New searches in astroparticle physics with noble element detectors enabled by developments in SiPM technology

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Carleton University

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Overview

- New searches in astroparticle physics
  - Dark matter detection
  - Neutrino detection
  - Neutrinoless double beta decay ($0\nu\beta\beta$)
- Noble elements in detectors
- Silicon photomultipliers (SiPMs)
  - Key requirements: high photon detection efficiency, low noise, low radioactivity
  - Analog SiPM
  - Digital SiPM
- Brief tour of experiment designs
  - Examples taken from astroparticle physics, with Canadian participation

Astroparticle physics

- Looking for rare signals to answer fundamental physics questions:
  - What is dark matter?
  - What are the properties of neutrinos?
  - Are neutrinos their own antiparticles?
  - Why is there more matter than antimatter in the universe?
- Detecting particles of cosmic origin
  - … or not (neutrino*less*)
- Using large underground detectors
  - Multi-tonnes scale, multi-year exposure

Canadian Subatomic Physics Long Range Plan 2022-2026

Detectors with noble elements

- Target material doubles as an excellent scintillator
  - High purity material transparent to own **UV scintillation light**
  - Ionization signal can also be collected separately
- Most common noble elements used:
  - Helium
    - Sensitive to lower-energy nuclear recoils
    - Hard to operate, even harder to scale
  - Argon
    - Easier to scale, though large detectors require underground argon (UAr) depleted in ^{39}Ar
  - Xenon
    - Higher signal cross-sections, and 0νββ candidate isotope ^{136}Xe
    - Proposed experiments represent significant fraction of annual world supply

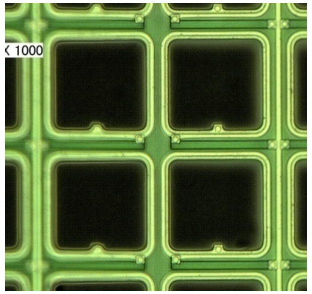
Noble elements:
Atomic number
Boiling point [K]

Scintillation peak wavelength	
LHe	80 nm
LNe	80 nm
LAr	128 nm
LKr	150 nm
LXe	175 nm
LRn	*forget it*

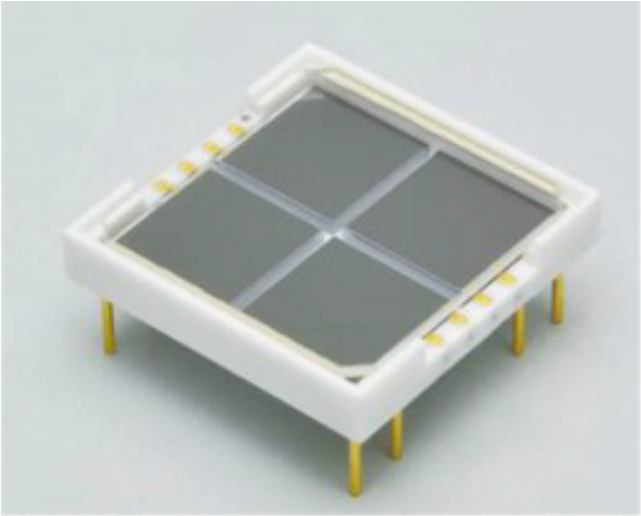
Atomic number			Boiling point [K]
2	He	Helium	4.22
10	Ne	Neon	27.07
18	Ar	Argon	87.3
36	Kr	Krypton	119.93
54	Xe	Xenon	165.03

Silicon photomultipliers (SiPMs)

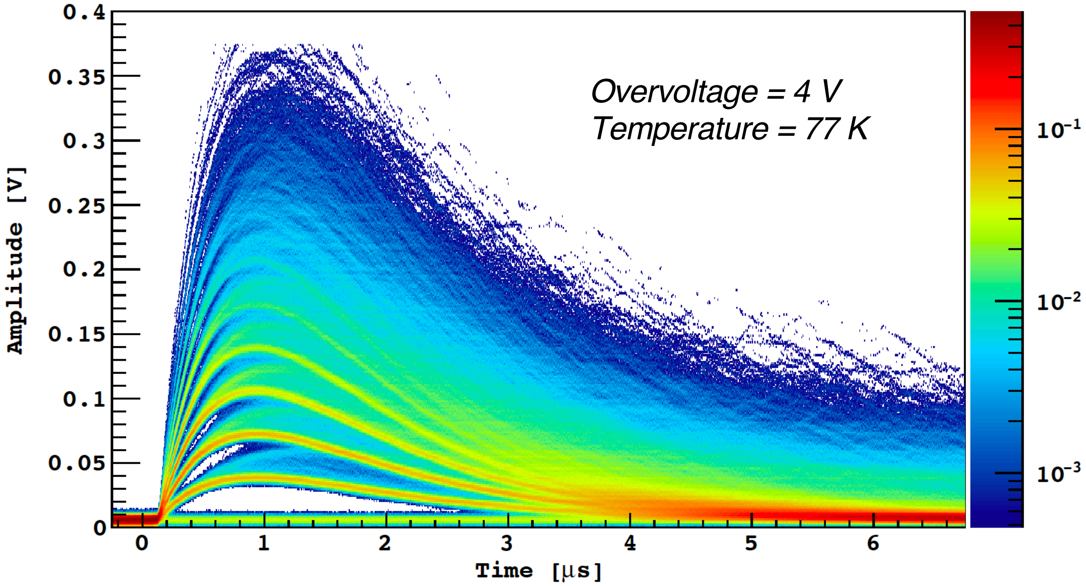
- **2D array of single-photon avalanche diodes (SPADs)**
  - Operated in Geiger mode
    i.e. reverse bias > breakdown voltage
- Diodes typically connected in parallel: each array is read out as one channel
  - Signal proportional to number of photons detected
- Many advantages:
  - Low mass → **Low radioactivity**
  - Operating voltage around 50 V
  - Resistant to electromagnetic fields
  - Operation at noble liquid temperatures



SPADs: 50 x 50 μm²



Hamamatsu VUV4 MPPC 2x2 array



Example persistence plot from
FBK NUV-HD-LF-HRq SiPM

Photodetection and noise in SiPMs

- Signal photons
  - Electron-hole pair creation in high-field region causes avalanche, resulting in detectable charge pulse
- Dark count rate (DCR)
  - Thermal e-h pair creation, low at cryogenic temperatures
- Internal correlated avalanches
  - After-pulsing (AP): carrier trap and release
  - Direct cross-talk (DiCT)
  - Delayed cross-talk (DeCT)
- External cross-talk
  - Infrared light is emitted, travels and hits another SiPM

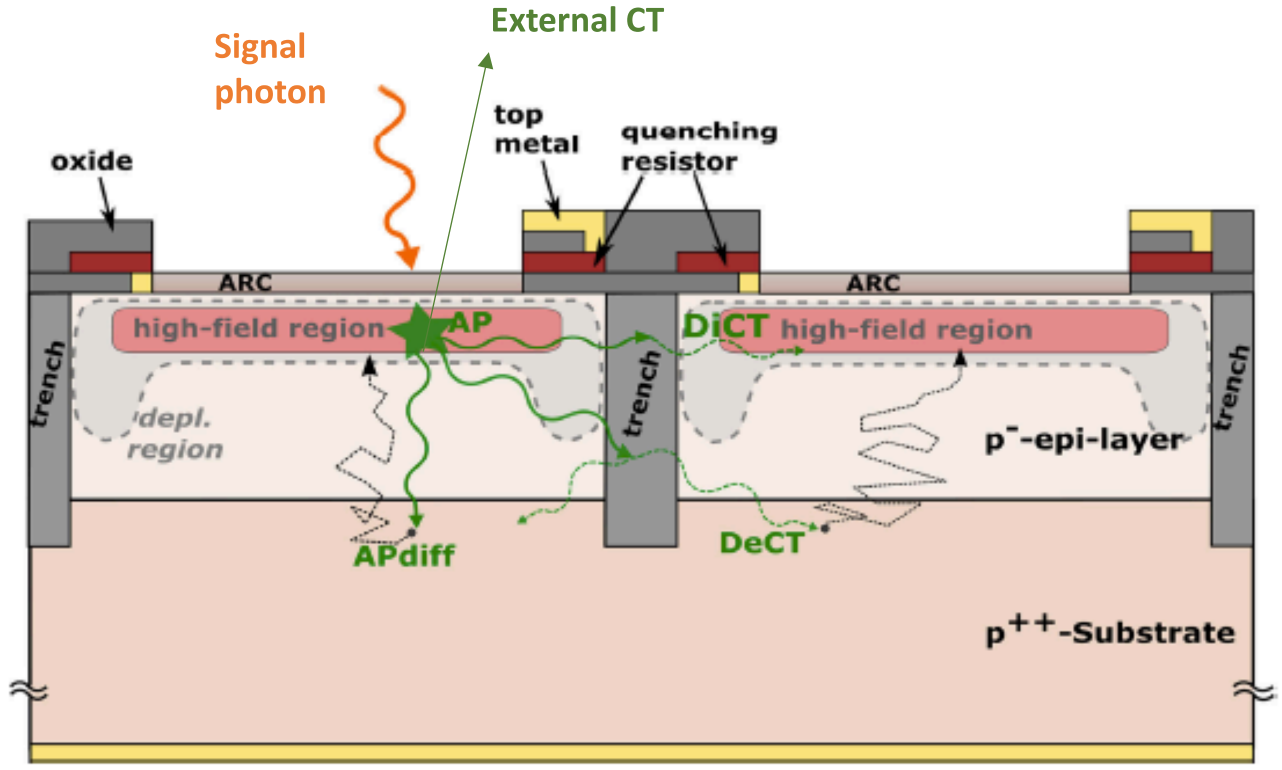


Fig. 1. Schematic representation of the internal structure of FBK Silicon photomultiplier, made in RGB-HD or RGB-UHD technology, with deep trenches between cells (SPADs).

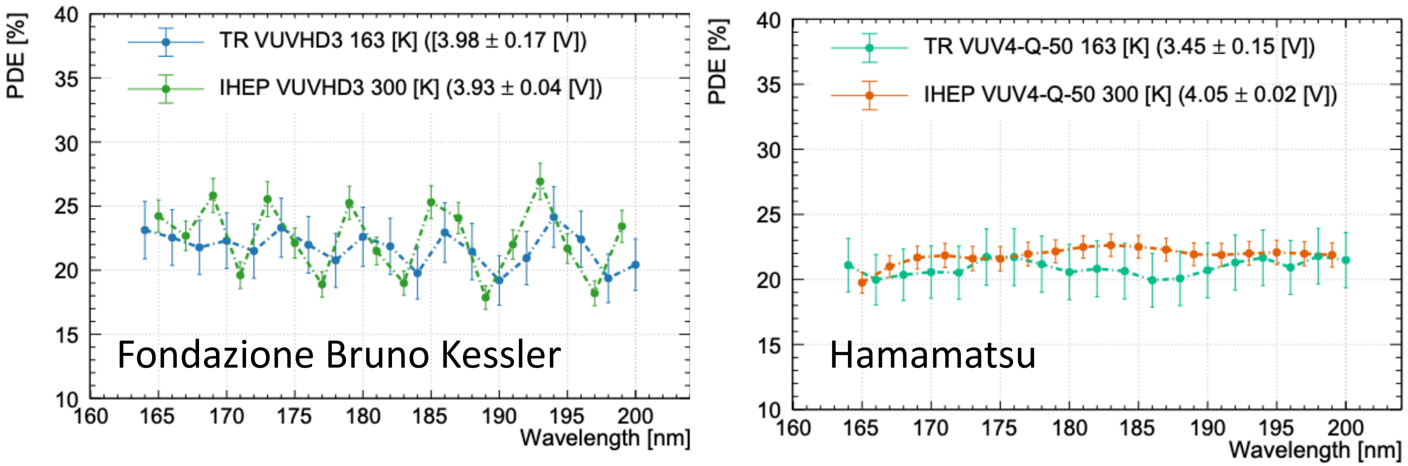
F. Acerbi et al. (2018) “"High Efficiency, Ultra-High-Density Silicon Photomultipliers," in IEEE Journal of Selected Topics in Quantum Electronics, 24, 2

