中国科学院高能物理研究所
Institute of High Energy Physics Chinese Academy of Sciences

DARKSIDE

The R&D of the Dual Phase Argon TPC from DS-50 to DS-20k

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for the Global Argon Dark Matter Collaboration

Nagoya Workshop on Technology and Instrumentation in Future Liquid Noble Gas Detectors

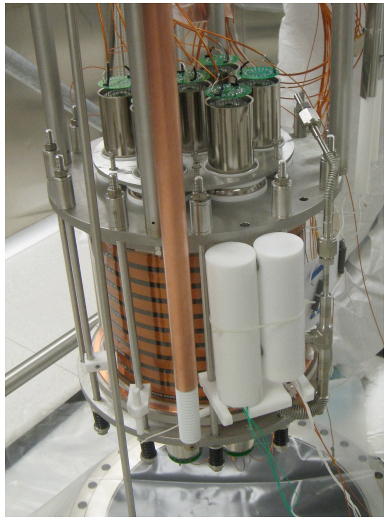
Nagoya, Japan 02/15/2024

The Roadmap of DarkSide

- Direct WIMP dark matter search with argon;
- Dual phase argon time projection chamber (TPC);
- Deep underground laboratory.

ARGO

3000 tonne-year exposure



DarkSide-10 @PU/LNGS

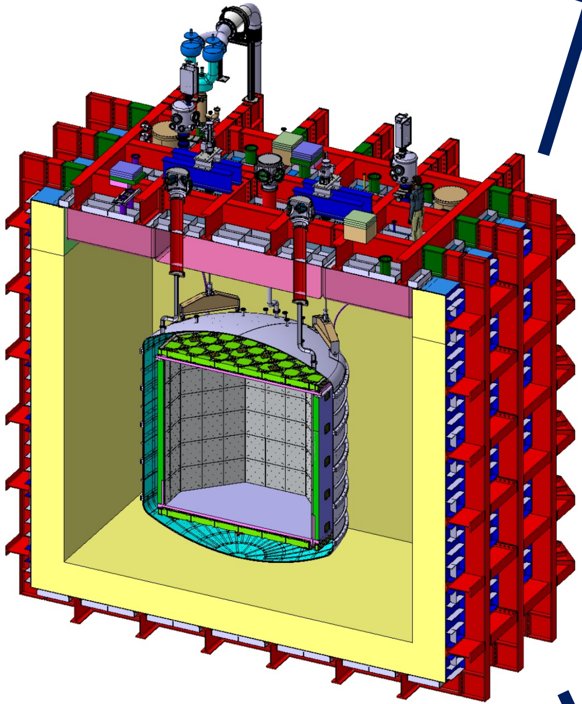
10 kg

2010~2011

DarkSide-50 @LNGS

46.4 kg (active)

2013~2021



DarkSide-20k @LNGS

49.7 tonnes (active)

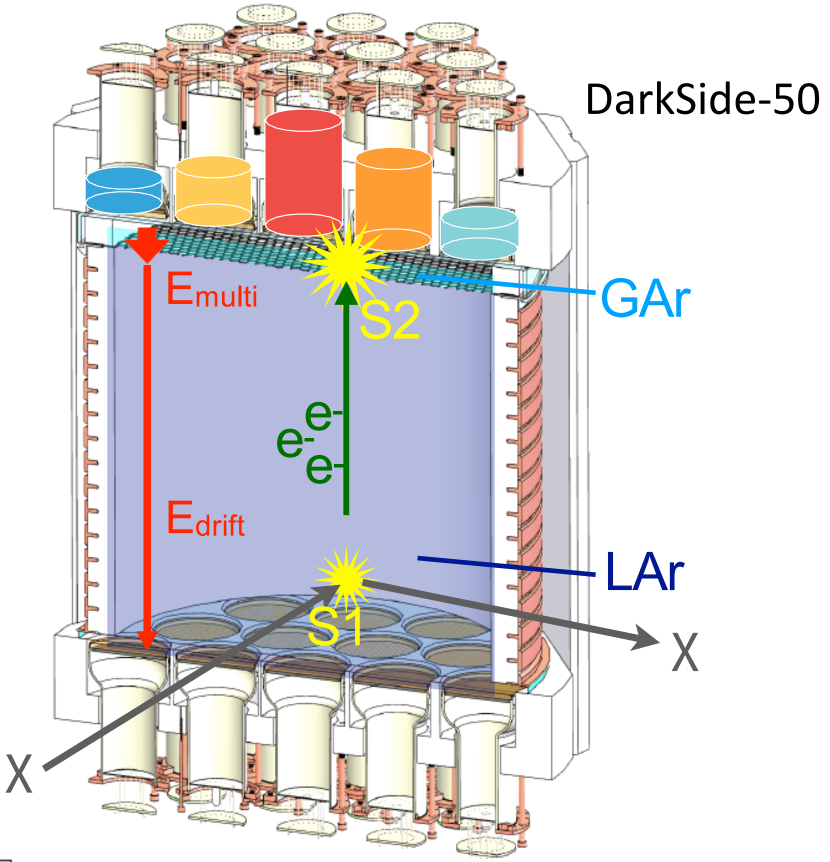
2026~

DarkSide-LowMass

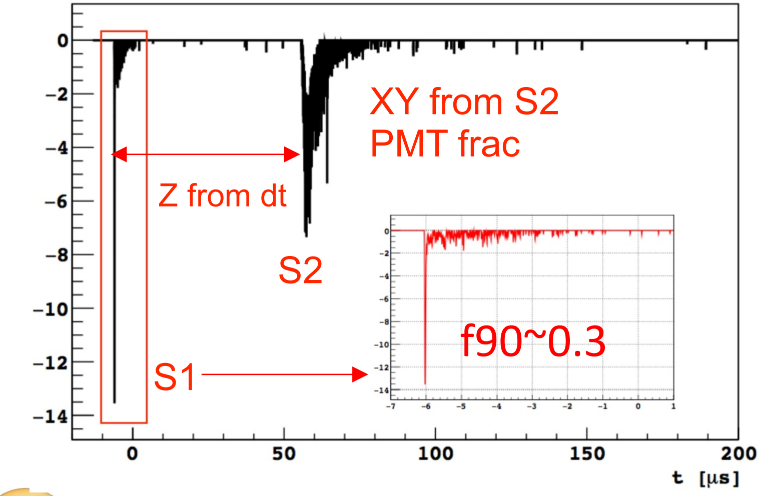
1 tonne-year exposure

Dual-phase Argon TPC

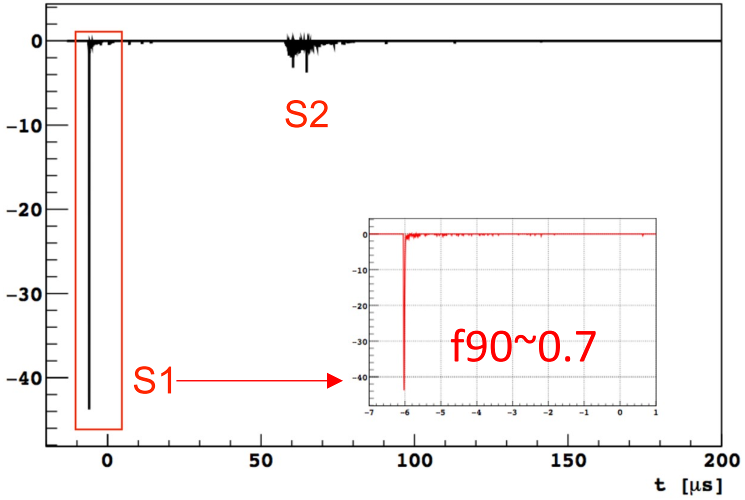
- Scintillation (S1) + Ionization (S2);
- 3D positioning using Tdrift and S2 distributions;
- 128 nm -> wavelength shifter -> 420 nm;
- Pulse shape discrimination (PSD):
  - De-excitation time: singlet 6 ns, triplet 1.5 us;
  - Electron recoil background rejection > 1×10^8;
  - f90: ratio of light in the first 90 ns (S1).

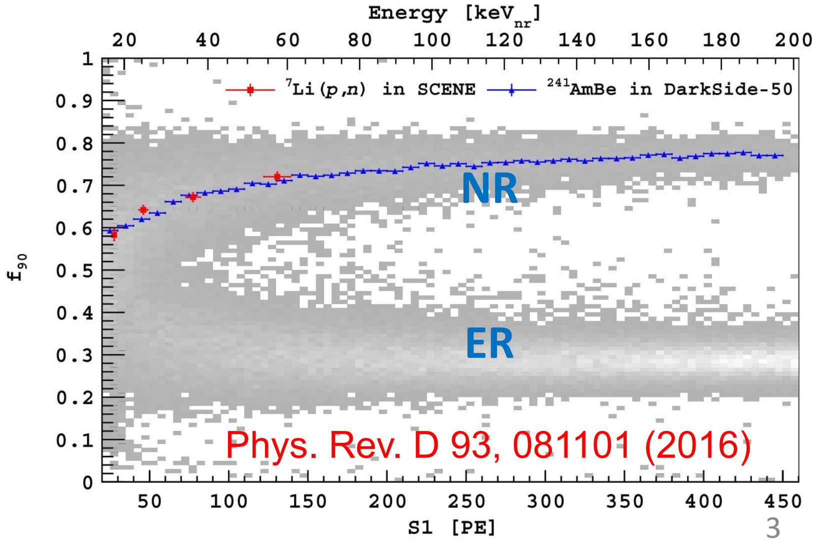


Electron Recoil (ER)



Nuclear Recoil (NR)





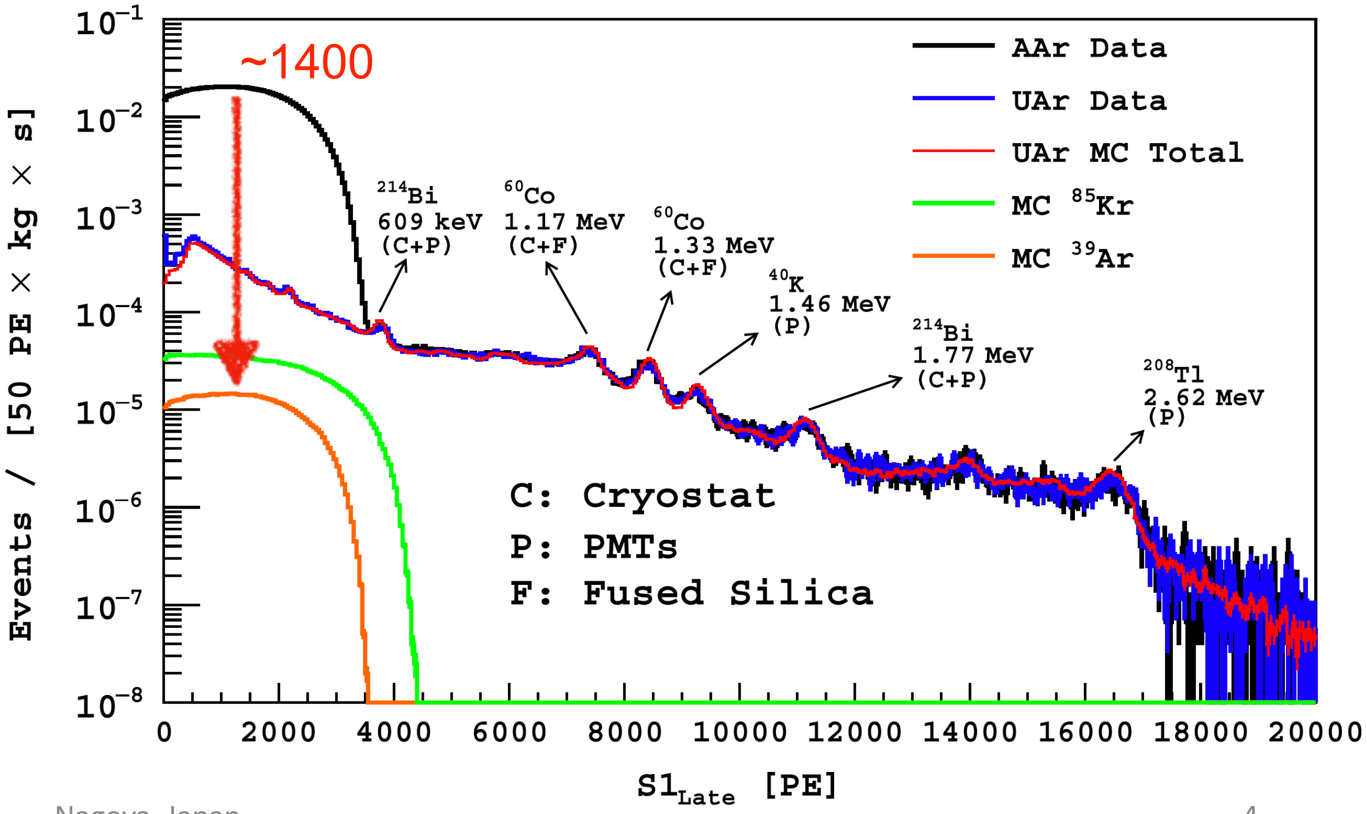
Underground Argon (UAr)

More details in Federico Gabriele's talk

- Atmospheric argon (AAr) has intrinsic ^{39}Ar radioactivity ~1 Bq/kg;
- β decay with 565 keV endpoint, 269 years half-life;
- ^{39}Ar activities set the threshold at low energies.

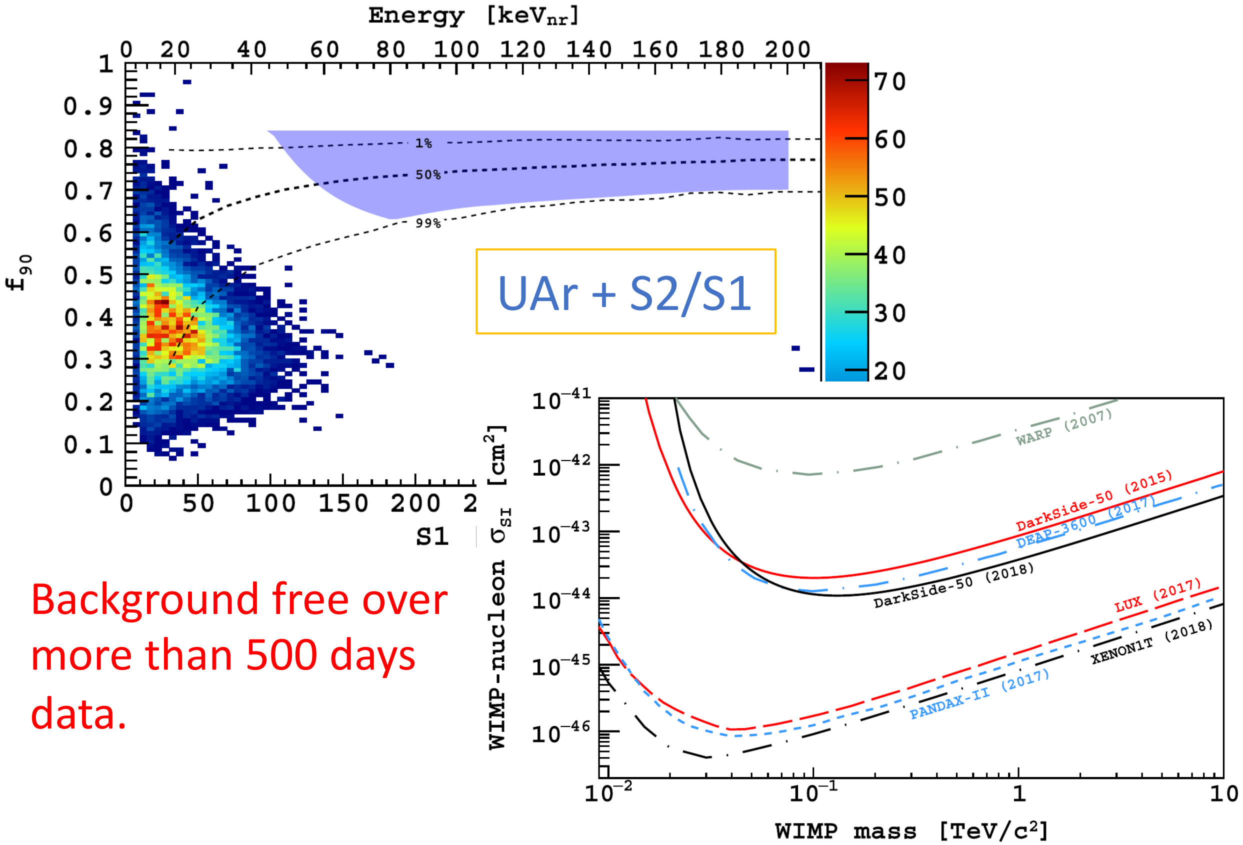
- ^{39}Ar is a cosmogenic isotope;
- Argon from underground sources has significantly lower ^{39}Ar concentration than AAr;
- CO_2 well in Colorado, USA;
- 160 kg UAr extracted for DarkSide-50:
  - ➢ ^{39}Ar reduction factor ~1400.

Phys. Rev. D 93, 081101 (2016)



DarkSide-50 Results

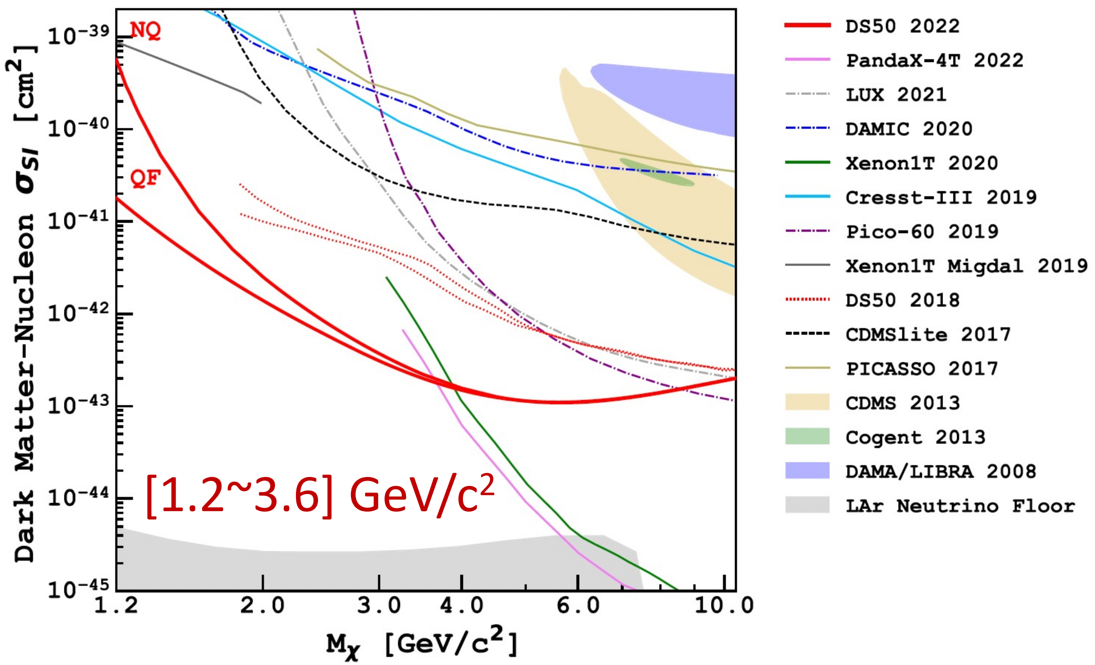
High Mass WIMP Searches



Background free over more than 500 days data.

