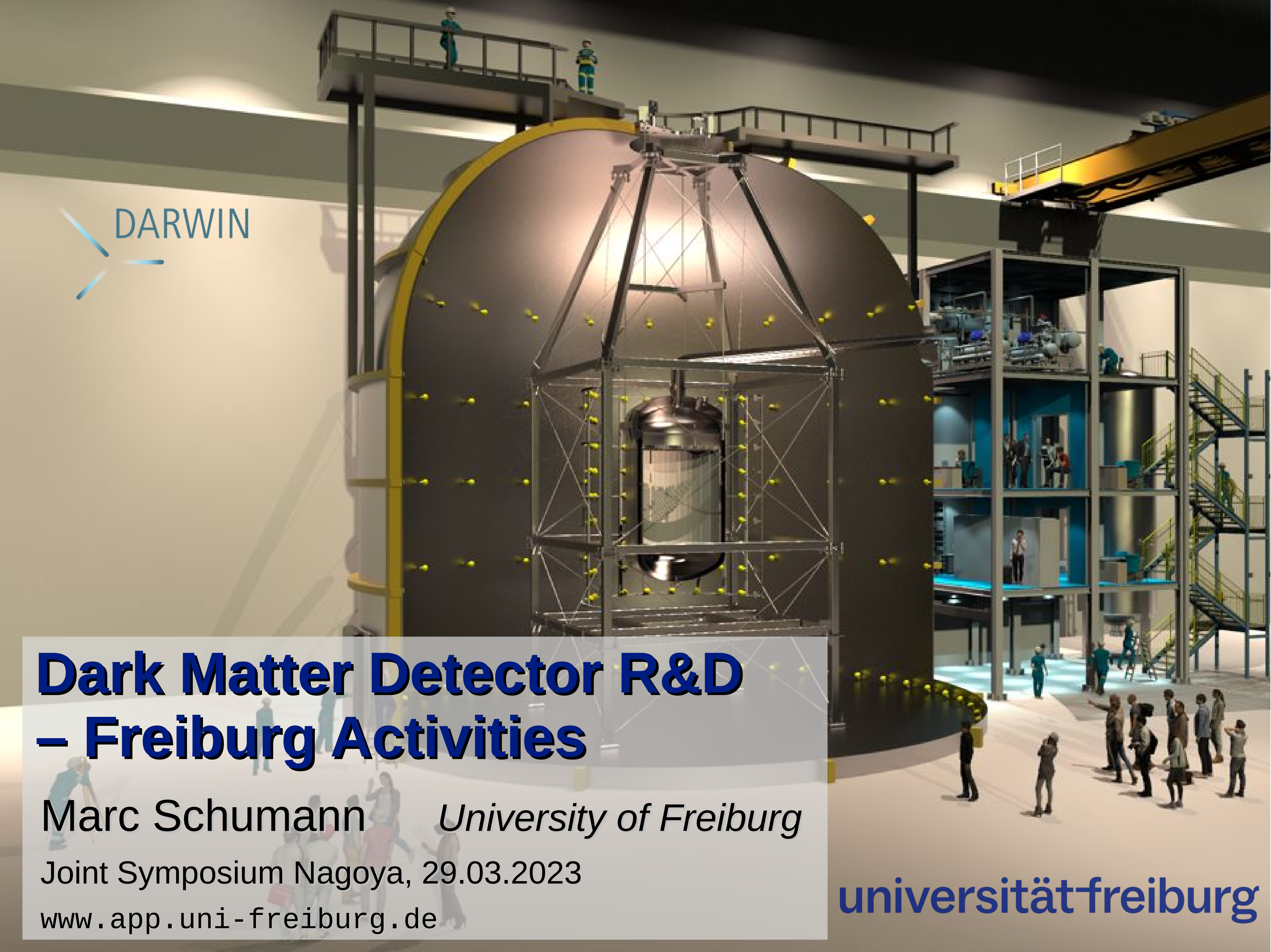


Dark Matter Detector R&D – Freiburg Activities

Marc Schumann *University of Freiburg*

Joint Symposium Nagoya, 29.03.2023

`www.app.uni-freiburg.de`

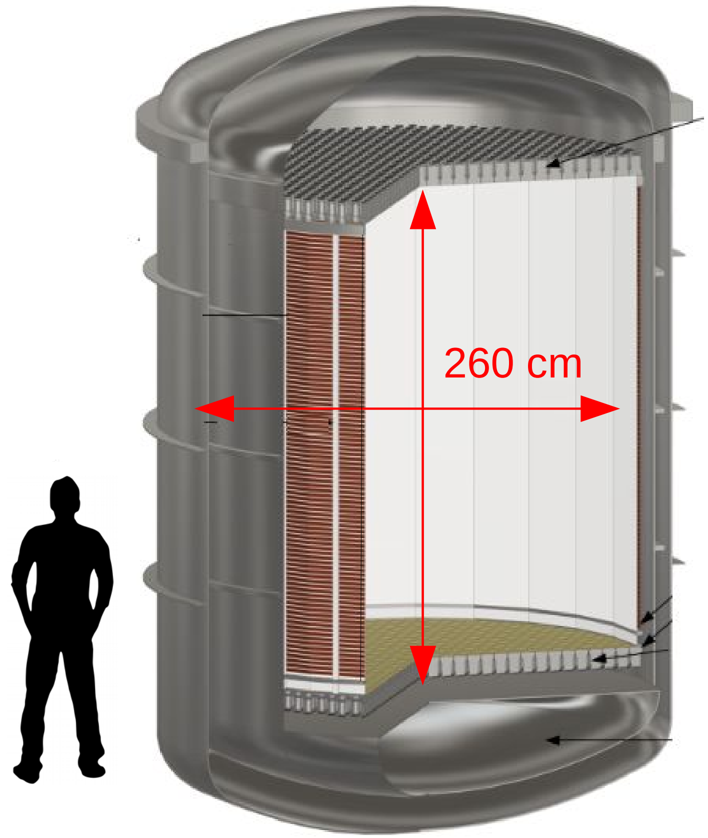
universität freiburg

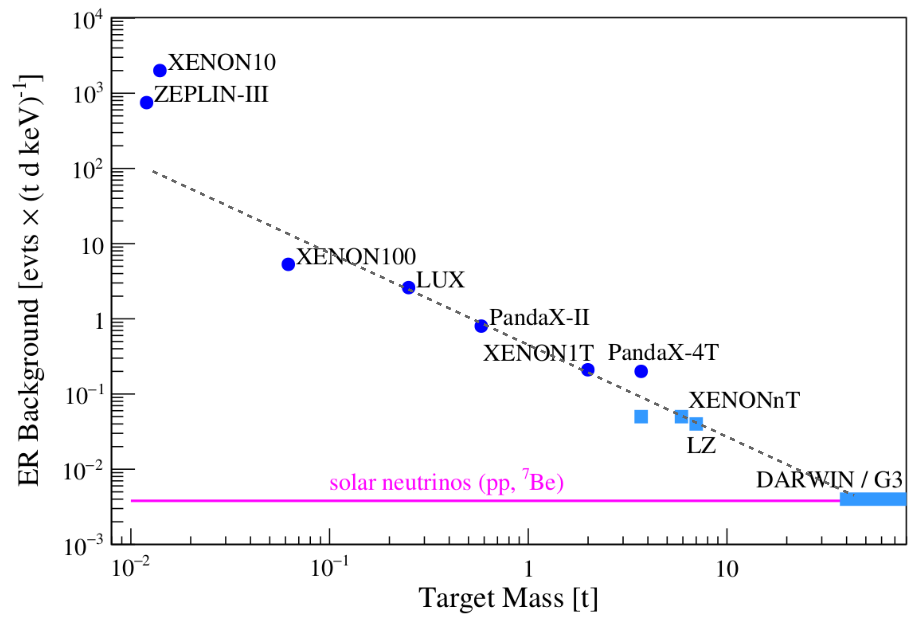
DARWIN: The ultimate LXe WIMP Detector

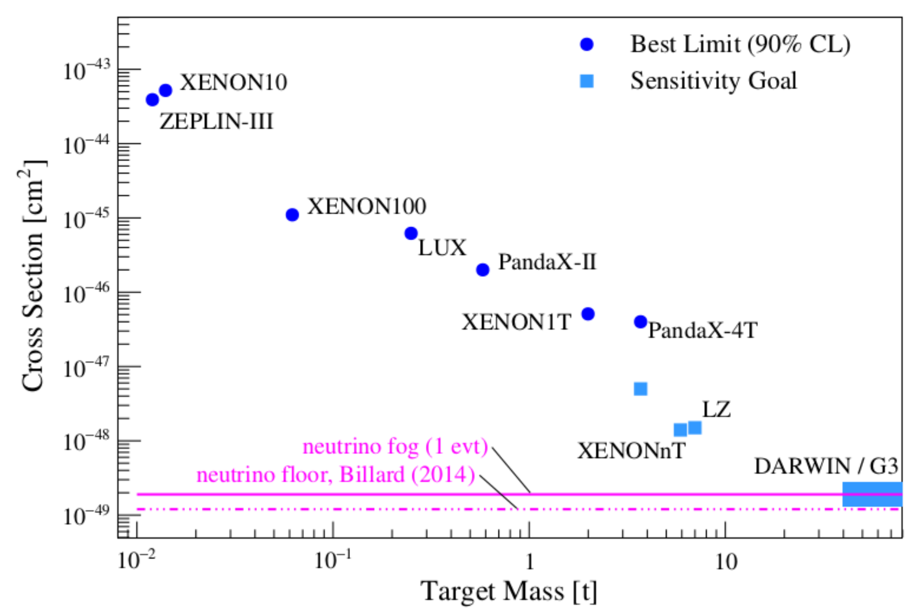
darwin-observatory.org JCAP 11, 017 (2016)

Background dominated by **irreducible neutrinos**

Baseline design
~50t total LXe mass
~40 t LXe TPC
~30 t fiducial mass





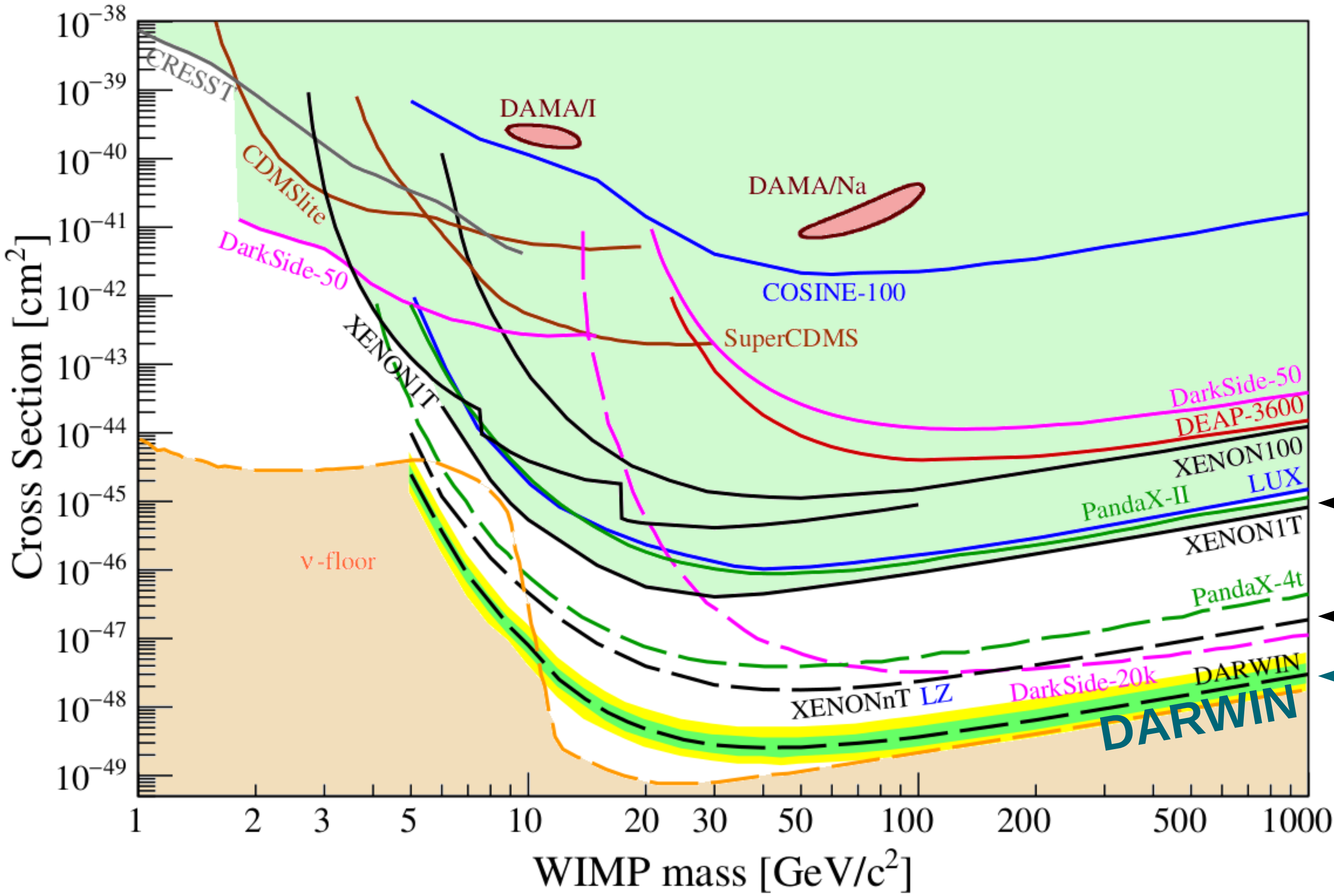


universität freiburg

DARWIN: The ultimate LXe WIMP Detector

DARWIN

darwin-observatory.org
JCAP 11, 017 (2016)



Exposure

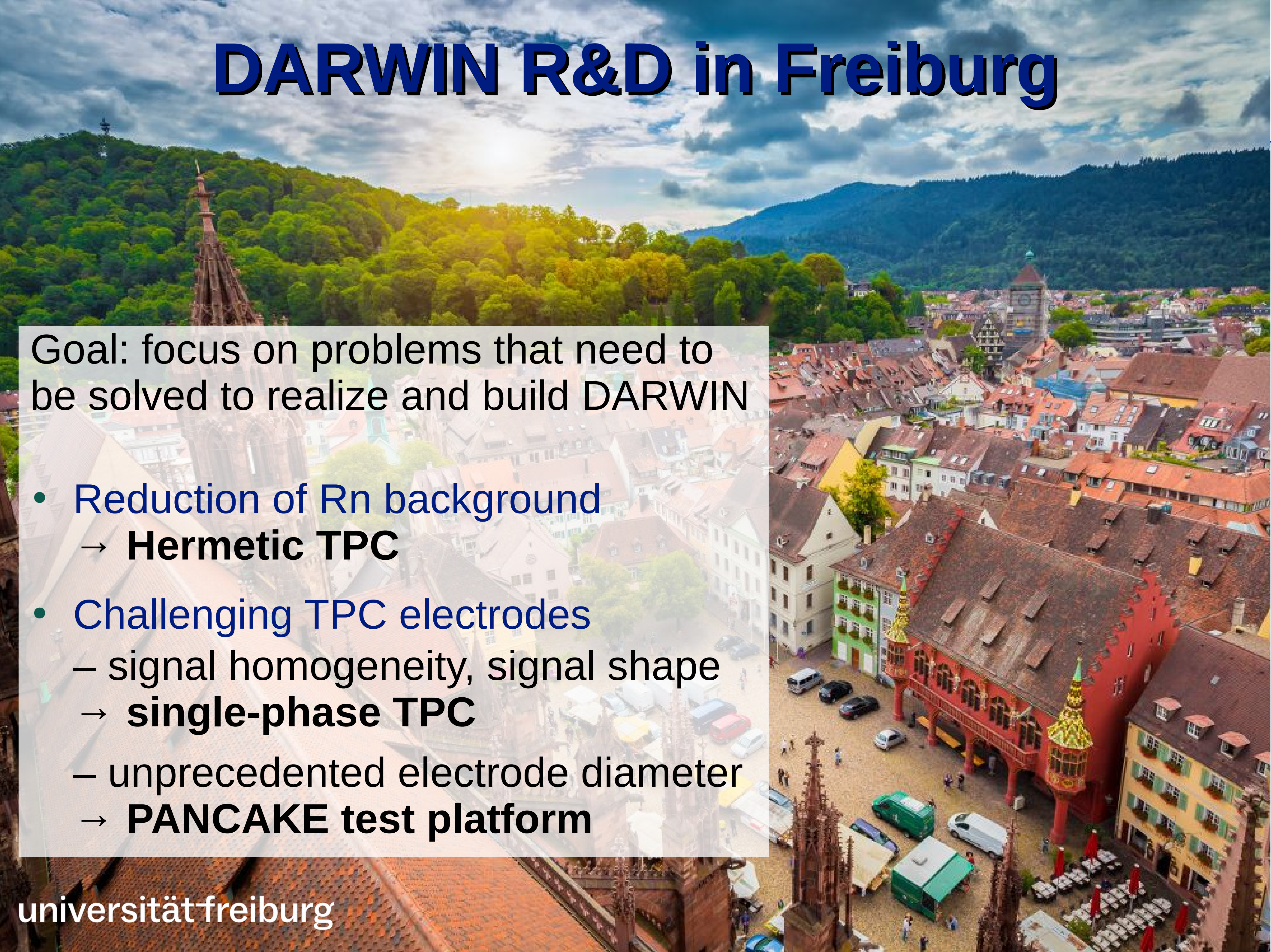
1 t×y

20 t×y

200 t×y

DARWIN R&D in Freiburg

universitätfreiburg



DARWIN R&D in Freiburg

Goal: focus on problems that need to be solved to realize and build DARWIN

- Reduction of Rn background
  → **Hermetic TPC**
- Challenging TPC electrodes
  – signal homogeneity, signal shape
  → **single-phase TPC**