Ultraviolet sensitivity

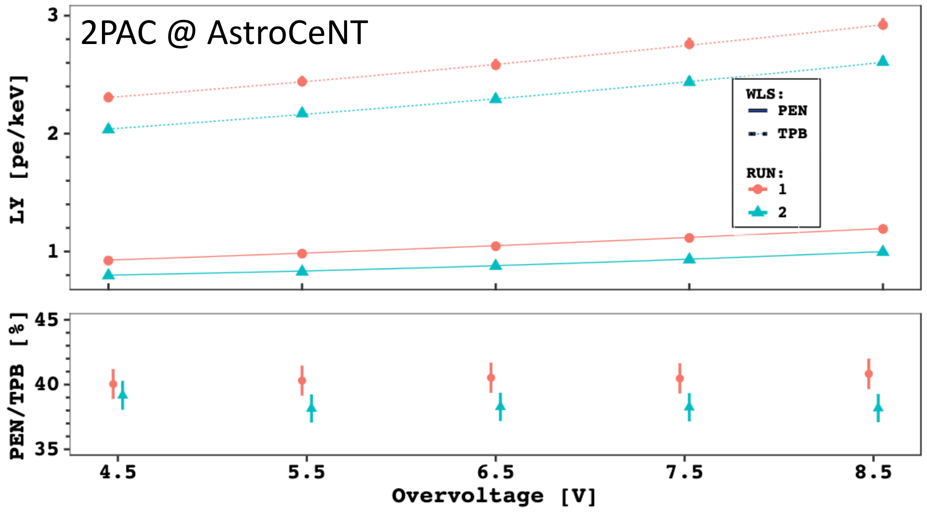
- Direct UV photon detection
  - Challenge: UV light in silicon has small absorption depth
    - High-field region must be close to surface
  - Achieved for LXe scintillation (175 nm)
    - Much harder for LAr scintillation (128 nm)

- Wavelength shifter (WLS)
  - Convert UV light to visible range
  - Examples:
    - Tetraphenyl butadiene (TPB)
    - Polyethylene naphthalate (PEN)

Photodetection efficiency (PDE)



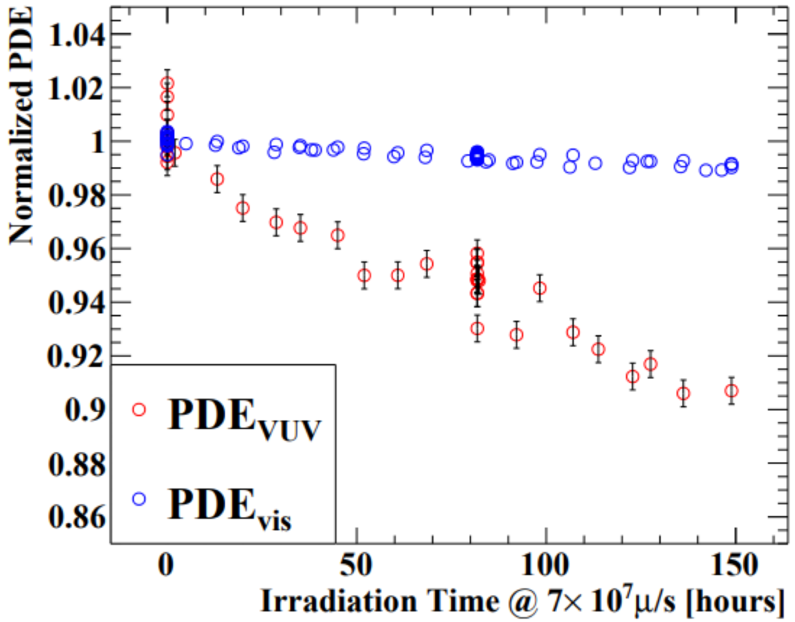
nEXO Collaboration: G. Gallina et al. (2022) EPJC 82, 1125, arXiv:2209.07765



M. Boulay et al. (2021) EPJC 81, 1099
arXiv:2106.15506

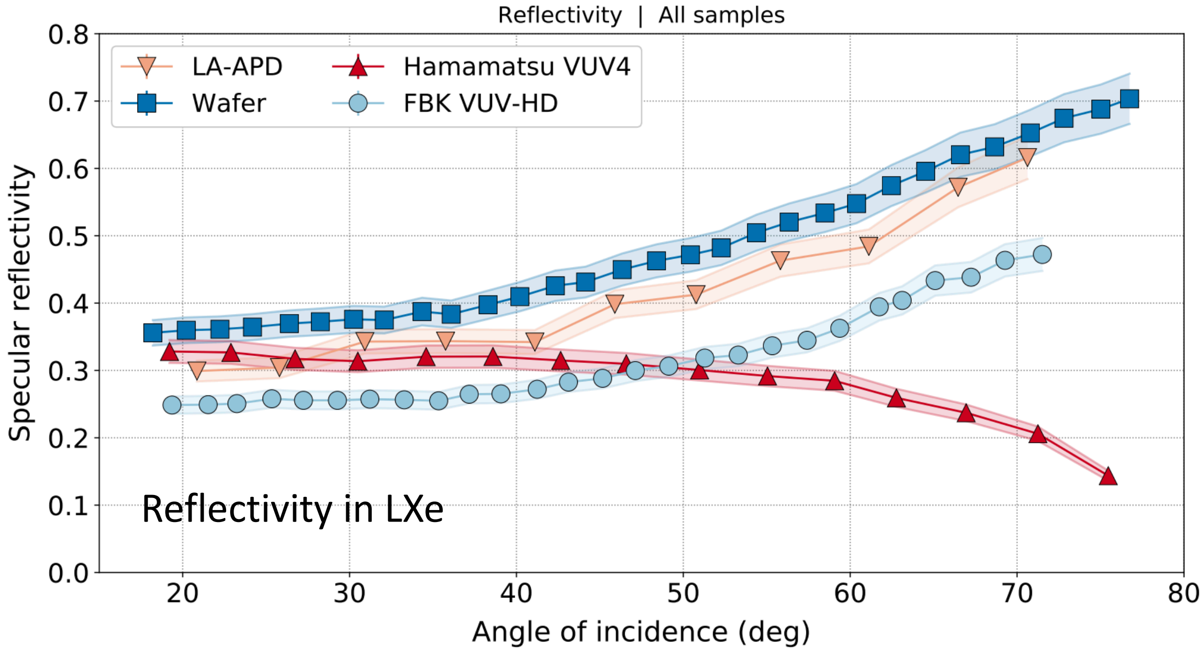
Risk mitigation: R&D on SiPMs for experiments

- Degradation of UV sensitivity due to radiation damage?
  - Observation by MEG II experiment
  - More of a concern at colliders and nuclear reactors



K. Ieki et al. (2022) NIMA 1053, 168365, arXiv: 2211.09882

- Optical modeling in noble liquids
  - Measurements in cryoliquid are necessary to validate models in simulations (NEST, GEANT4, Chroma…)



nEXO Collaboration: M. Wagenpfeil et al. (2021)
JINST 16, P08002, arXiv:2104.07997

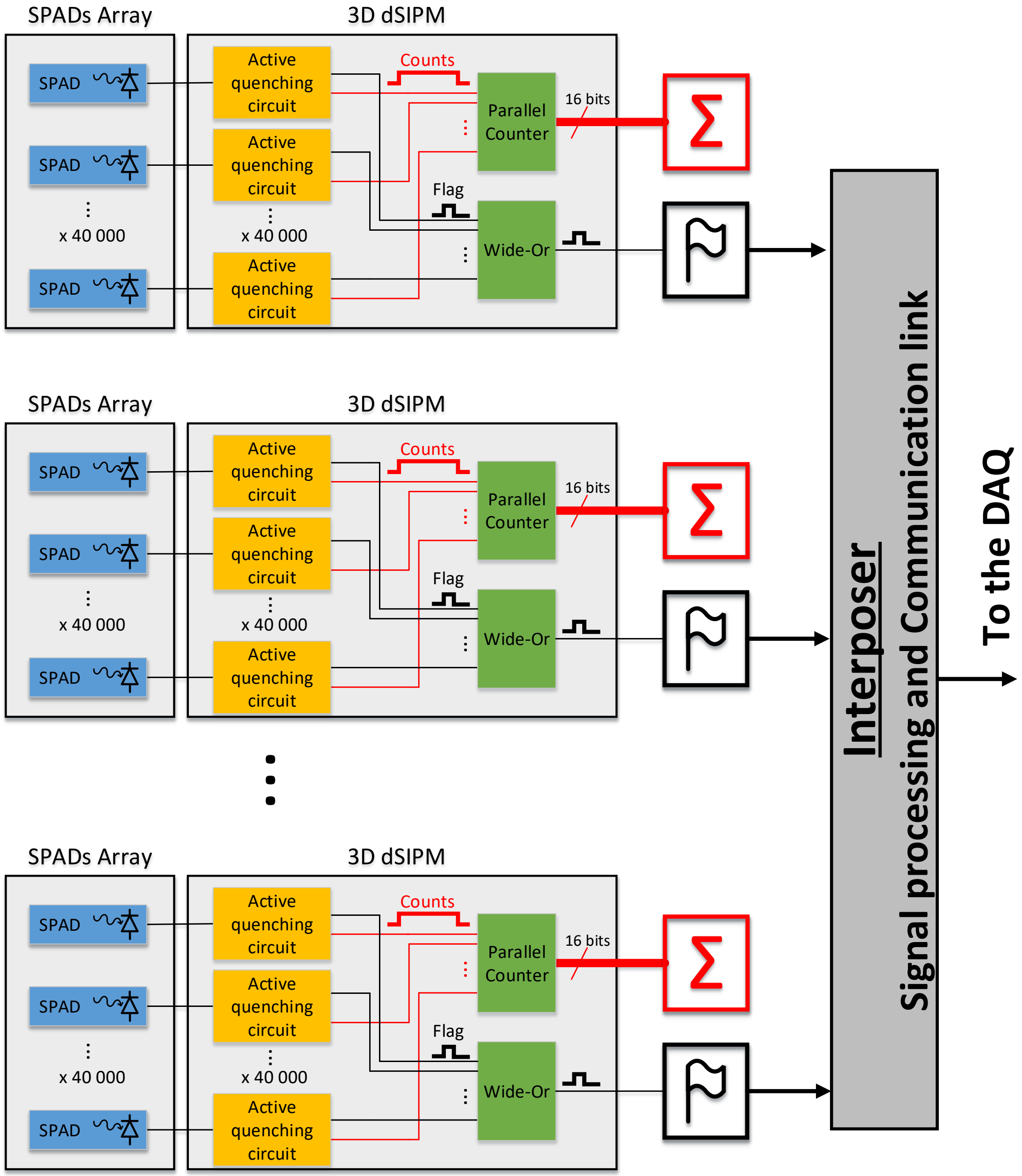
Digital SiPMs

Next-generation photon detectors with silicon

Photon-to-digital converters

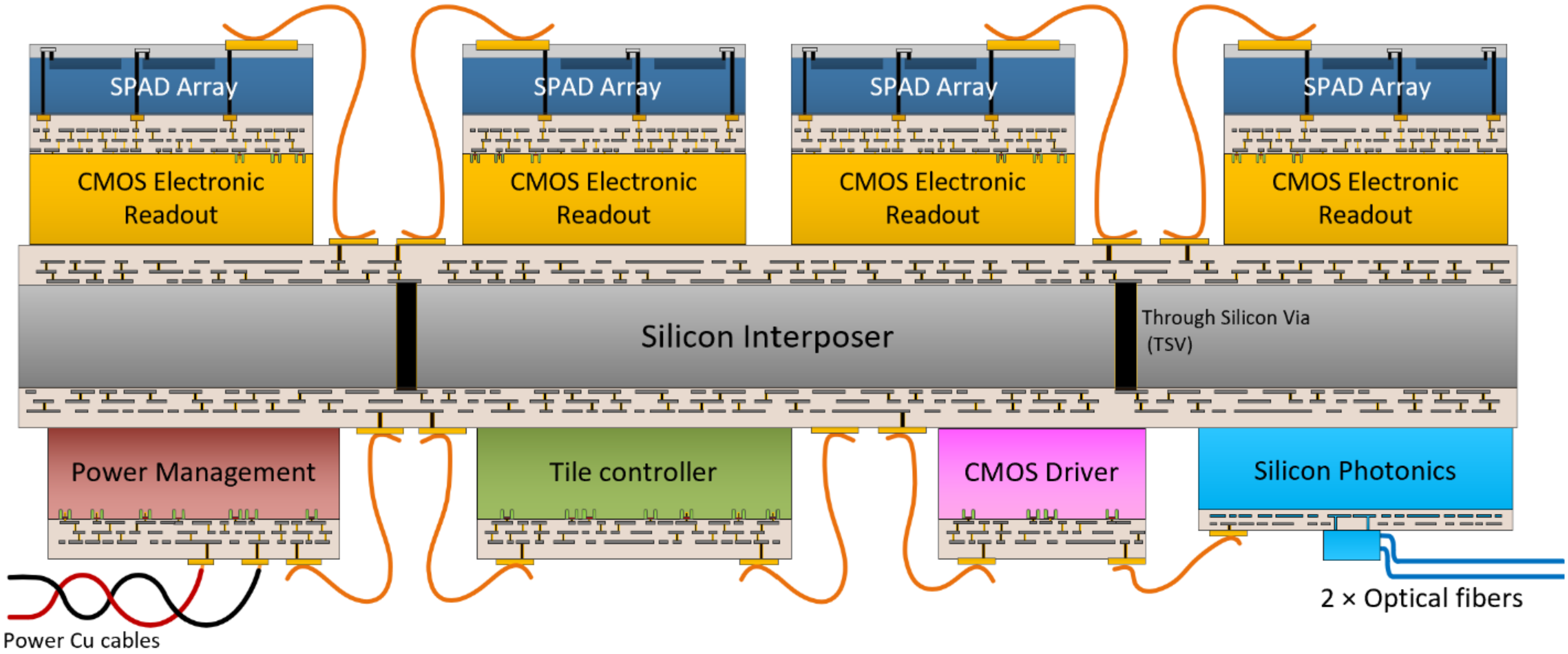
- Developed at U. Sherbrooke (3IT) with C2MI and TELEDYNE-DALSA
- Incoming photon is always a digital signal!
- Analog front-end circuit replaced by **digital active quenching circuits**
  - Digitize signals from each SPAD directly
  - Reduced power dissipation
  - Noise reduction comes from enhanced capability and flexibility of *configurable digital readout electronics*