Phys. Rev. D 98, 102006 (2018)
Phys. Rev. D 93, 081101 (2016)

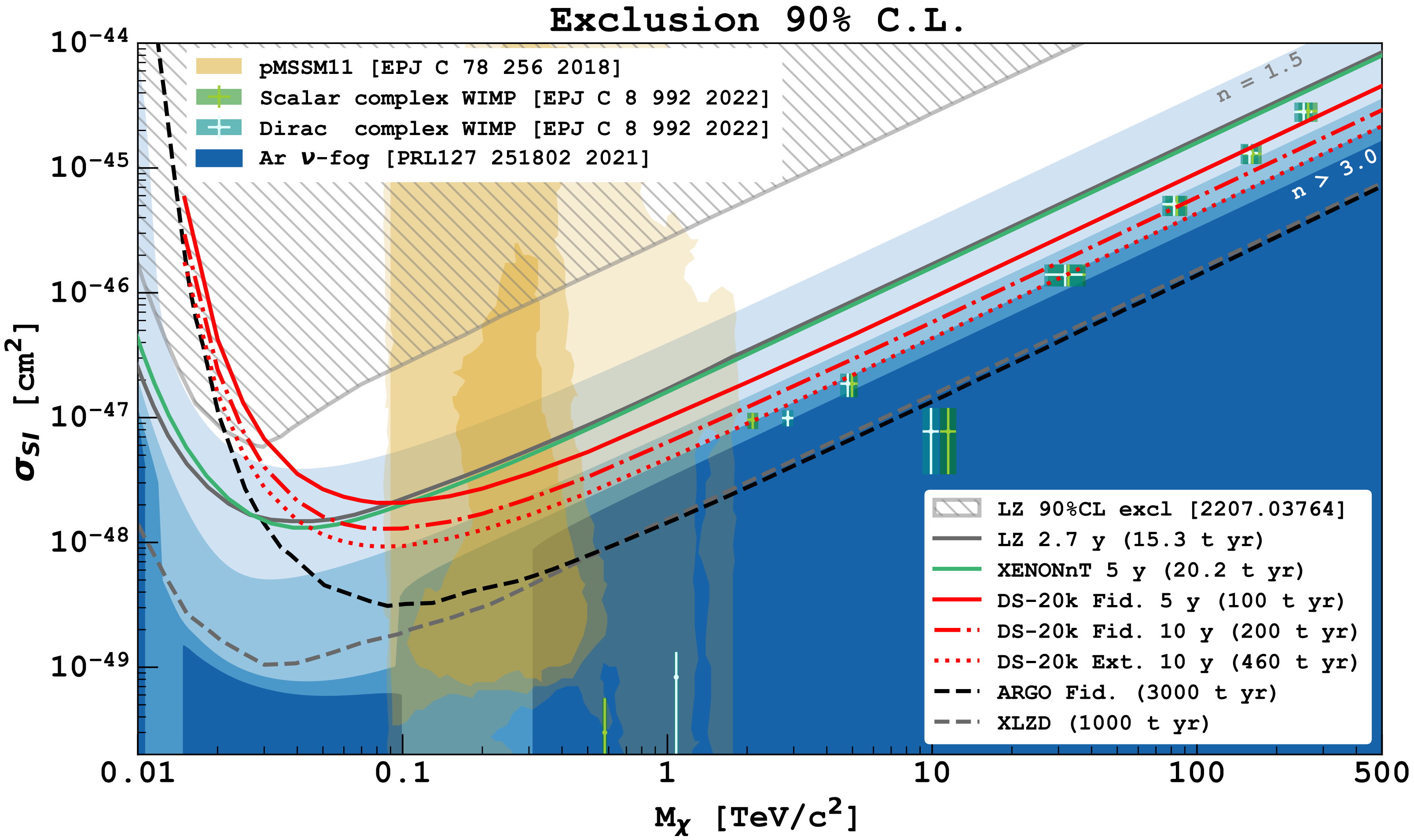
Low Mass WIMP Searches



Phys. Rev. D 107, 063001 (2023)
Phys. Rev. Lett. 130, 101001 (2023)
Phys. Rev. Lett. 130, 101002 (2023)
Phys. Rev. Lett. 121, 111303 (2018)
Phys. Rev. Lett. 121, 081307 (2018)

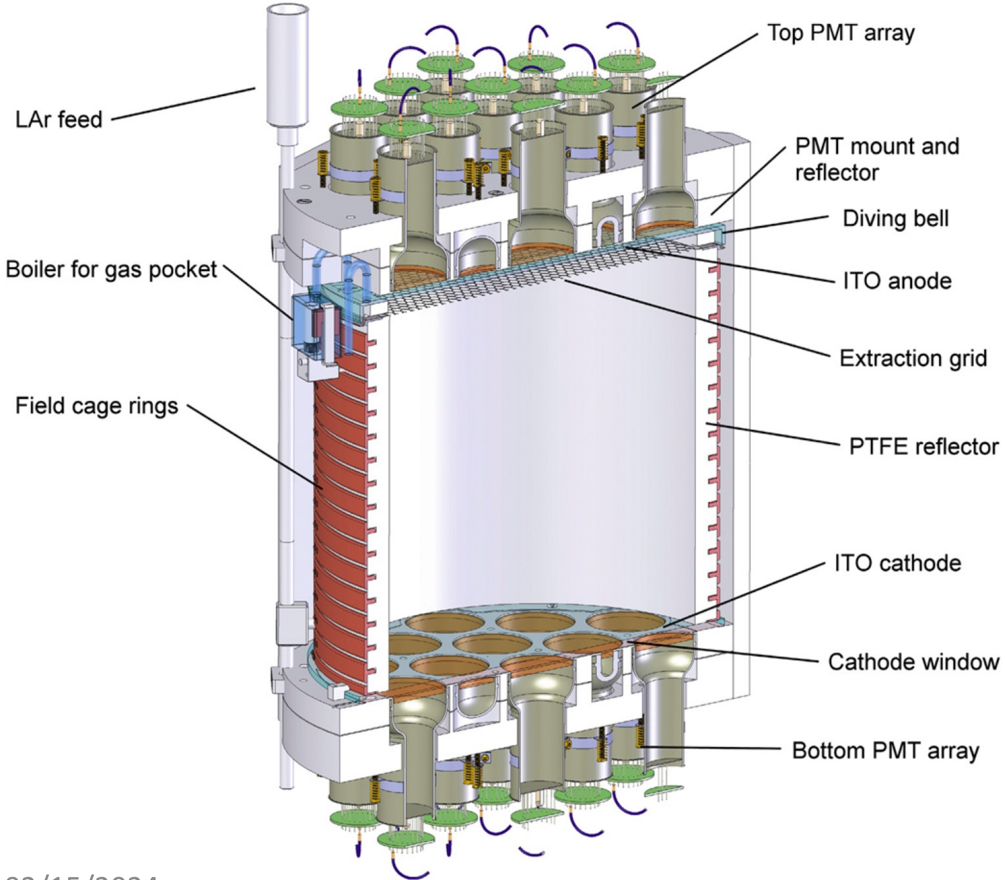
DarkSide-20k Projections

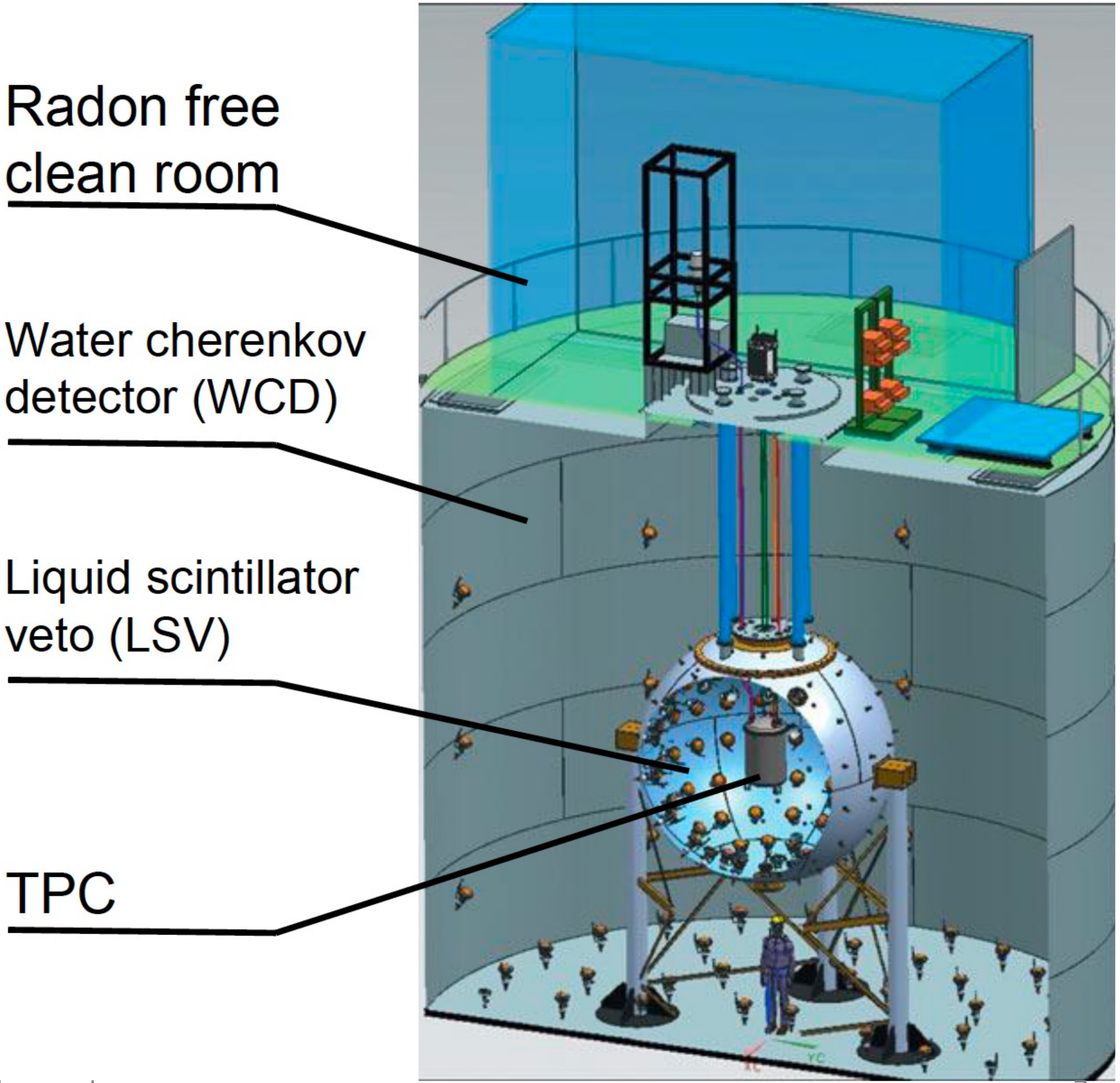
- Sensitivity to Spin-Independent WIMPs;
- With nominal exposure 200 t-y (20 t x 10 years):
  - 90% C.L. exclusion: 6.3 x 10^{-48} cm^2 @1 TeV/c^2 ;
  - 5 σ discovery: 2.1 x 10^{-47} cm^2 @1 TeV/c^2 ;
  - Sensitivity of core-collapse supernova neutrinos.
- Instrumental background: < 0.1 neutrons in RoI (30~200 keVnr) with 200 t-y exposure.

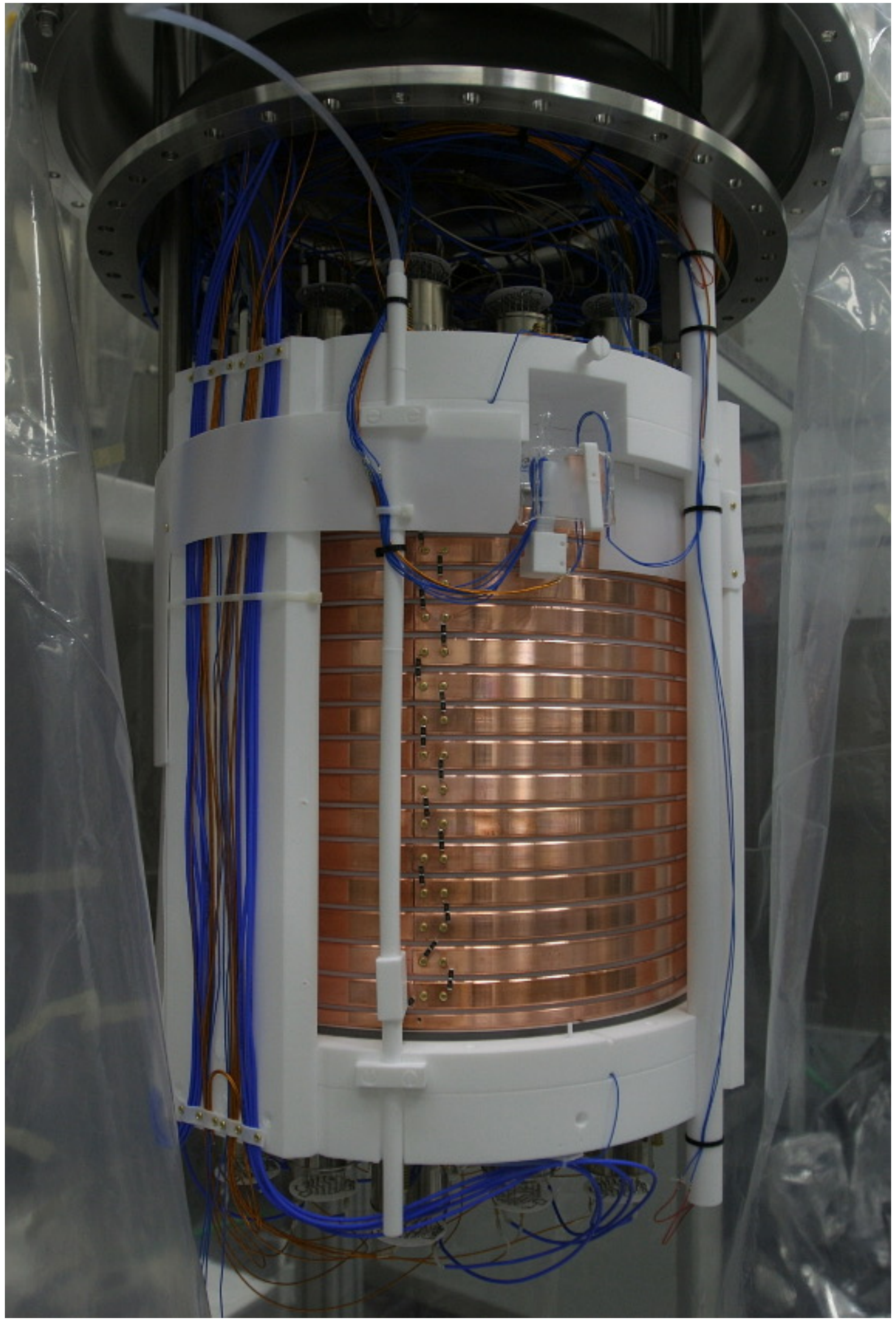


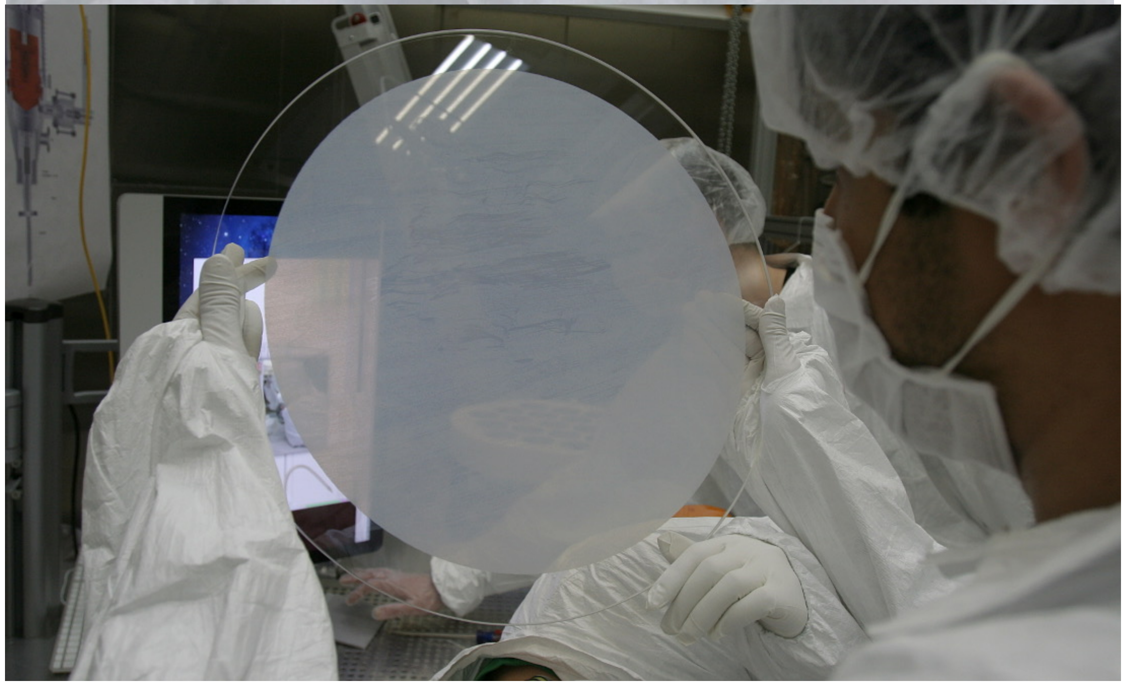
The DarkSide-50 Detector

- Dual phase argon TPC;
- 46.4 kg active mass;
- Light yield (@null field) ~ 8 p.e./keVee.

