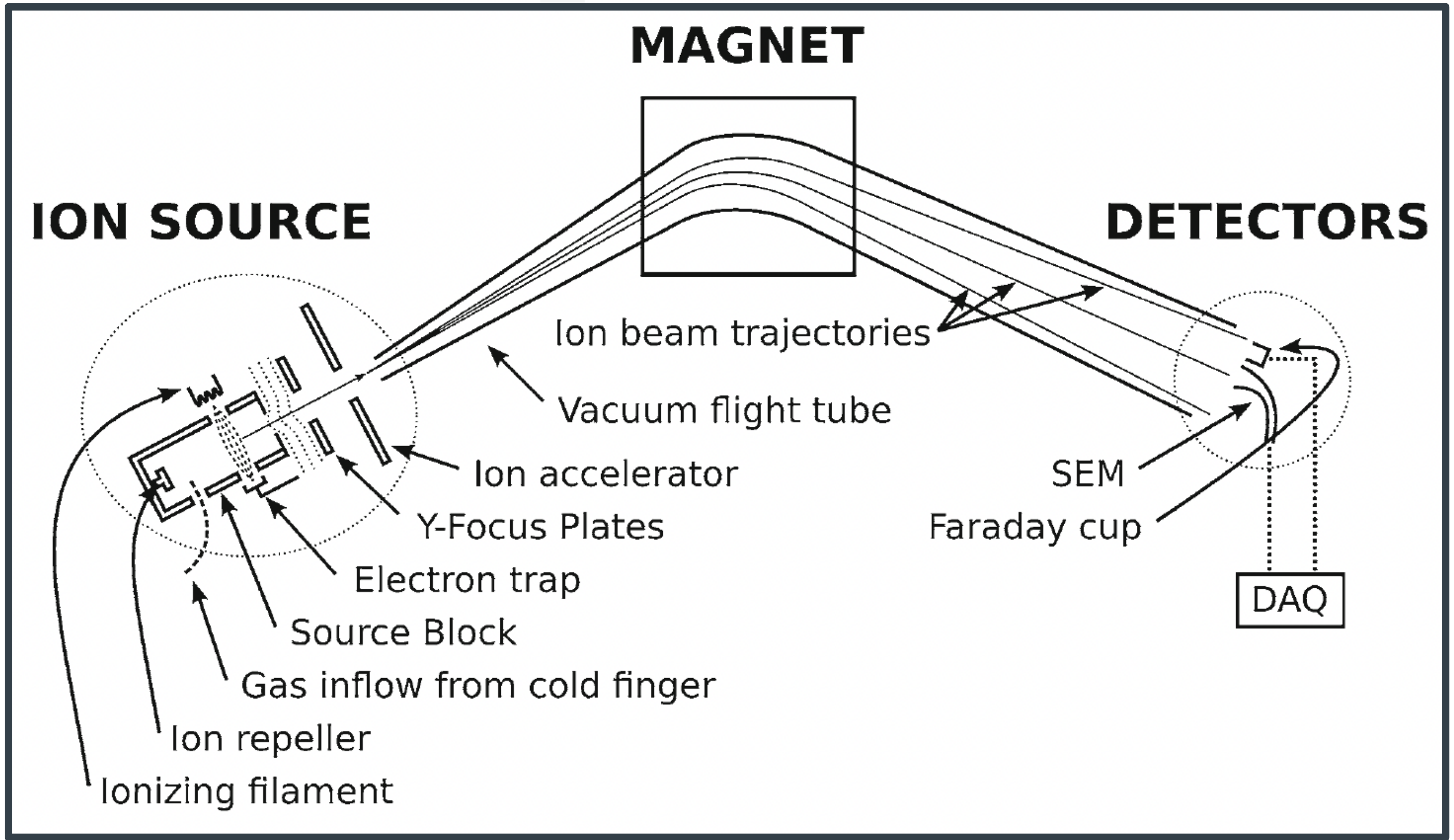
RGMS Procedure

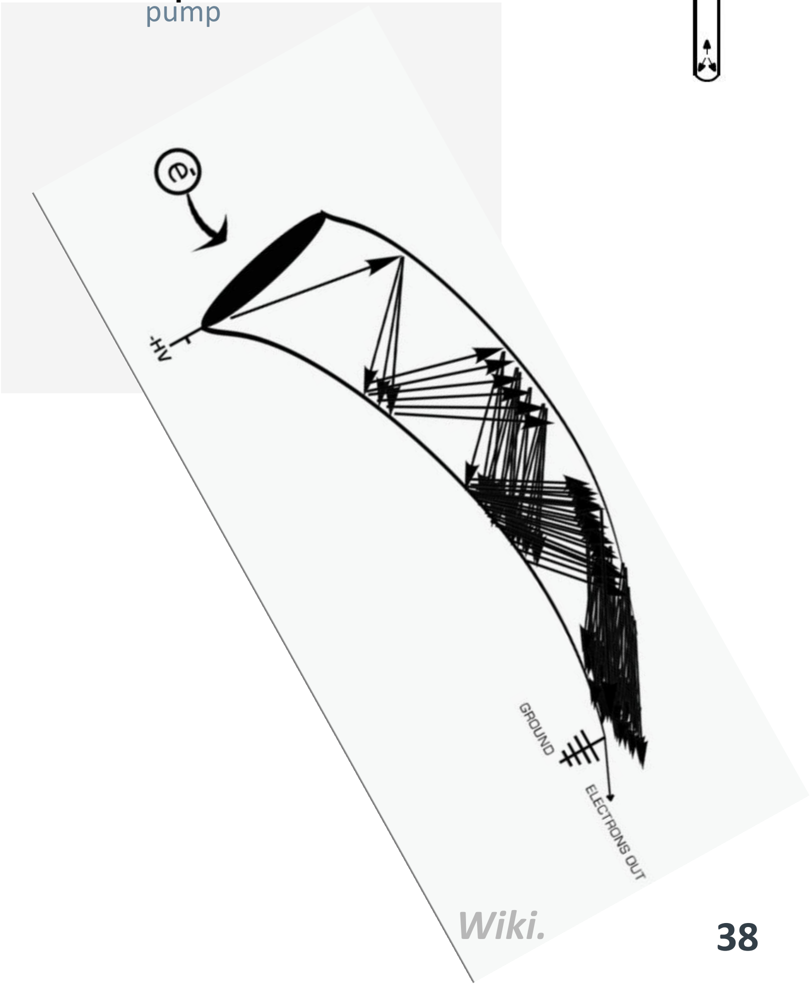