- **3D integration**, maximizing sensitive area
- Silicon interposer
  - Signal processing capability at tile controller



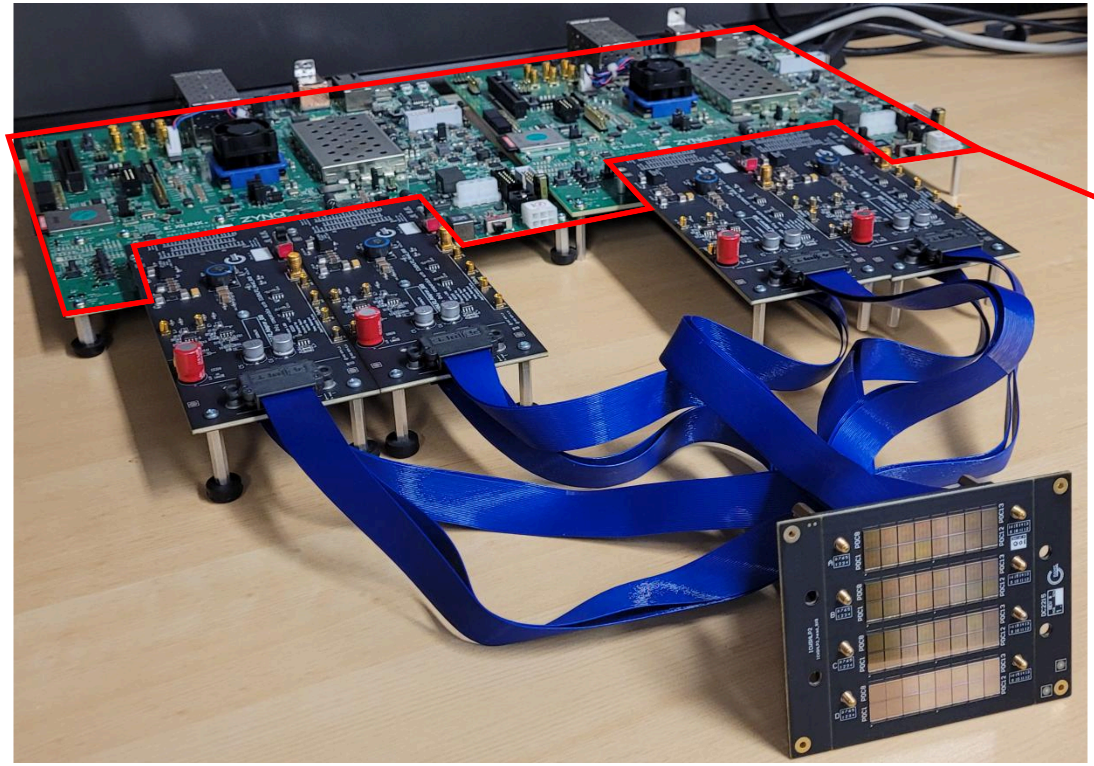
J.-F. Pratte et al. (2021) Sensors 2021, 21(2), 598

Photon-to-digital converters: Tile design



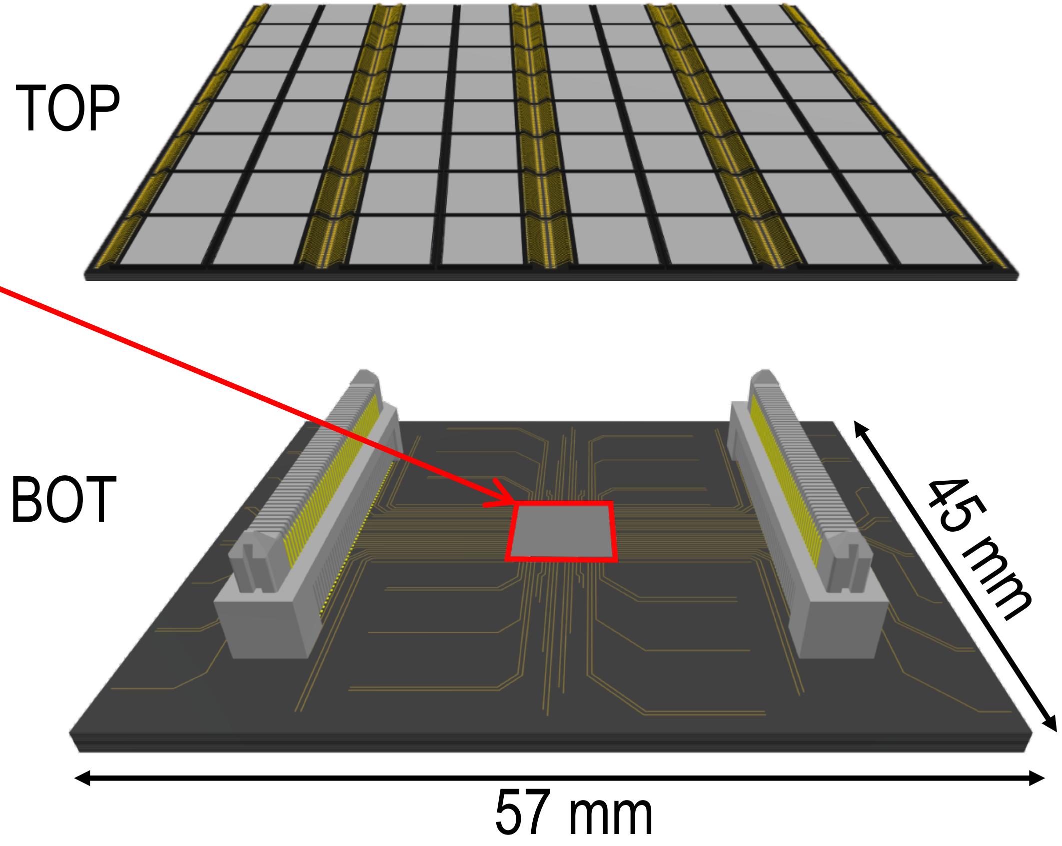
Photon-to-digital converters: Tile integration

FPGA-based tile controller



Tile of CMOS readout chips

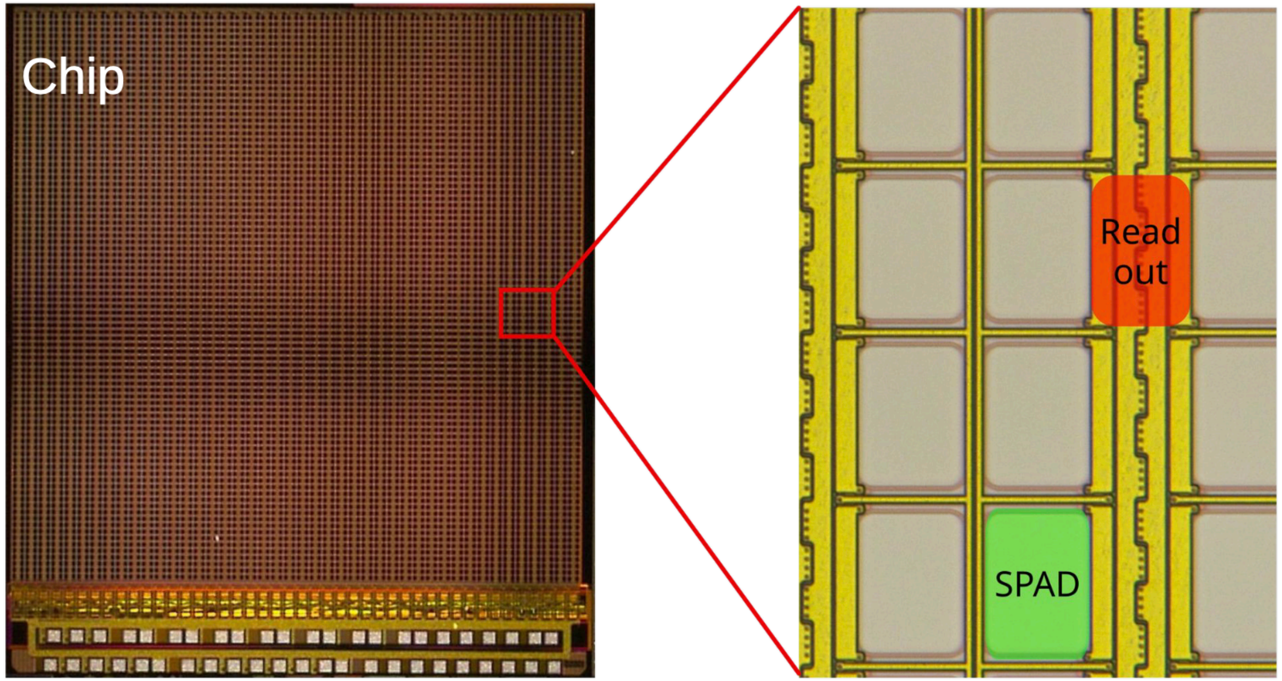
ASIC-based tile controller

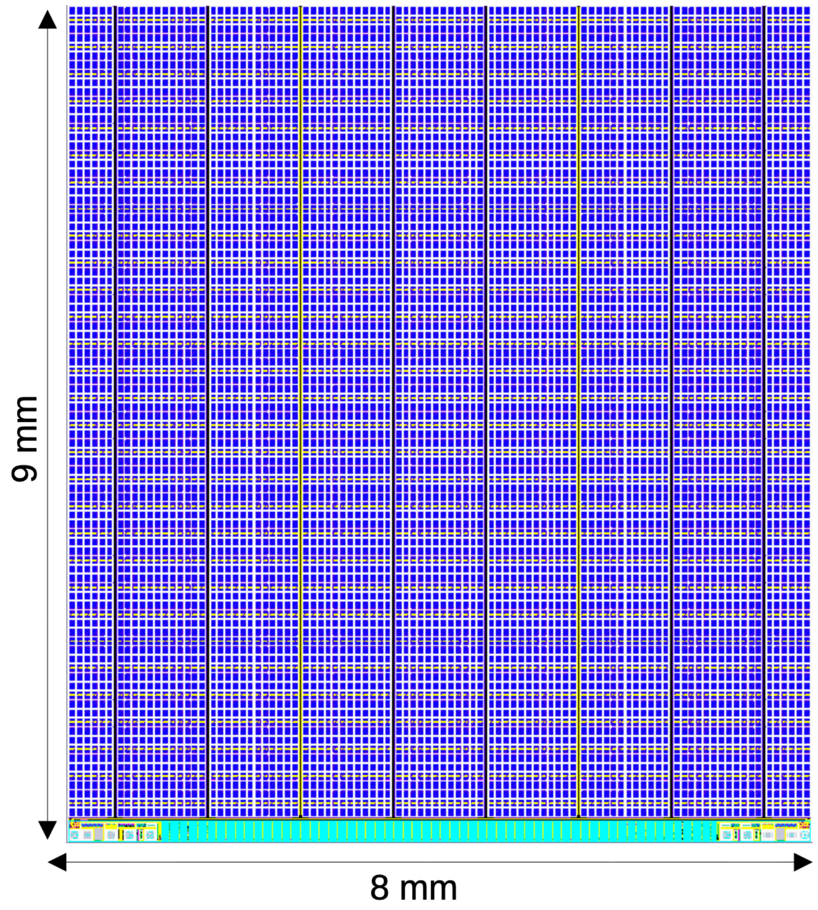


M. Keller, P. Fischer, R. Zimmermann, M. Ritzert (2023)

2D digital SiPM

- SPAD array with digital readout on a **single chip**
  - Designed at U. Heidelberg, built by Fraunhofer IMS
  - Very low dark count rates achieved
  - Lower fill factor (sensitive area), but easier assembly