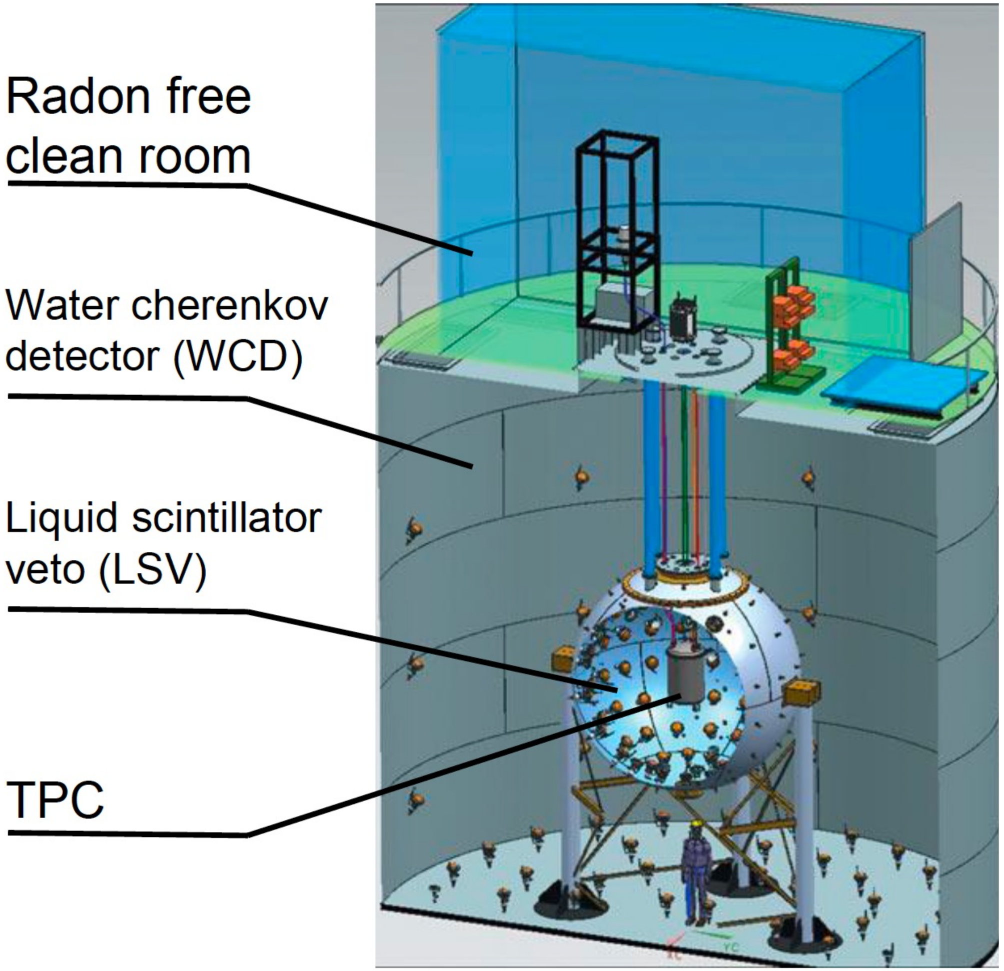




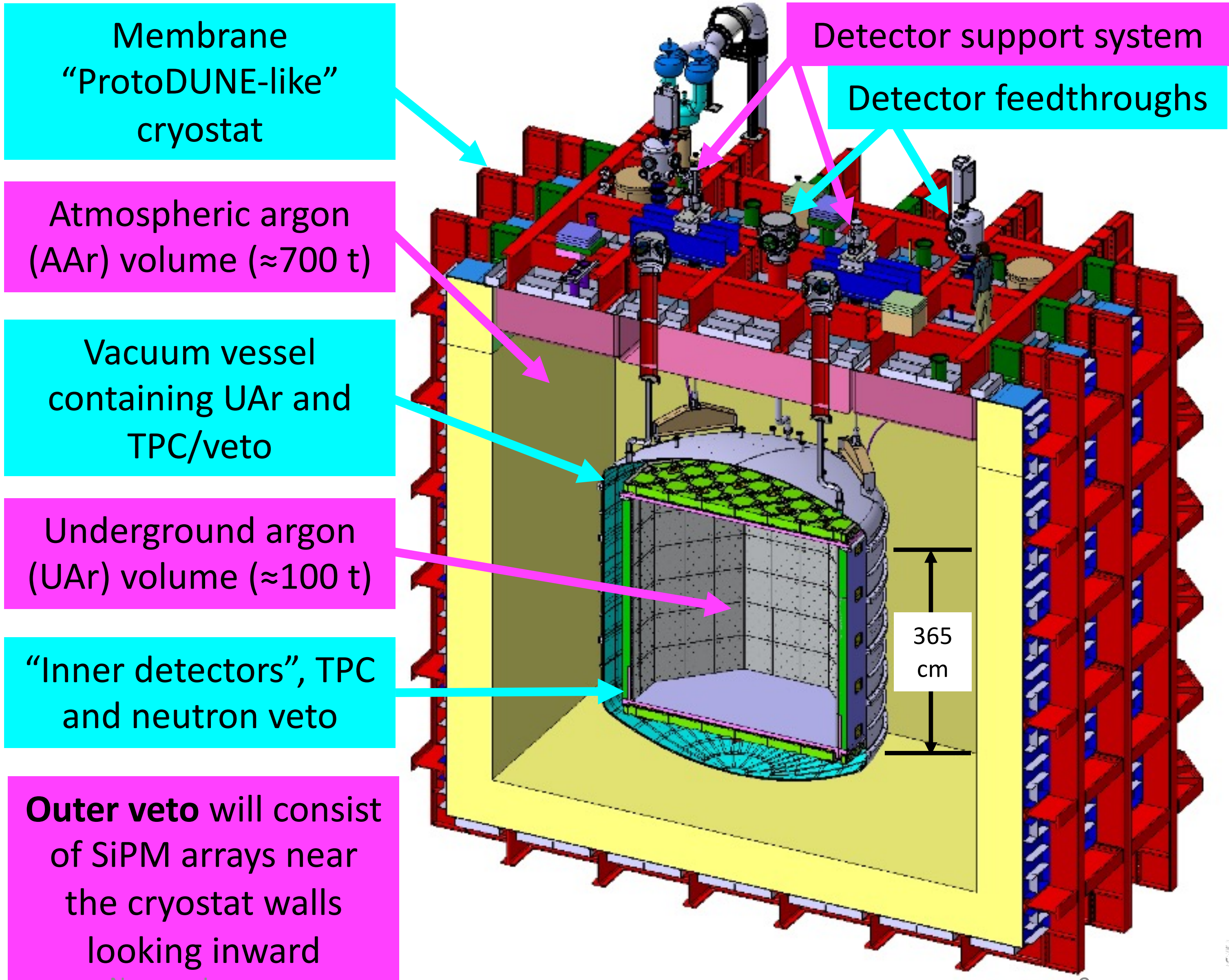




DarkSide-50



DarkSide-20k



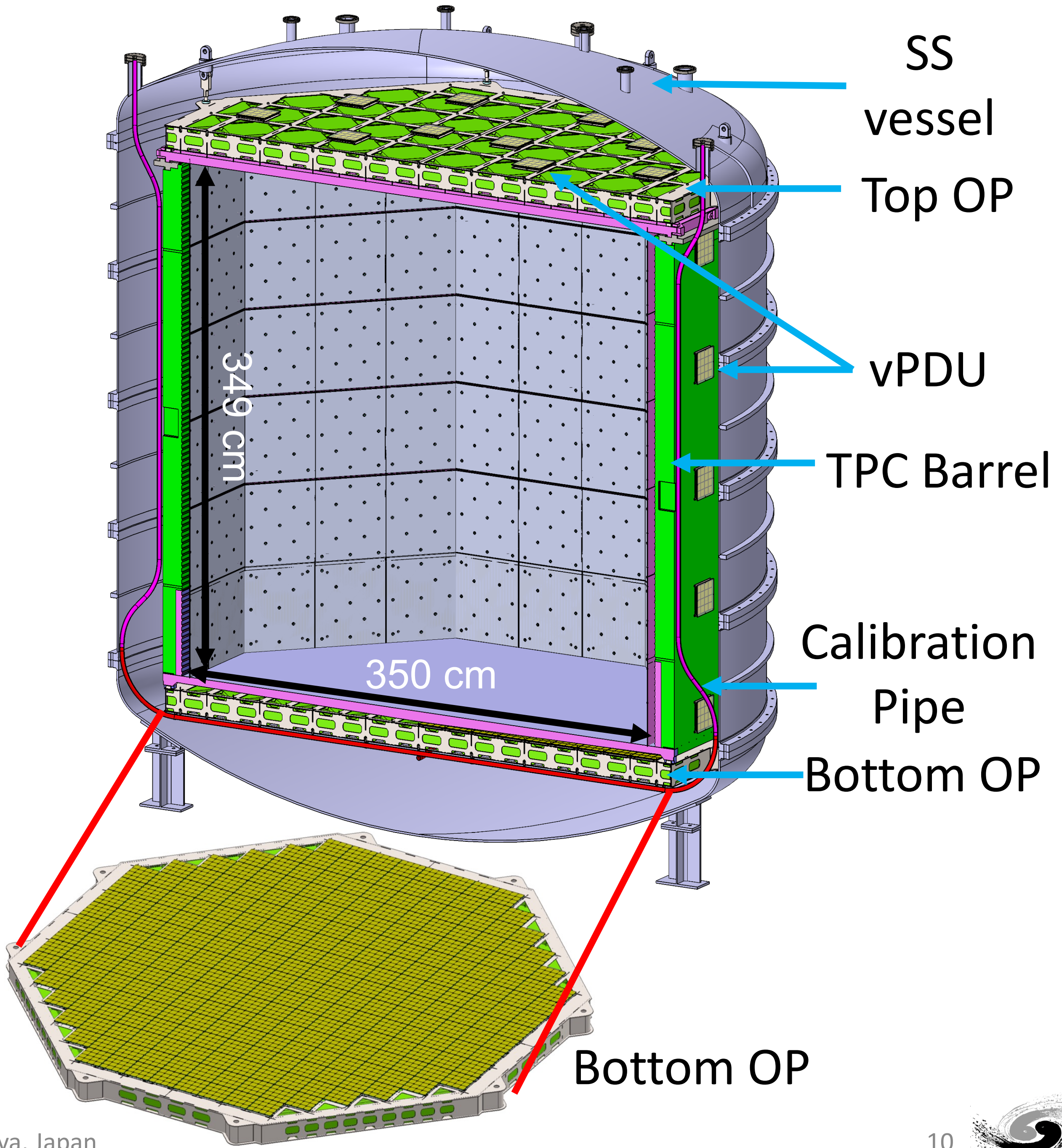
Outer veto will consist of SiPM arrays near the cryostat walls looking inward

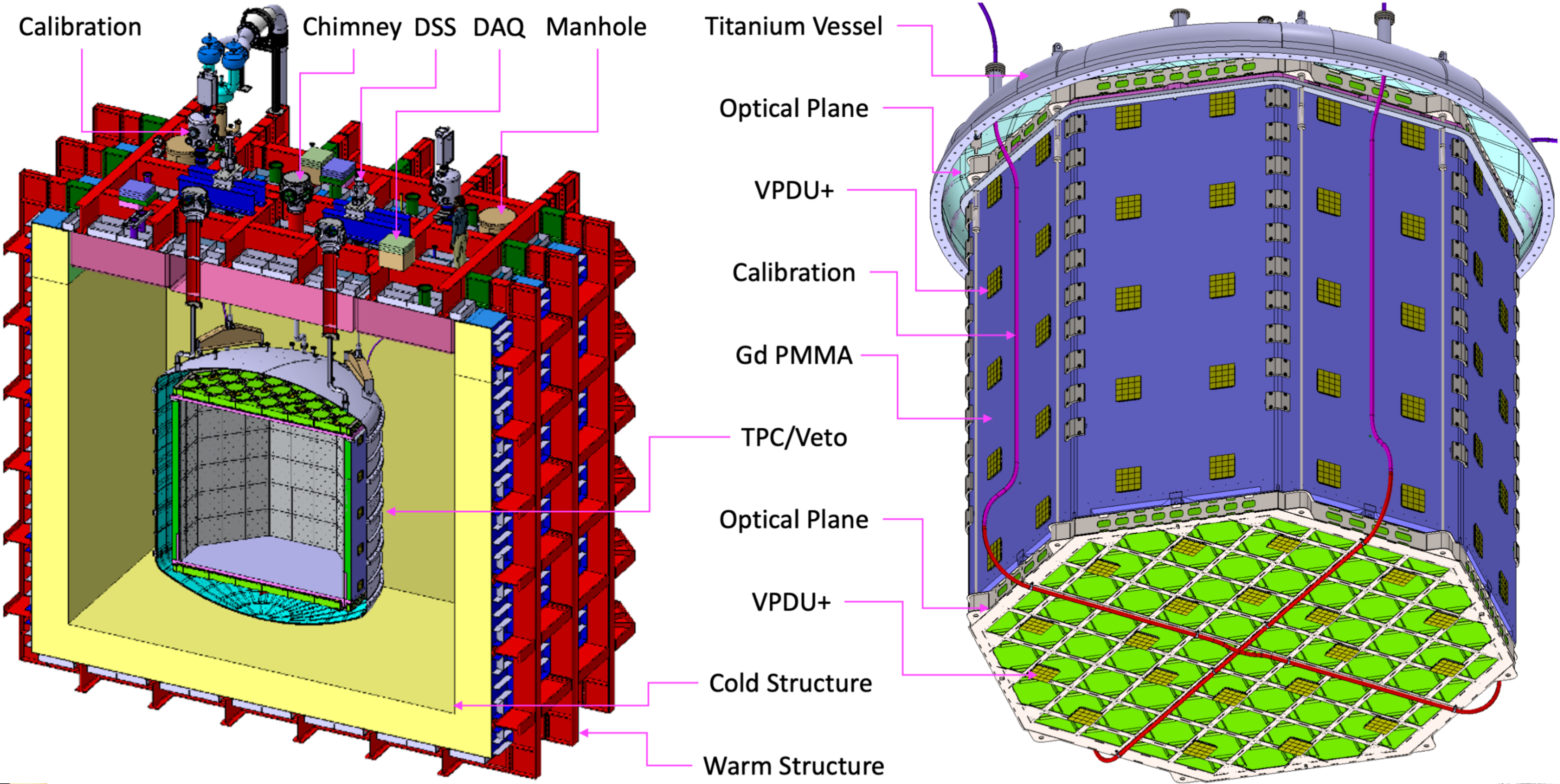
The Inner Detector

- TPC + neutron veto;
- Octagonal shape dual phase argon TPC:
  - Active UAr mass: 49.7 tonnes;
  - Fiducial UAr mass: 20.2 tonnes;
- Neutron veto:
  - Active UAr mass: 32 tonnes;
- ~100 tonnes argon in total.

More details in Giacomo Gallina’s talk

- SiPM as the photosensor;
- PMMA + Gd-PMMA as the main structure.




Calibration
Chimney
DSS
DAQ
Manhole
Titanium Vessel
Optical Plane
VPDU+
Calibration
Gd PMMA
TPC/Veto
Optical Plane
VPDU+
Cold Structure
Warm Structure

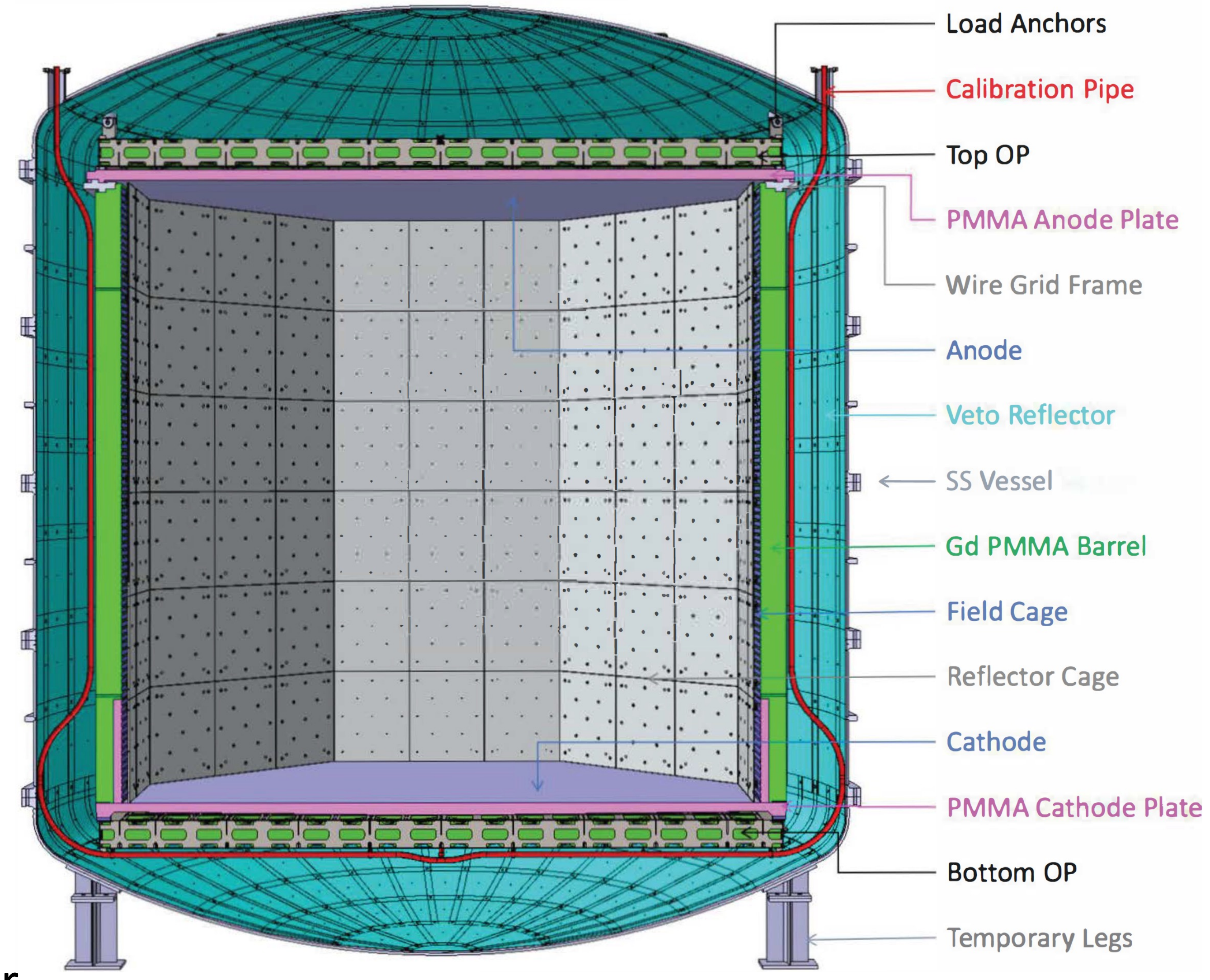
The Inner Detector - TPC

- Drift field: 200 V/cm;
- Extraction field: ≧2.8 kV/cm;
- Cathode voltage: -73.38 kV (min).

- LY (@null field) ~10 p.e./keVee;
- S2 yield > 20 p.e./e^-.

- Gas pocket thickness: 7.0±0.5 mm.

- PMMA + Gd-PMMA as the main structure;
- E-field:
    - Conductive polymer (Clevios™) coating as anode, cathode and field cage rings;
    - SS wire grid;
- ESR as reflector and TPB as wavelength shifter.