  – unprecedented electrode diameter
  → **PANCAKE test platform**

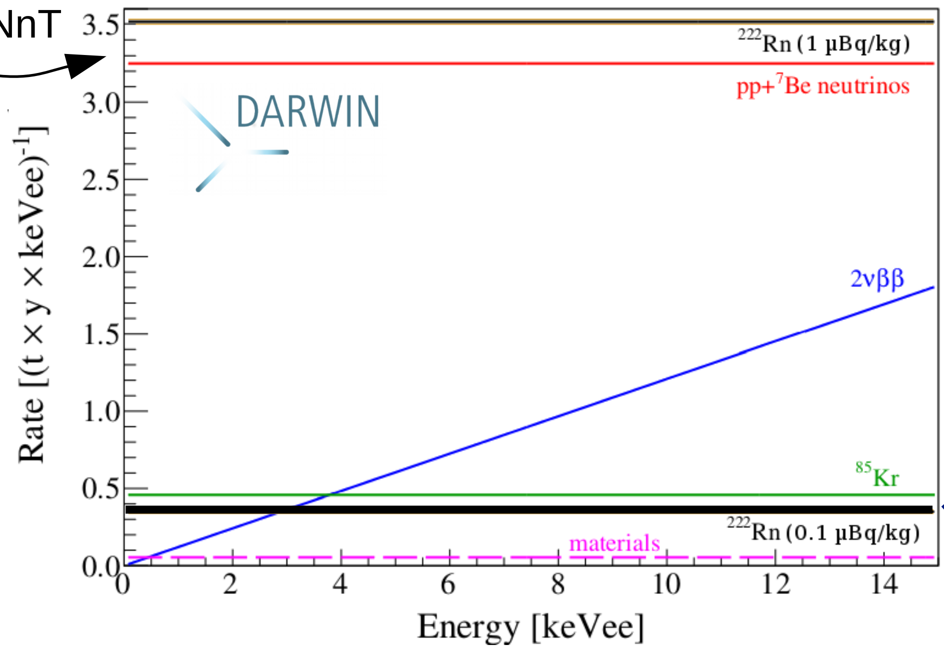
universität freiburg

PhD work of Julia Dierle
Eur. Phys. J C 83, 9 (2023)
arXiv:2209.00362

Hermetic TPC

DARWIN: Radon Background

XENONnT level



DARWIN goal:
ER background dominated by solar neutrinos
→ everything else subdominant (=at ~10% level)

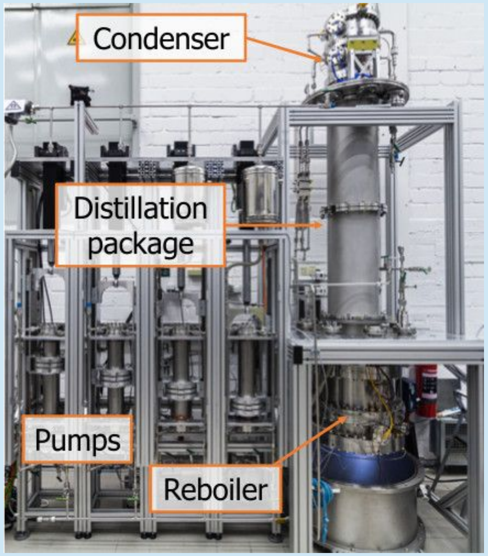
^{222}Rn concentration goal: 0.1 μBq/kg

→ **main background challenge**

Strategy DARWIN

– avoid Rn emanation by
→ optimal material production
→ material selection
→ surface treatment
→ **optimized detector design**

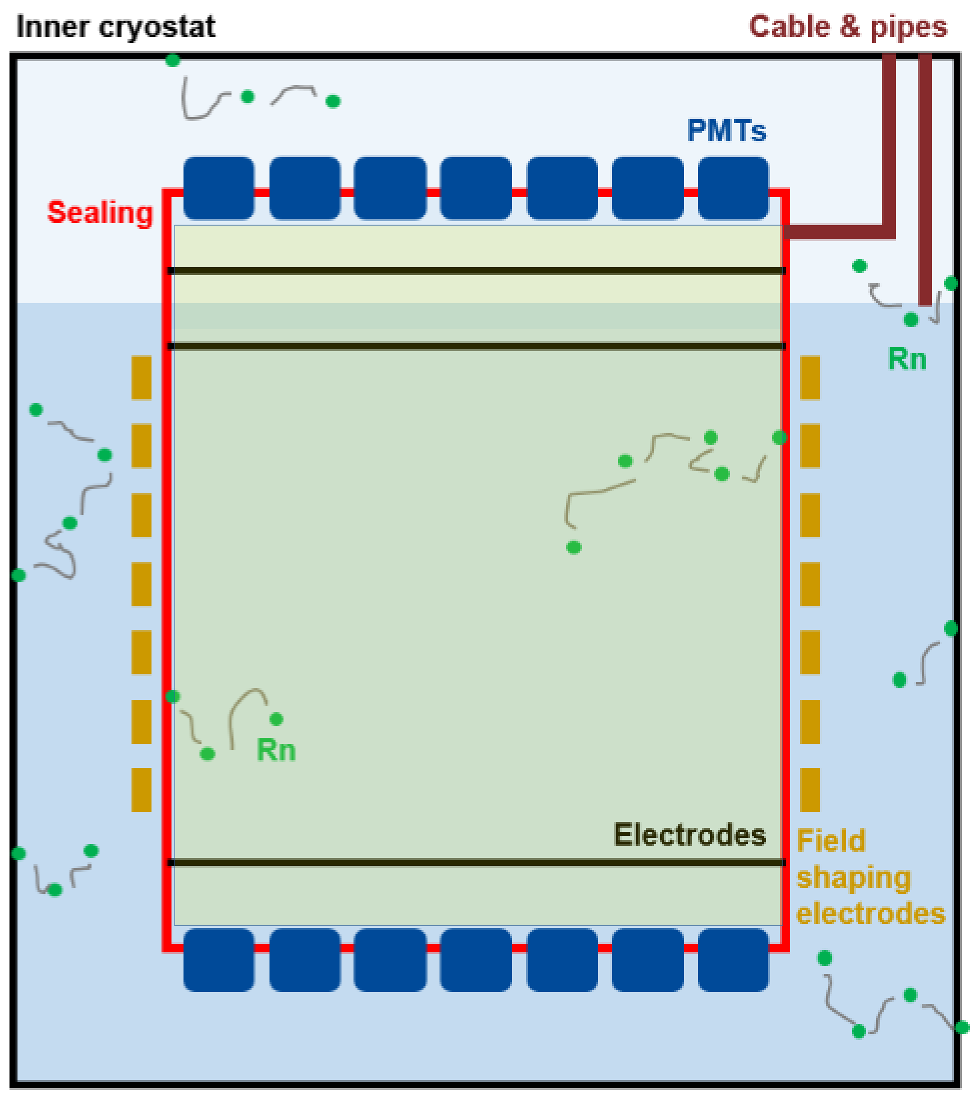
– **active Rn removal, e.g., via cryogenic distillation**
→ column developed for XENONnT is R&D for DARWIN
idea: *EPJ C 77, 358 (2017)*



Motivation and Concept

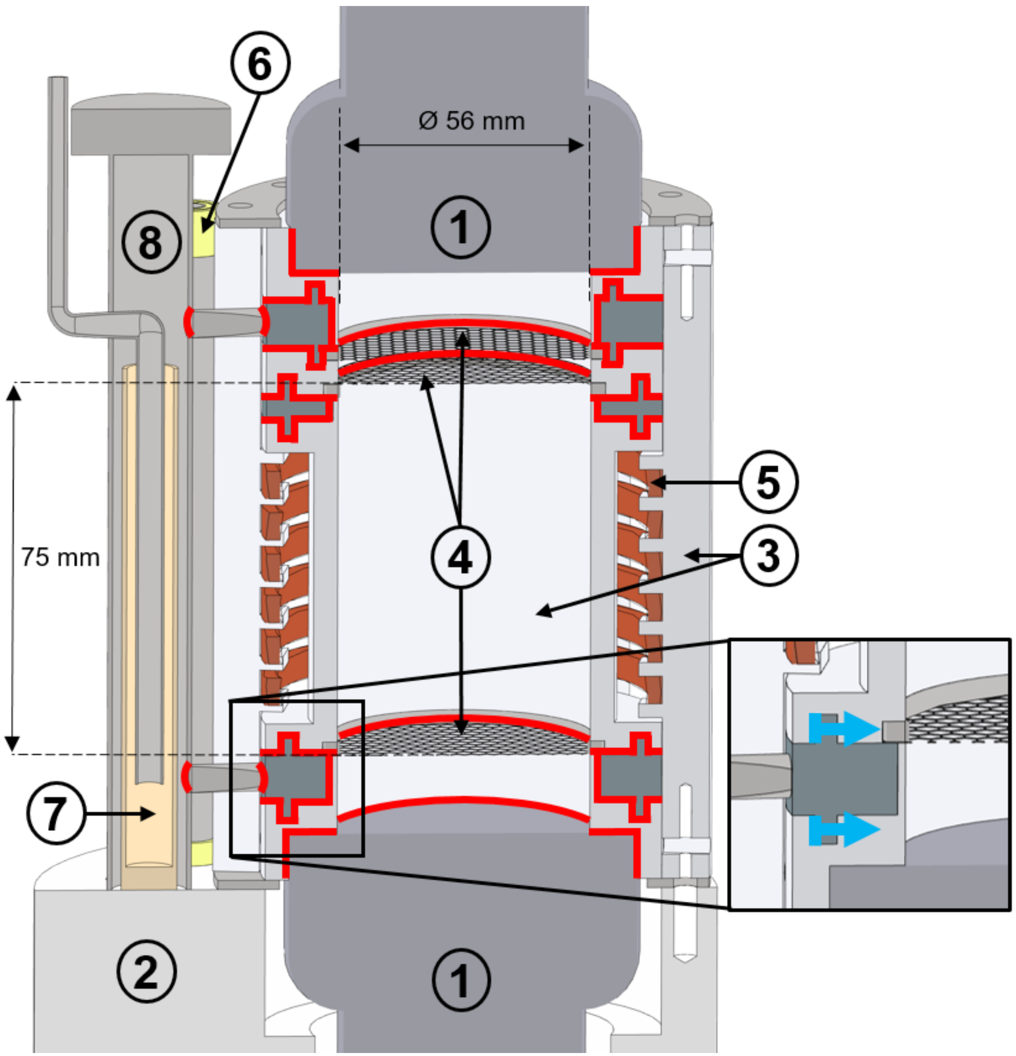
- Rn emanated from surfaces
- About 10x more surfaces outside of active TPC target
- In addition: all „dirty“ components in outer volume (cables, HV dividers)

- Reduce Rn by mechanically separating inner and outer volumes
- BUT: depart as little as possible from well-established, successful TPC designs



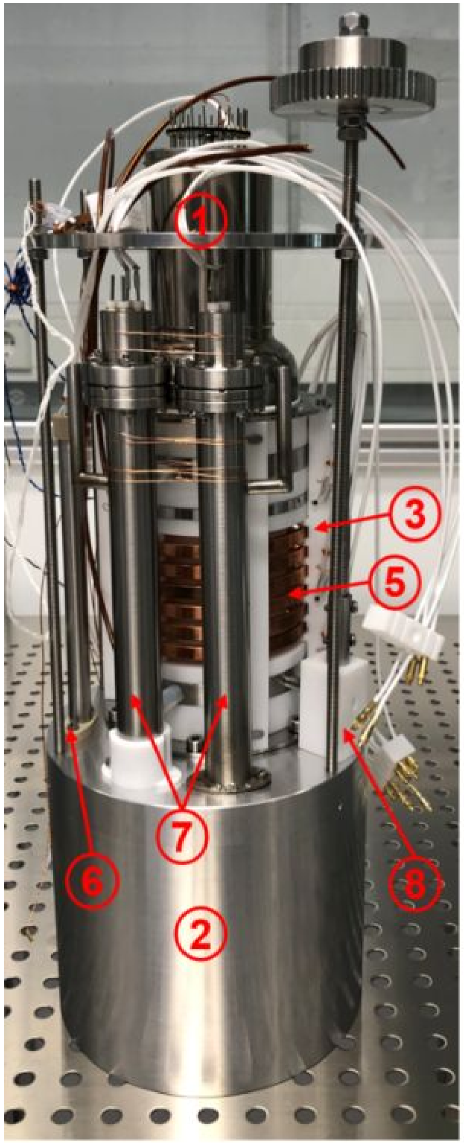
Design

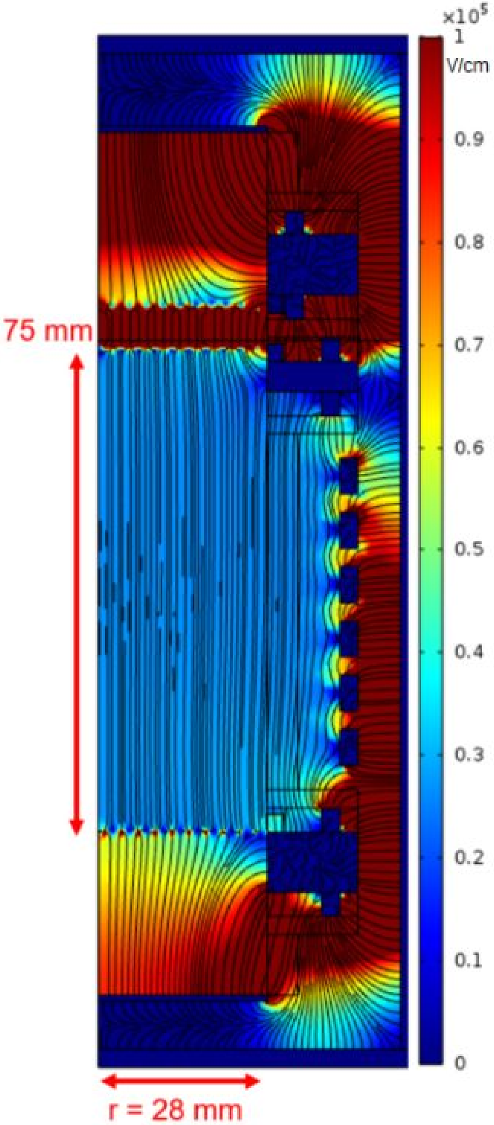
- „Typical“ TPC
  - – 3 mesh electrodes
  - – PTFE reflector tube
  - – 2 PMTs in contact with target
- Sealing done via cryofitting
  (=exploit difference in
  linear expansion coefficients)
- LXe level controlled with weir