RGMS Procedure







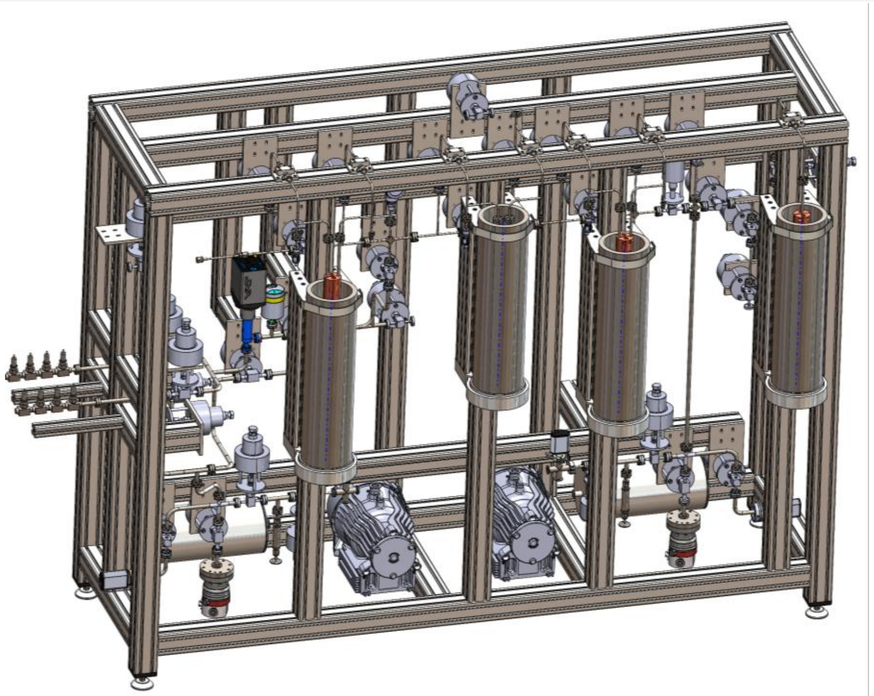
Wiki.