SPADs: 97 x 80 μm²

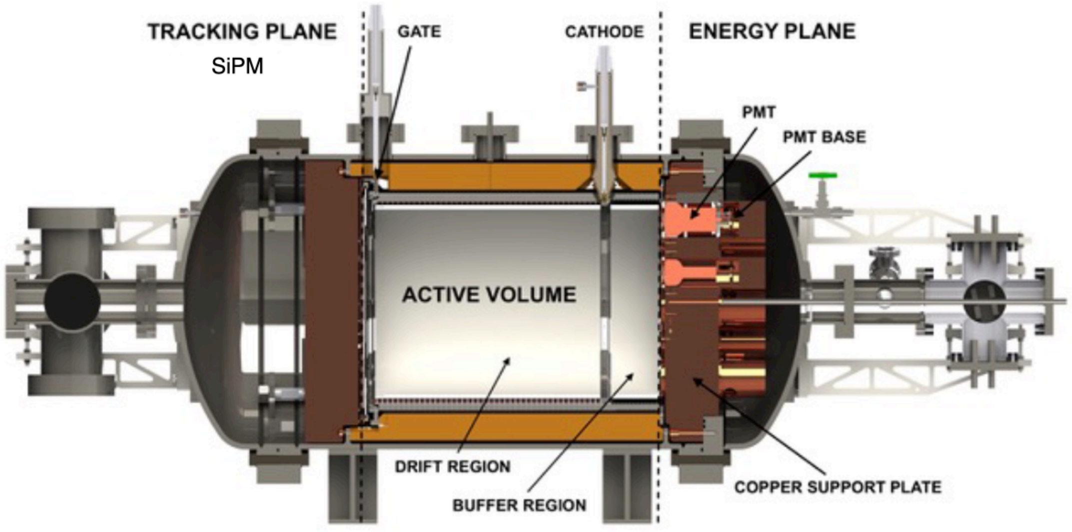
36 SPADs on each region of 1000 x 291 μm²

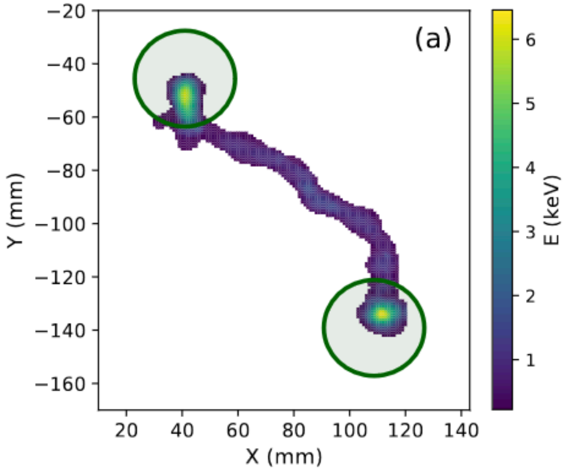
Experiments

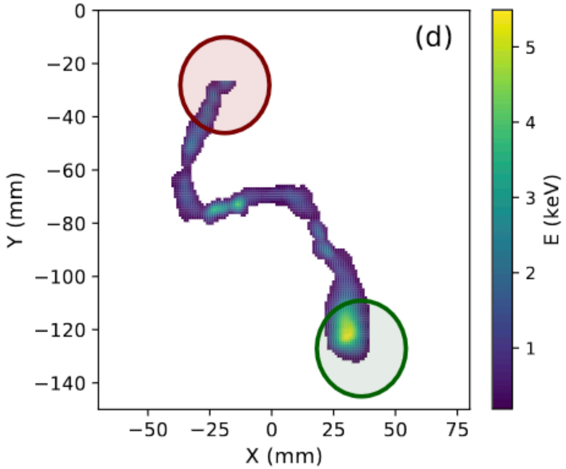
Detectors to discover new physics

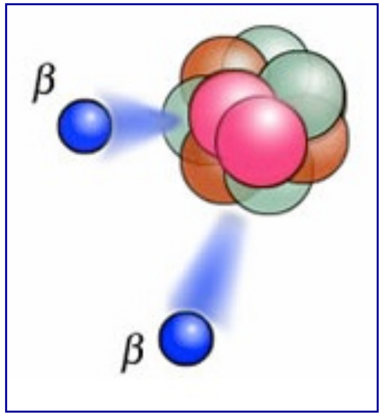
NEXT: Neutrinoless double beta decay with GXe

- **High-pressure gas xenon** time projection chamber (TPC) to search for $0\nu\beta\beta$
- NEXT-White detector
  - Operated at Canfranc 2016-2021
  - 1792 SensL series-C 1 mm^2 SiPM
  - TPB wavelength shifter









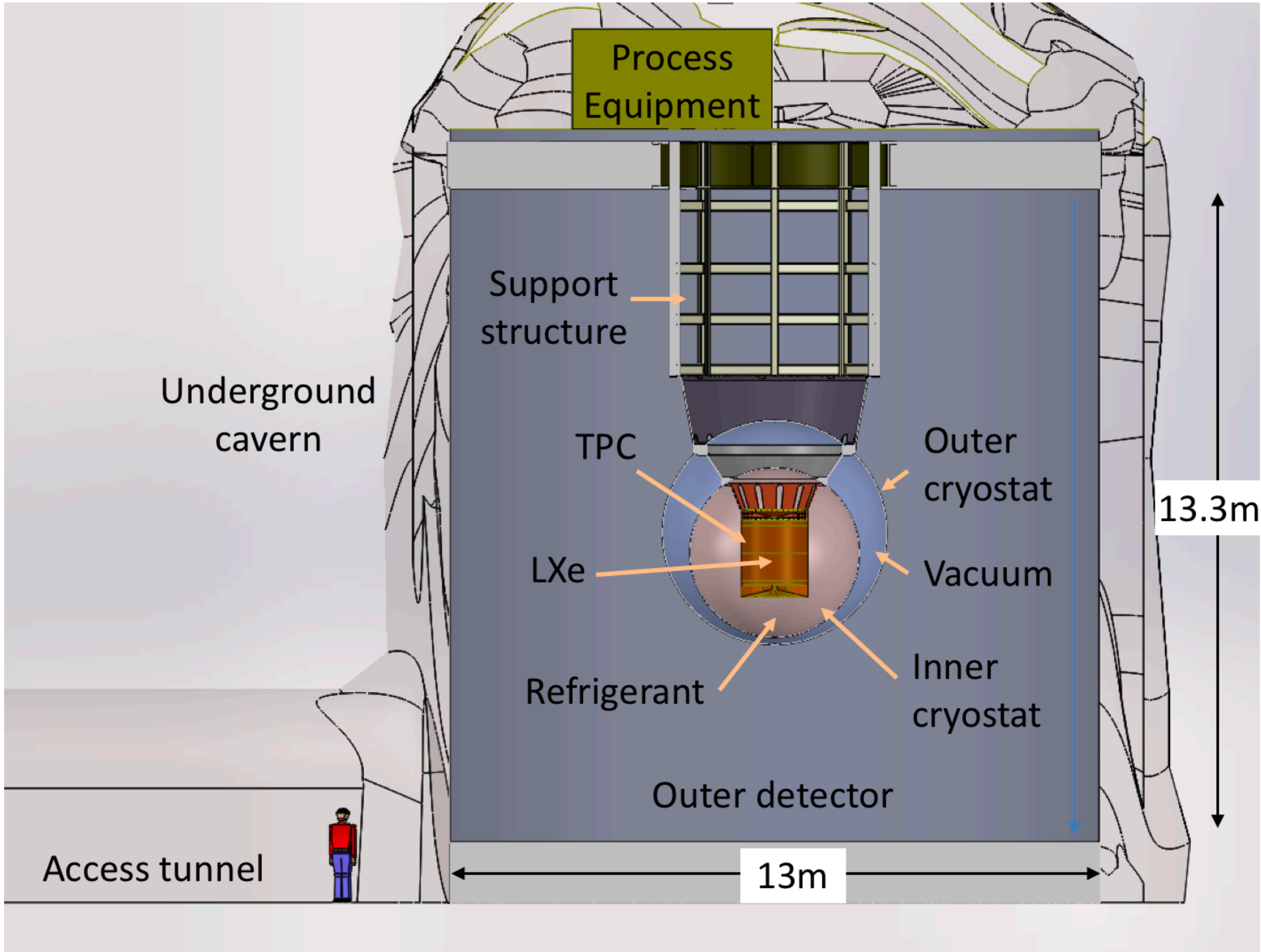
Double-beta vs.
single-beta discrimination
by observing **Bragg peaks**

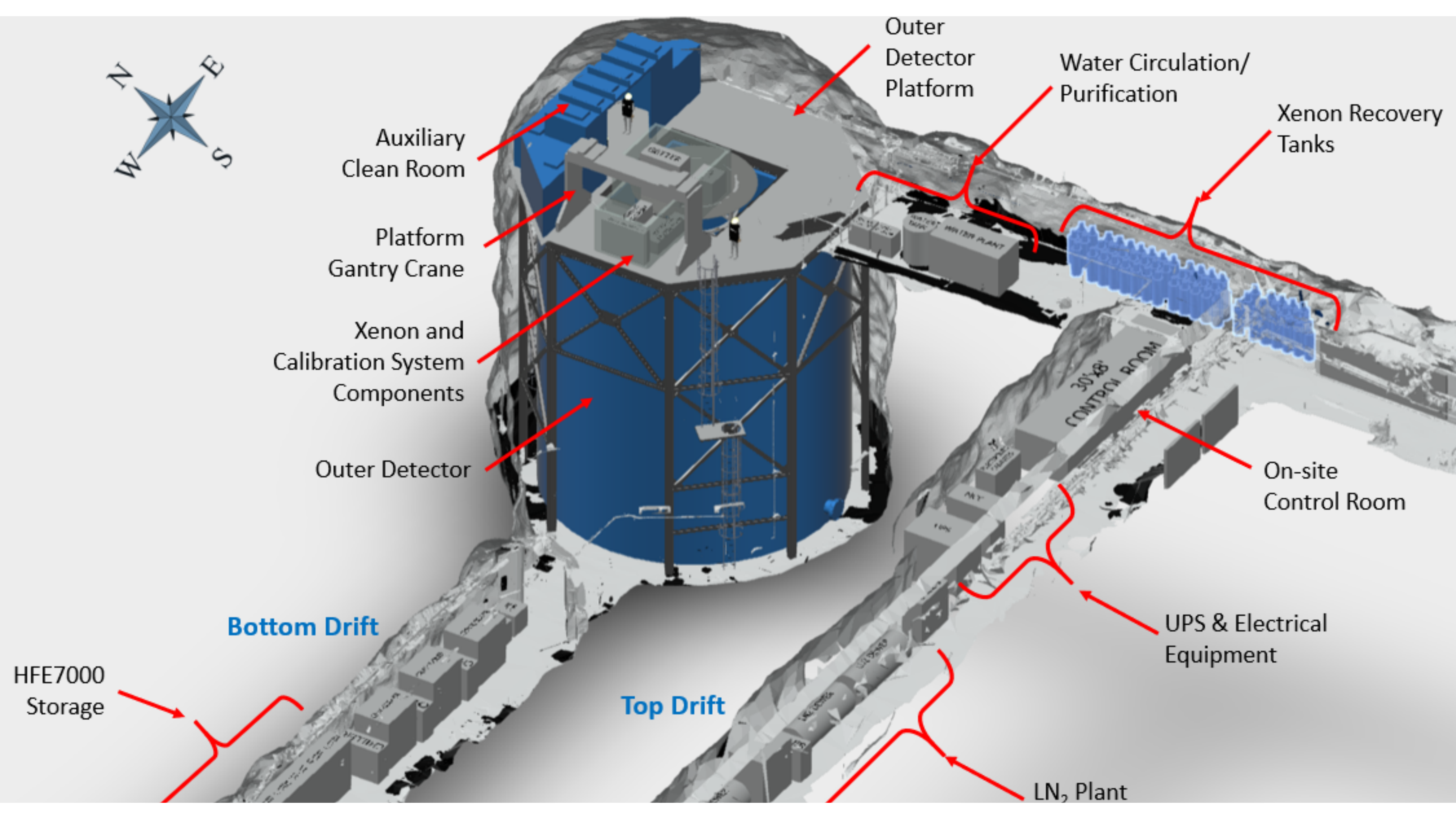
^{136}Xe $2\nu\beta\beta$ half-life measurement