Design

- „Typical“ TPC
  - 3 mesh electrodes
  - PTFE reflector tube
  - 2 PMTs in contact with target
- Sealing done via cryofitting (=exploit difference in linear expansion coefficients)
- LXe level controlled with weir
- Valve connecting both volumes for filling and recuperation
- Electric field homogeneity confirmed with COMSOL



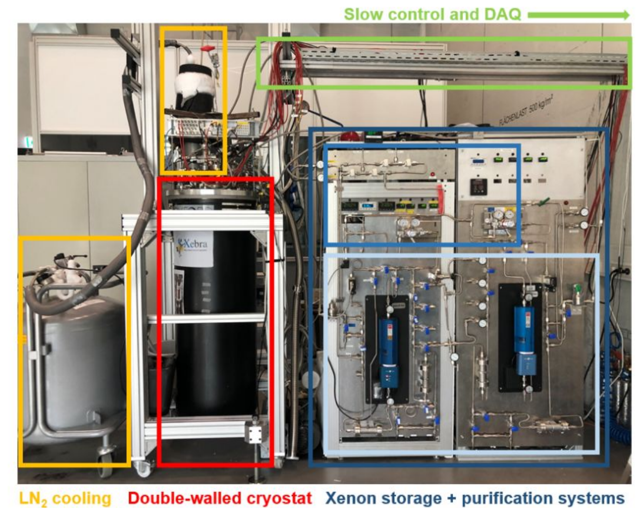


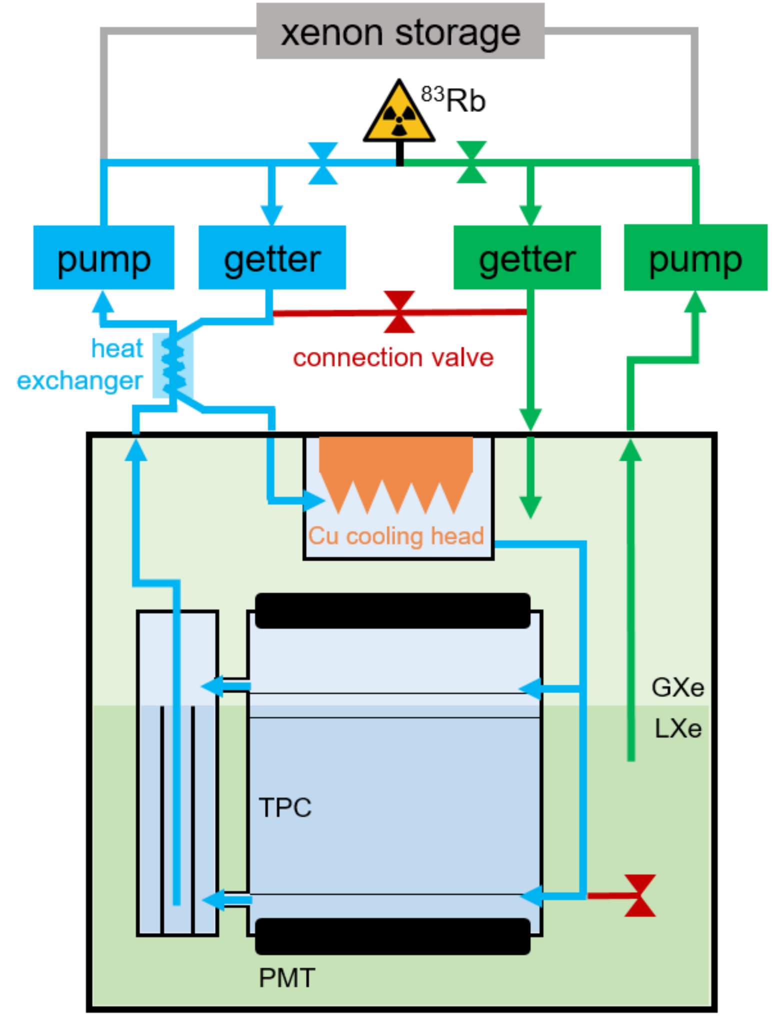
Design

- „Typical“ TPC
  – 3 mesh electrodes
  – PTFE reflector tube
  – 2 PMTs in contact with target
- Sealing done via cryofitting
  (=exploit difference in
  linear expansion coefficients)
- LXe level controlled with weir
- Valve connecting both volumes for filling and recuperation
- Electric field homogeneity confirmed with COMSOL

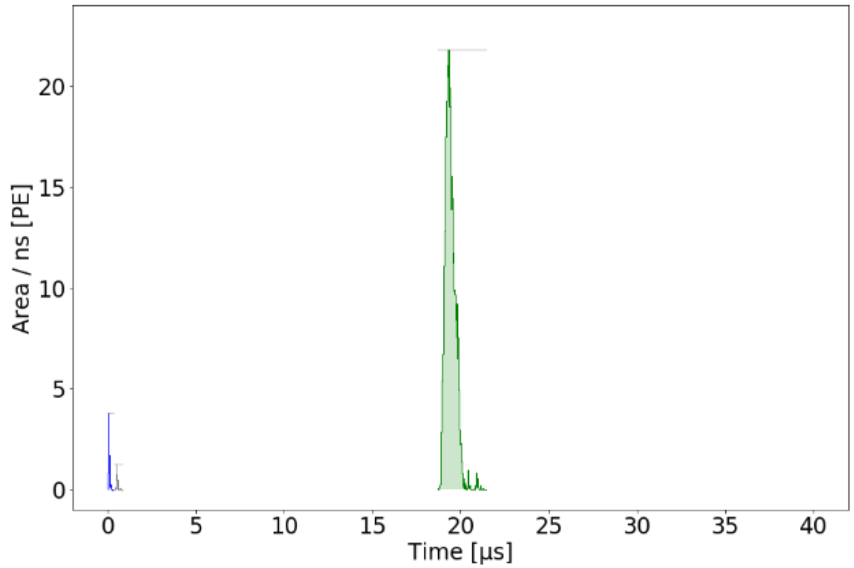
- 2 independent gas systems
- Only one coldfinger, connected to inner volume
- TPC operated on Freiburg Xebra Test Platform

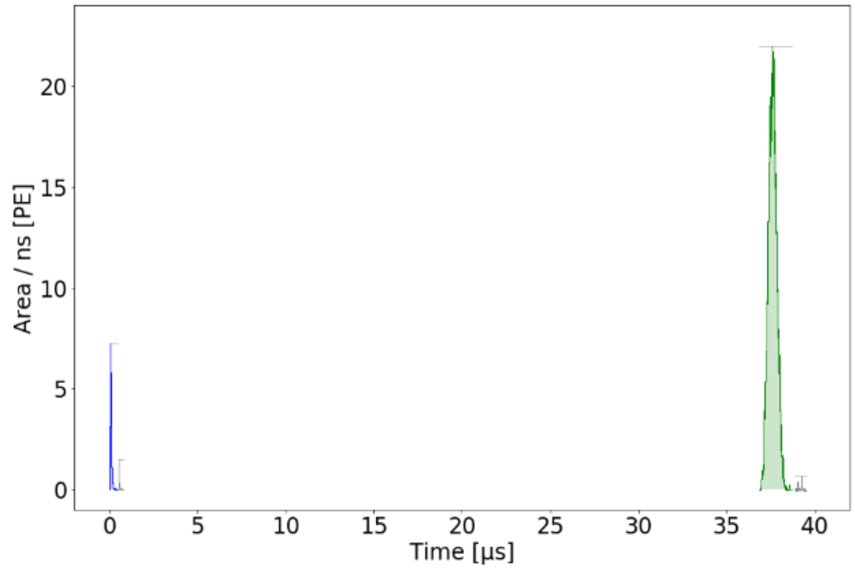
JINST 18 T02004 (2023)

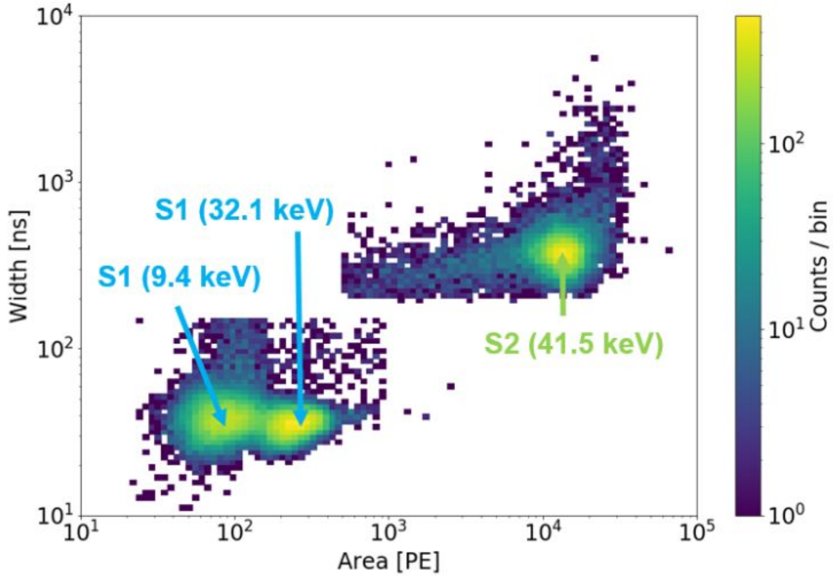




TPC Performance



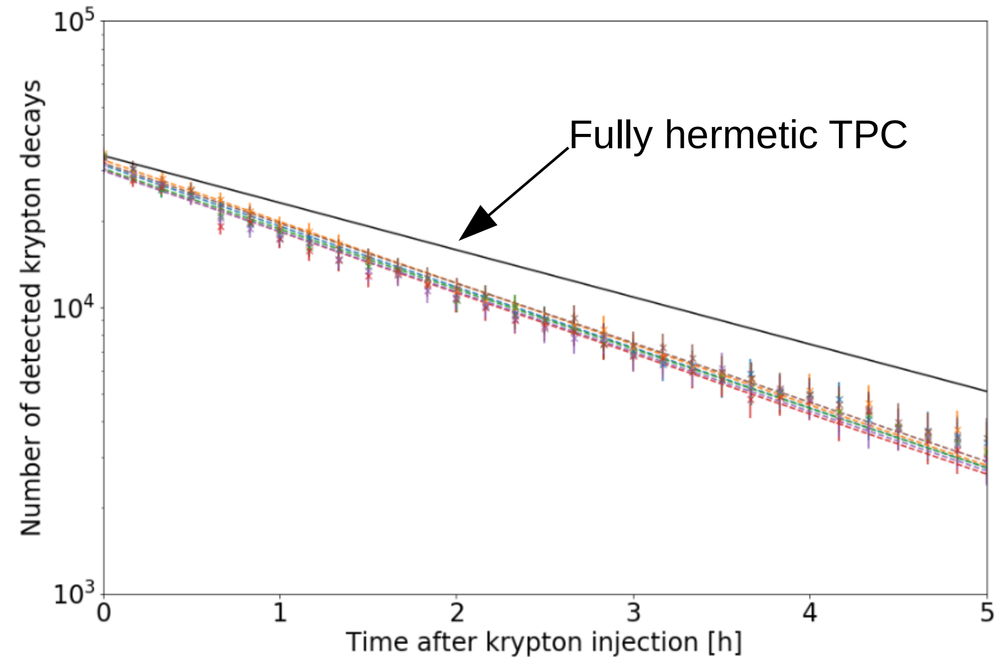




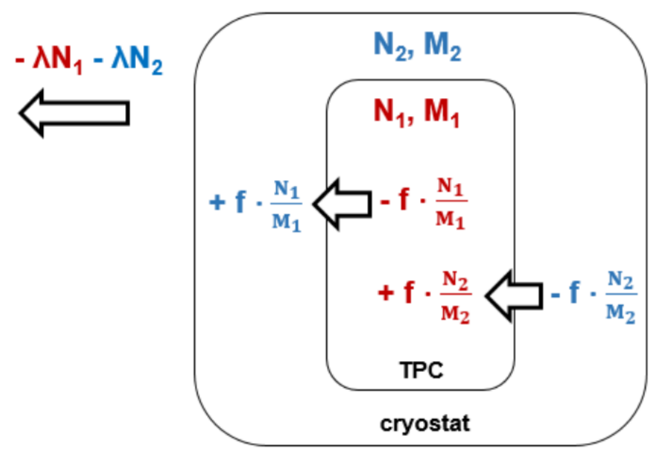
- TPC performance studied with ^{83m}Kr
- max e$^-$-lifetime ~300 μs (dt_{max}=43 μs)
- correct for z-dependence of signals
- decent light and charge-yields:
  - g_1=0.089(4) PE/γ
  - g_2=7.1(7) PE/e$^-$
- stable operation only <u>without</u> purifying outer volume (→ level fluctuations)

Hermeticity

- Prototype test: leak rate of seals $O(10^{-2})$ mbar l s^{-1} („watertight")
- Measure Xe leak rate with ^{83m}Kr injected into inner volume via detailed model
- Leakage flow f~0.1 kg/h
  → **semi-hermetic TPC**



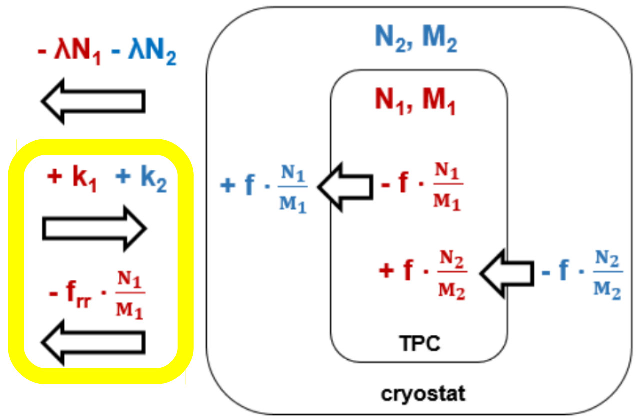
- Origin of leakage unknown. Scale up result to 40t-TPC assuming 3 hypotheses:
  – leak around PMTs
    → r^2 ~1000
  – leak around electrodes
    → r ~ 50
  – leak around tubes
    → ~ 1



f:	leakage flow
N_1/N_2:	^{83m}Kr atoms inner/outer volume
M_1/M_2:	inner/outer volume mass
λ:	^{83m}Kr decay constant