The Inner Detector - TPC

- From DS-50 to DS-20k:

➢ Main structure: PTFE -> Acrylic

➢ Reflectors: PTFE -> ESR

➢ Wavelength shifter: TPB -> TPB

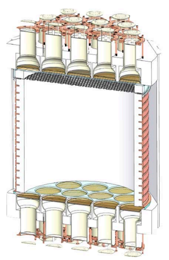
➢ Grid: Hexagonal mesh -> Parallel wires

➢ Field cage rings: Copper -> Clevios™

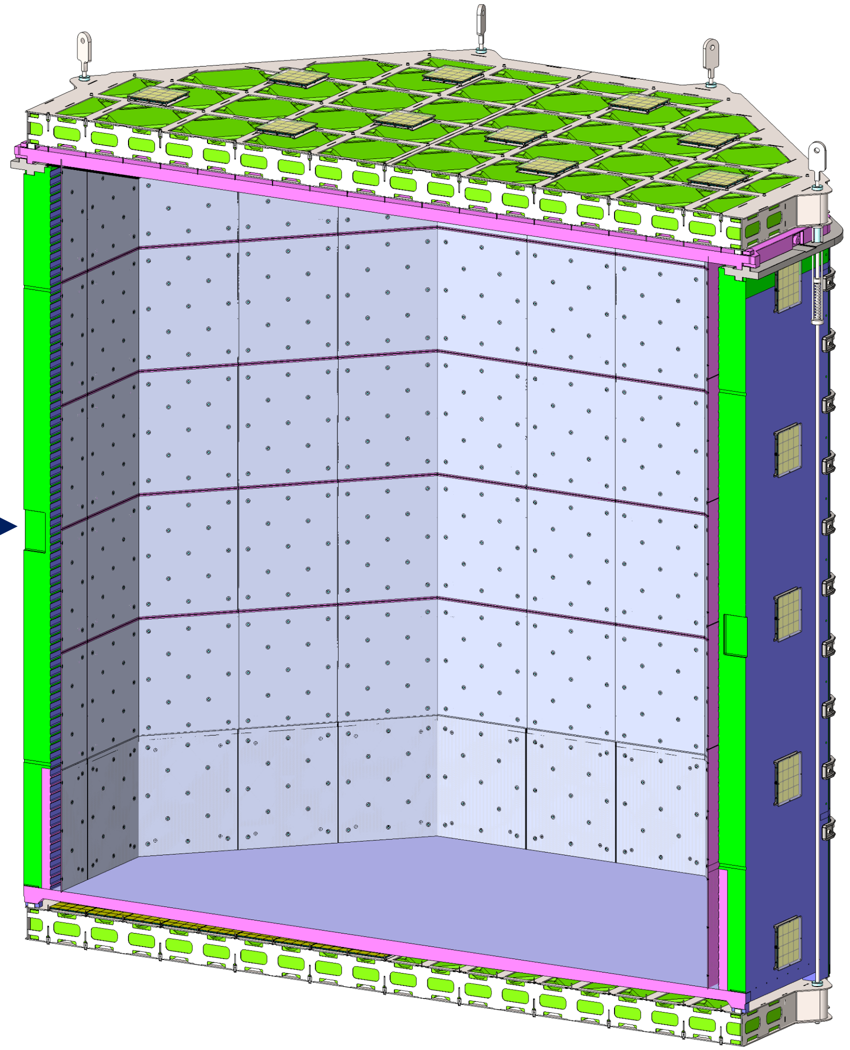
➢ Windows: Fused silica -> Acrylic

➢ Electrodes: ITO -> Clevios™

➢ Photosensors: PMT -> SiPM



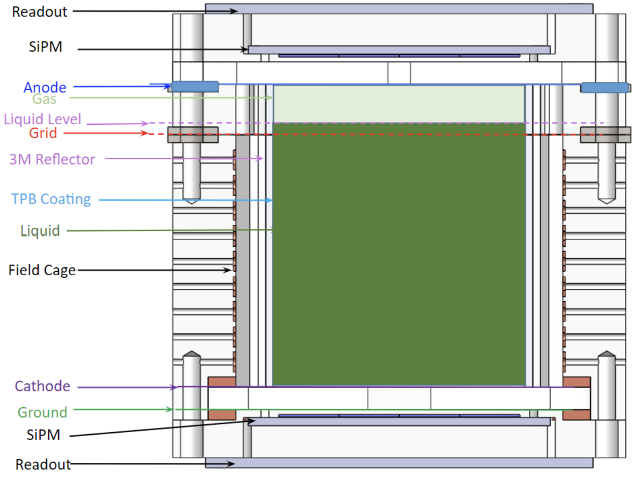
DS-50 ~20 kg

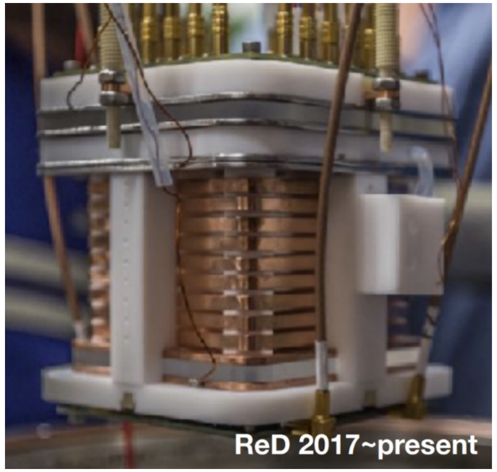


DS-20k ~20 tonnes

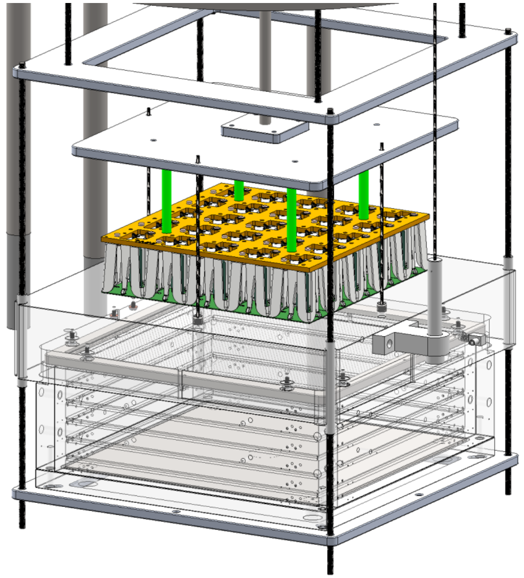
R&D TPCs before DarkSide-20k

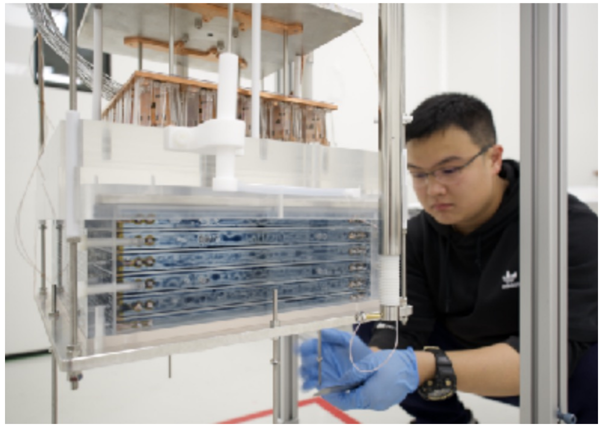
ReD (2017~present)
Constructed at UCLA
Tested at Naples and LNS



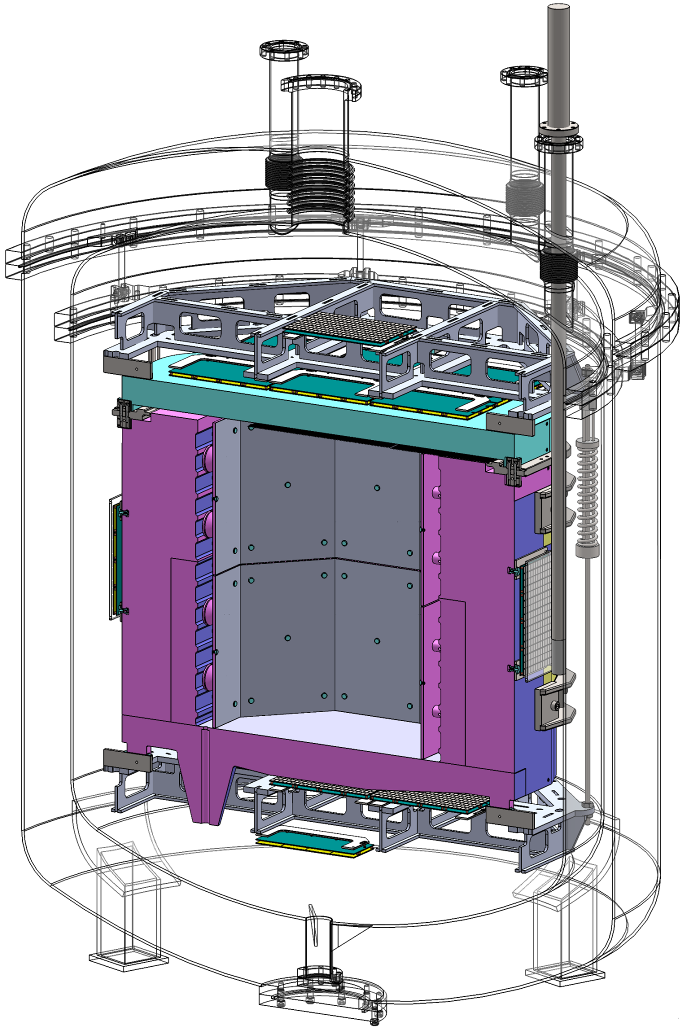


Proto_0 (2018~present)
Constructed and tested at CERN





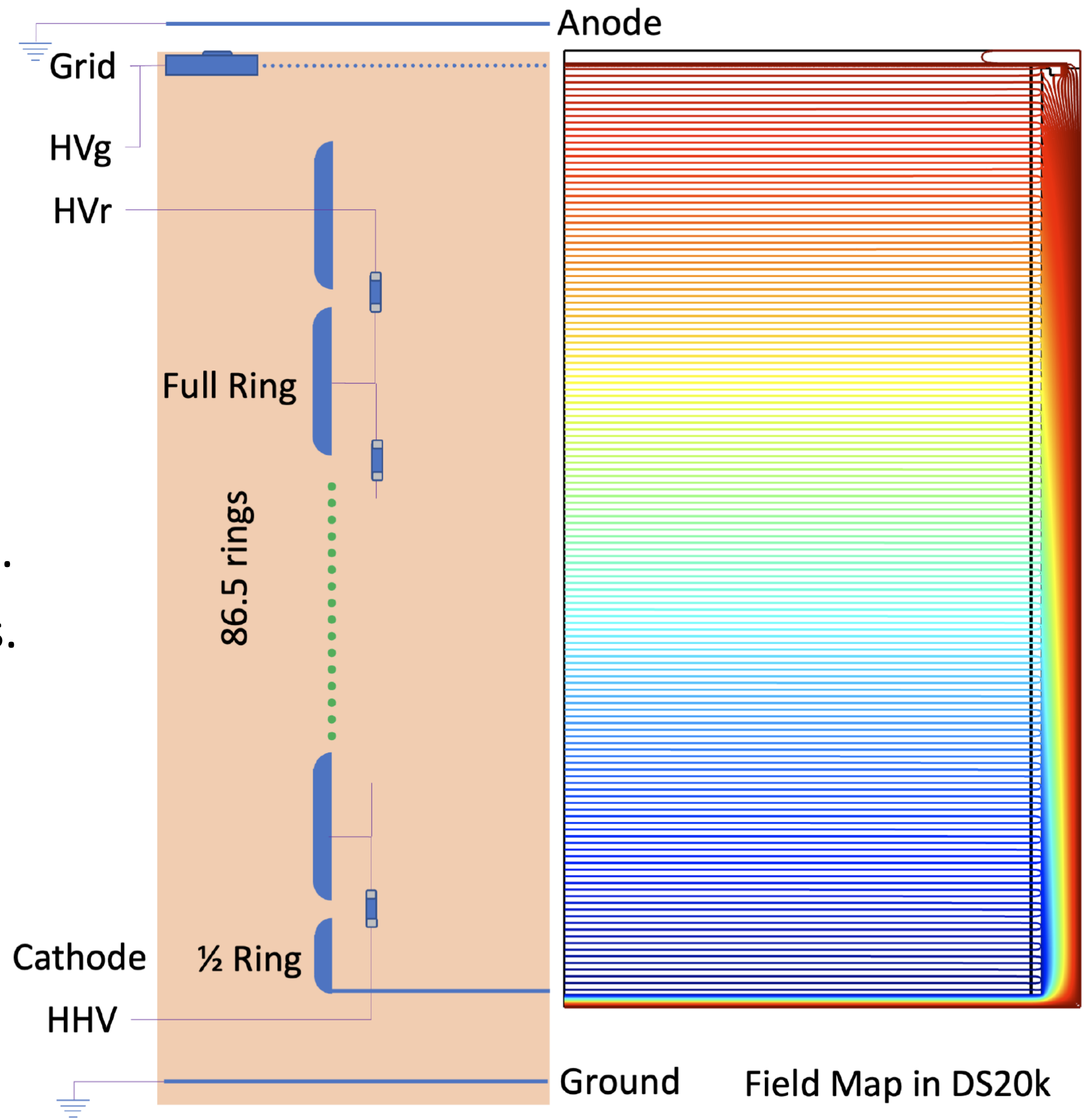
The mockup
Under construction at LNGS



The Electric Field

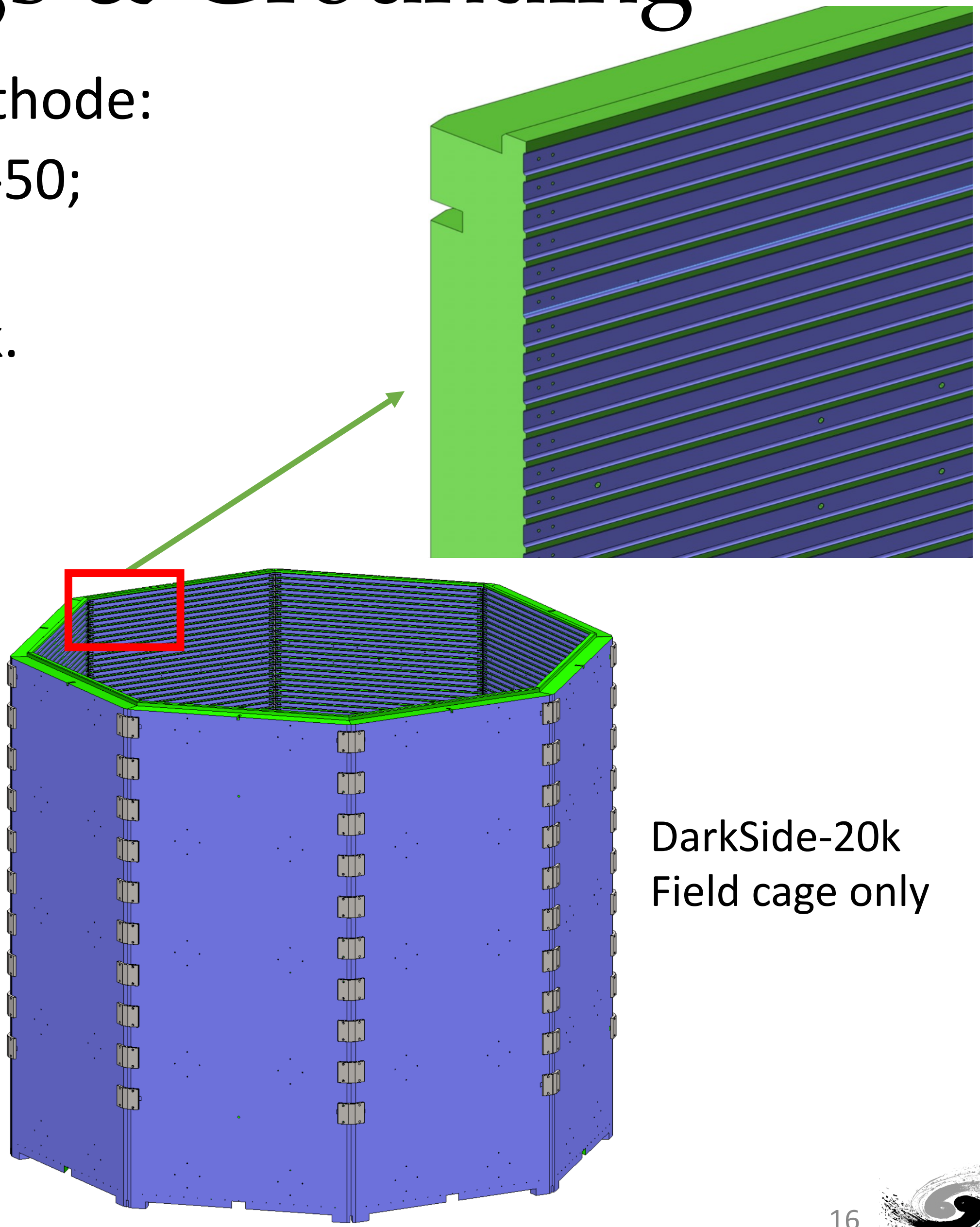
- Drift field: 200 V/cm;
- Extraction field: ≧2.8 kV/cm;
- Electroluminescence field: ≧4.2 kV/cm.

- Electrode: anode, cathode, grid, 1st ring.
- Field cage: shaping rings & resistor links.
- HV:
  - Grid: 3.78 kV;
  - First shaping ring: ~4.58 kV;
  - Cathode: ~73.38 kV.
- HV feedthroughs.



Electrode & Field Shaping Rings & Grounding

- Planar electrode is chosen to be the anode and the cathode:
  - ITO (Indium Tin Oxide) on fused silica -> DS-10, DS-50;
  - ITO on PMMA -> ReD;
  - Clevios on PMMA -> Proto_0, the mock-up, DS-20k.
  - From DS-50 to DS-20k,
    - Fused silica -> PMMA:
      - ➢ Dimension increased to ~4m in diameter;
    - ITO -> Clevios:
      - ➢ TPB durability, complexity of coating.
- Field shaping rings:
  - Copper ring -> Clevios coating on acrylic grooves.
  - ➢ Significantly reduce the materials.
- TPC grounding.



DarkSide-20k
Field cage only

Clevios

- A conductive polymer;
- Blue aqueous dispersion.

- Rn emanation:
  - No signal has been observed after 3 months.

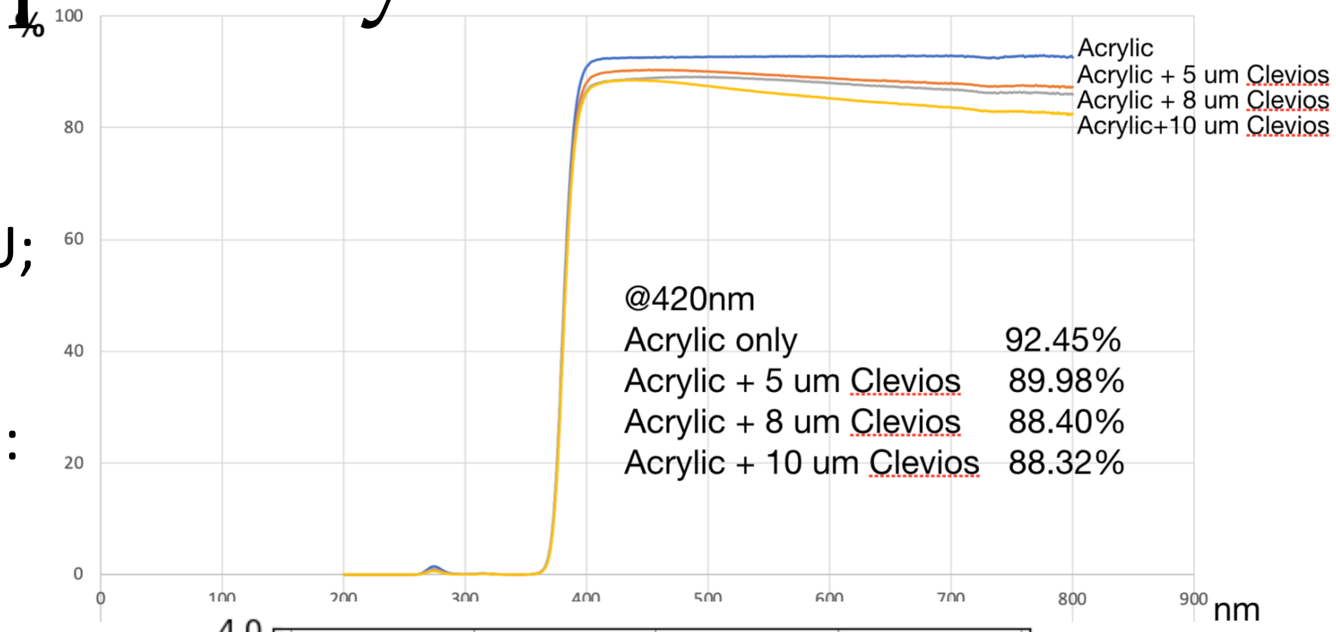
- Radioactivity (by ICP-MS):