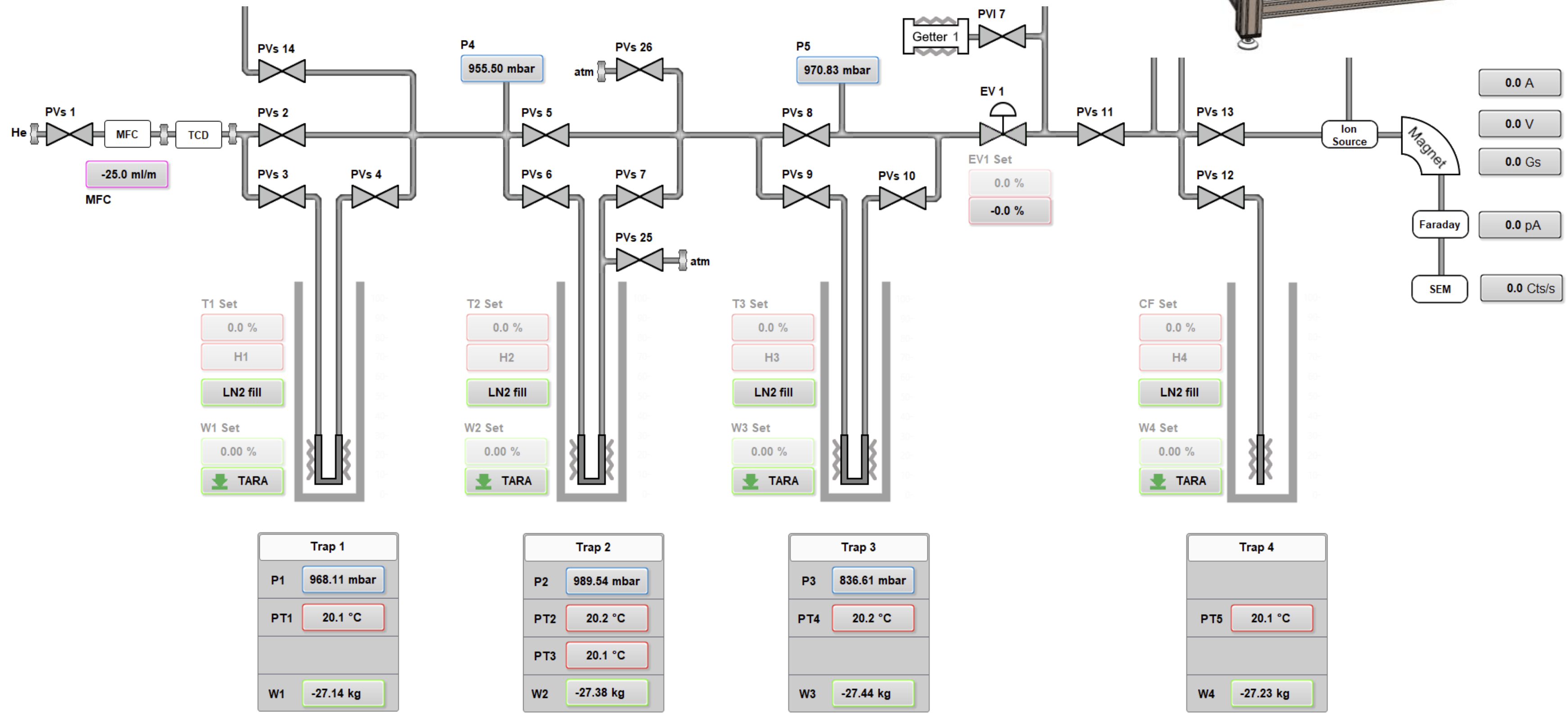
Auto-RGMS: Design Philosophy

Fully automized valve system and data-acquisition system, reducing manpower and improving the reproducibility of the results

Optimized sample inlet with 2 input ports, increasing the efficiency of sample usage

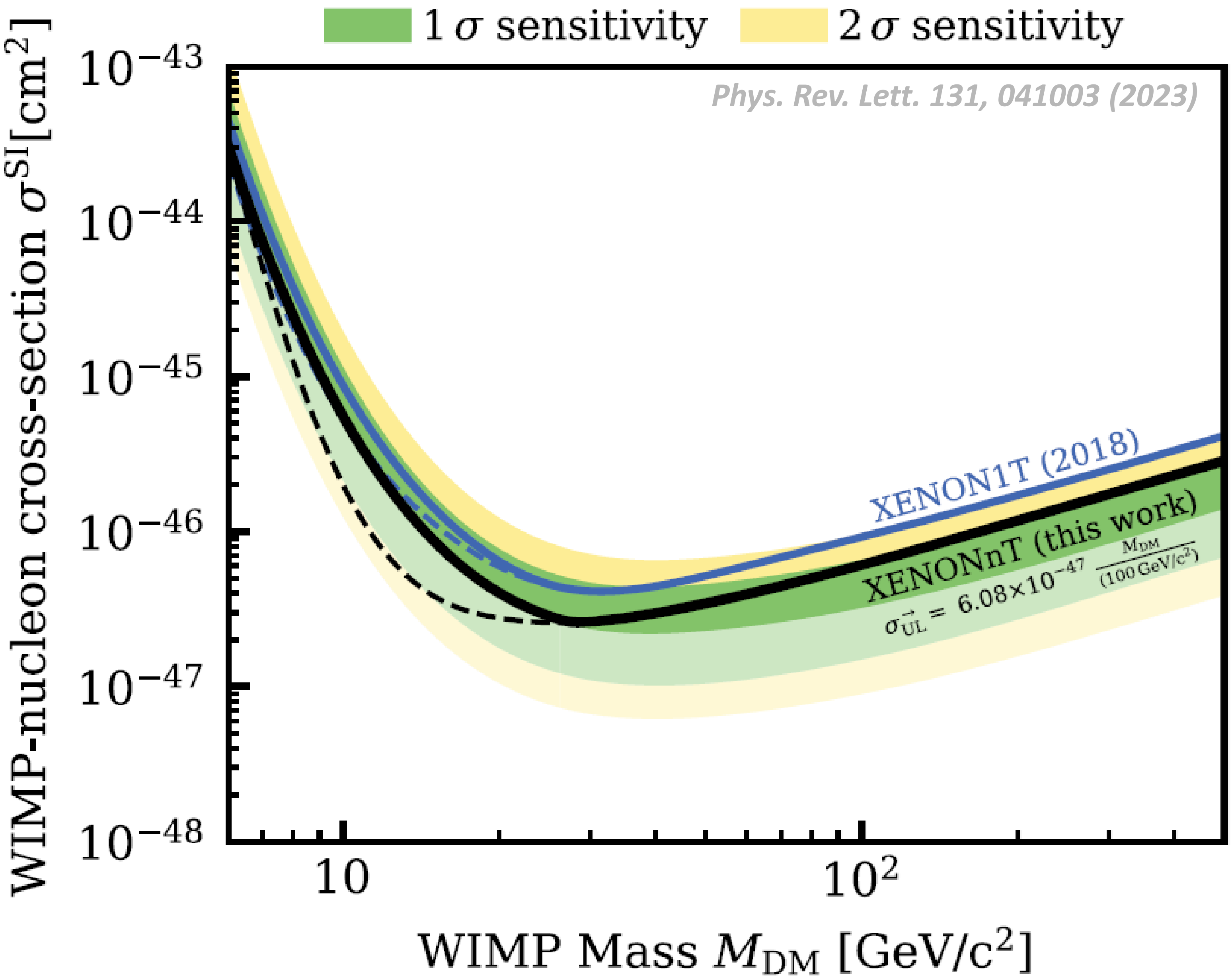
More compact design with flexible bypass lines, allowing a variety of studies to better understand our system