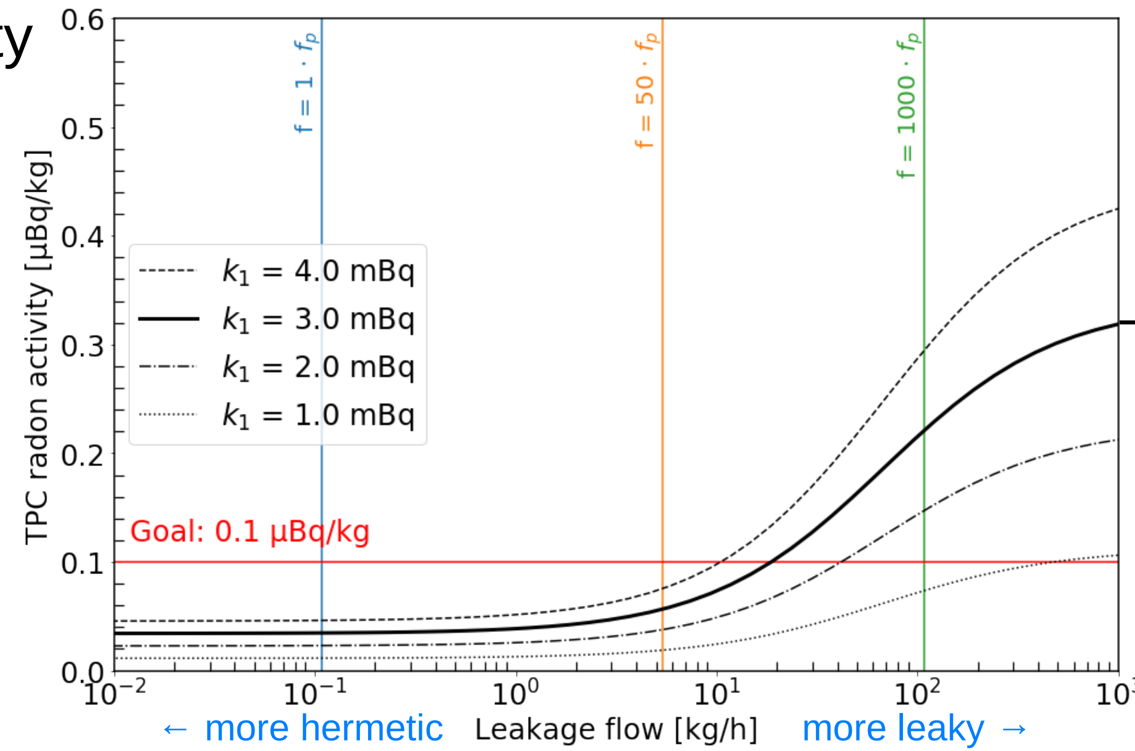
Scaling to DARWIN: ^{222}Rn

- Expand model to include
  - Rn emanation
    (k_1..inner, k_2..outer volume)
  - Rn removal system
    (flow f_{rr} of Xe through removal system)



f:	leakage flow
f_{rr}:	radon removal flow
N_1/N_2:	^{222}Rn atoms inner/outer volume
M_1/M_2:	inner/outer volume mass
k_1/k_2:	^{222}Rn emanation inner/outer volume
λ:	^{222}Rn decay constant

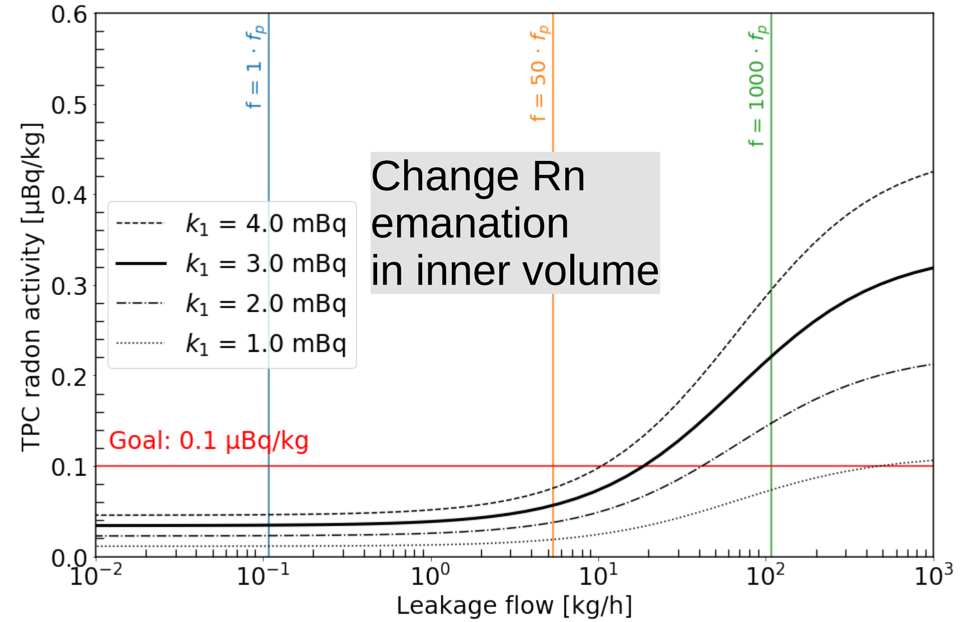
- Expected Rn-activity in 40t active target:

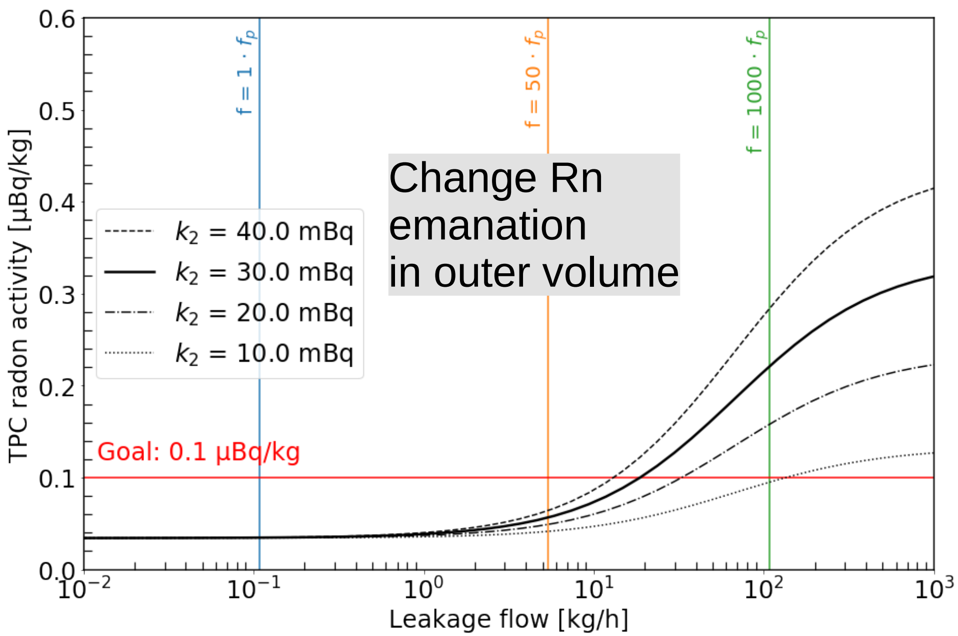


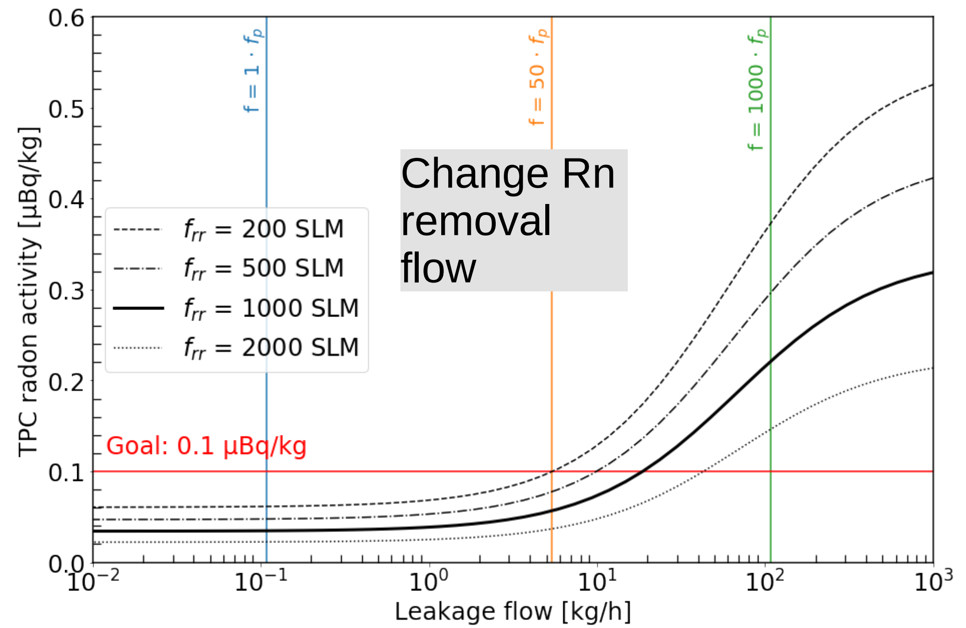
Benchmark numbers:
k_1=3 mBq
k_2=30 mBq
f_{rr}=1000 SLM

Scaling to DARWIN: ^{222}Rn

- Study impact of individual Rn parameters
- **Even moderate levels of hermeticity have a significant impact**
- Great potential in combination with other Rn-abatement techniques







Conclusion I

Eur. Phys. J C 83, 9 (2023)

- We built and operated a small-scale hermetic TPC which follows the well-established „standard“ TPC design
- Achieved moderate hermeticity using cryofitting
  → method not yet fully optimized
- Need two independent cooling systems
  to also purify outer volume

- Already moderate levels of hermeticity can significantly reduce the Rn level
- Hermetic TPC concept:
  promising and rather easy approach to reduce Rn in combination with all other methods
  → **we should not miss this opportunity**

PhD work of Florian Tönnies, Patrick Meinhardt
+ Fabian Kuger, Adam Brown
Simulation study: *JINST 17, P03027 (2022), arXiv:2112.11844*
Detector platform: *JINST 18, T02004 (2023), arXiv:2208.14815*

Bundesministerium für Bildung und Forschung

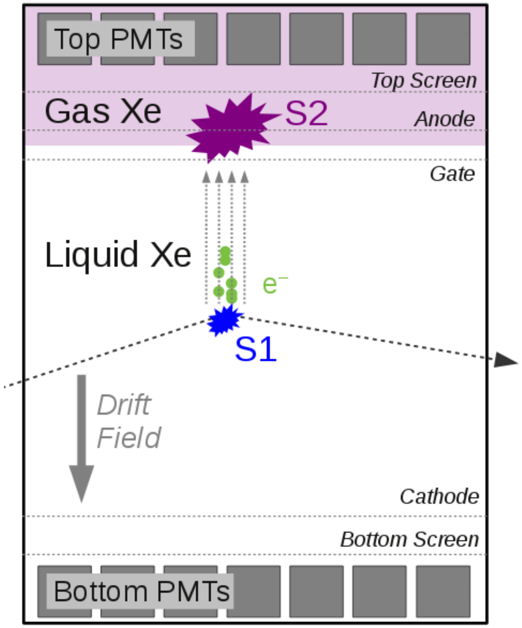
erc

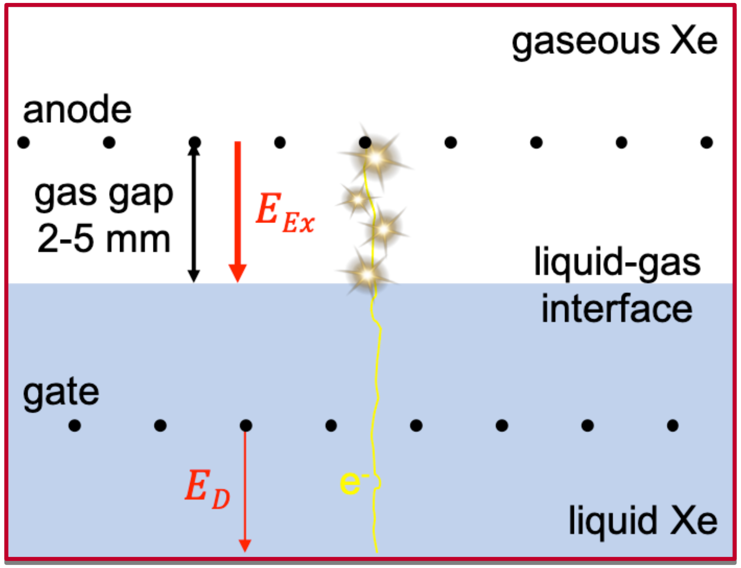
Single-phase TPC

universität freiburg

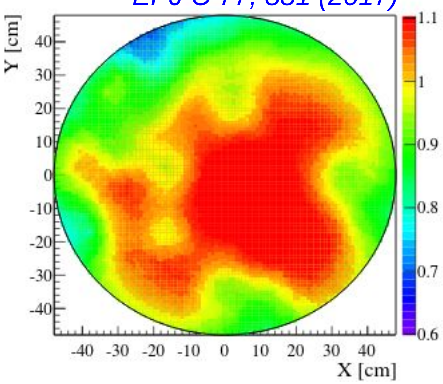
Motivation

JINST 17, P03027 (2022)
arXiv:2112.11844





EPJ C 77, 881 (2017)



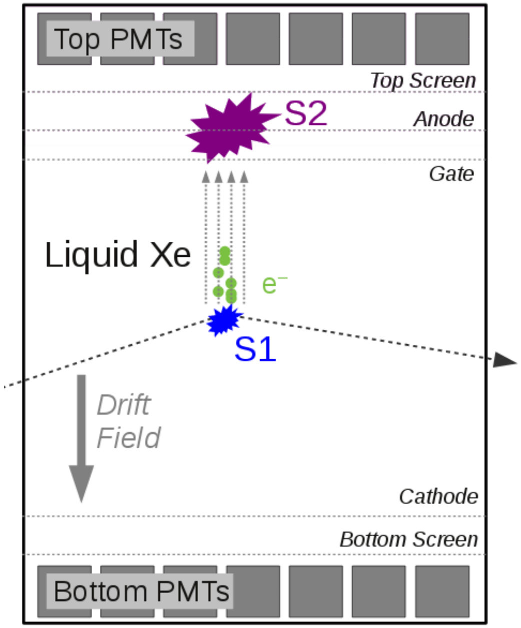
S2 signals on XENON1T top PMT array: ±20%

- well established technique
- good signal amplification

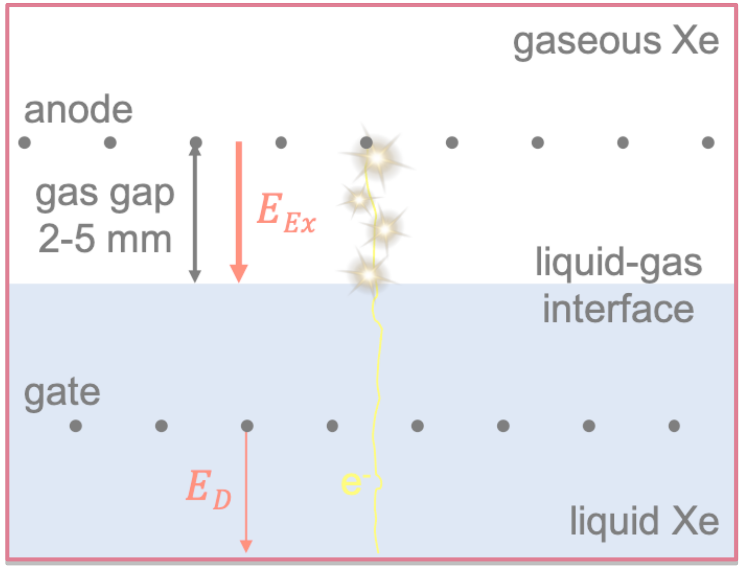
- requires precise LXe level
- inhomogeneous response
- wide signals (~1 µs)
- electrode sagging: nonfunctional TPC if anode touches LXe surface

Motivation

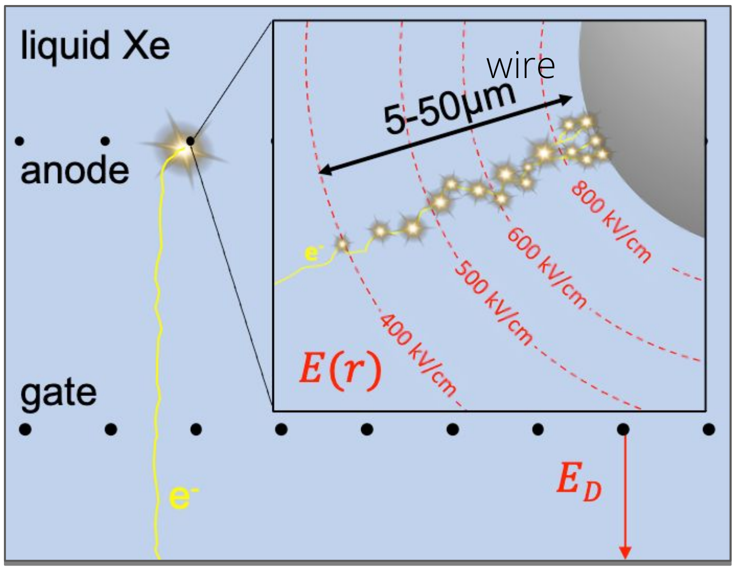
JINST 17, P03027 (2022)
arXiv:2112.11844