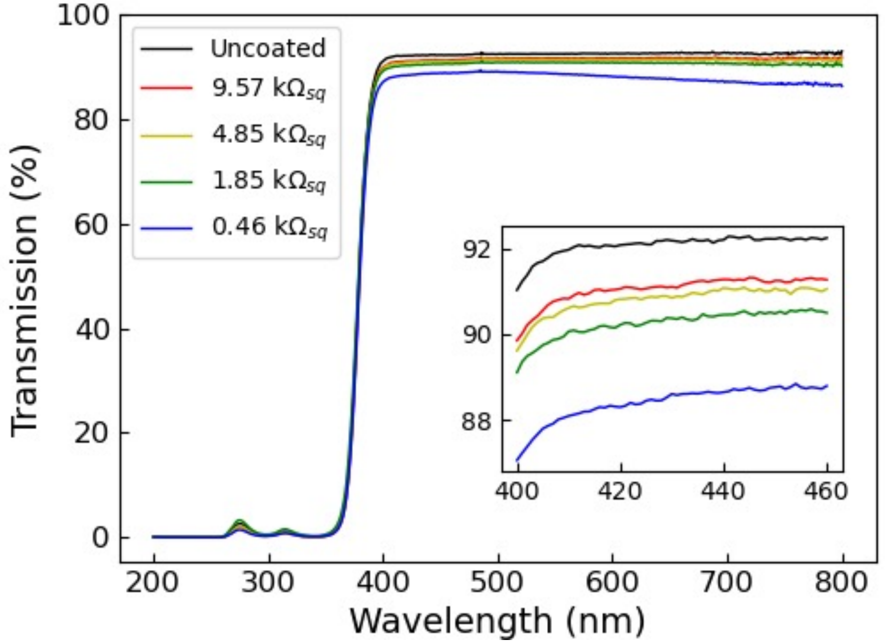
^{232}Th	^{238}U
117 ppt	111 ppt

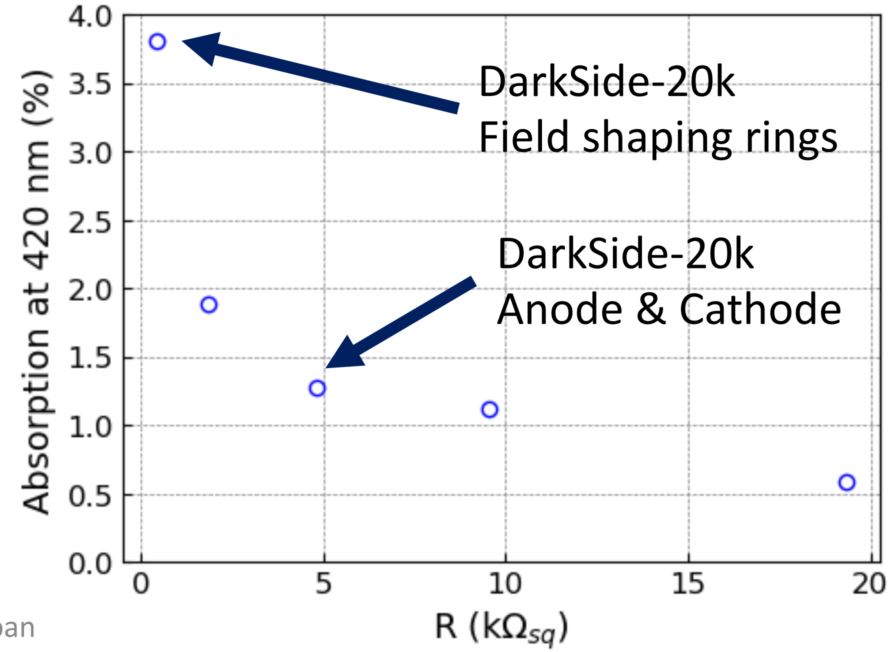
Heraeus Clevios™

Clevios: Optical Transparency

- Measurement done by 420 nm light;
- By wet thickness, measured at Princeton U;
- By resistance, measured at Carleton U;
- DS-20k electrode is designed as 5000Ω/sq:
  - ➢~1% non-transparency from Clevios.

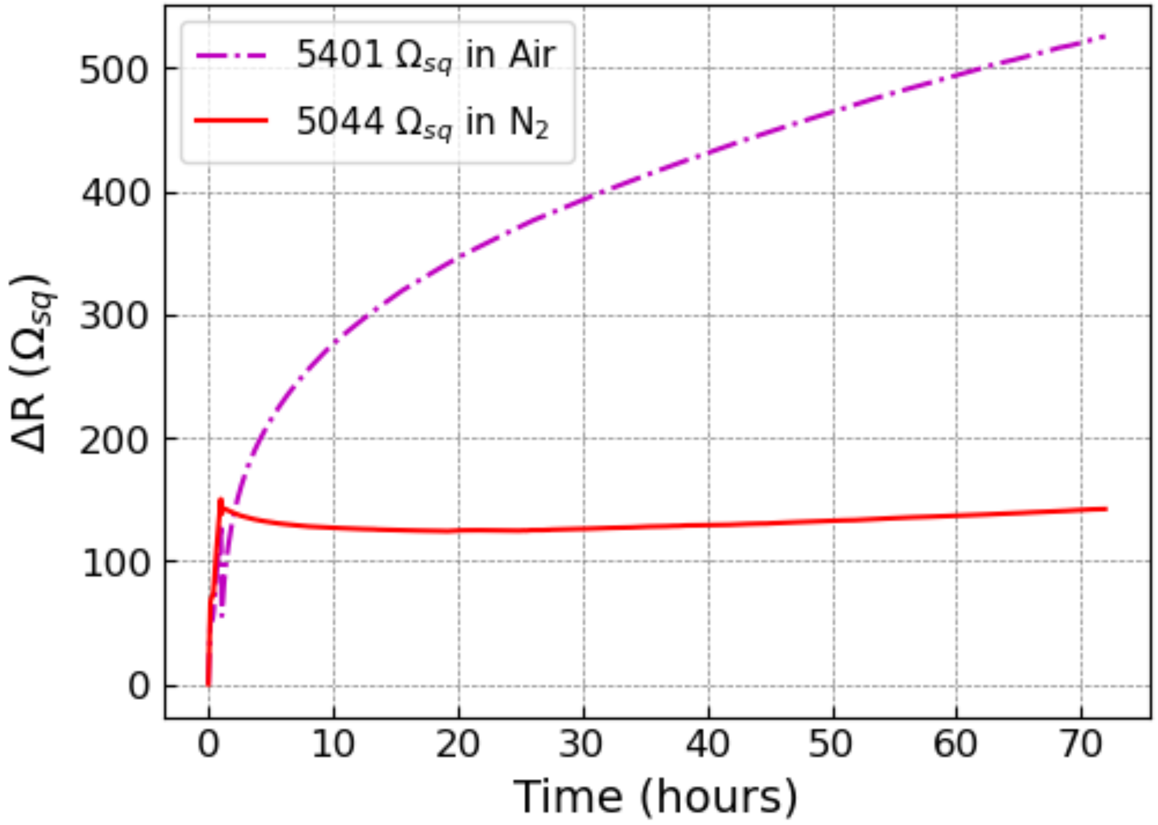




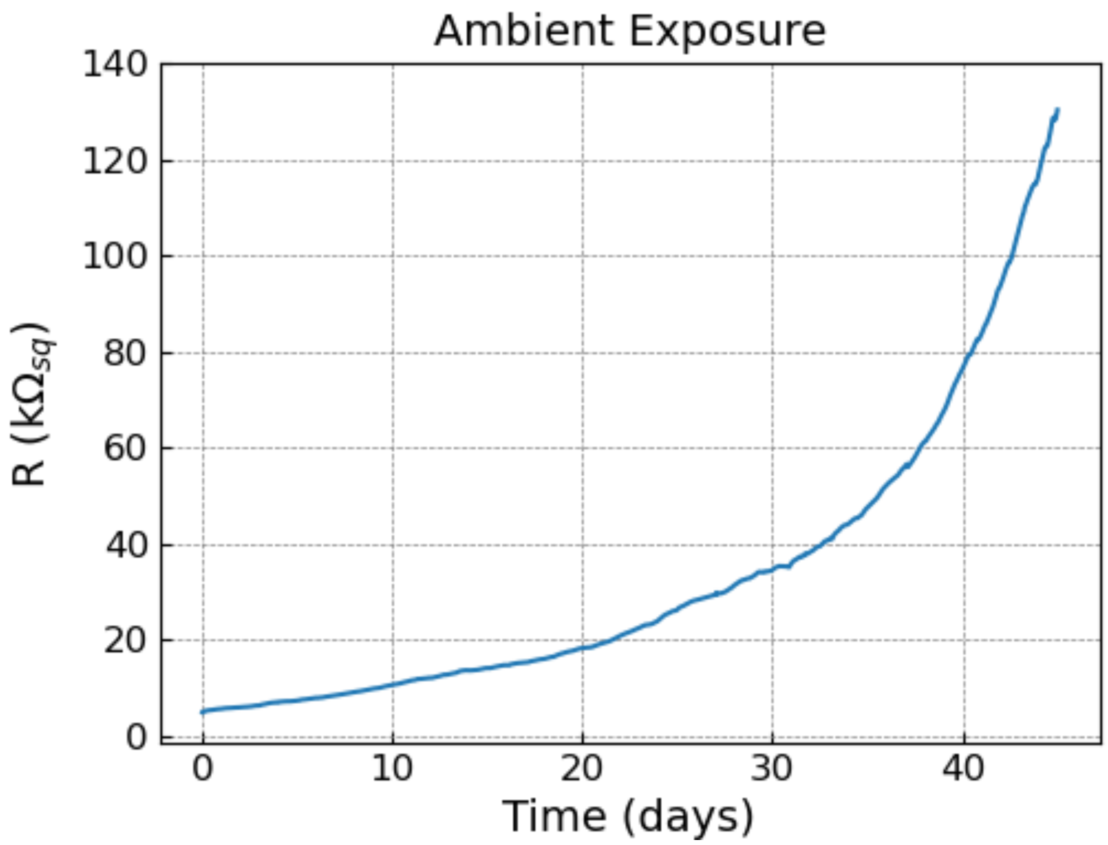


Clevios: Degradation

- Clevios degrades when exposes to the air;
- TPB seems to protect Clevios & prevent rapid aging.



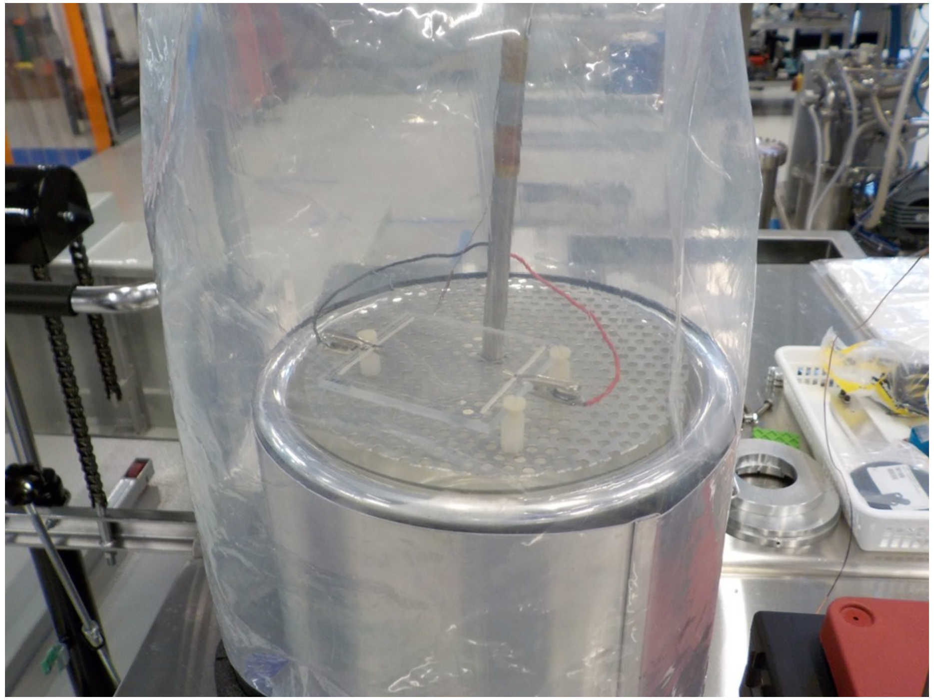
Cleanroom air, dark

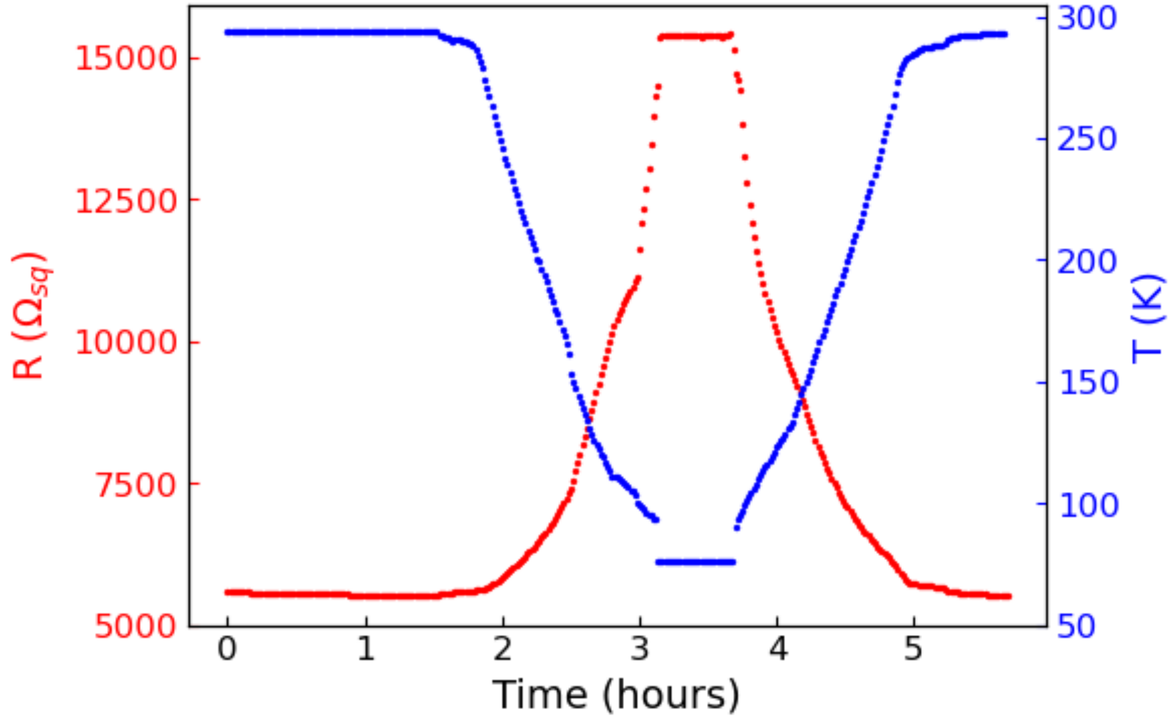


At 20° C, RH=40%, lab LED lights

Clevios: Resistance at Different Temperatures

- To understand resistance vs temperature.
- @Carleton University.
- Cool down by raising LN_2 surface towards sample;
- Purge plastic bag with N_2 gas to keep moisture away from sample.

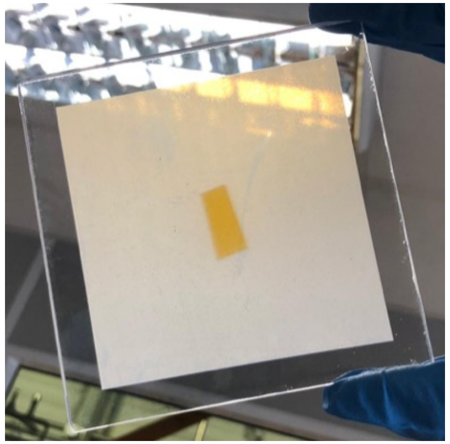


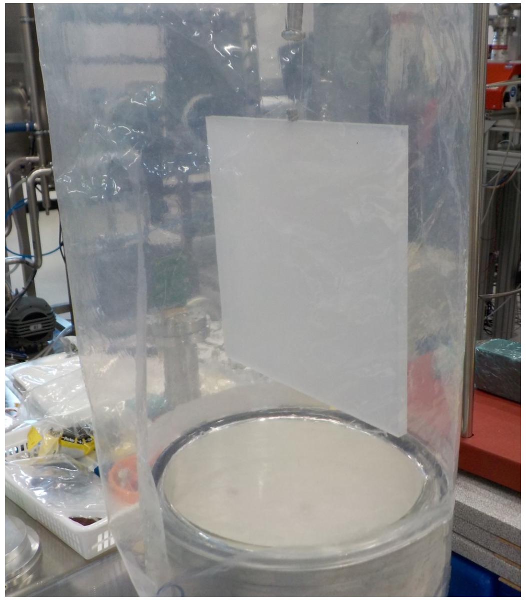


Clevios + TPB

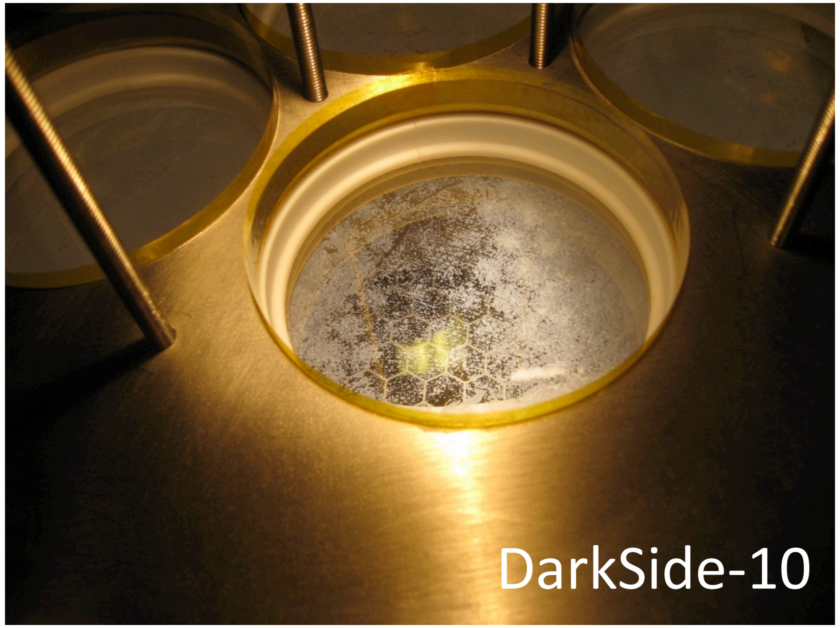
- With ITO as the substrate, TPB defection was observed.
- TPB coating on Clevios seems more robust.