Pipe heating		
on / off	Setpoint	actual val
TH1	80.0 °C	20.1 °C
TH2	80.0 °C	20.2 °C
TH3	80.0 °C	20.1 °C
TH4	0.0 °C	20.2 °C
TH5	0.0 °C	20.1 °C
TH6	0.0 °C	20.1 °C
TH7	0.0 °C	20.1 °C
TH8	0.0 °C	20.1 °C

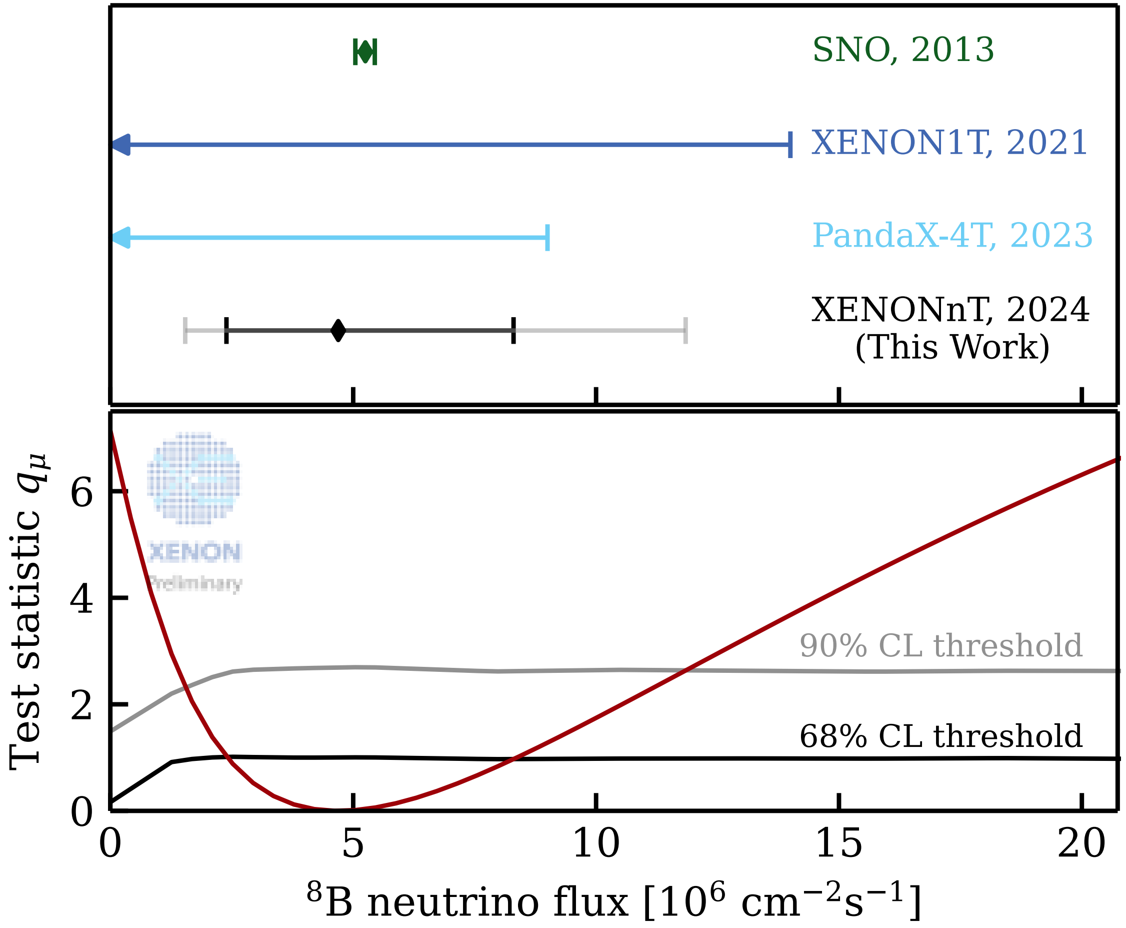
WIMP Blind Analysis: Science Run 0 (SR0) WIMP Limit