Dual-Phase TPC

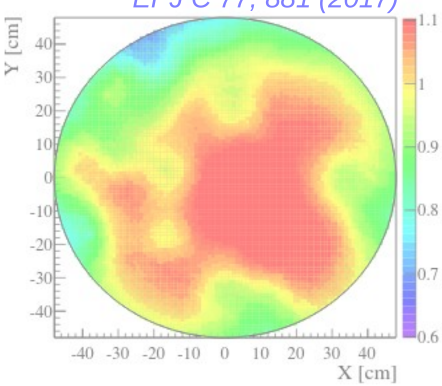


Single-Phase TPC



F. Kuger *et al* 2022 *JINST* 17 P03027

EPJ C 77, 881 (2017)



S2 signals on XENON1T top PMT array: ±20%

- well established technique
- good signal amplification

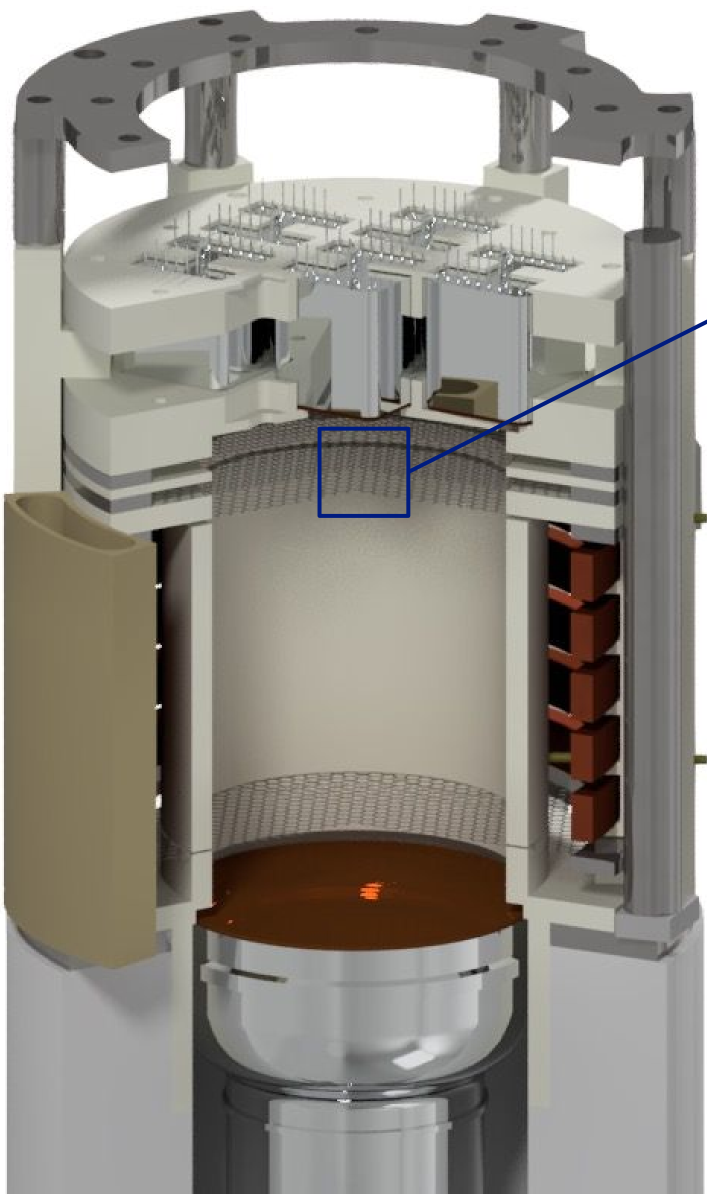
- requires precise LXe level
- inhomogeneous response
- wide signals (~1 µs)
- electrode sagging: nonfunctional TPC if anode touches LXe surface

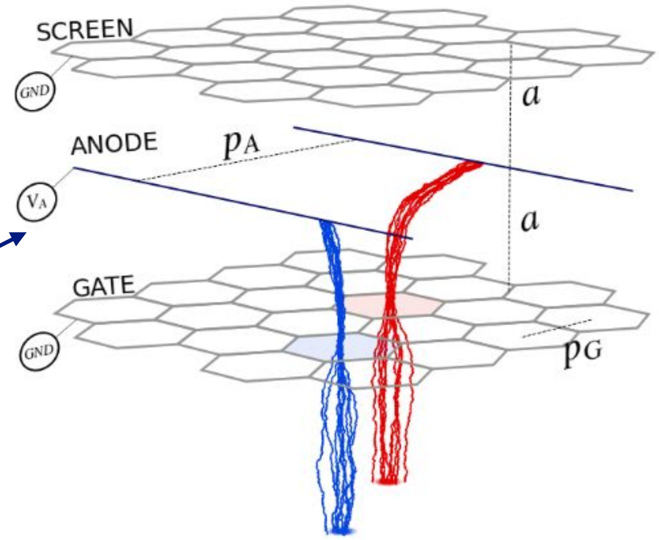
- local signal generation
  → homogeneous response
  → ~~sagging~~, lightweight electrodes
- no liquid-gas interface
- fast signals

- very high fields required
  → thin wires + high voltage
- signal amplification?
- does it even work?

?

The **first** single-phase TPC





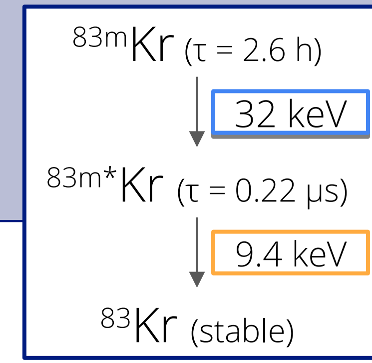
Proof-of-concept: 1 wire
Aprile *et al*, *JINST* 9, P11012 (2014)

Radial TPC (1 wire)
Wei *et al*, *JINST* 17, C02002 (2022)

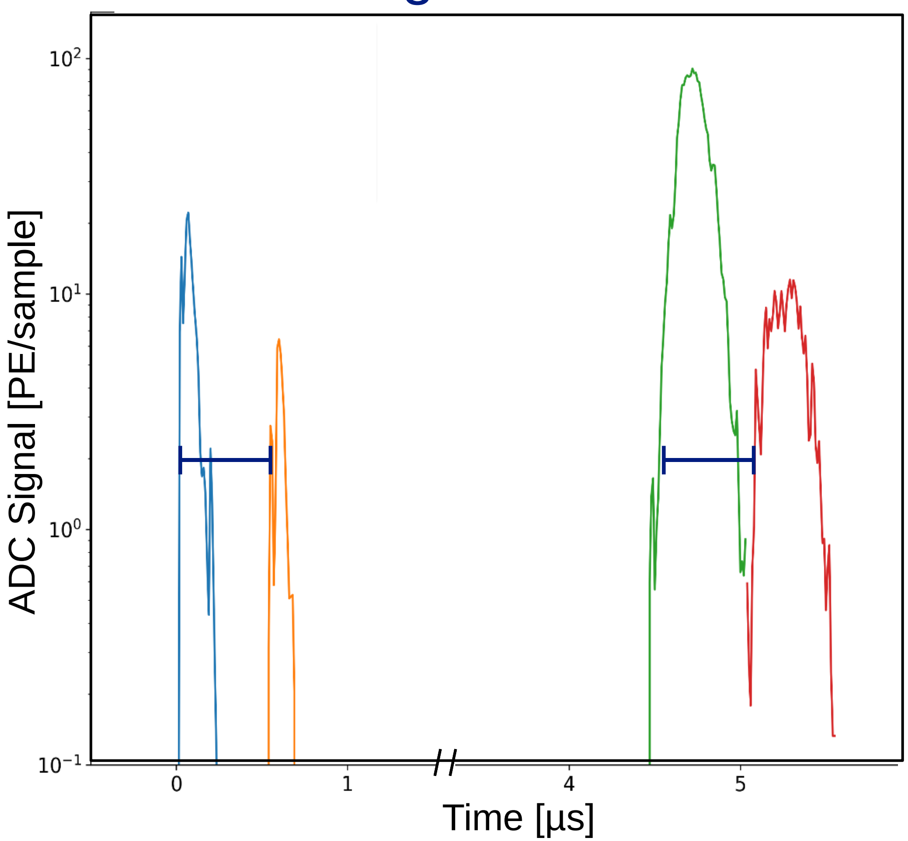
Simulation study multi-wire TPC
Kuger et al, JINST 17, P03027 (2022)

- 70 mm TPC, 0.8 kg LXe target
- top PMTs: 7x R8520
  bottom: 1x R11410
- TPC was previously operated in dual-phase mode
  JINST 18, T02004 (2023)
- gate, cathode, screen: SS etched hex mesh
  (d=200 µm, 5 mm opening)
- **wire anode: Ø=10µm, pitch=10mm, Au-plated W**
  voltage range: 3.0 – 4.6 kV