NEXT Collaboration:
P. Novella et al. (2021)
Phys. Rev. C 105, 055501,
arXiv:2111.11091

nEXO: Neutrinoless double beta decay with LXe

- Single-phase liquid xenon TPC
- **5 tonnes LXe**, **enriched in ^{136}Xe** to 90% isotopic purity
- Large outer detector veto, and LXe self-shielding
- Pending selection by US DOE of 0νββ detector technology and host site
- **SNOLAB Cryopit** cavern is committed to a large-scale 0νββ detector that could be nEXO, and is the nEXO collaboration's preferred site

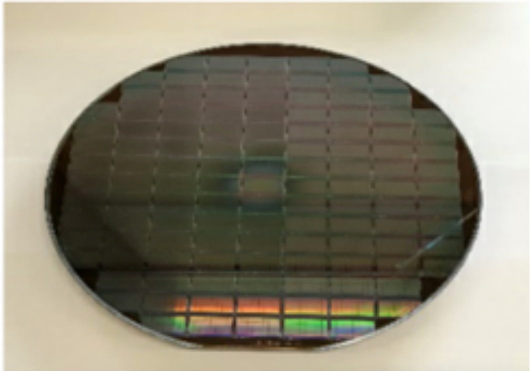




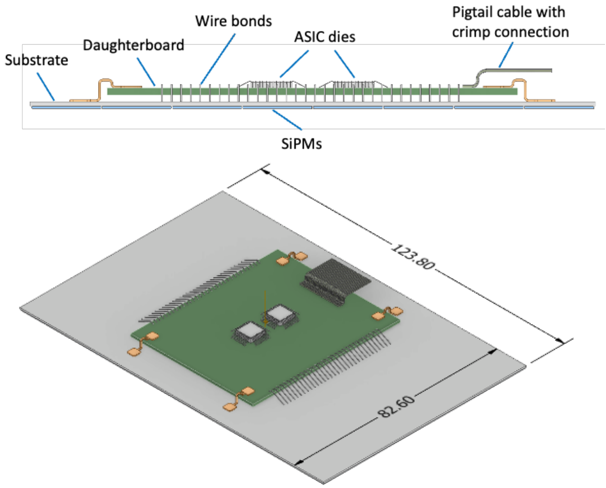
N
E
W
S
Auxiliary Clean Room
Platform Gantry Crane
Xenon and Calibration System Components
Outer Detector
Outer Detector Platform
Water Circulation/ Purification
Xenon Recovery Tanks
On-site Control Room
UPS & Electrical Equipment
LN_2 Plant
Bottom Drift
Top Drift
HFE7000 Storage
30'x8' CONTROL ROOM

nEXO photodetector system

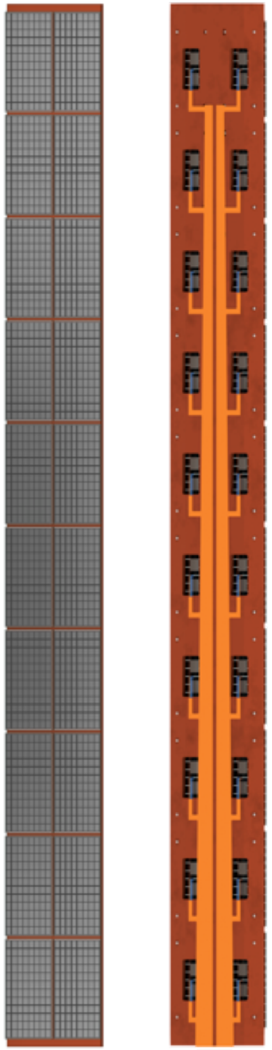
- Barrel photodetector in modular design:
  - **SiPMs** are mounted on **Tiles**
  - Tiles are mounted on **Staves**
  - Staves form the full **Barrel**
- SiPM characterization, tile + stave design, getting ready for mass production



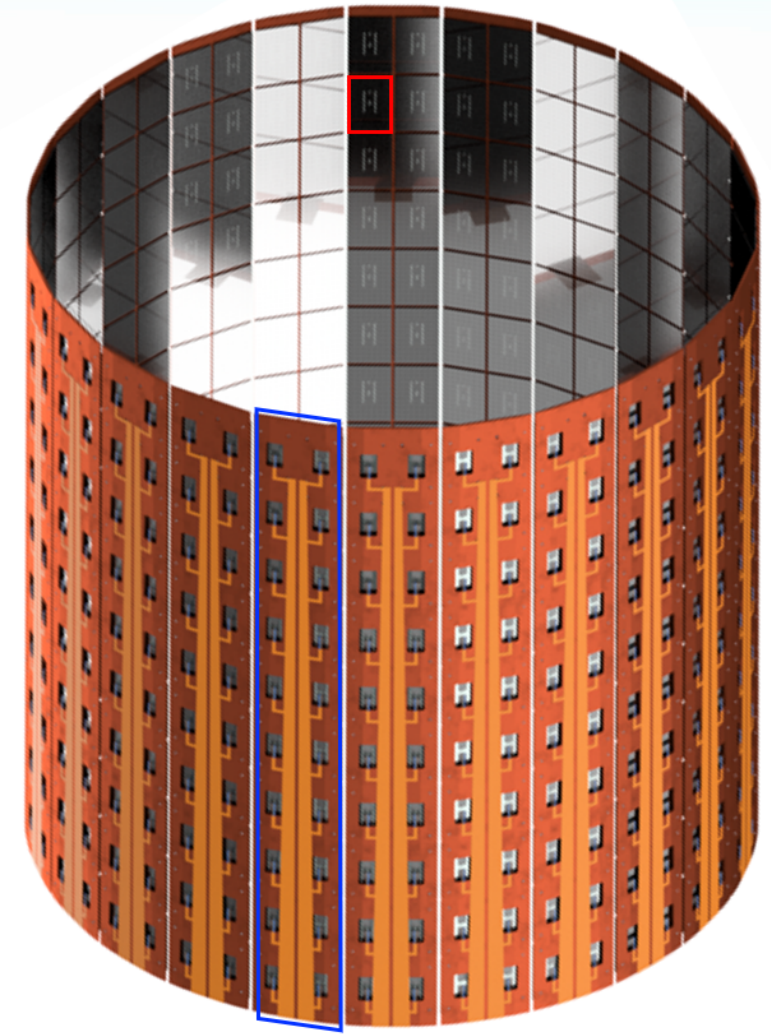
SiPM fabrication: 1 x 1 cm² dice with SPADs 50 x 50 µm²
Vendor: Hamamatsu (HPK) or FBK



Preliminary tile design: 8x12 SiPM



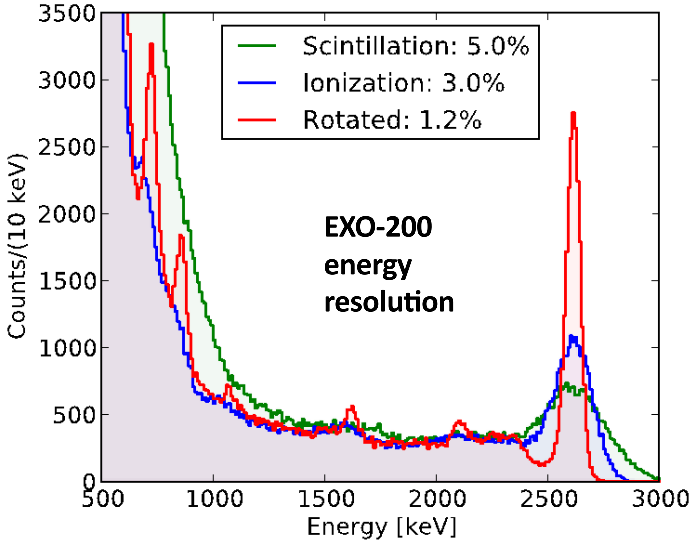
Preliminary stave design: 10 tiles

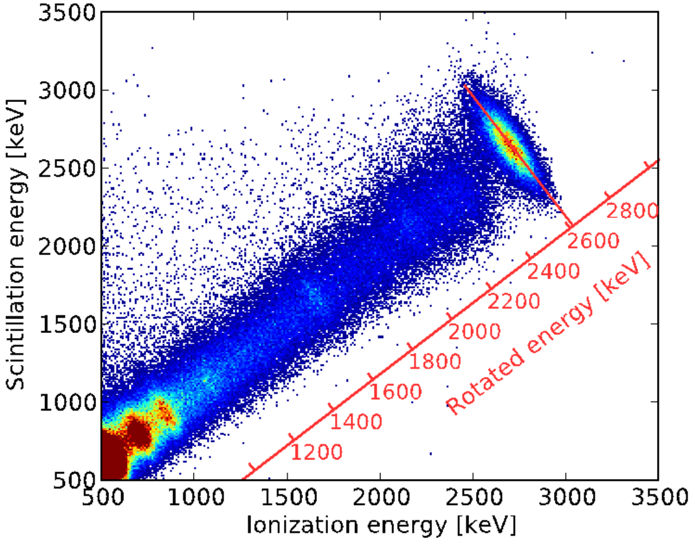


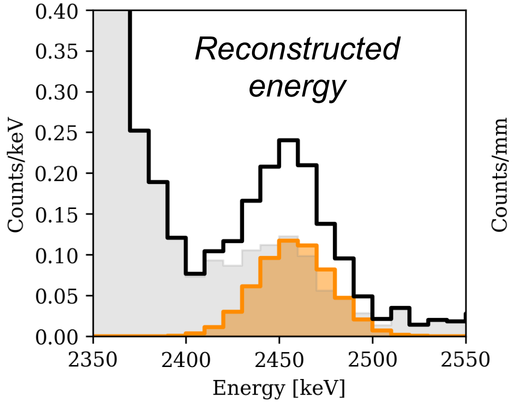
Preliminary barrel design: 24 staves

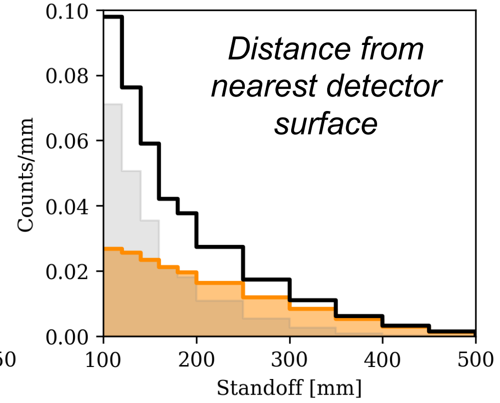
nEXO: Event reconstruction and analysis

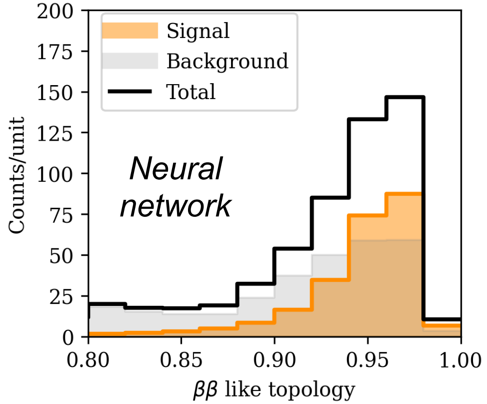
- Sensitivity to 0νββ requires the best possible **energy resolution**
  - Relies on the combination of **charge and light collection** in the single-phase liquid xenon TPC
  - Anti-correlation between ionization vs. scintillation yield











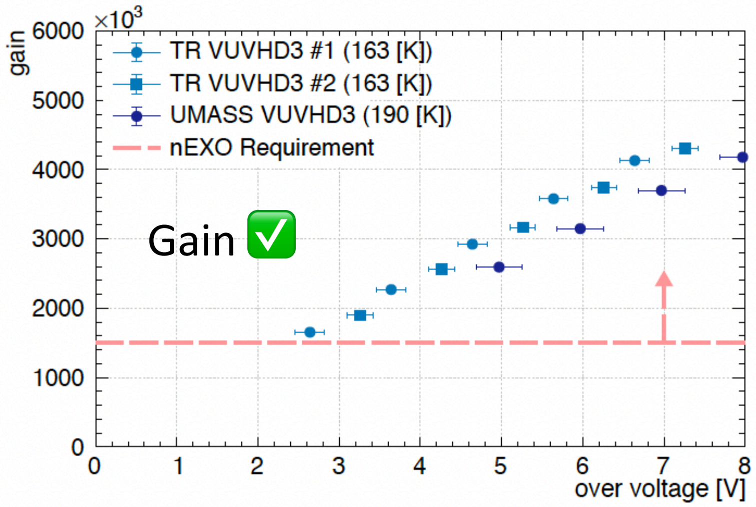
Likelihood fit of 3 variables – ^{136}Xe 0νββ *half-life sensitivity: 10^{28} years*