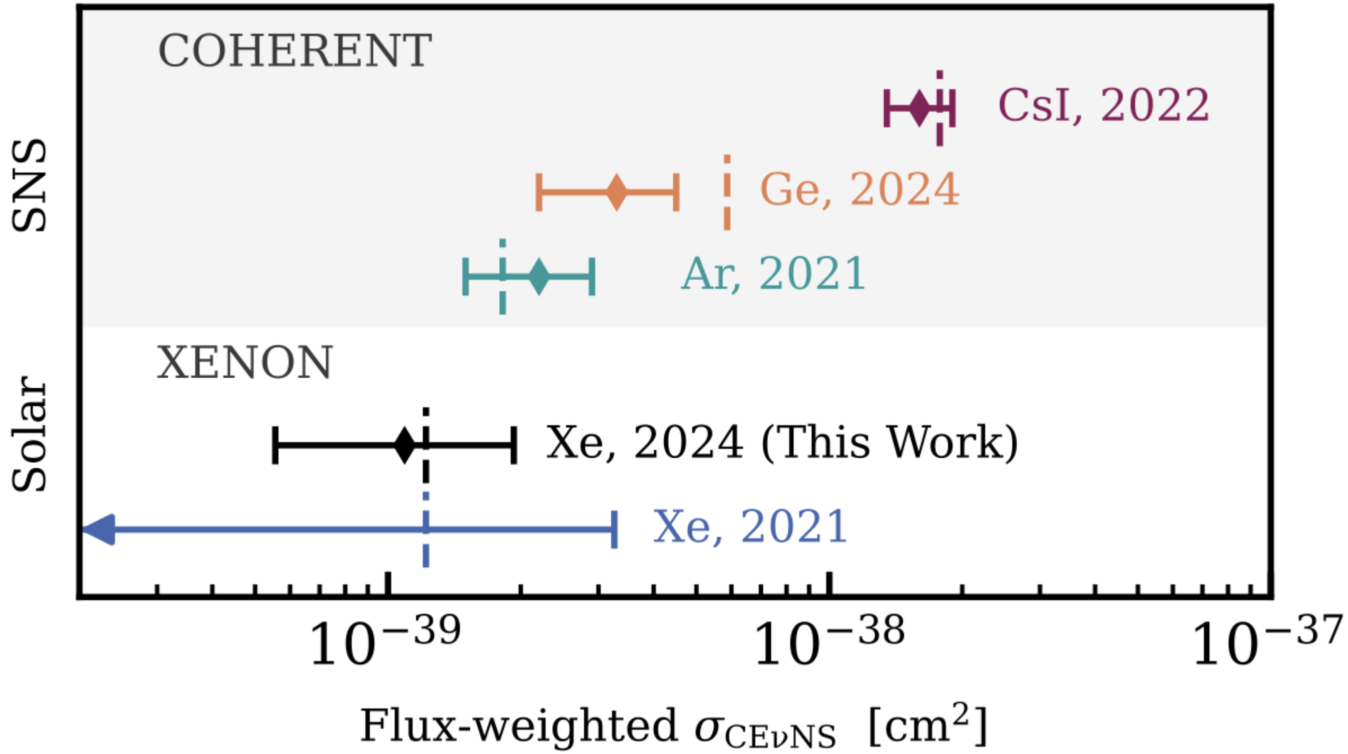
- Power constraint limits (PCL) applied on media. The effect is indicated by the dashed line
- No significant WIMP excess observed
- New constraints on spin-independent (SI) WIMP-nucleon cross section at 28 GeV/c^2: **2.58×10^{-47} cm^2**
- Spin-dependent (SD) result also available in the paper

^{8}B CEυNS Blind Analysis: Physics Result

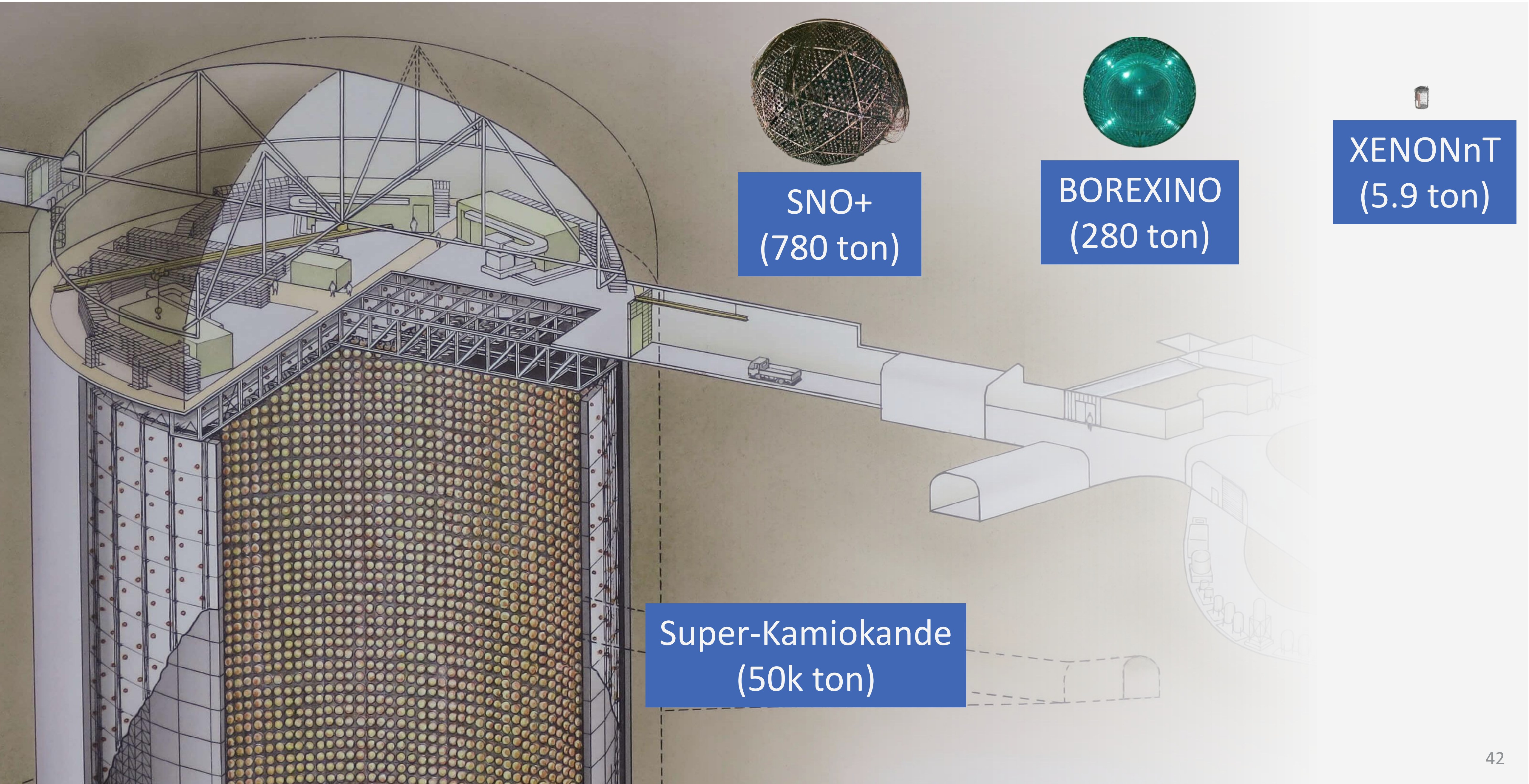
Fix CEυNS cross-section:



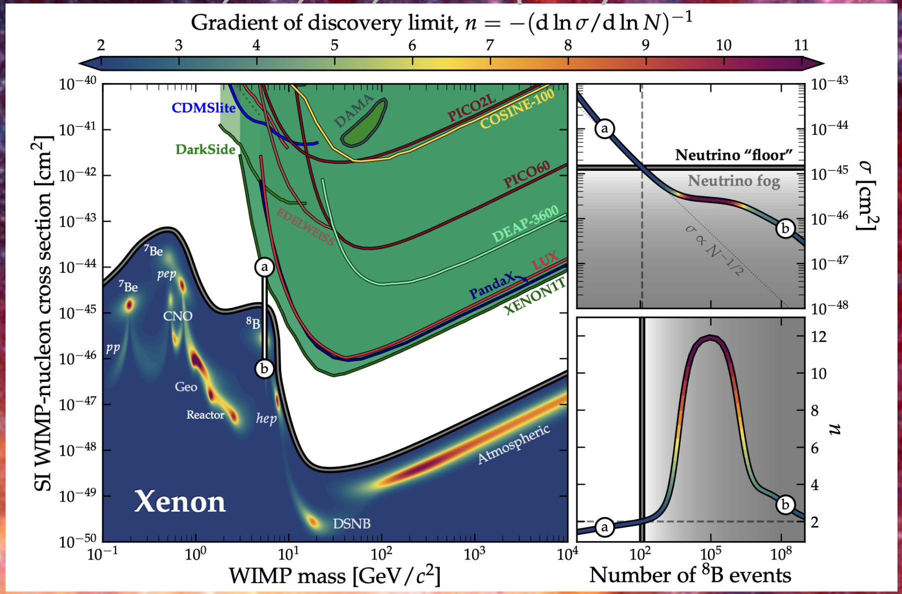
Fix solar neutrino flux:

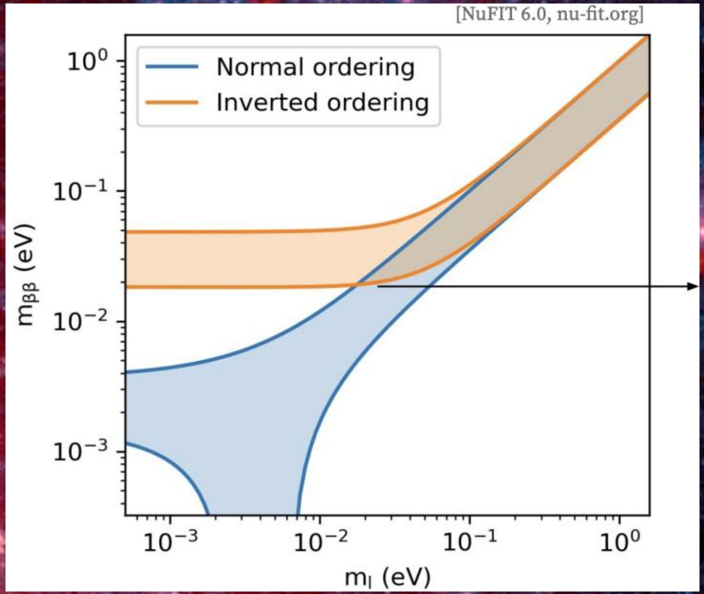


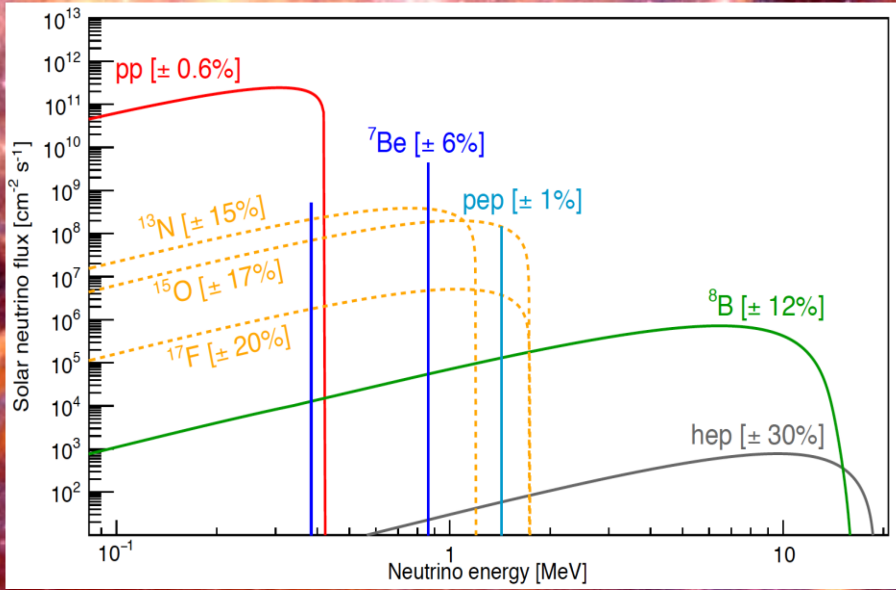
XENONnT: The Smallest Solar Neutrino Detector



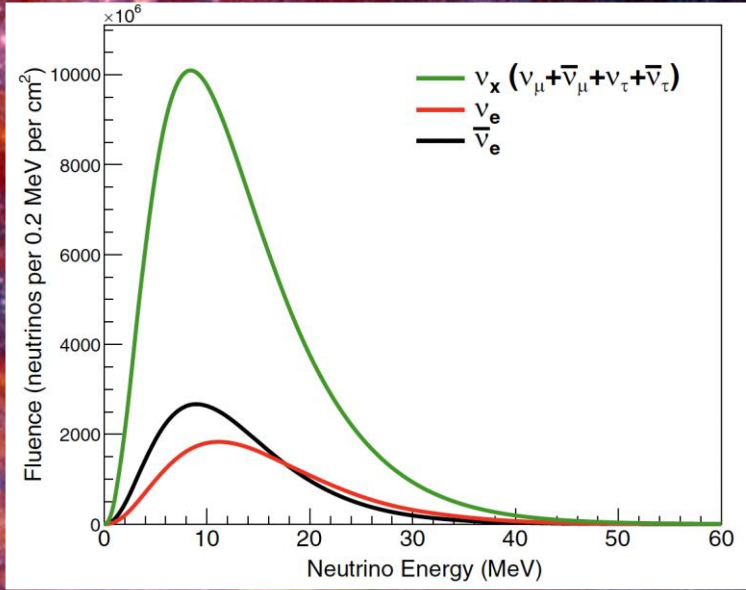
C. A. J. O'Hare, PRL, 127, 251802 (2021)







BOREXINO Collaboration, Nature 562, 505–510 (2018)