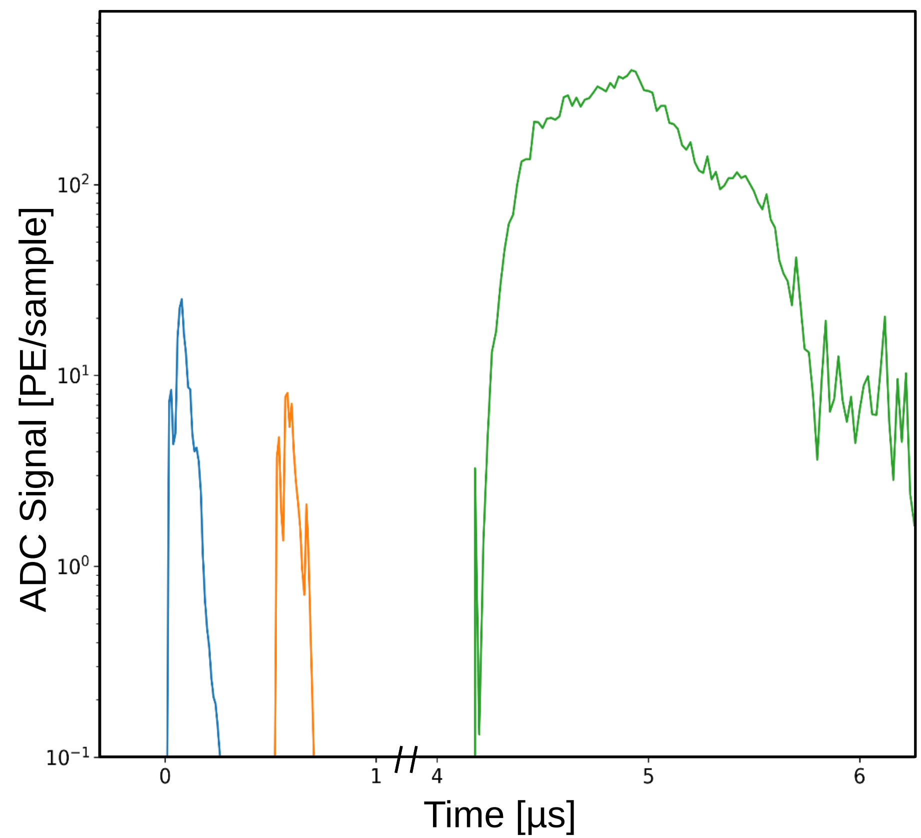
Signal Width



Single Phase

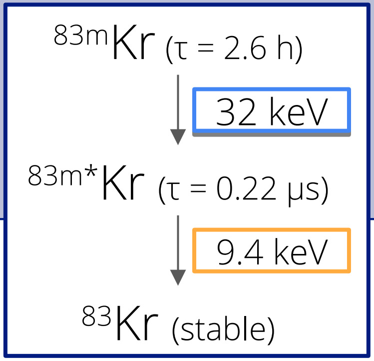


Dual Phase

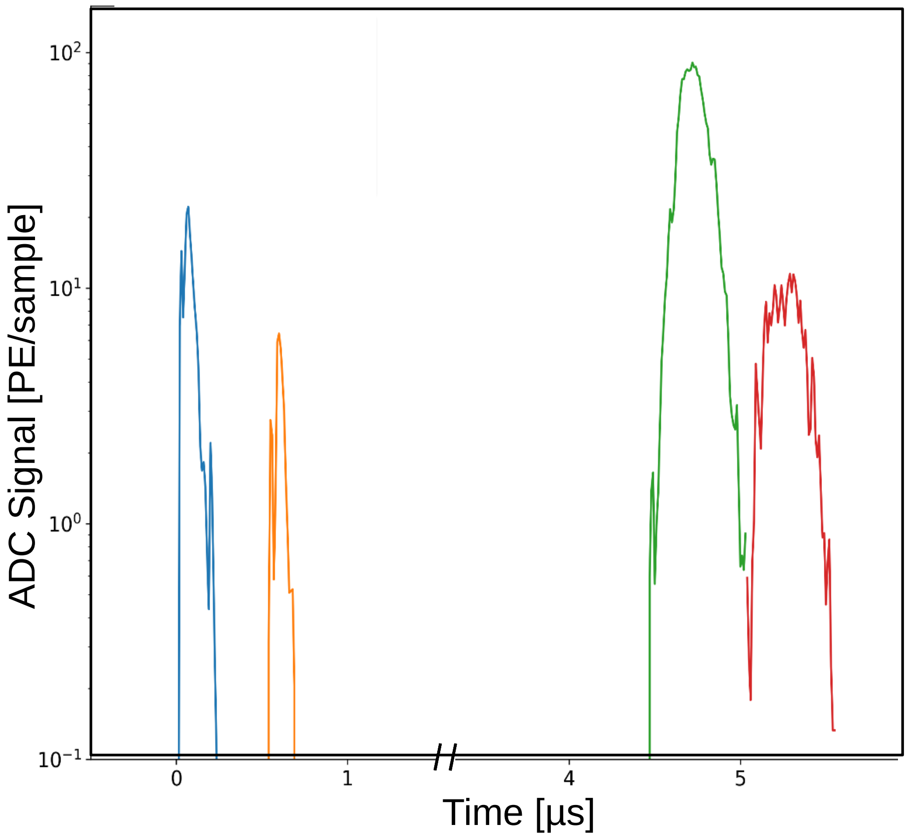


- S2 signals much faster → facilitate signal detection/timing

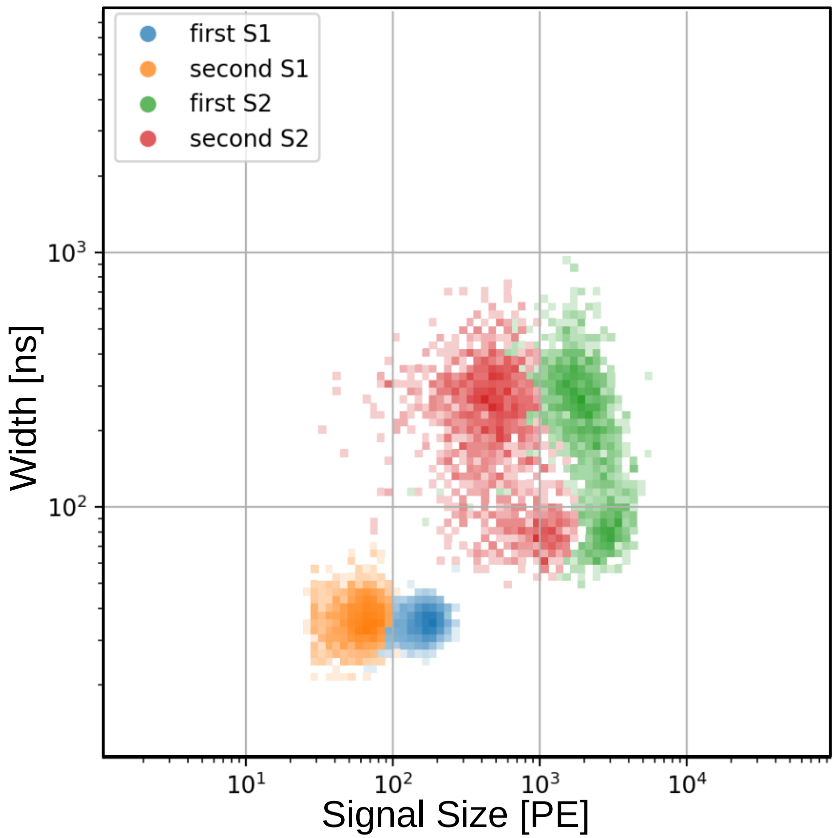
Signal Width



Single Phase

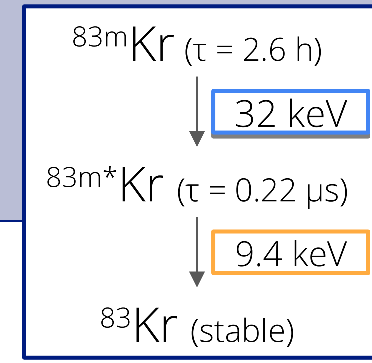


Single Phase

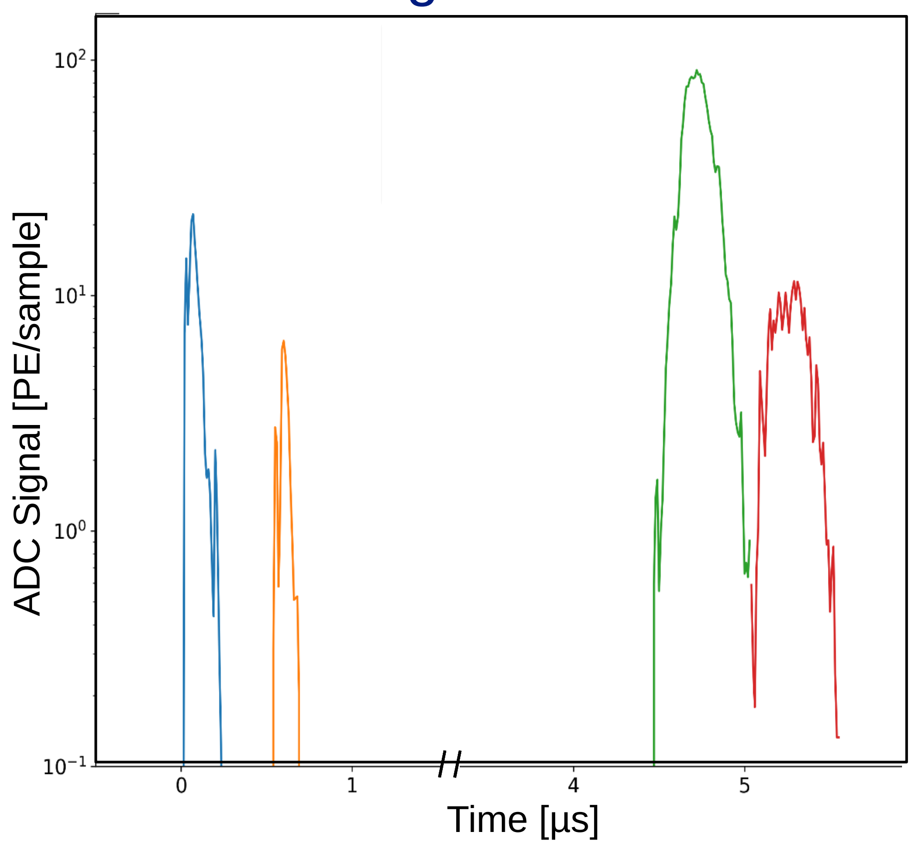


- S2 signals much faster → facilitate signal detection/timing

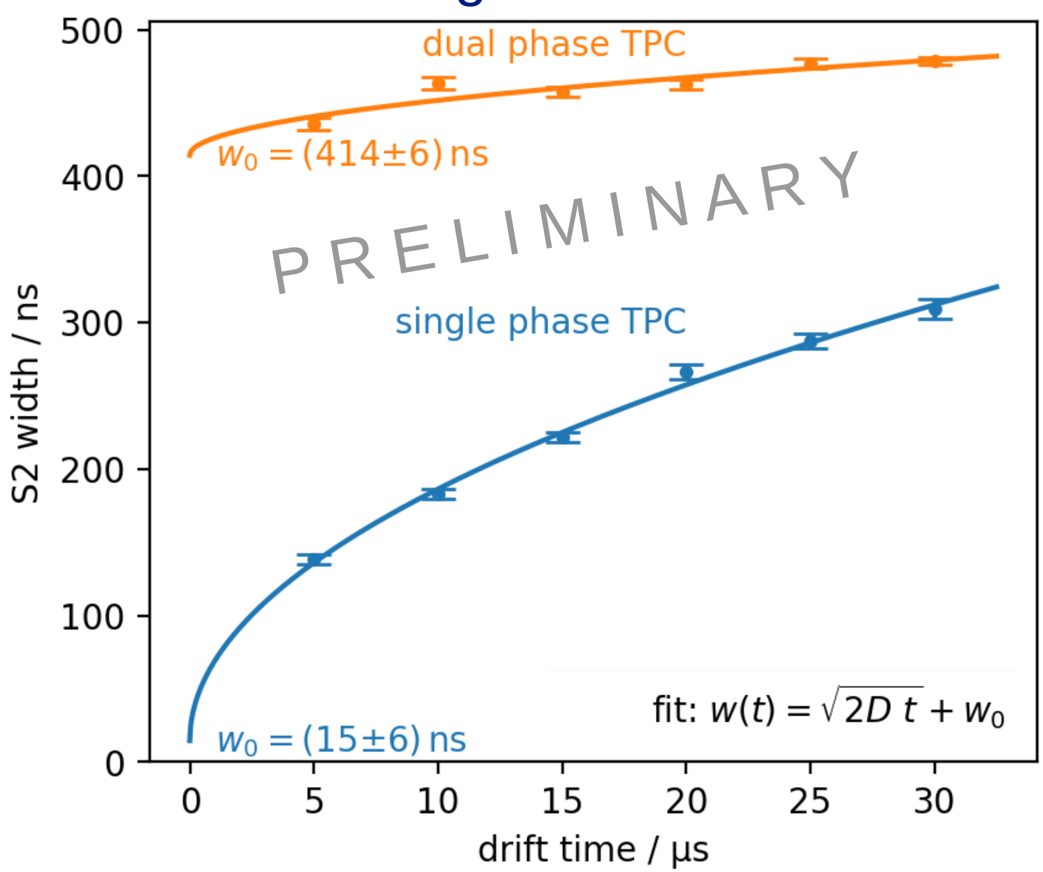
Signal Width



Single Phase



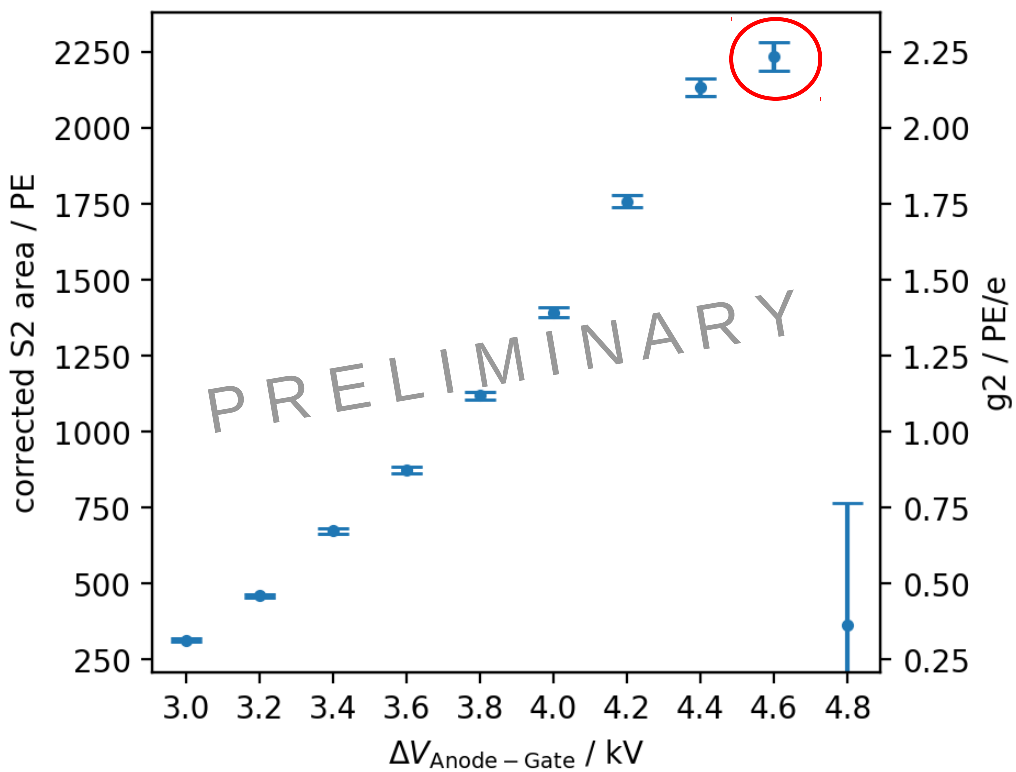
Single Phase



- S2 signals much faster → facilitate signal detection/timing
- width is diffusion limited (dual phase limited by signal generation)

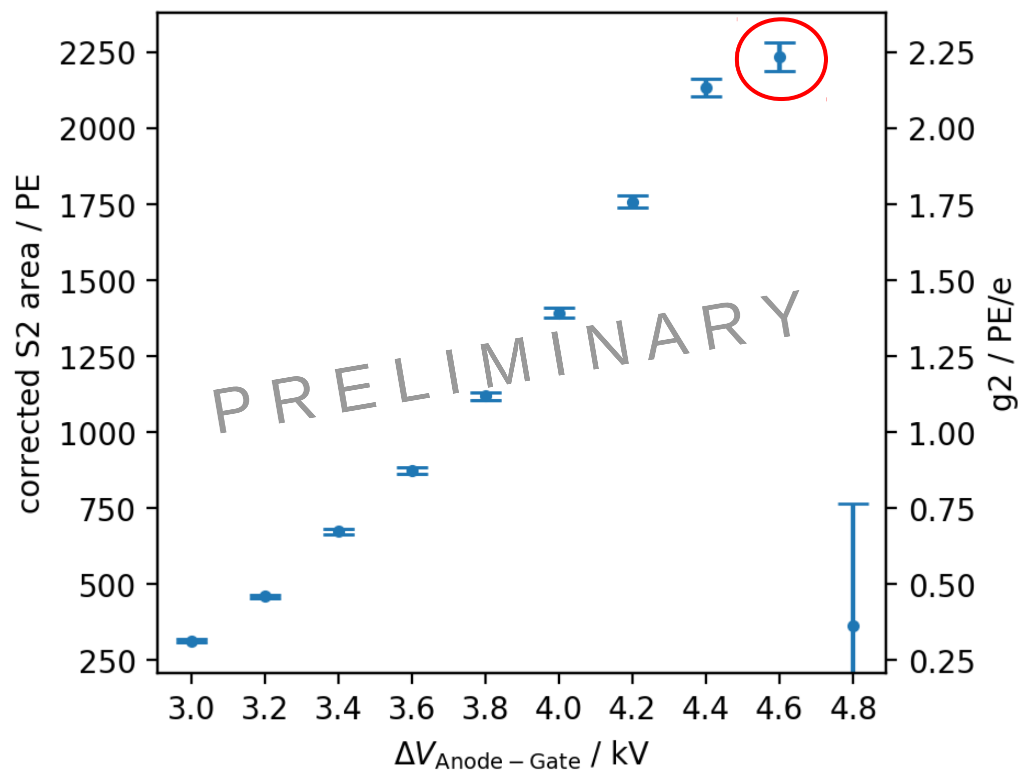
Charge Amplification Factor

- expected exponential signal dependence on anode field observed
- break-down effects above V=4.6 kV limit performance
  → investigation ongoing
- NEST prediction:
  ~1000 e^- created for ^{83m}Kr
  → ~2200 PE detected @ 4.6 kV
- $g_2 = 2.23 \pm 0.05$ PE/e^-
  rather low but not unexpected!
  (g_2=17.6 PE/e^- in dual phase mode)
- g_1~0.10 PE/γ
  as in dual phase mode
- analysis ongoing



Charge Amplification Factor

- expected exponential signal dependence on anode field observed
- break-down effects above V=4.6 kV limit performance
  → investigation ongoing
- NEST prediction:
  ~1000 e^- created for ^{83m}Kr
  → ~2200 PE detected @ 4.6 kV
- g_2 = 2.23 ± 0.05 PE/e^-
  rather low but not unexpected!
  (g_2=17.6 PE/e^- in dual phase mode)
- g_1~0.10 PE/γ
  as in dual phase mode
- analysis ongoing



Conclusion II

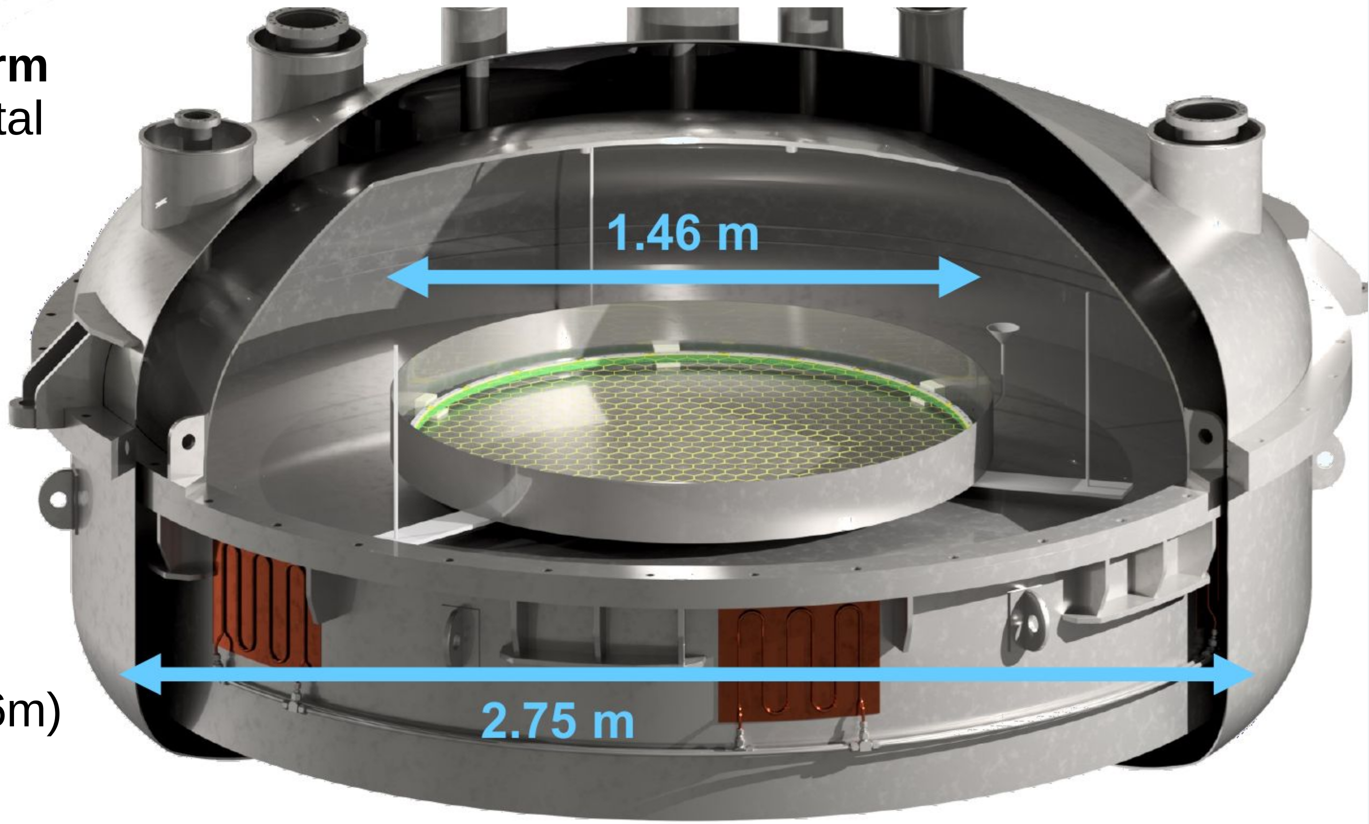
- operated single-phase TPC
- promising narrow S2 signals
- S2 signal size not yet competitive