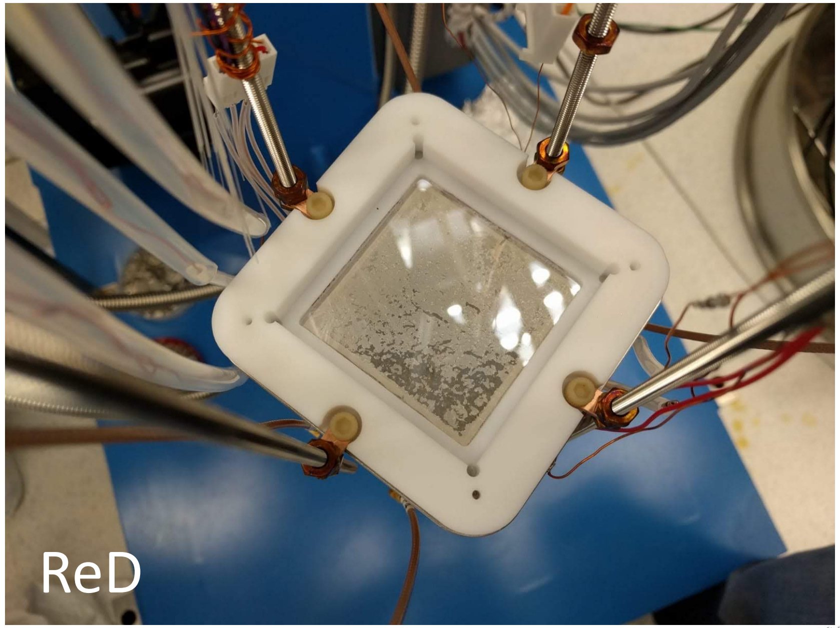
Test sample at CERN
5 µm wet thickness Clevios
200 µg/cm2 TPB
LAr dunking test and GAr blowing test.
TPB layer is stable (does not flake off)





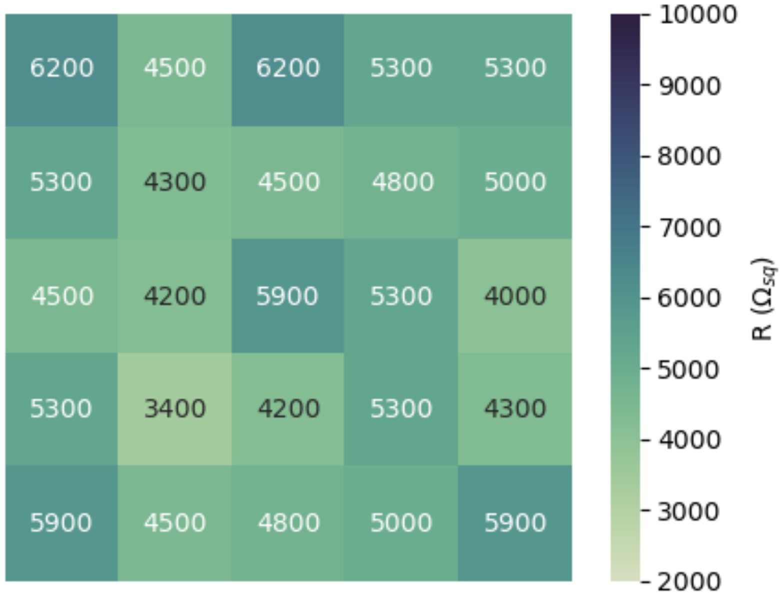
Test sample at Carleton
Clevios with 5000Ω/sq
3 µm TPB
LN2 dunking test.
TPB layer is stable (does not flake off)





Clevios + TPB

- Resistance measurements, before and after TPB coating.
- Sample：
  - 15 cm x 15 cm acrylic sample;
  - 5 cm x 5 cm square subregions.
- No contact Eddy current probe with 10 kΩsq sensitivity;
- The sensor is 2 mm above the sample.



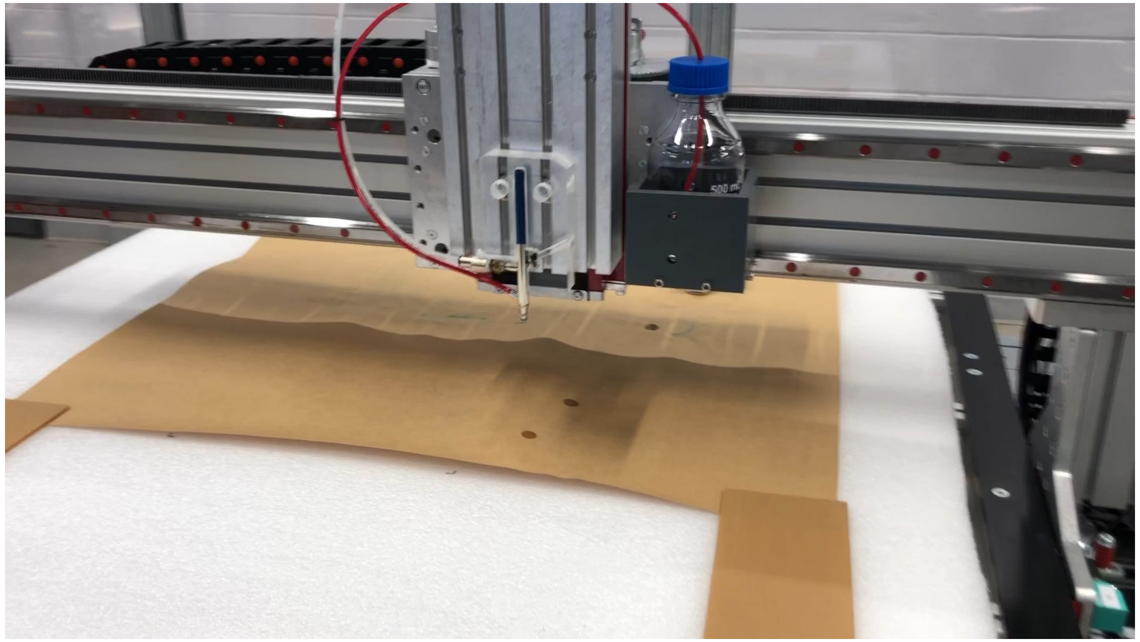
Clevios

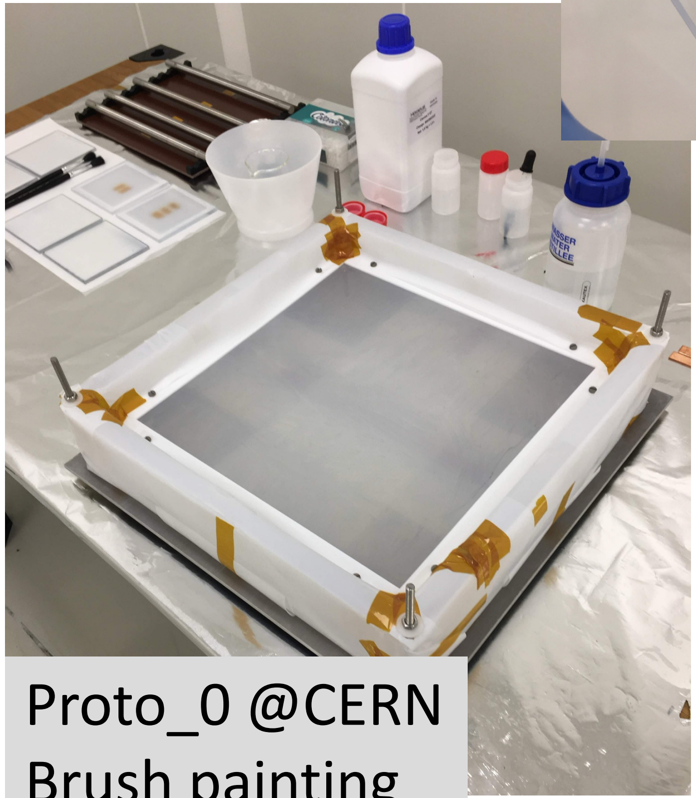
Clevios + TPB

Clevios: Coating Methods

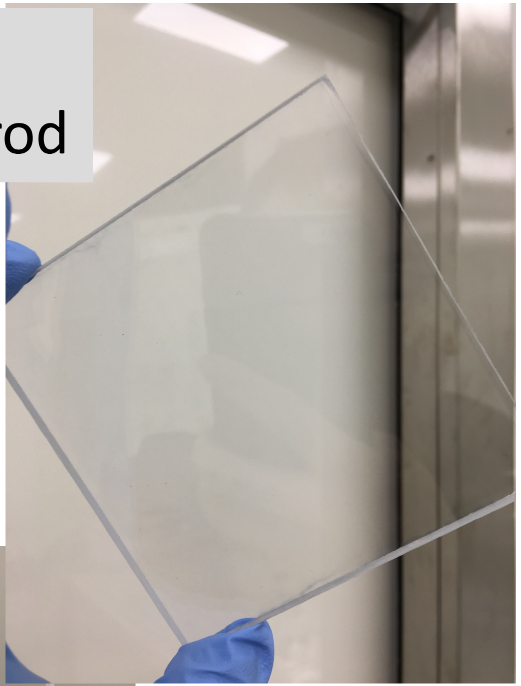
- Wire wound rod, for small area, ultra fine surface finish;
- Brush painting, for small area;
- Spray painting, for large area.

Automated spray painting system built at Carleton U.



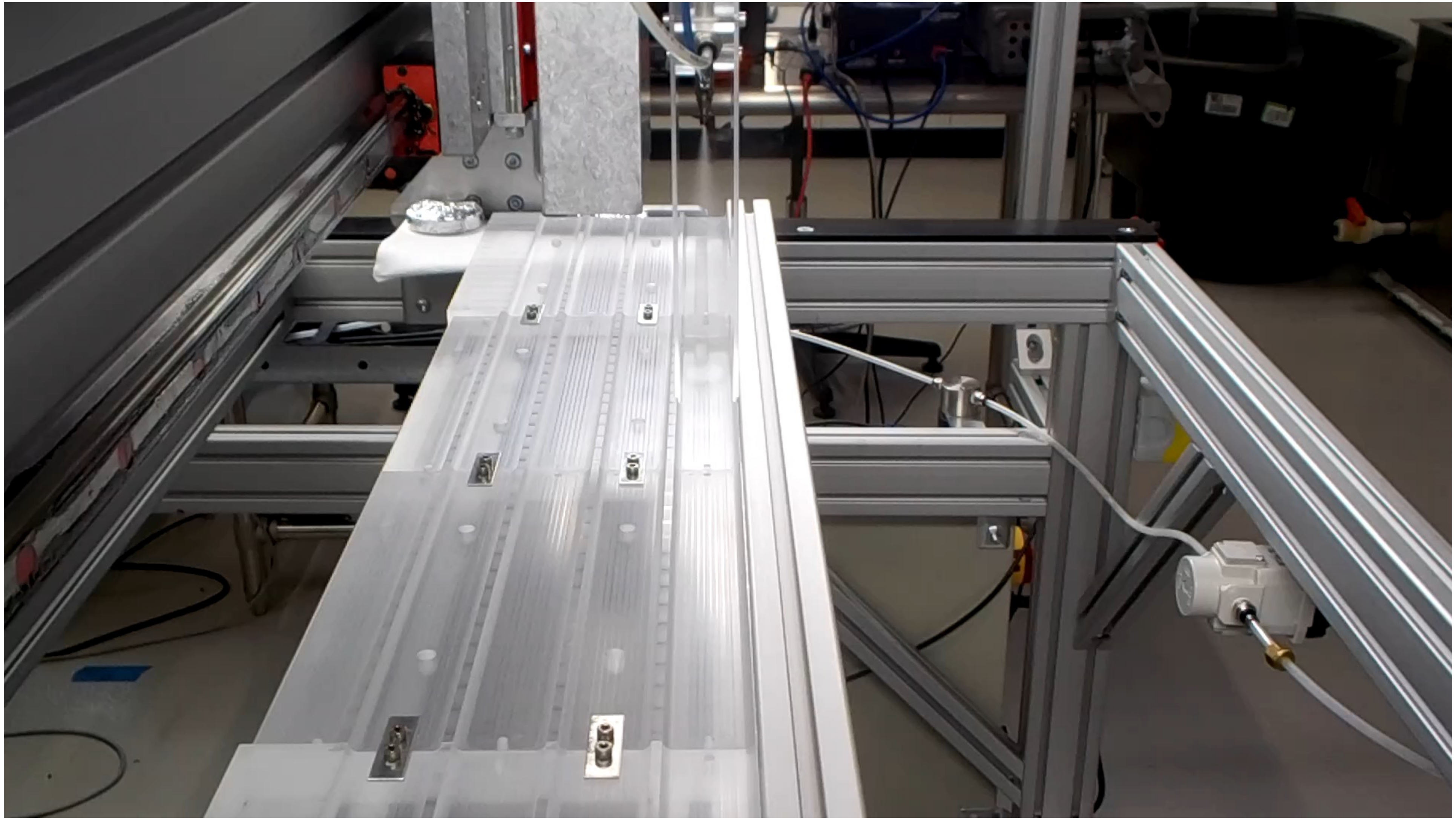


Proto_0 @CERN
Brush painting



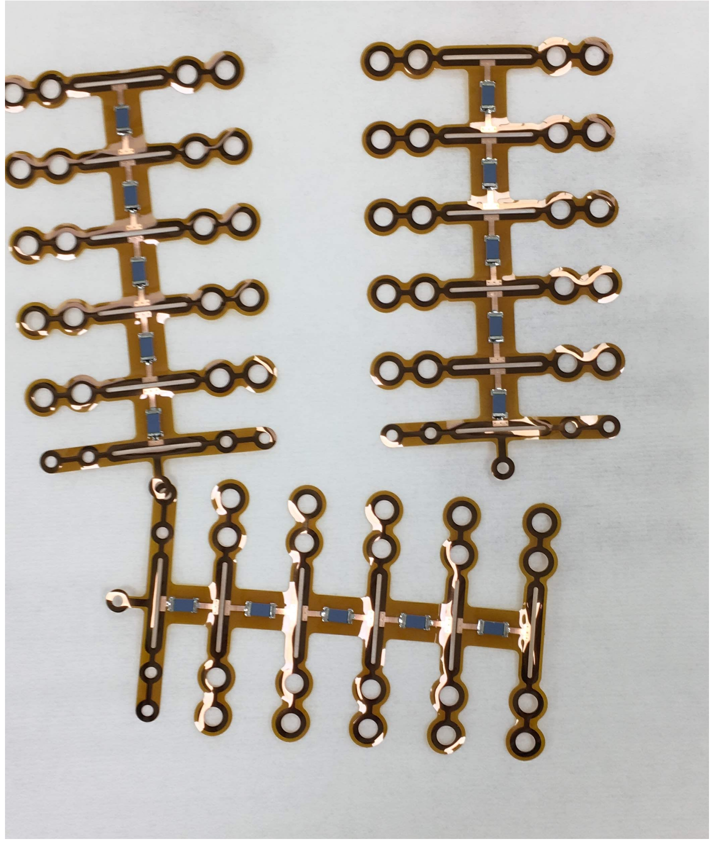
Test sample
Wire wound rod

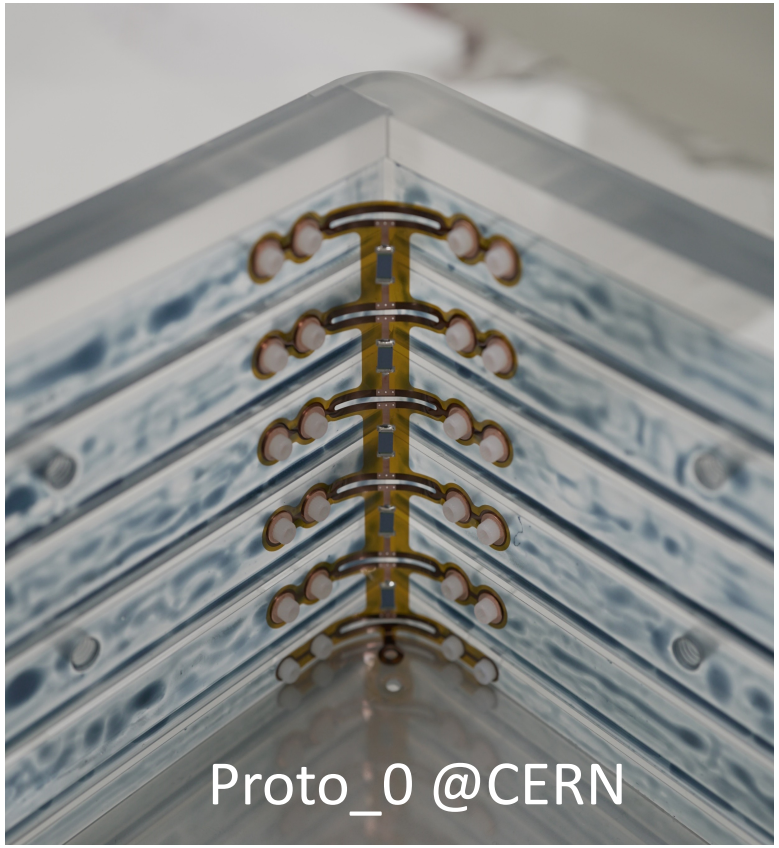
Test coating of the DarkSide-20k field cage.

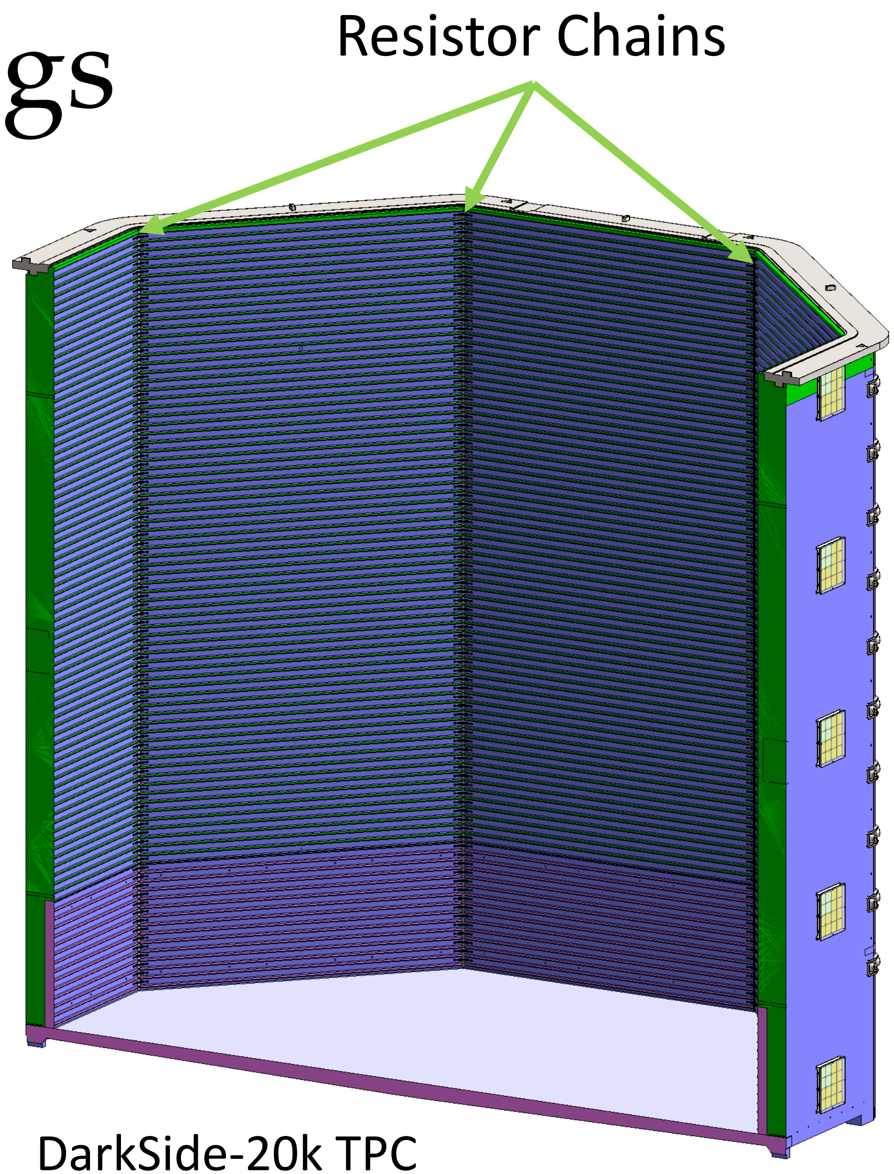


Link for the Field Shaping Rings

- Resistor chain: Kapton + copper;
- To be placed at TPC eight corners.