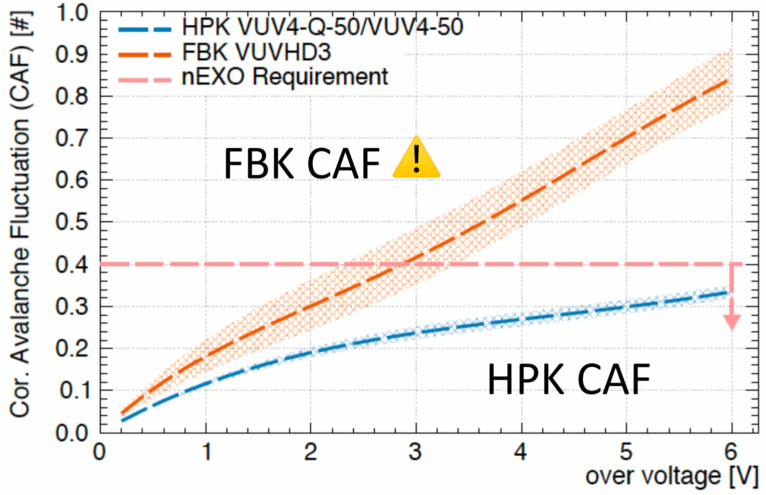
nEXO SiPM requirements:

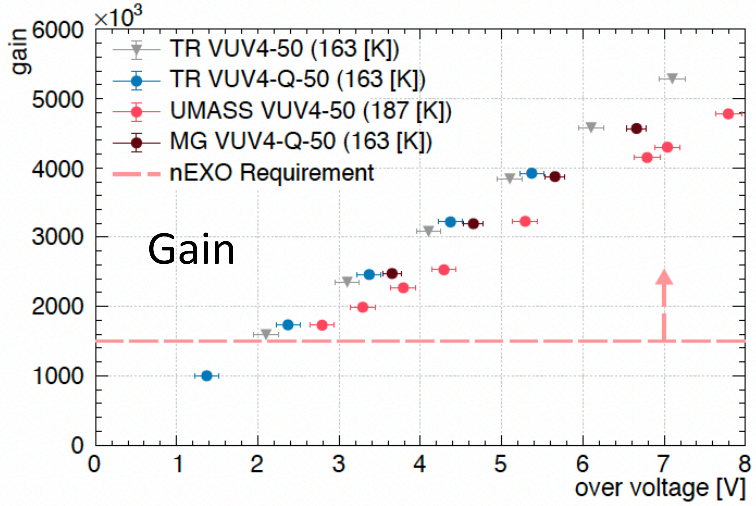
- **Direct UV sensitivity**: PDE > 15% at 175 nm
- Dark count rate < 10 Hz/mm^2 at LXe temp.
- Correlated avalanche fluctuation (CAF) per pulse in the 1 μs acquisition window < 0.4
- Gain > 1.5 x 10^6 e$^-$/PE

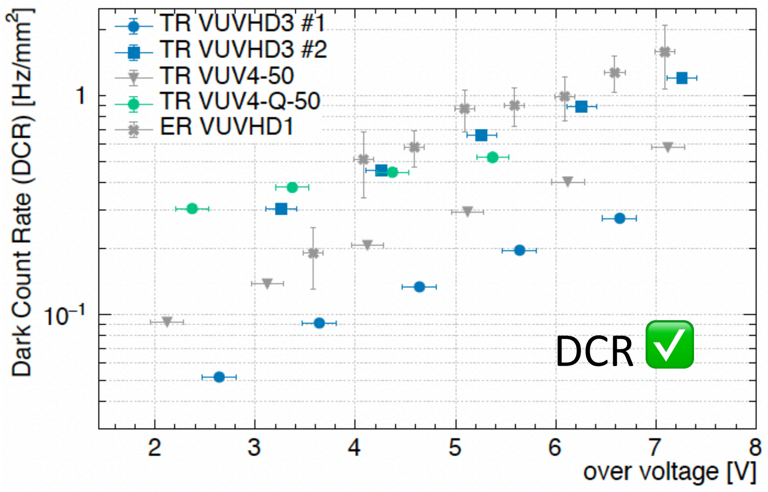
nEXO Collaboration: G. Adhikari et al. (2021) J. Phys. G: Nucl. Part. Phys 49, 015104, arXiv:2106.16243

Latest SiPM characterization results for nEXO







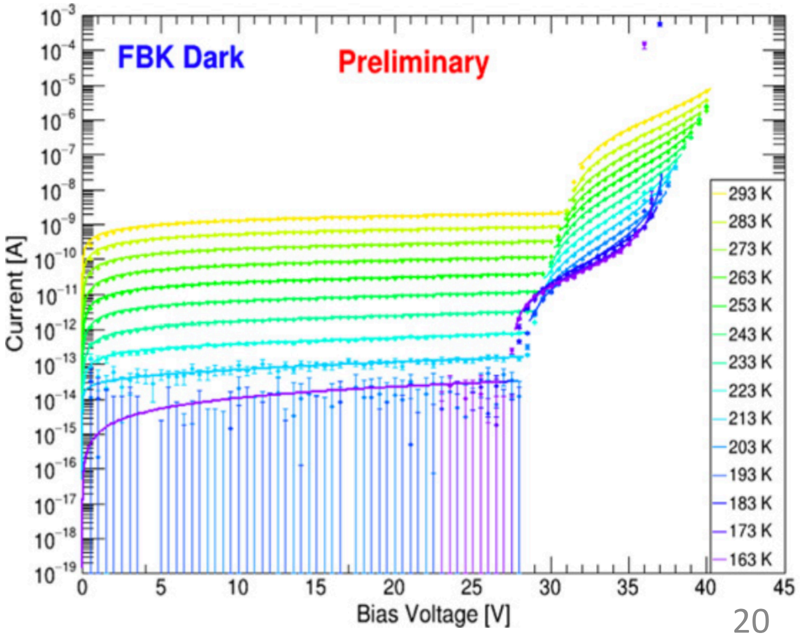


nEXO Collaboration: G. Gallina et al. (2022) EPJC 82, 1125, arXiv:2209.07765

- **HPK and FBK SiPMs meet nEXO requirements**
- HPK SiPMs have through-silicon vias (TSV)
- Scale up to 1 cm^2 channels on tiles, then staves
- Radiopurity of final modules to be performed

Rapid characterization methods developed for quality control during nEXO construction

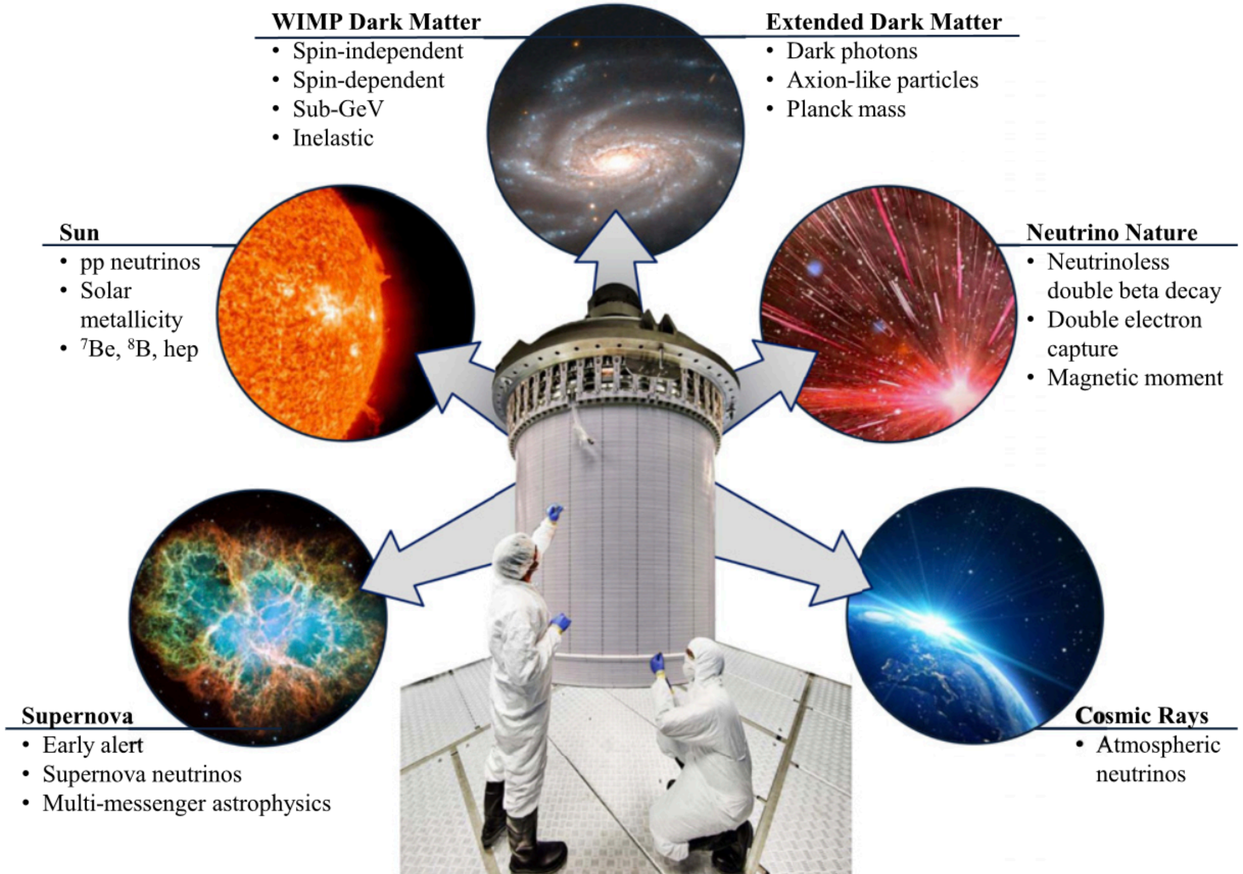
B. Chana, M. Mahtab, F. Retière, S. Viel (2023)
JINST 18, C03004

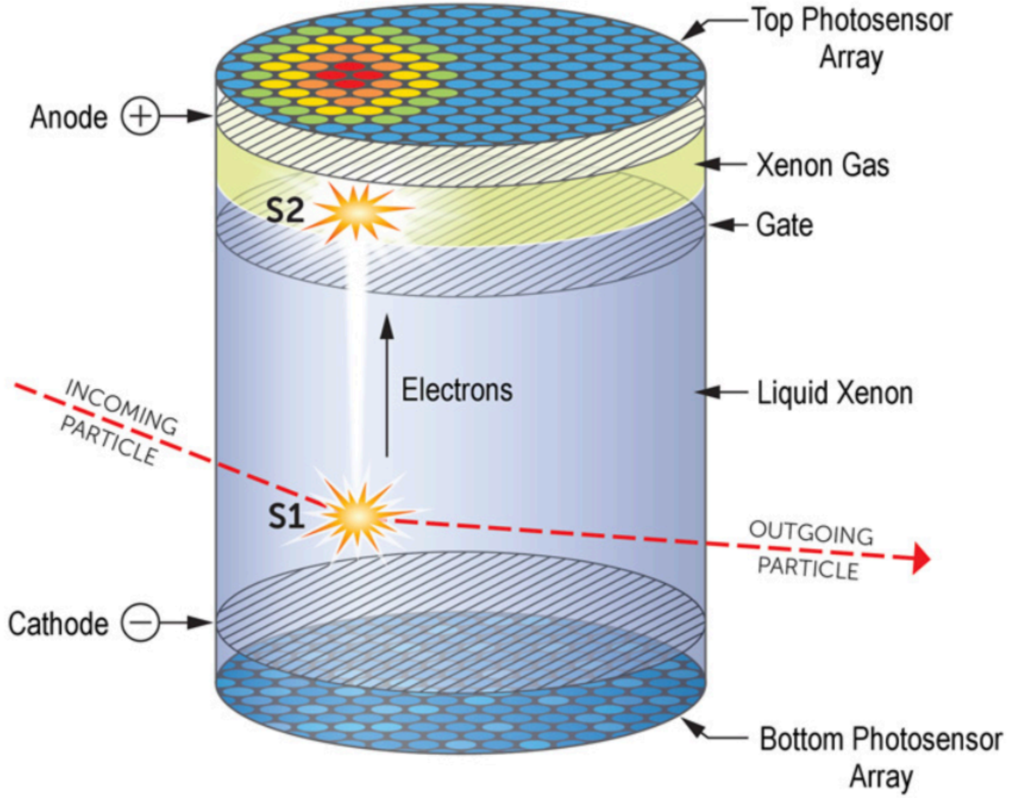


XLZD (XENON-LUX-ZEPLIN-DARWIN)