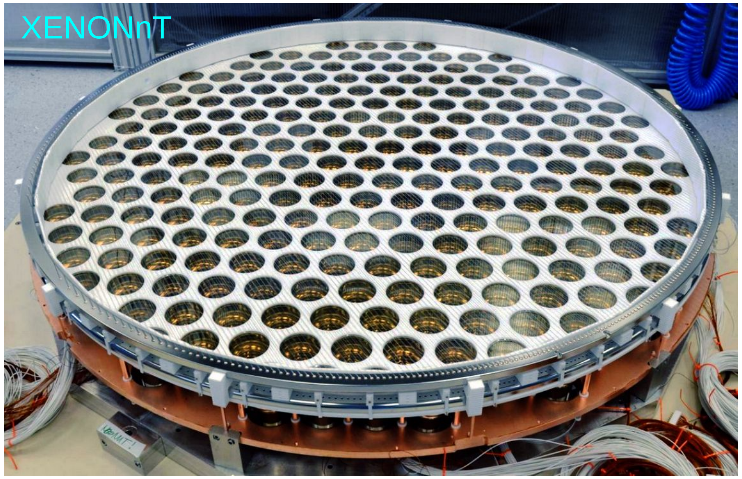
PANCAKE Detector Test Platform

universität freiburg

PANCAKE

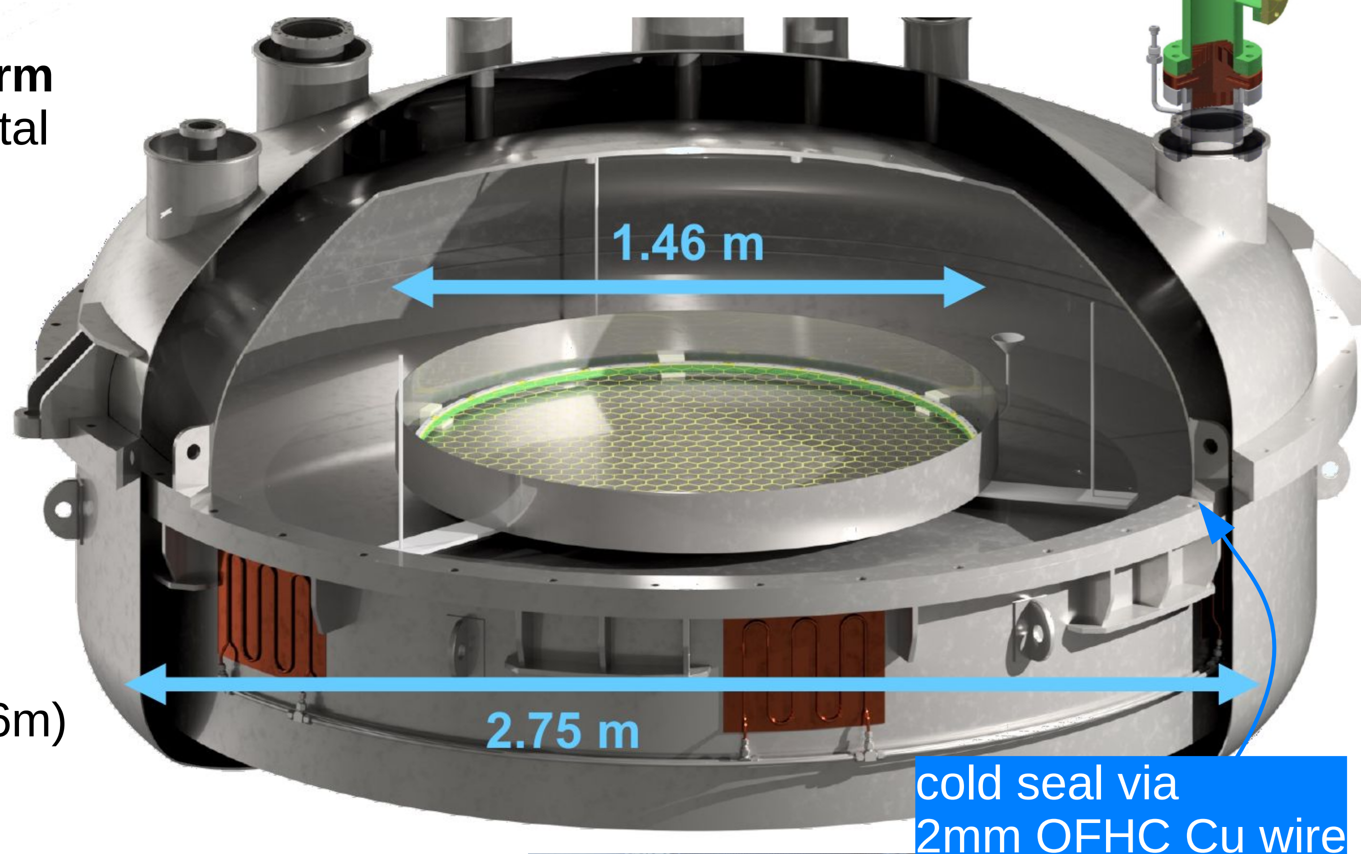
- DARWIN **LXe test platform** in Freiburg to test horizontal TPC components (electrodes …)
- **unique facility**
- double wall cryostat;
- **flat floor** (inner vessel)
- 2.75 m inner diameter
  → up to ~15 cm height
- ~400 kg Xe gas available
  → smaller „bathtub“ (1.46m)
  → LXe level: 6 cm



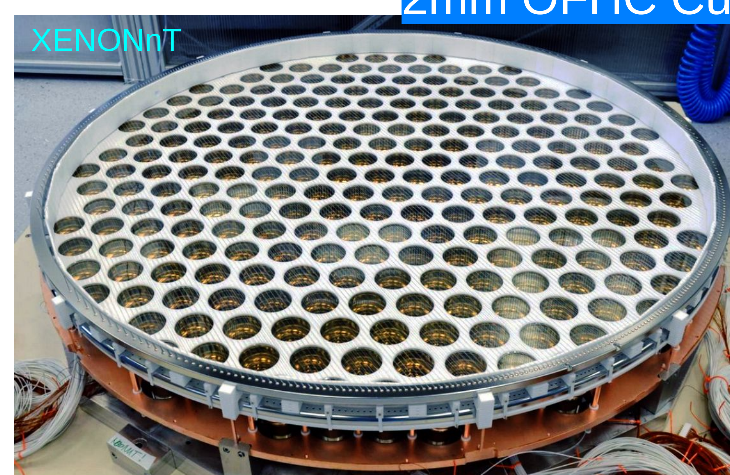


PANCAKE

- DARWIN **LXe test platform** in Freiburg to test horizontal TPC components (electrodes …)
- **unique facility**
- double wall cryostat;
- **flat floor** (inner vessel)
- 2.75 m inner diameter
  → up to ~15 cm height
- ~400 kg Xe gas available
  → smaller „bathtub“ (1.46m)
  → LXe level: 6 cm



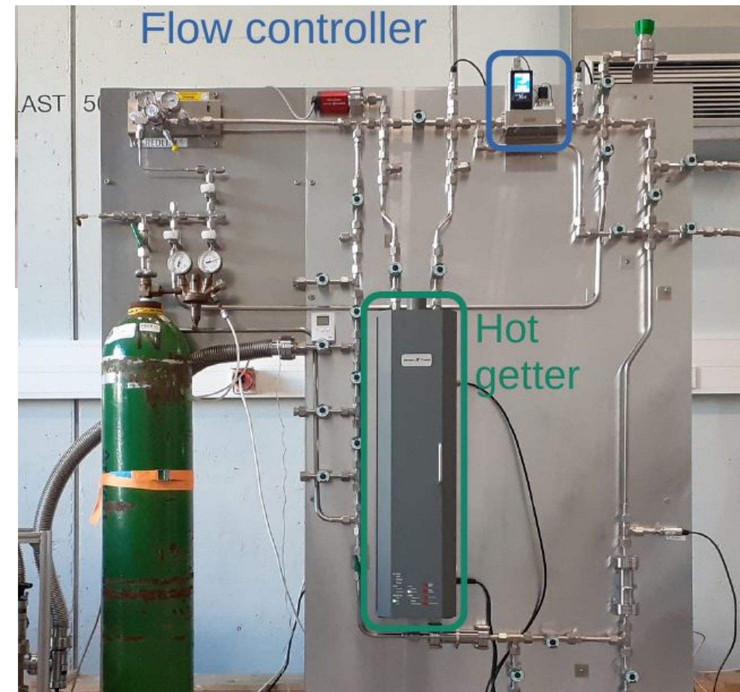
- **LN_2 Cooling** compensates ~80 heat intake
  - „fast“ cooling pads O(kW)
    to initially cool 3t of steel (~2 weeks)
  - **Thermosyphon** 200 W
    to operate in LXe mode

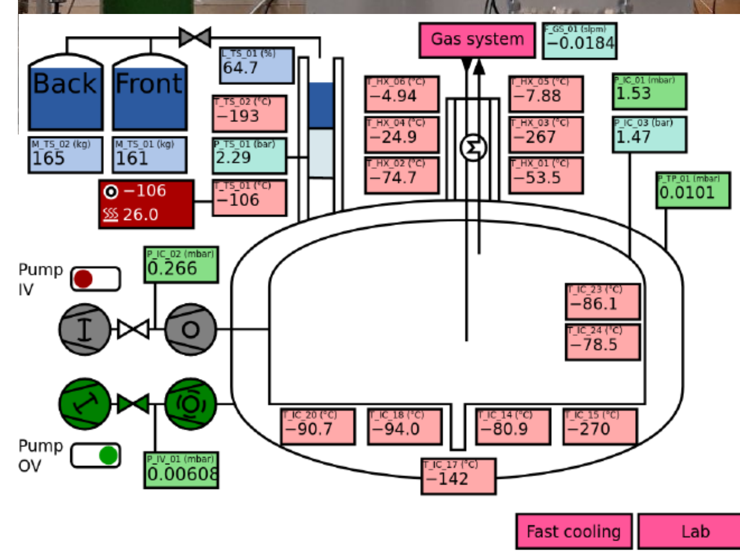


Xenon Handling

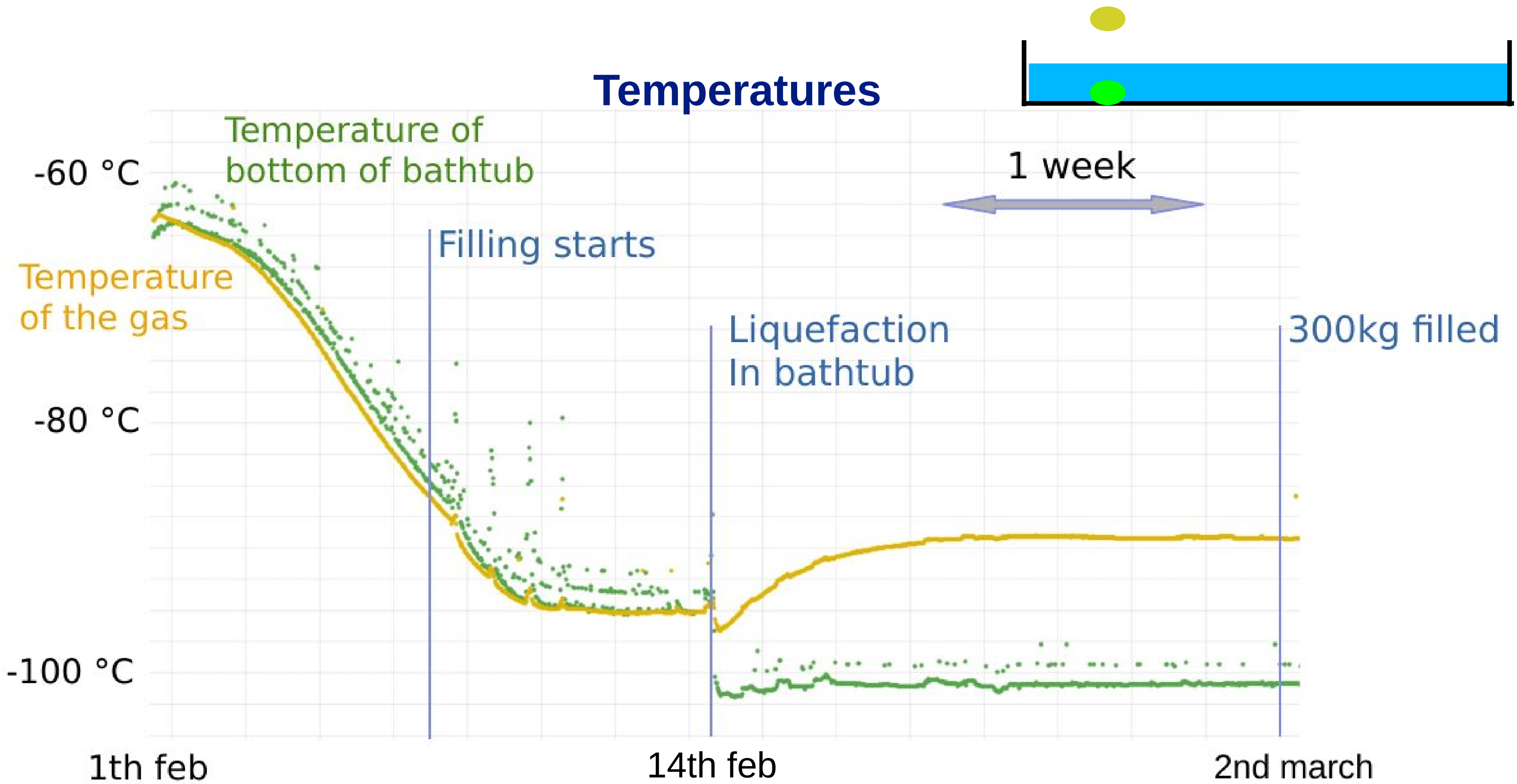
- Current Xe inventory: 380 kg
- 300 kg + 300 kg cold+warm **storage** in bottles
- **Recuperation** via cryogenic pumping
- Safety: 1 bottle cold during operation
- Gas **purification** flow via
  – heat exchanger (95%+)
  – SAES getter,
  – KNF diaphragm pump
  → 1/2“ VCR piping

- Sophisticated slow control system **Doberman**
  → web based, secure client&server, visualization, alarms (automated) control
  evolution of JINST 11, T09003 (2016)