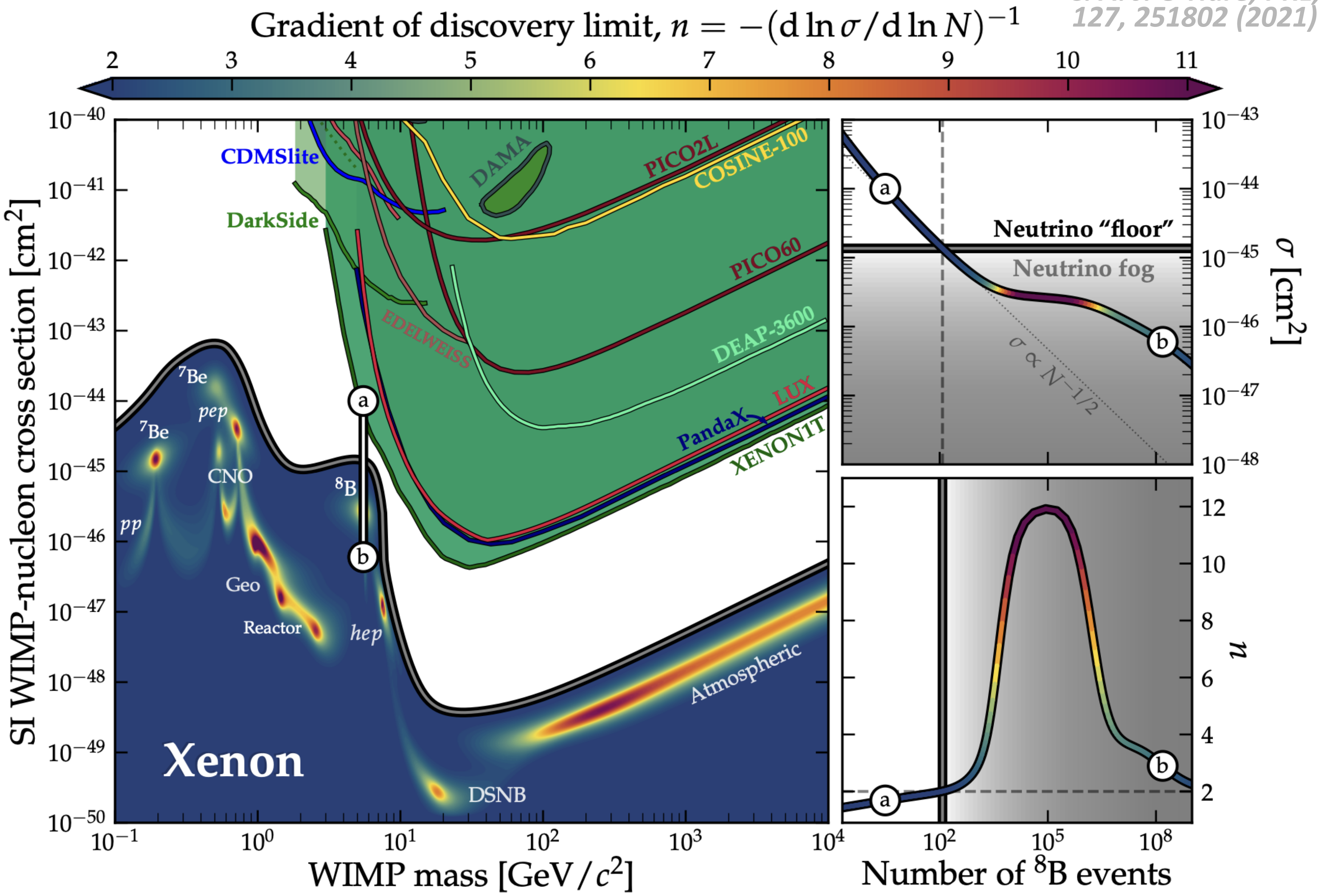


A. Abed Abud, et al., Phy. Rev. D. 107, 112012 (2023)

eso.org

Into the Neutrino Fog

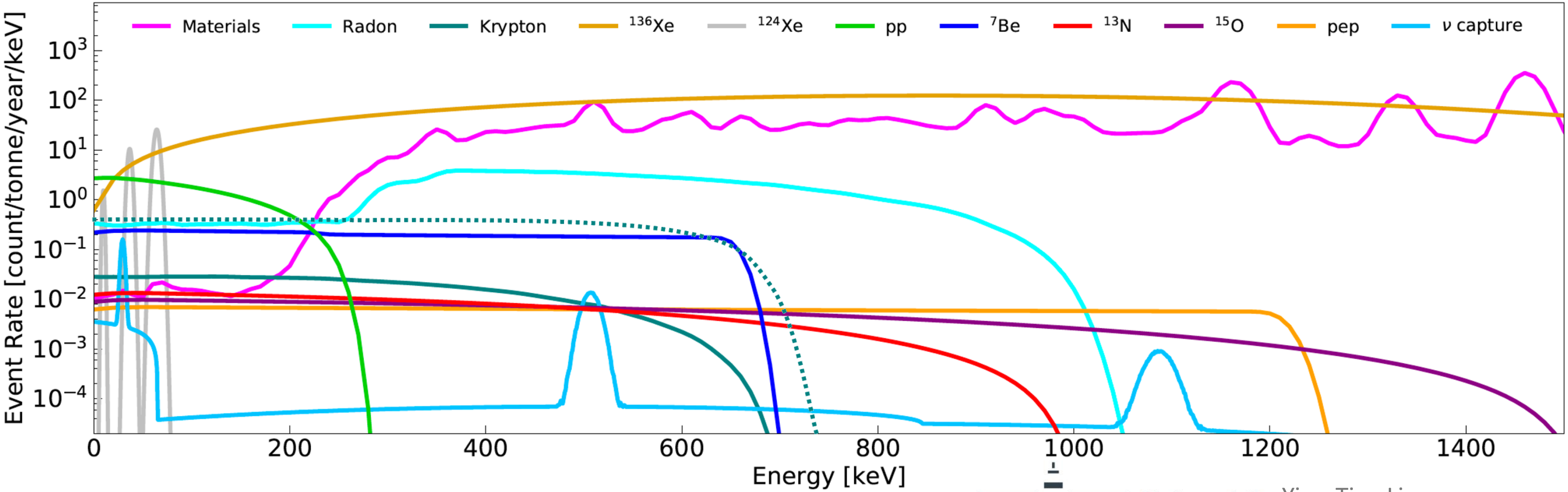
- Detecting solar neutrino is the first step; there are neutrino backgrounds from other origin
- Lots of unexplored parameter space at higher WIMP mass



C. A. J. O'Hare, PRL, 127, 251802 (2021)

Projected LowER Background

- Krypton level at 100x10^{-15} (^{nat}Kr/Xe)
- Radon level at 0.1 μBq/kg of xenon
- Goal: sub-percent level of pp-solar neutrino detection



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