S1: Scintillation
S2: Electroluminescence
S2 >> S1

- Dual-phase TPC with 40-80 tonnes LXe
  - Evaluating possible designs with PMTs and/or SiPMs





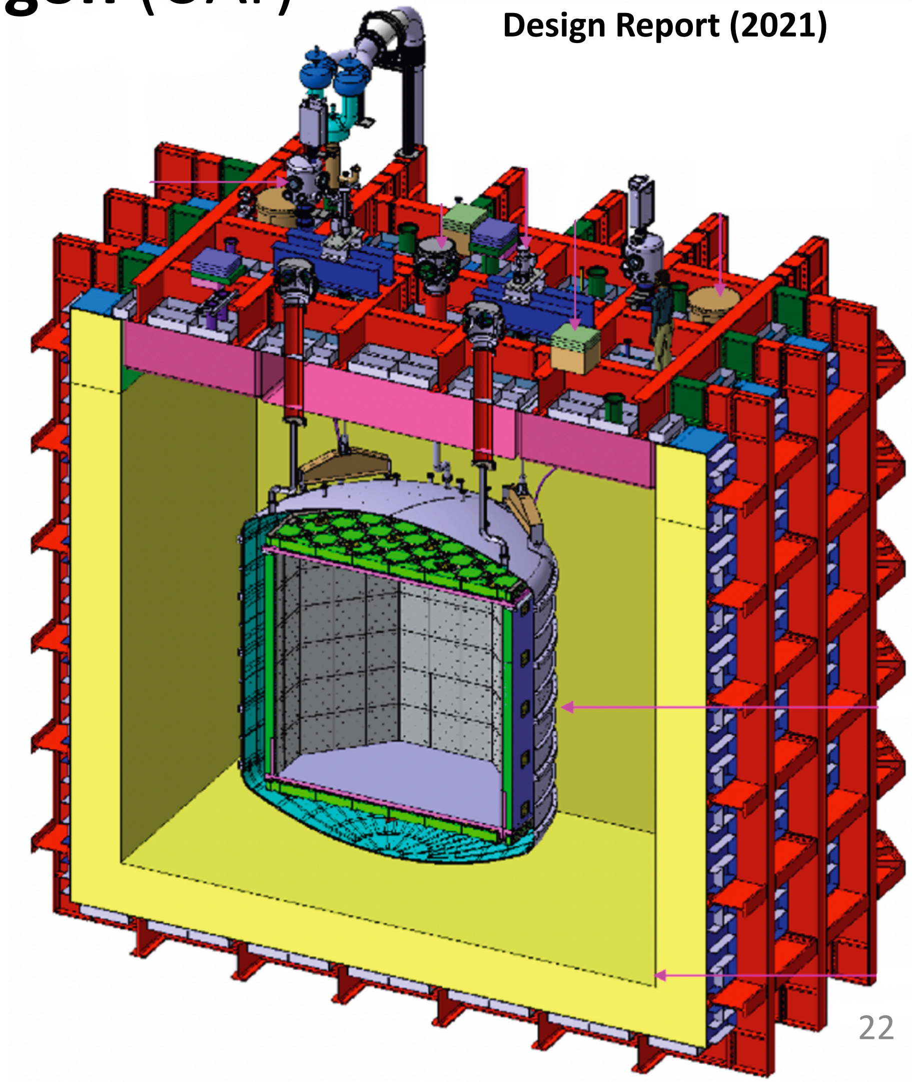
XLZD Consortium: P. Aalbers et al. (2023)
J. Phys. G: Nucl. Part. Phys. 50, 013001,
arXiv:2203.02309

DarkSide-20k: Dark matter search with LAr

- Dual-phase TPC with **50 tonnes underground argon** (UAr)
  - Extraction at Urania plant in Colorado
  - Purification at Aria facility in Sardinia
  - Experiment will be located at LNGS
  - 20 tonnes fiducial expected
- Sensitivity to **nuclear recoils** from dark matter
  - Careful control of alphas and neutrons
- Reject electronic recoil backgrounds using **pulseshape discrimination** (PSD)
  - DEAP-3600 demonstrated 10^{-10} leakage fraction at 50% nuclear recoil acceptance

DEAP Collaboration: P. Adhikari et al. (2021) EPJC 81, 823, arXiv:2103.12202

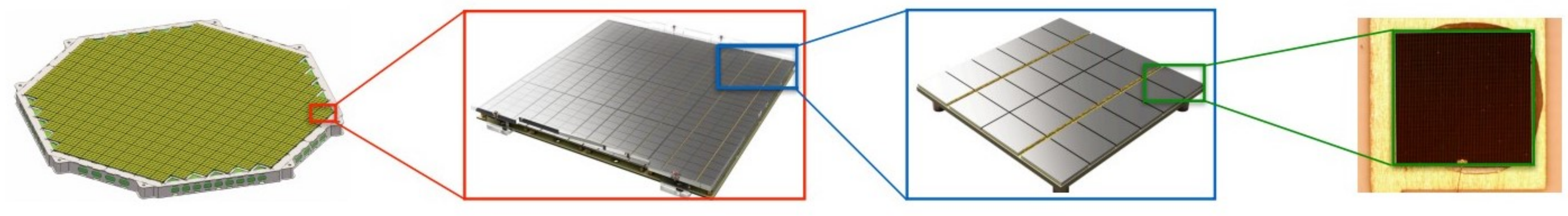
DarkSide-20k Technical Design Report (2021)



DarkSide-20k photodetector system

- Photo-detection units each 400 cm^2
  - **SiPMs by FBK**, model NUV-HD-CRYO
    - Technology transferred to **LFoundry**
  - Device meets all requirements:
    - Photodetection efficiency > 40% at 420 nm
    - Low noise at LAr temperature and 9 V overvoltage: DCR < 0.1 Hz/mm^2, AP < 0.1 in 5 μs
    - Radiopurity: expected tile contribution to neutron background << 0.1 event / 200 t-y

Parameter	LFoundry SiPMs
Pixel size	$30 \times 30\ \mu m^2$
Fill Factor	76.6%
Active area single microcell	$689\ \mu m^2$
Number of Cells (N_{cell})	94904
Total Area	$11.7 \times 7.9\ mm^2$
Expected Breakdown Voltage [87K]	[27-28] V



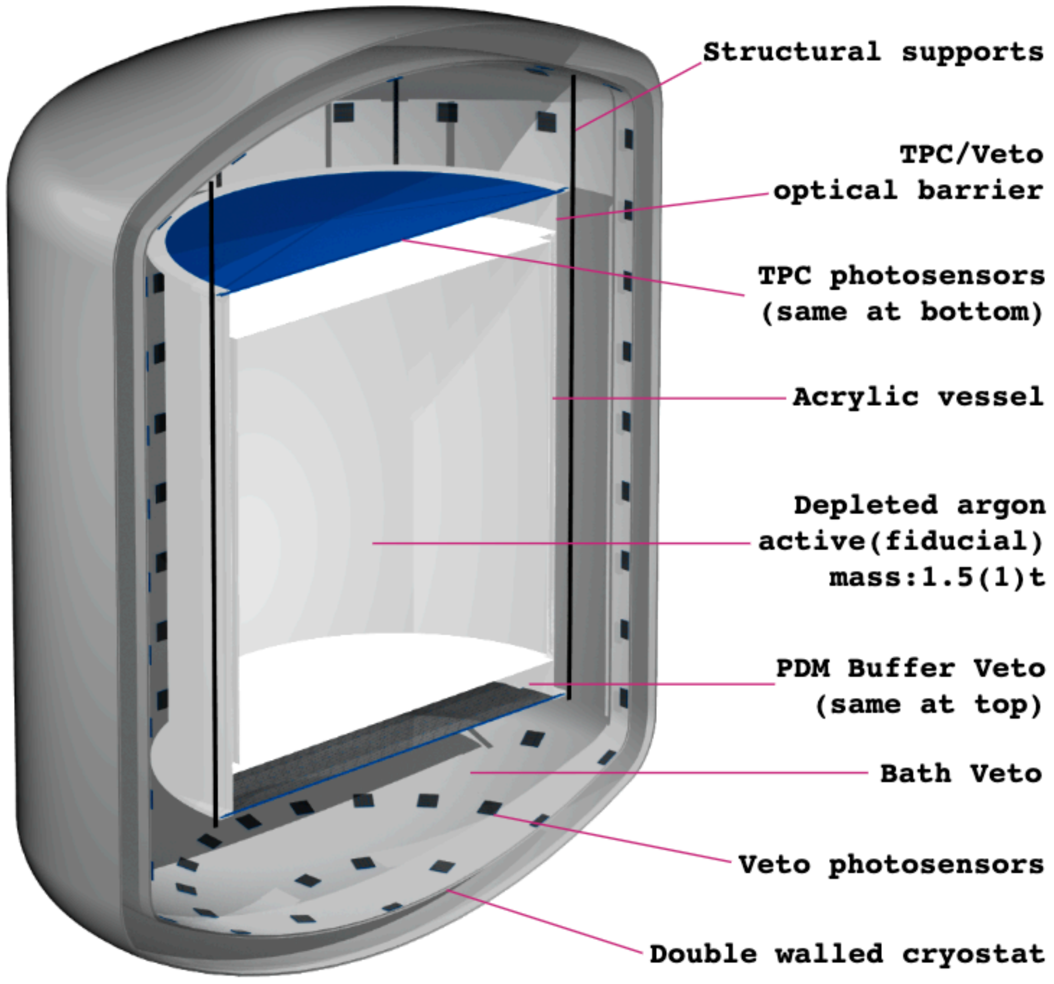
TPC optical plane ($\sim 21\ m^2$)
525 PDUs

Photo-detection unit
16 tiles arranged into 4 channels

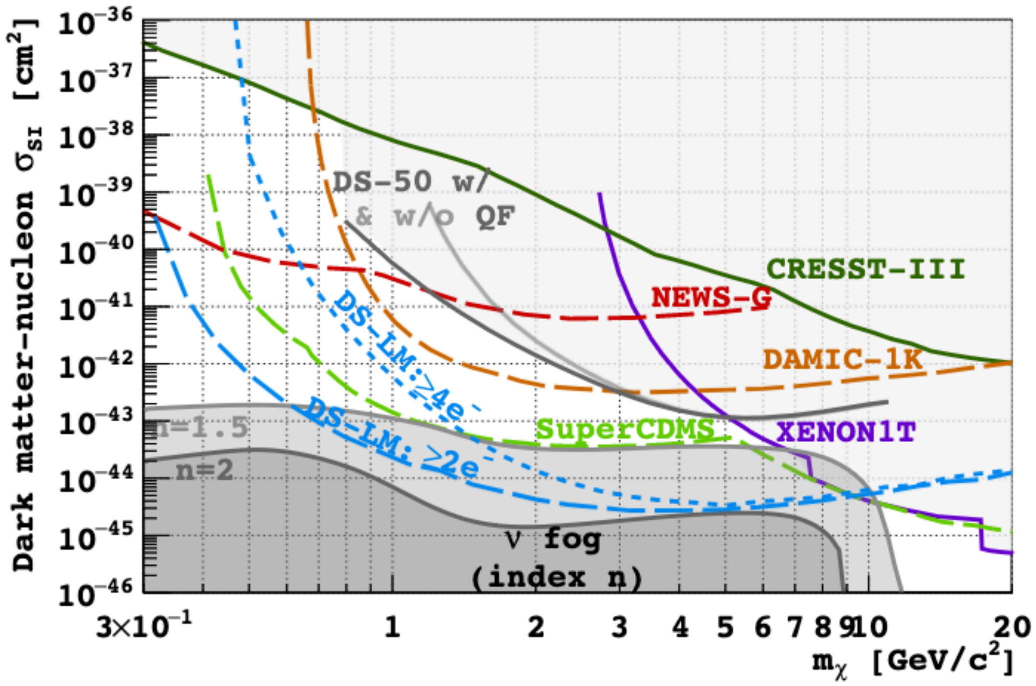
Tile / photo-detector module
24 SiPMs + signal amplifier

SiPM ($\sim 1\ cm^2$)