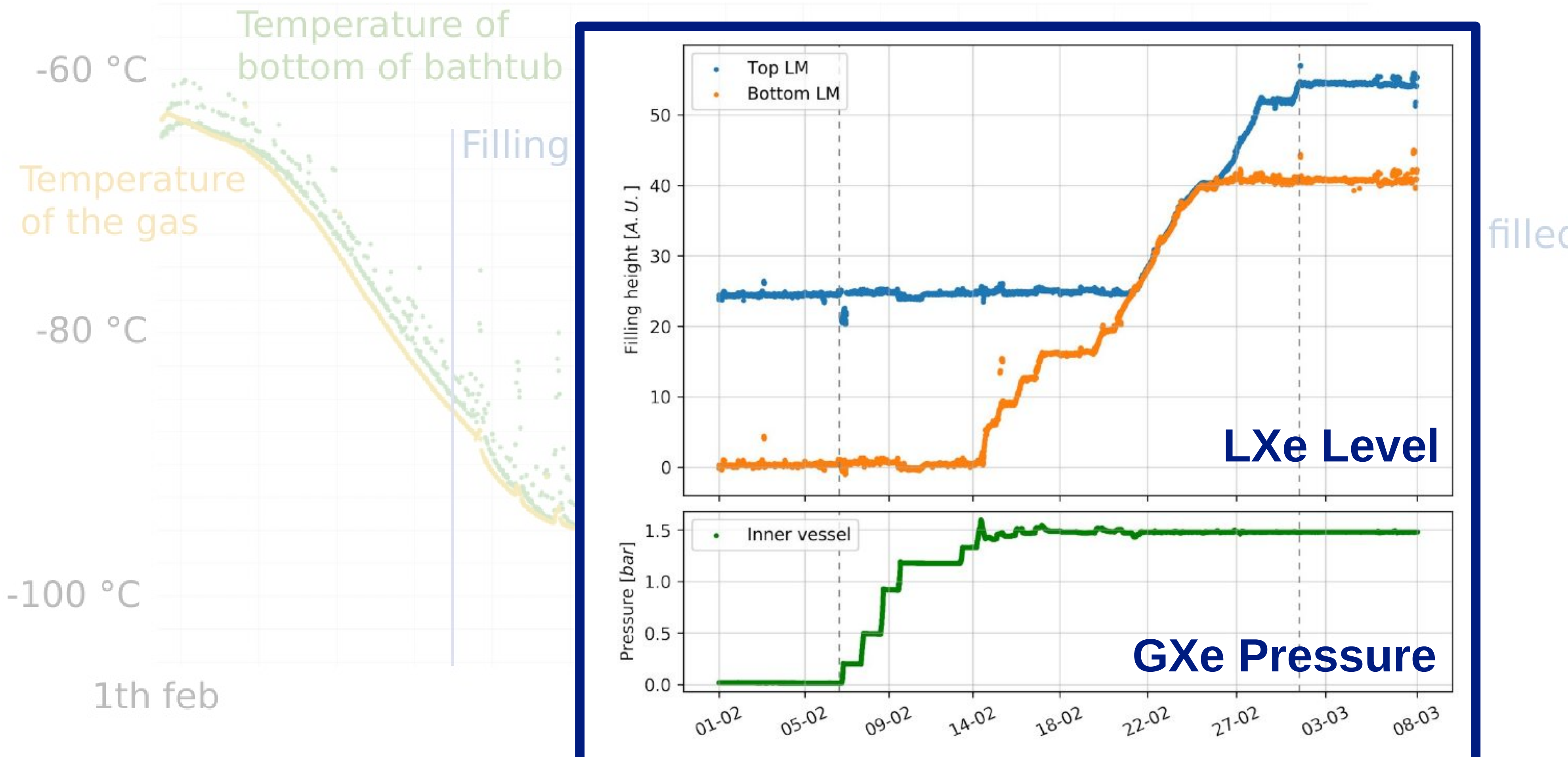


Cool-Down and Filling



Cooling down 3t of steel takes time; filling procedure was not yet optimized for speed.

Cool-Down and Filling



Cooling down 3t of steel takes time; filling procedure was not yet optimized for speed.

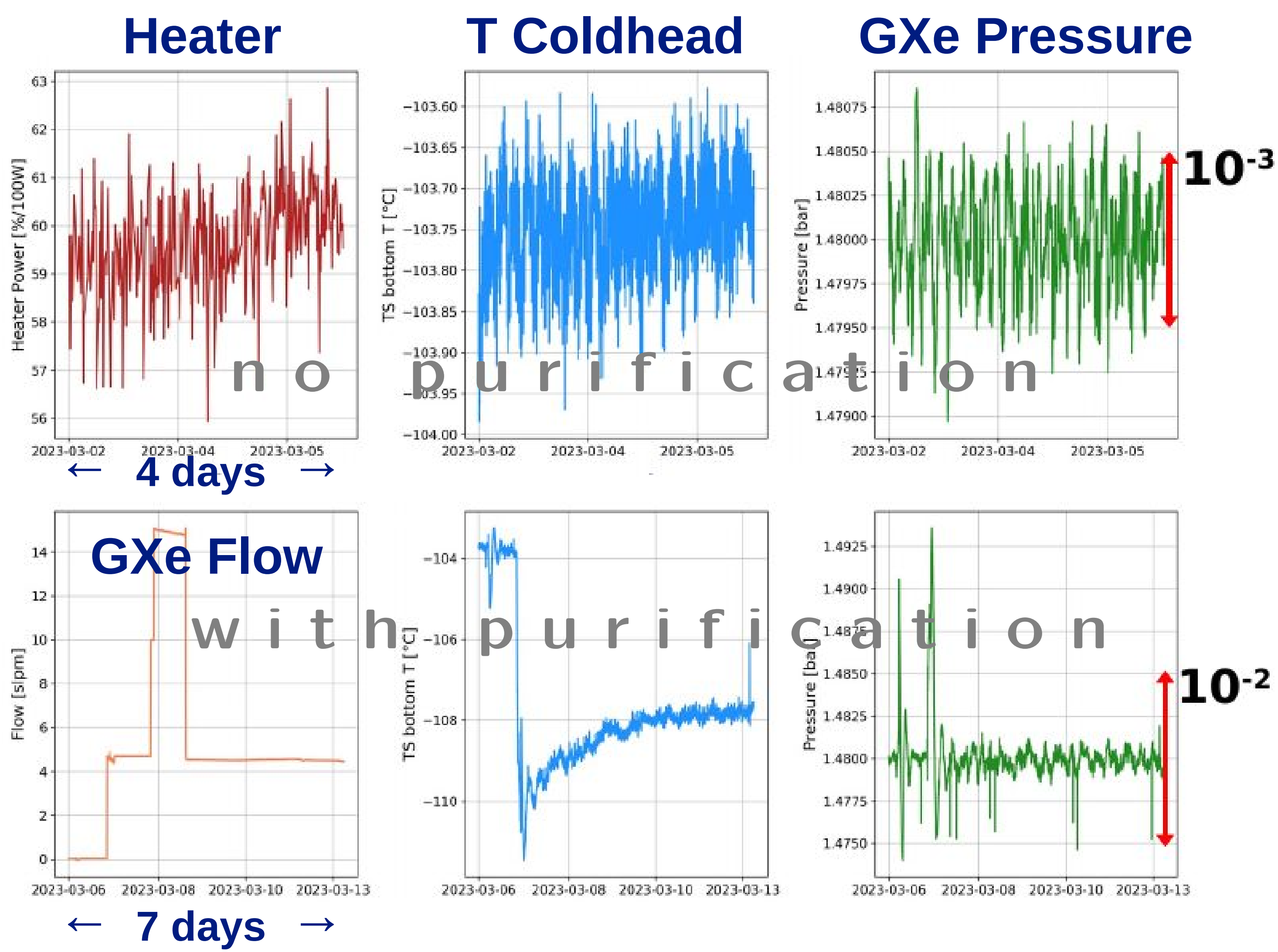
LXe Filling

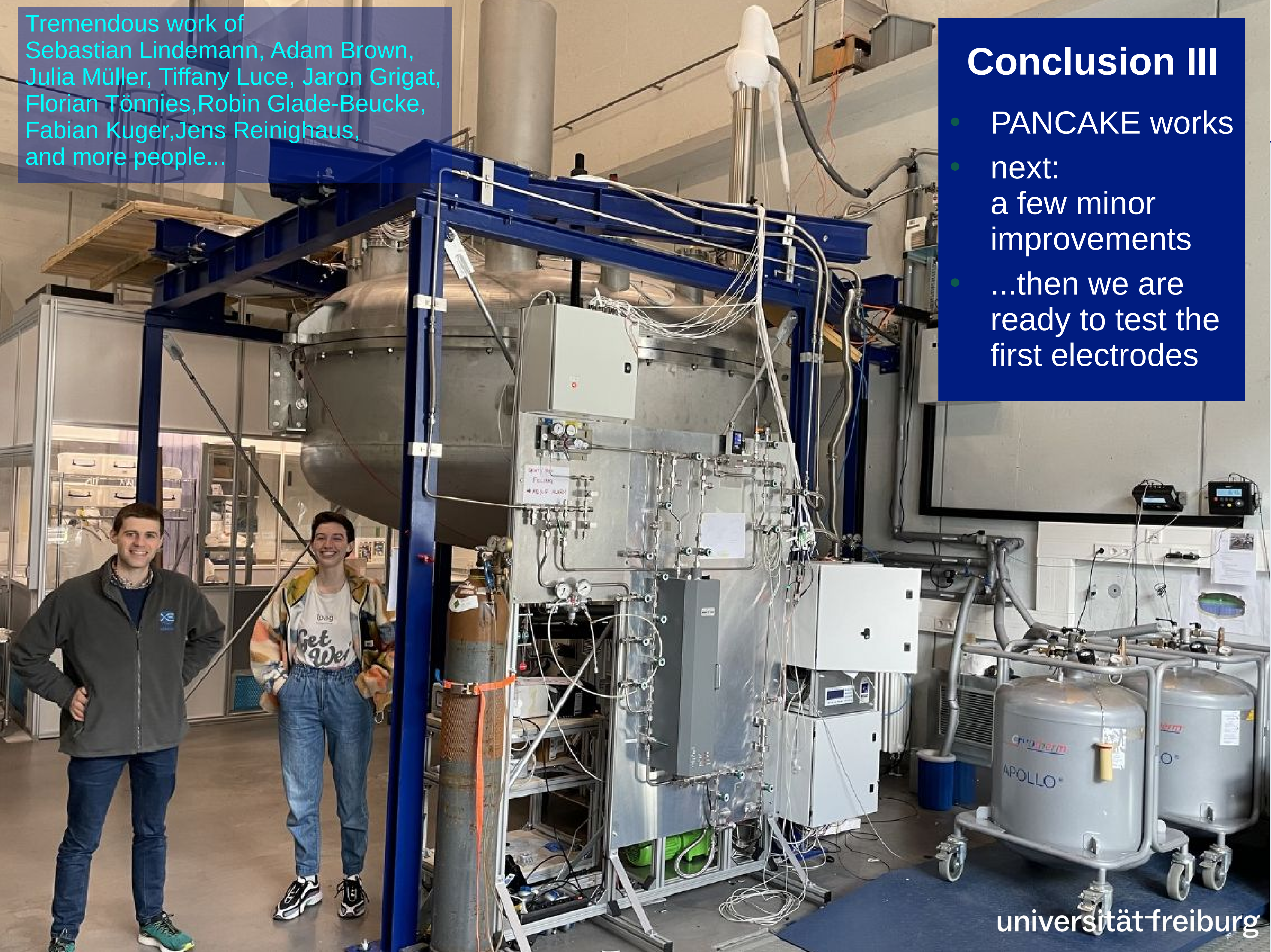
14 days in 10 seconds

PANCAKE is equipped with cameras.

Stable Operation

- filled PANCAKE was operated stably for 11 days
- test of gas purification system (15 and 5 slpm)
  - → Xe pressure stable within a few 10^{-3}
- very efficient heat exchanger





Tremendous work of
Sebastian Lindemann, Adam Brown,
Julia Müller, Tiffany Luce, Jaron Grigat,
Florian Tönnies,Robin Glade-Beucke,
Fabian Kuger,Jens Reinighaus,
and more people...

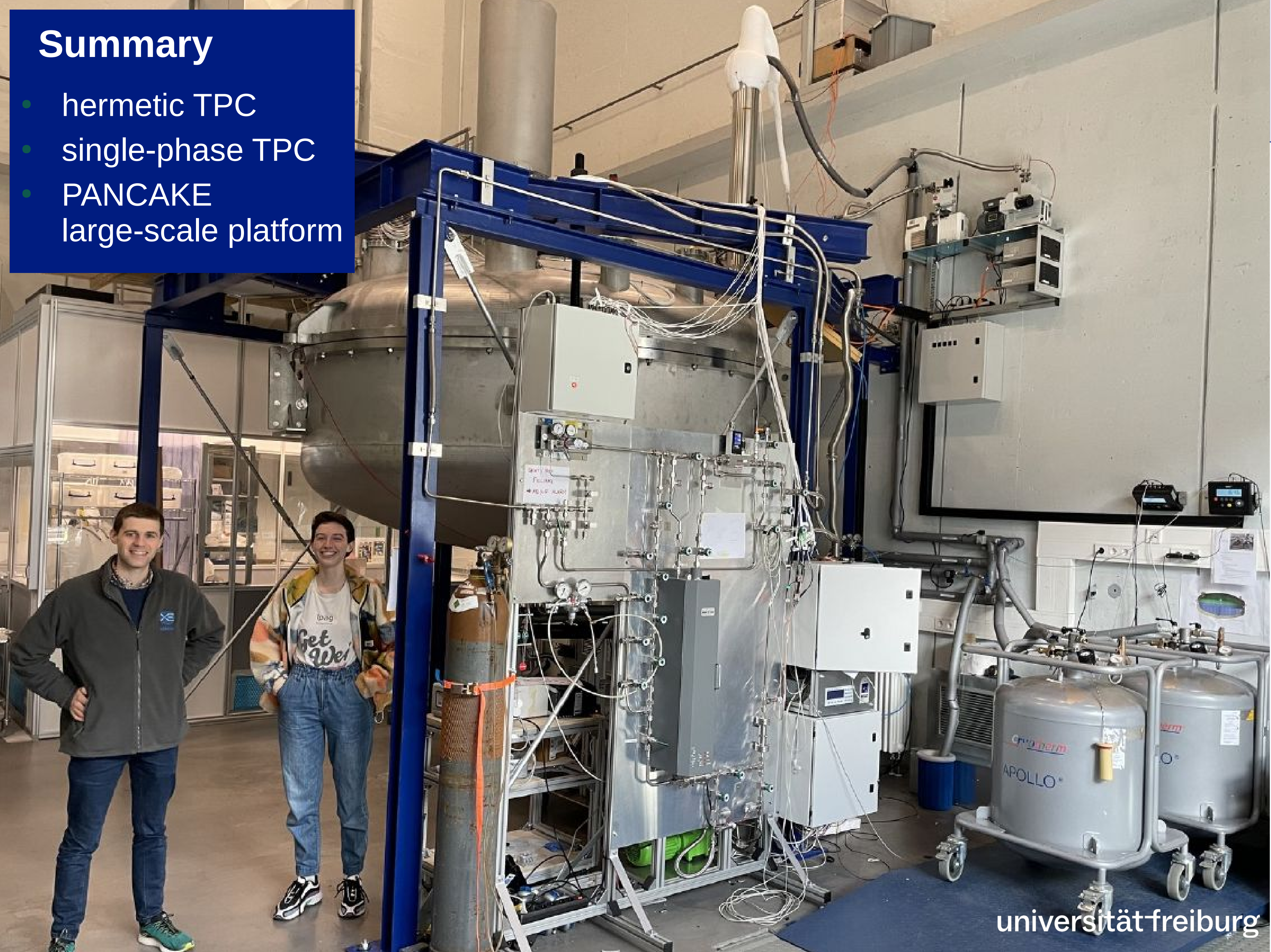
Conclusion III

- PANCAKE works
- next:
  a few minor improvements
- ...then we are ready to test the first electrodes

universität freiburg

Summary

- hermetic TPC
- single-phase TPC
- PANCAKE
  large-scale platform



universität freiburg