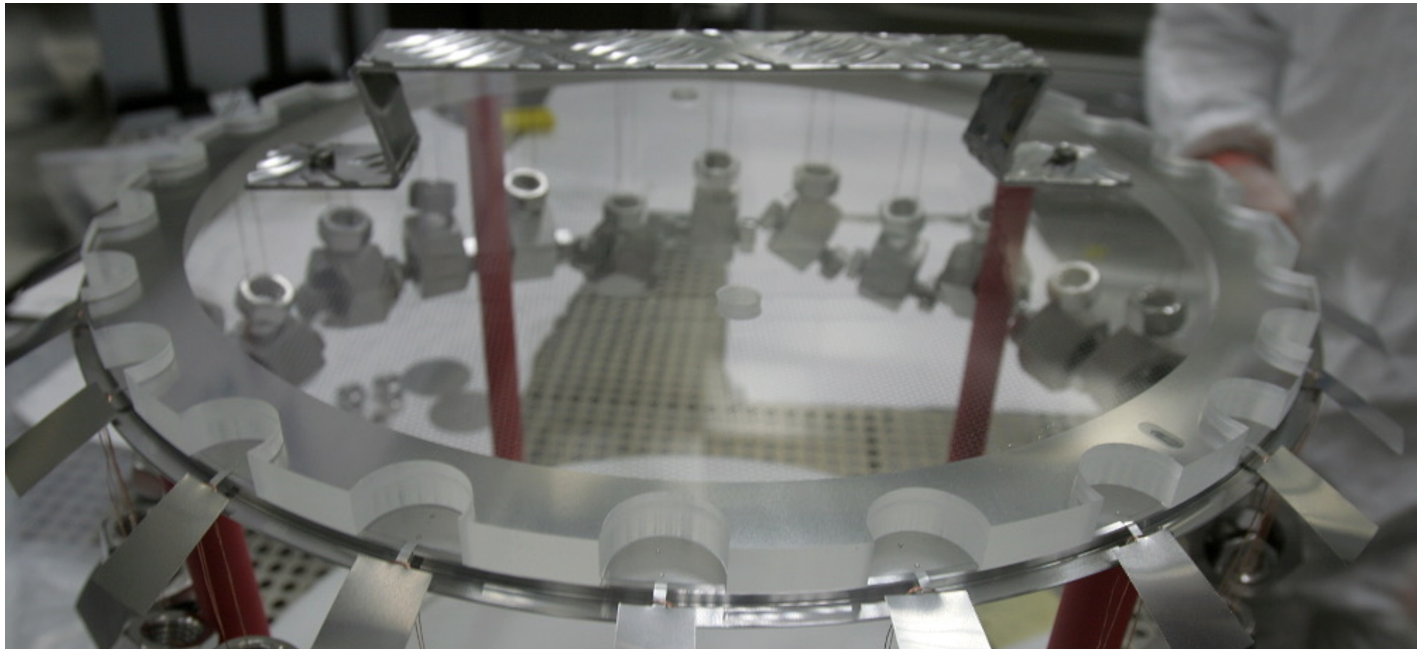




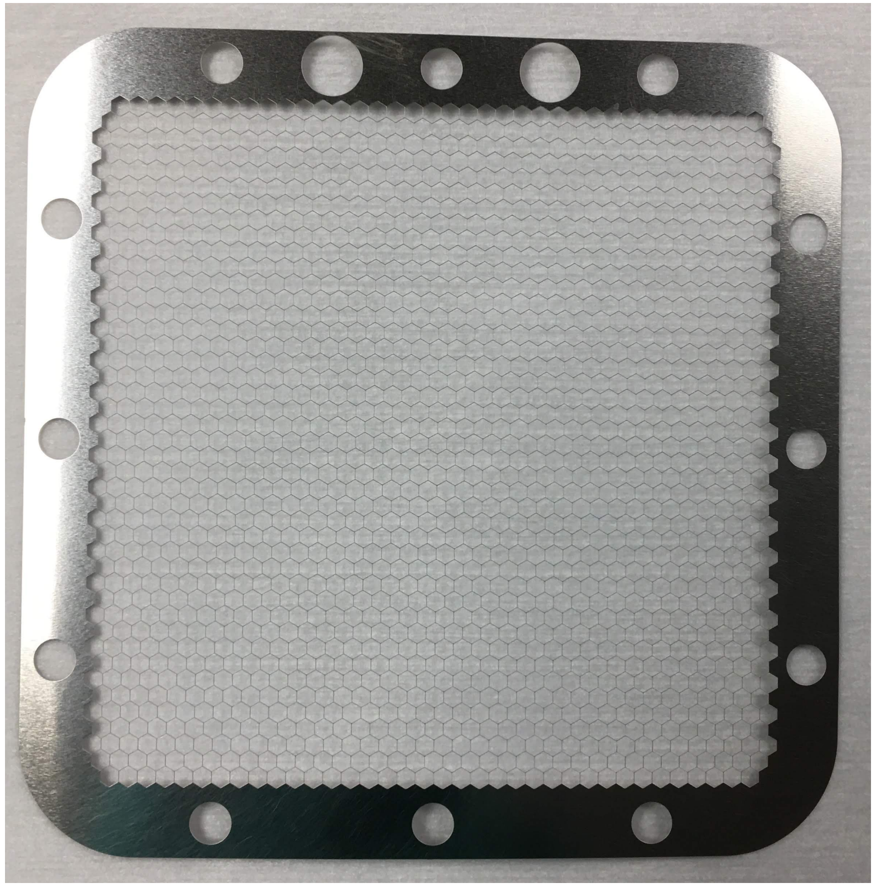
DarkSide-20k TPC
Anode and reflector cage are removed for better visualization.

Wire Grid

- DarkSide-50->DarkSide-20k;
- Chemical etched SS mesh -> wounded parallel wires:
  - Easy to extend the dimension;
  - Easy to apply desired tension -> sagging;
  - Electric field uniformity.



DarkSide-50 mesh



ReD mesh

Wire Grid

- Maintain the optical transparency > 97%:

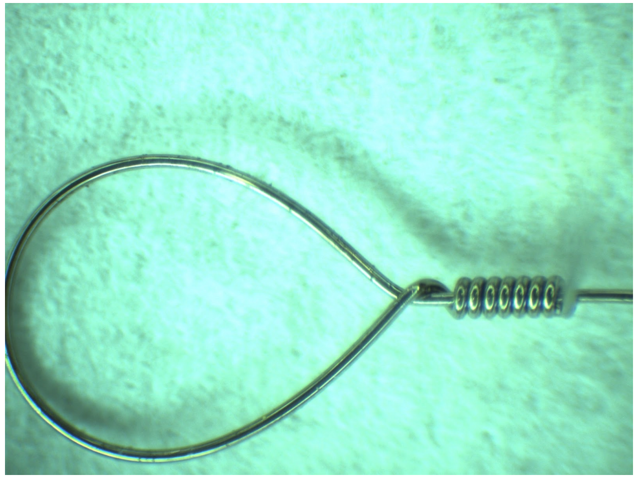
➢~150 μm diameter, 3 mm pitch.

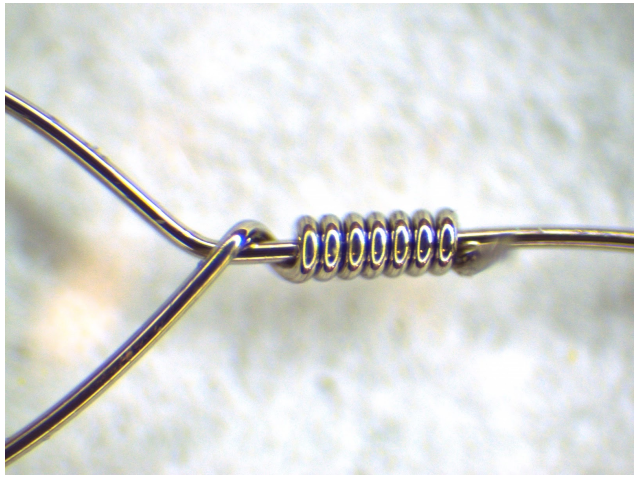
- Guitar wire wound:

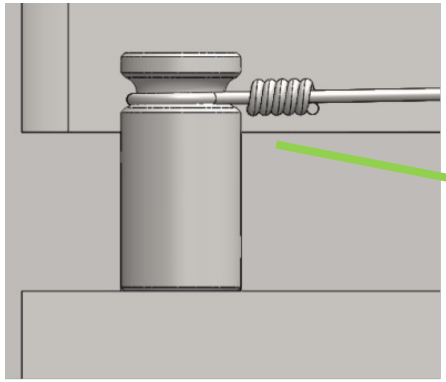
➢Tension ~1 N, wire sagging < 0.03 mm;

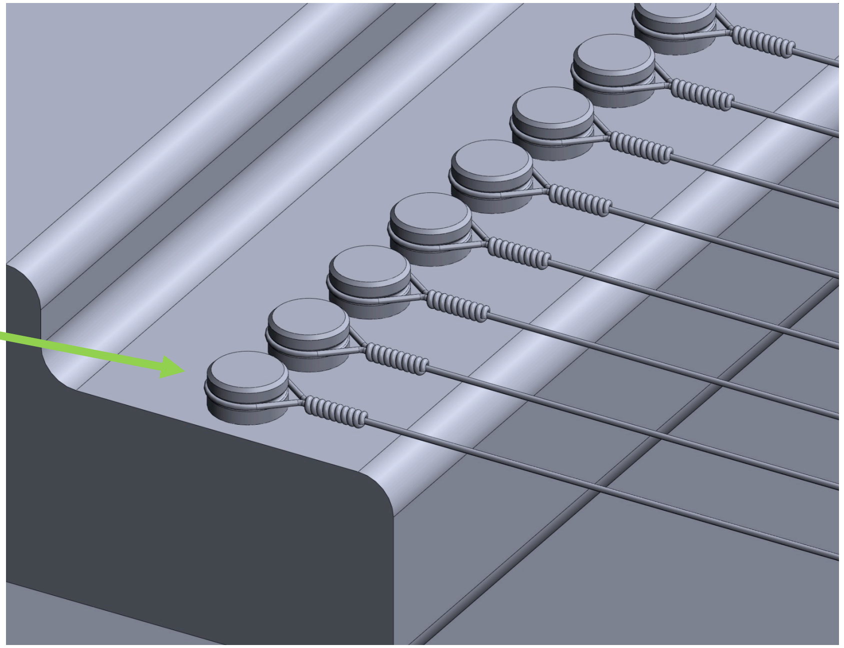
➢The variation of S2 light yield is < 3%.

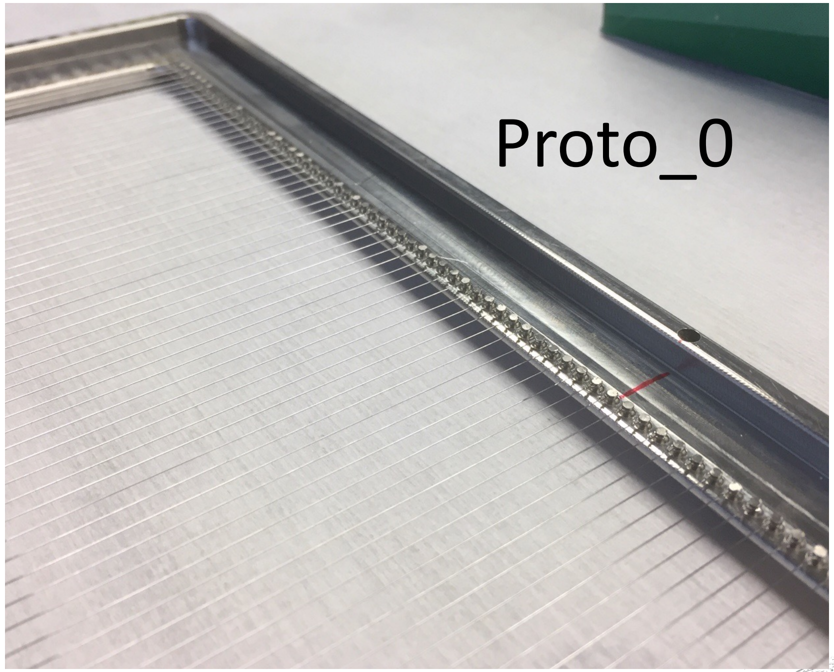
Wire wounding test done at U of Houston





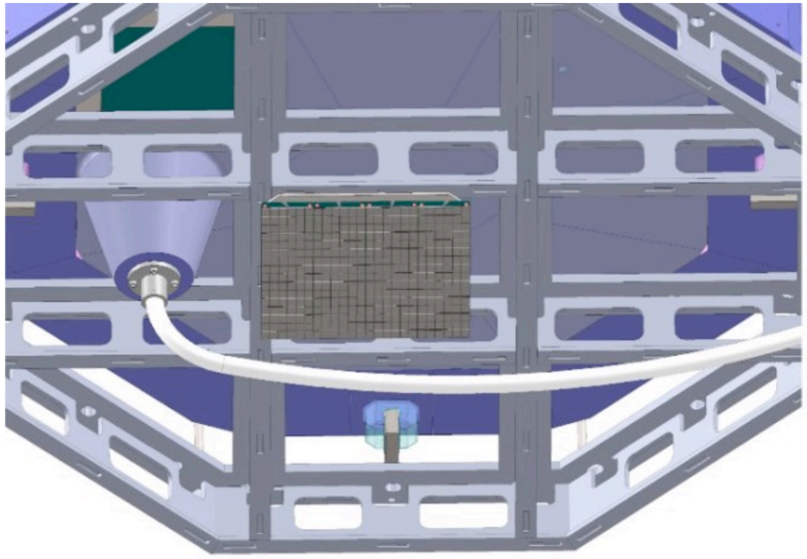




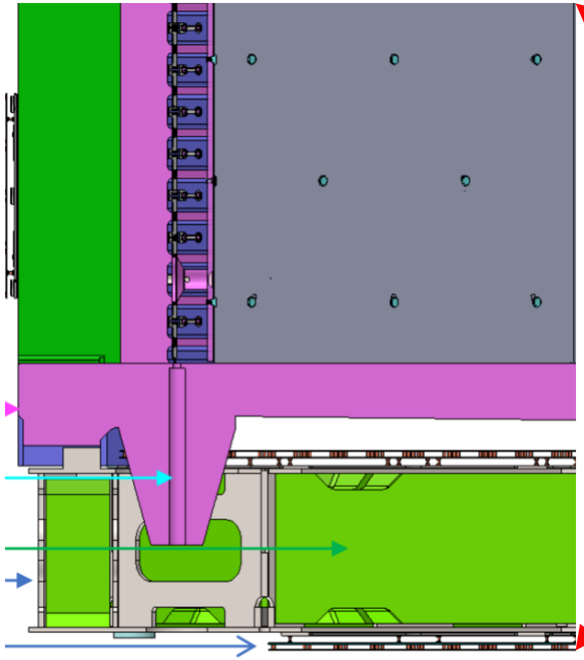


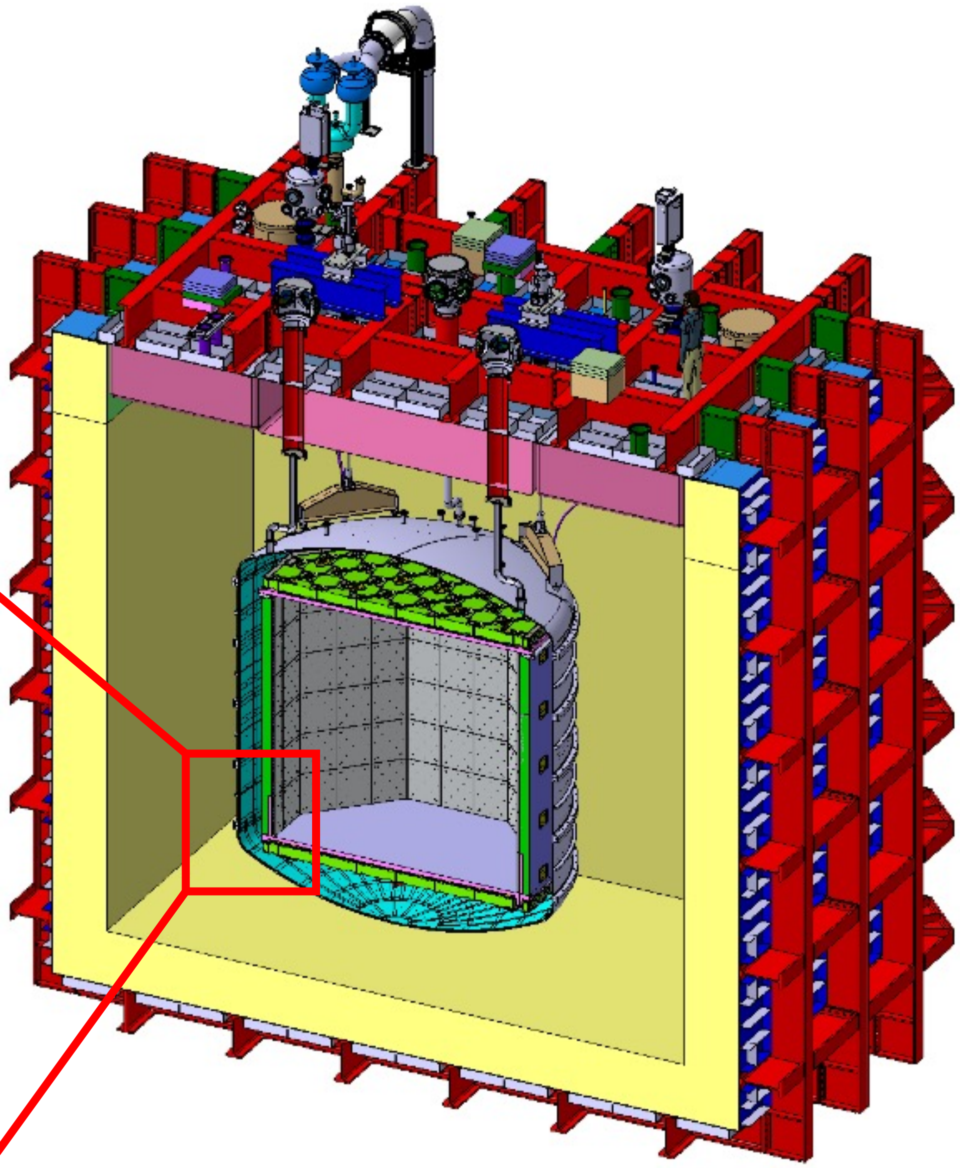
HHV Feedthrough

- Long delivery through membrane cryostat, AAr volume, TPC…; total length ~12 m;
- A fully-plastic, coextruded cable for HV delivery:
  - Good flexibility;
  - Uniform thermal contraction.



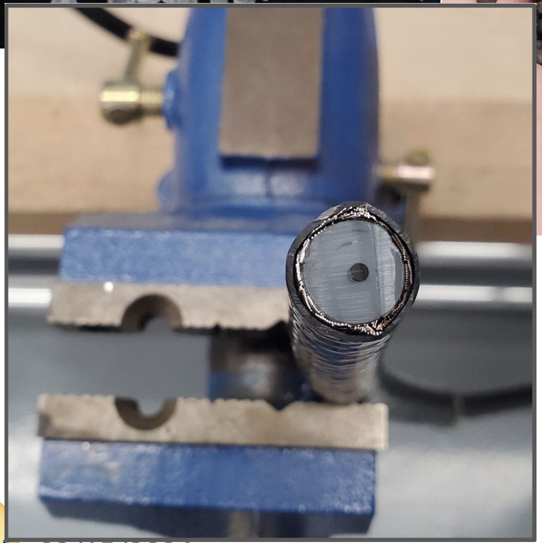
To be tested in the mock-up





Cable-like HHV Feedthrough

- A semi-conductive layer to suppress field concentration around the breaking ground.