DarkSide-LowMass



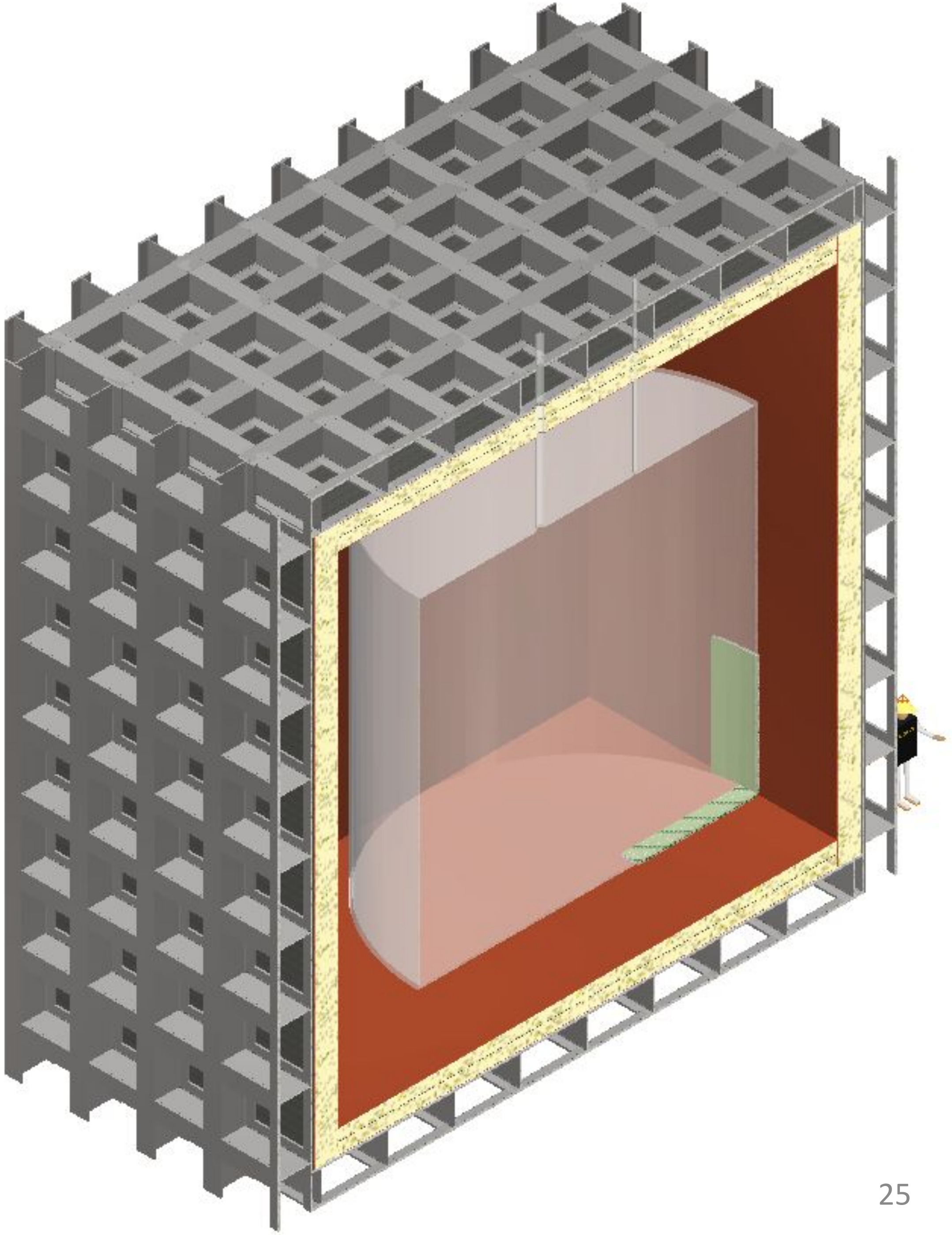
- Dual-phase UAr TPC (1.5 tonnes) optimized for low-mass dark matter search in **ionization-only channel** (S2)
  - Plan to use DarkSide-20k PDMs
  - Sensitivity all the way to neutrino fog

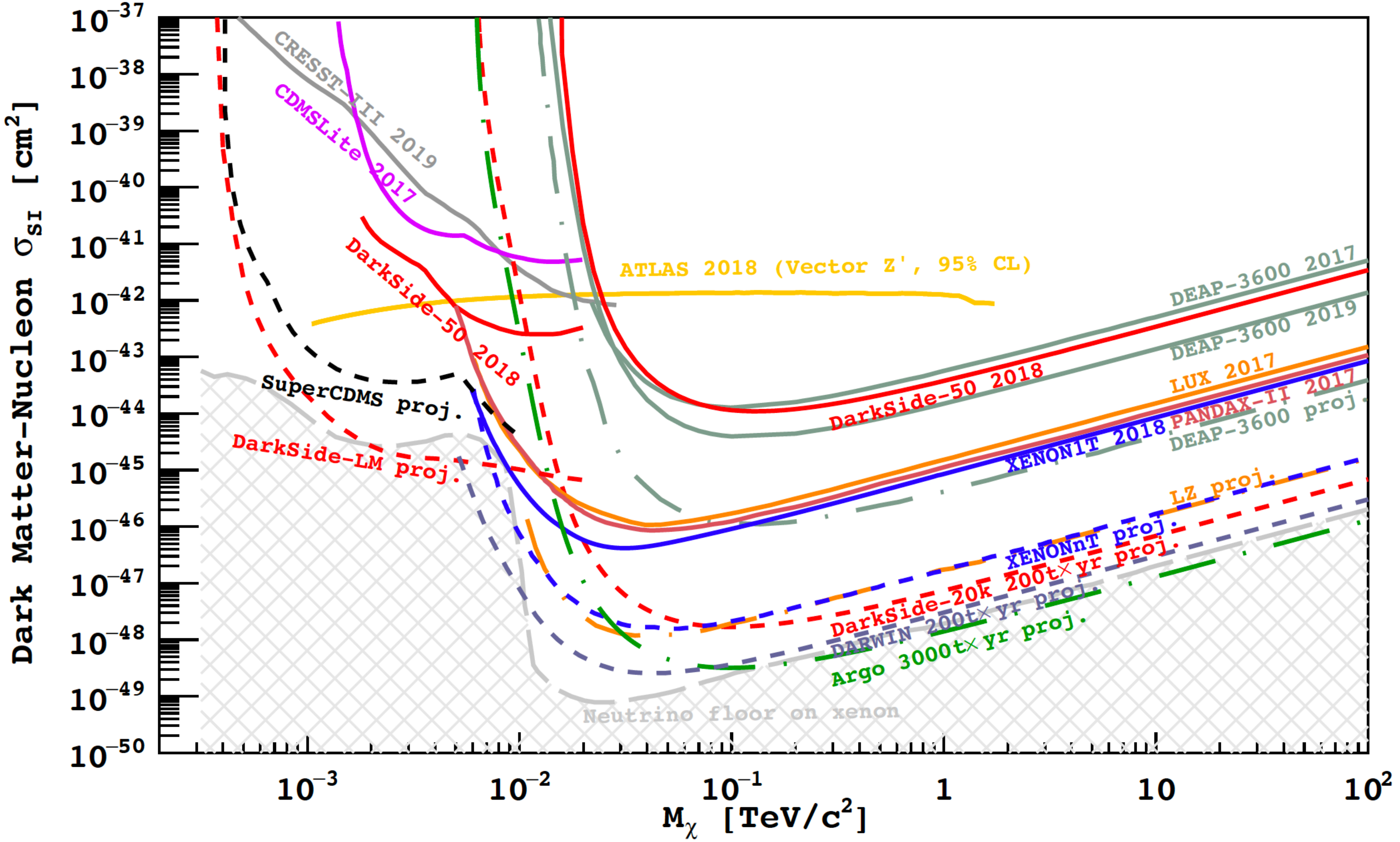


Global Argon Dark Matter Collaboration: P. Agnes et al. (2022) arXiv:2209.01177

ARGO @ SNOLAB

- Ultimate direct detection sensitivity to dark matter with an argon target
  - 400 tonnes underground argon (UAr)
  - **200 m^2 of digital SiPMs** for full coverage
- Investigating design options:
  - UAr – WLS – Acrylic – “SiPMs outside”
  - UAr – WLS – “SiPMs inside” – Acrylic
  - Direct UV sensitivity? Quantify advantages
- Smart DAQ: machine-learning in FPGA
  - At tile-level (α counting, noise suppression…) and at event-level (high-level trigger)




Dark Matter-Nucleon σSI [cm2]
Mχ [TeV/c2]
CRESST-III 2019
CDMSLite 2017
DarkSide-50 2018
ATLAS 2018 (Vector Z', 95% CL)
SuperCDMS proj.
DarkSide-LM proj.
DEAP-3600 2017
DEAP-3600 2019
DarkSide-50 2018
LUX 2017
PANDAX-II 2017
XENON1T 2018
DEAP-3600 proj.
LZ proj.
XENONnT proj.
DarkSide-20k 200t× yr proj.
DARWIN 200t× yr proj.
Argo 3000t× yr proj.
Neutrino floor on xenon

Scintillating Bubble Chamber (SBC)

Hunt for the unseen
A whir, bubble, flash of light
Dark matter escapes

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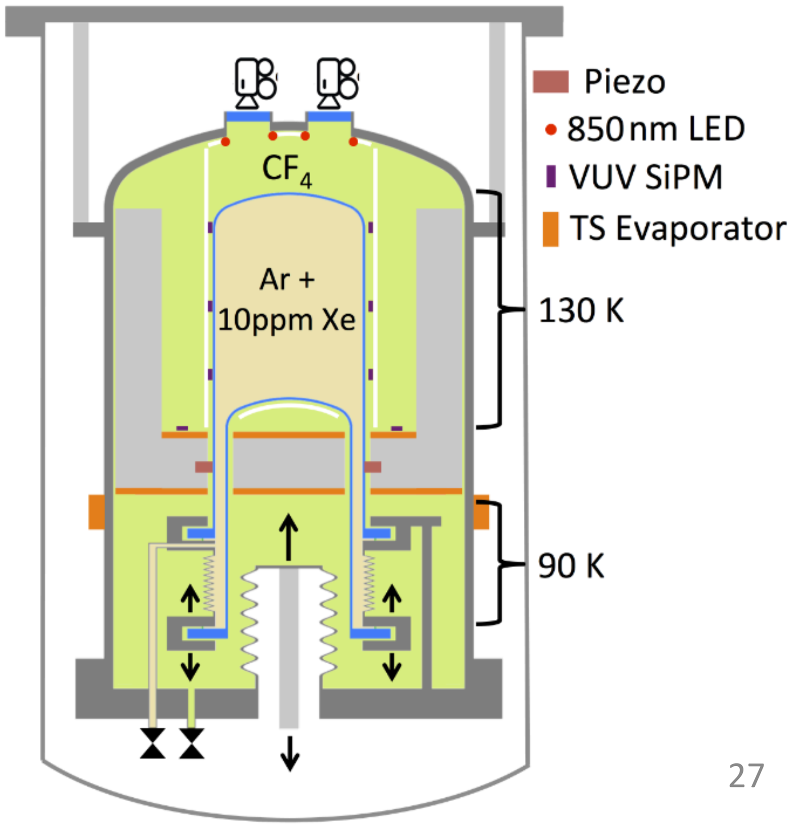
- **Noble liquid bubble chamber**
  - Sensitive to nuclear recoils from dark matter and CEvNS
  - Insensitive to electronic recoil backgrounds, as they don't create bubbles
- "SBC-LAr10" with 10 kg liquid argon
  - Twin units at Fermilab and SNOLAB
  - Objective: scale up technology to reach 1 t-y exposure
- **UV-sensitive SiPMs** detect scintillation light
  - 10 ppm Xe doping acts as wavelength shifter to 175 nm
  - Same candidate vendors as nEXO: Hamamatsu and FBK
  - Radiopurity is key



SBC Collaboration: E. Alfonso-Pita et al. (2022) arXiv:2207.12400

Summary

- Silicon photomultipliers (SiPMs) are the photodetector technology chosen in the design of next-generation experiments in particle physics
  - Especially with noble liquid detectors!
    - I talked briefly about NEXT, nEXO, XLZD, DarkSide-20k, DarkSide-LM, ARGO, SBC
    - There are more examples in accelerator-based experiments: DUNE, MEG II, PIONEER…
    - Plus smaller-scale experiments and demonstrators: ReD, LoLX, Argon-1, and many more…
    - With many applications outside the field
  - Main benefit: lower radioactive backgrounds, for similar photodetection performance
- Analog SiPMs are well-established
- Digital SiPMs are demonstrated
  - Next steps: 3D integration, UV sensitivity, mass-production, commercialization
- Design detectors towards a discovery