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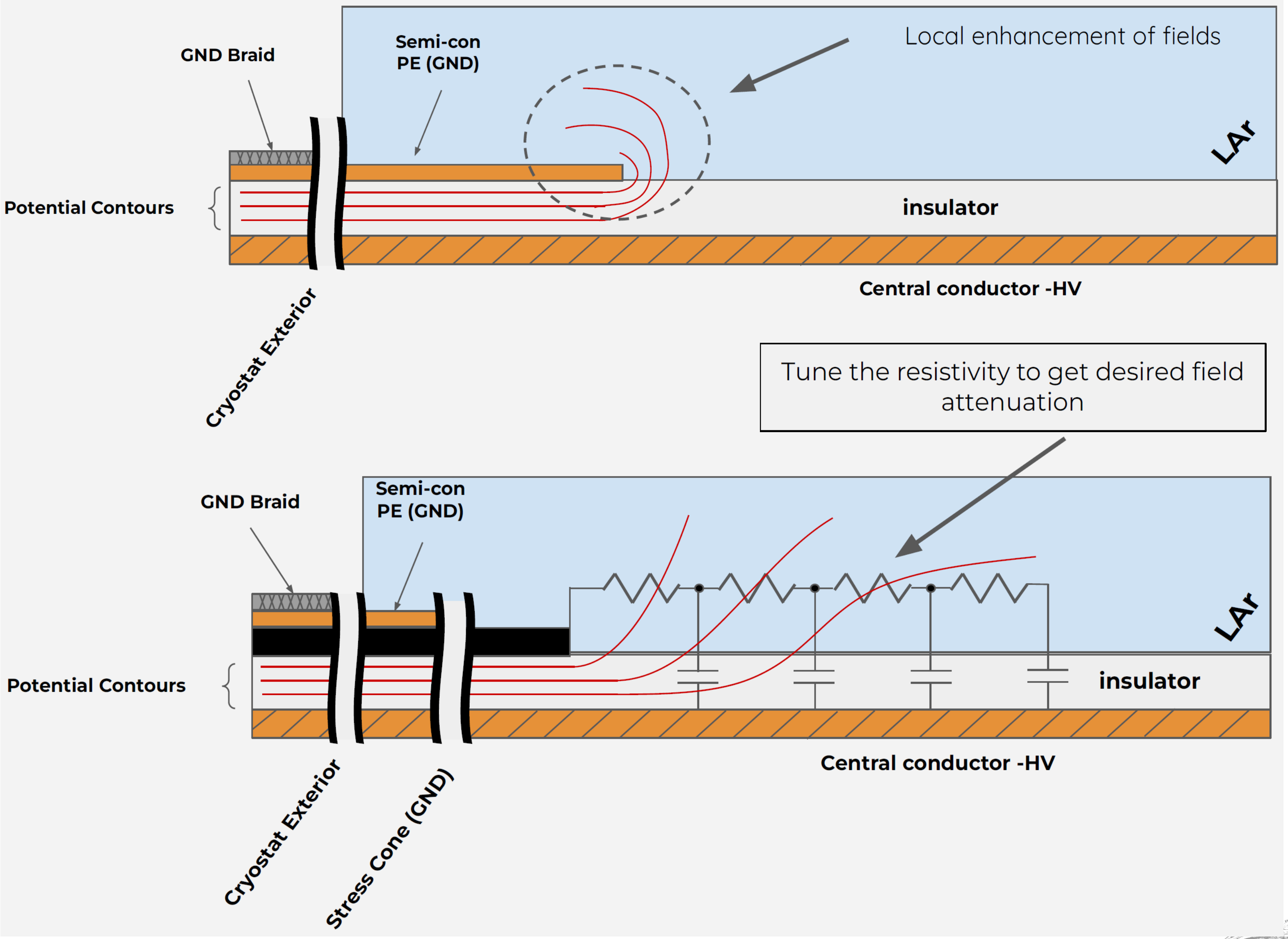
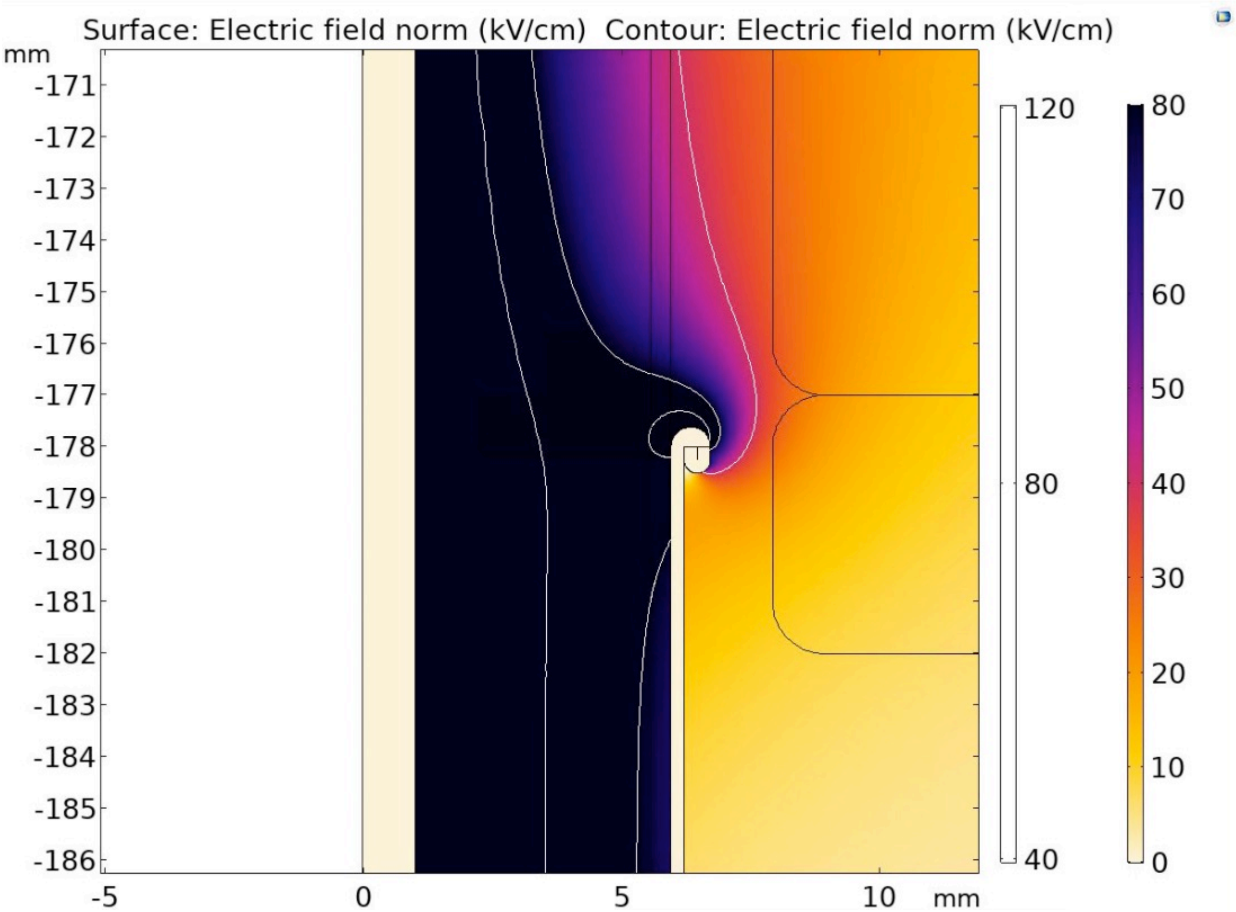
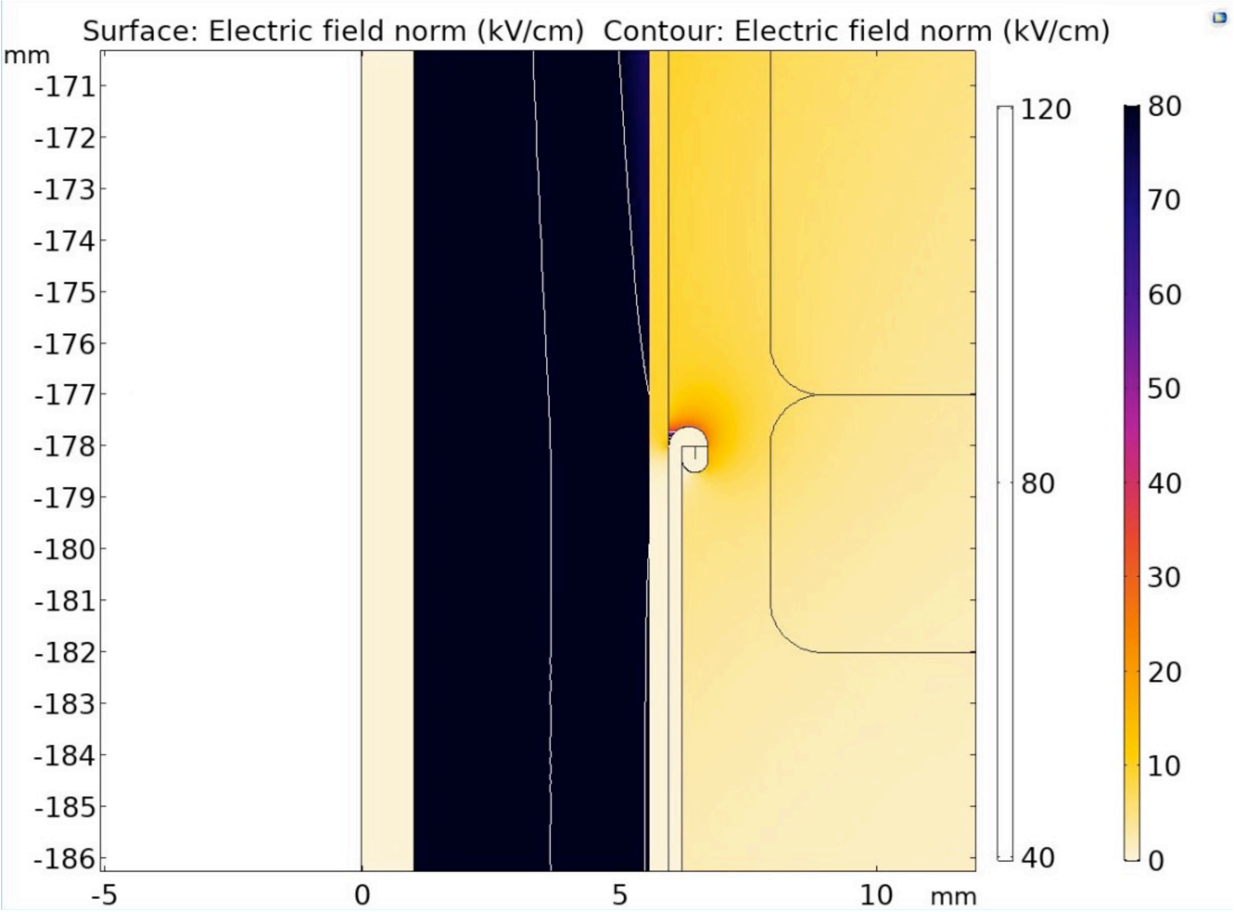


w/o semi-conductive layer



w/ semi-conductive layer



The resistivity is optimized to be $\rho_{vol}=10^8\ \Omega\bullet$cm.

Reflector and WLS

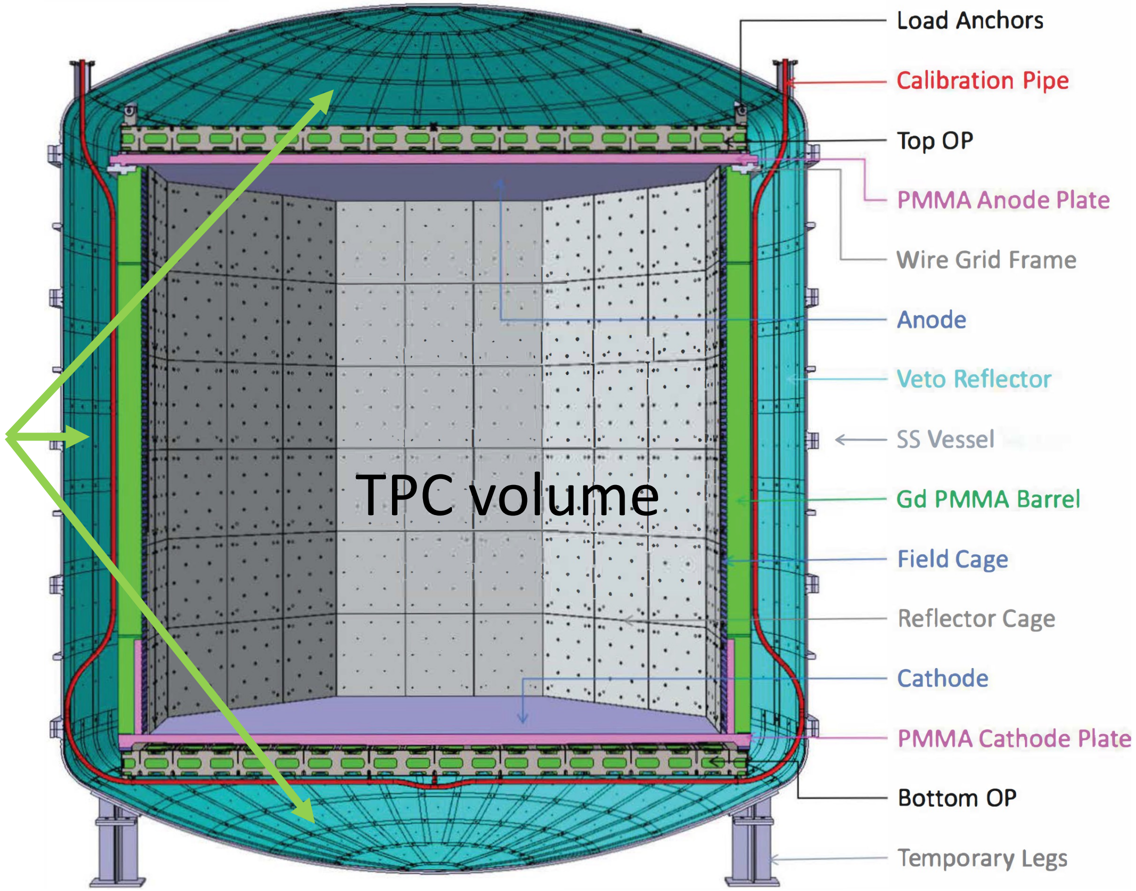
- TPC light yield: 10 p.e./keV;
- Veto light yield: 2 p.e./keV.

	TPC	Veto
Reflector	ESR (film)	ESR (film)
WLS	TPB (evaporation)	PEN (film)

Main R&D work:

- TPC: ESR with PMMA substrate, thermal contraction;
- Veto: PEN+ESR for ease of installation.

Veto volume



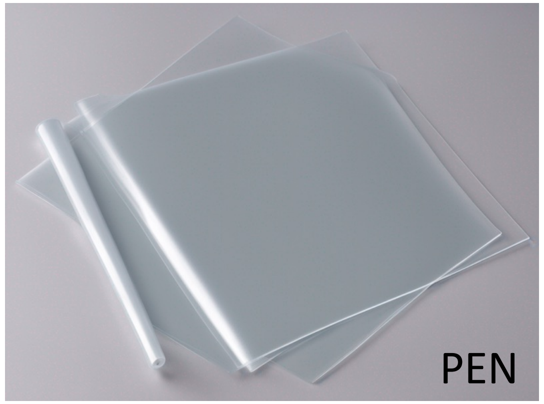


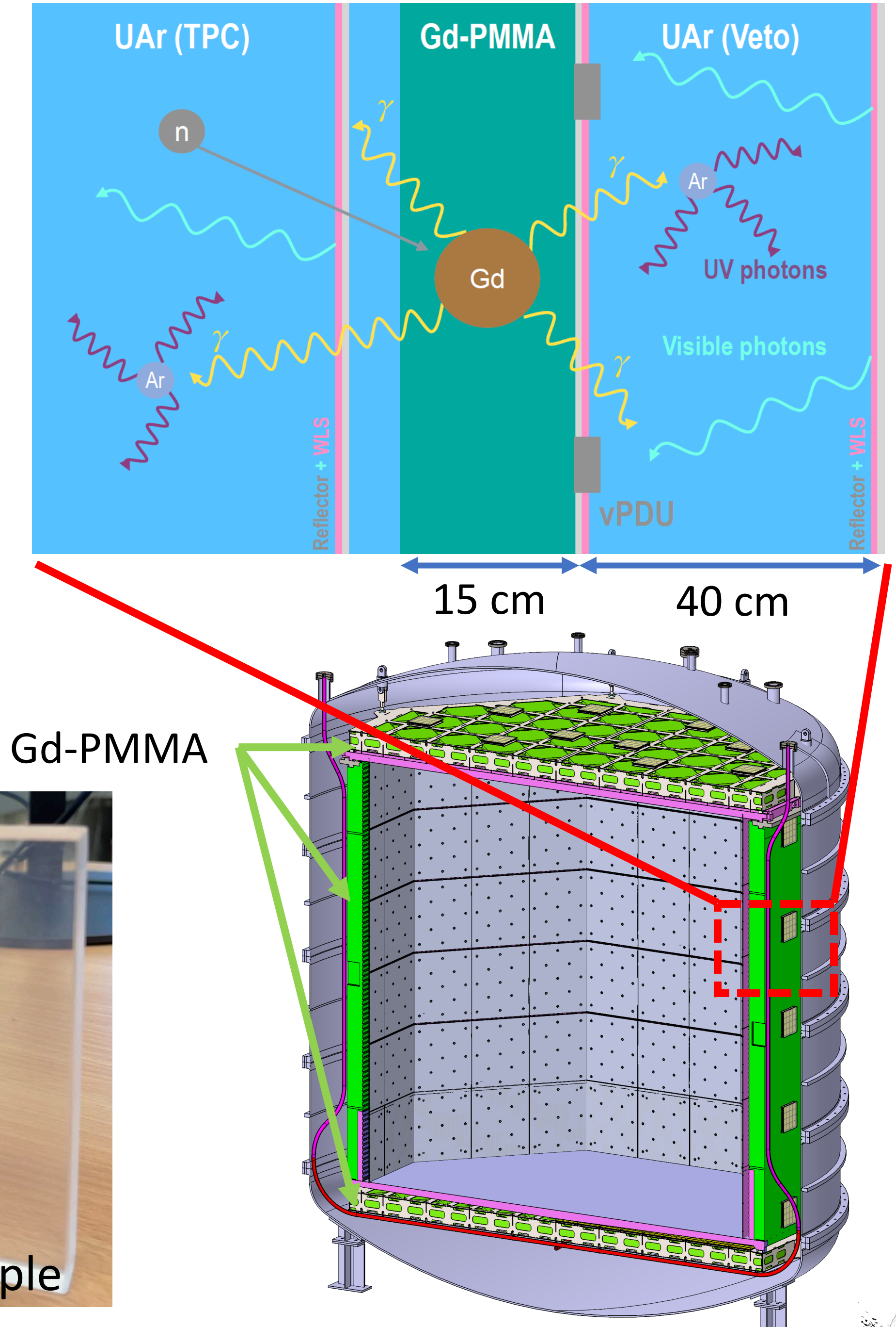
Table 1. Fundamental properties of common WLS materials used in LAr detectors: peak emission wavelength (λ_{em}), PLQY, re-emission lifetime (τ), refractive index (n), vapour pressure (p_{sat}), and approximate sublimation temperature (T_m).

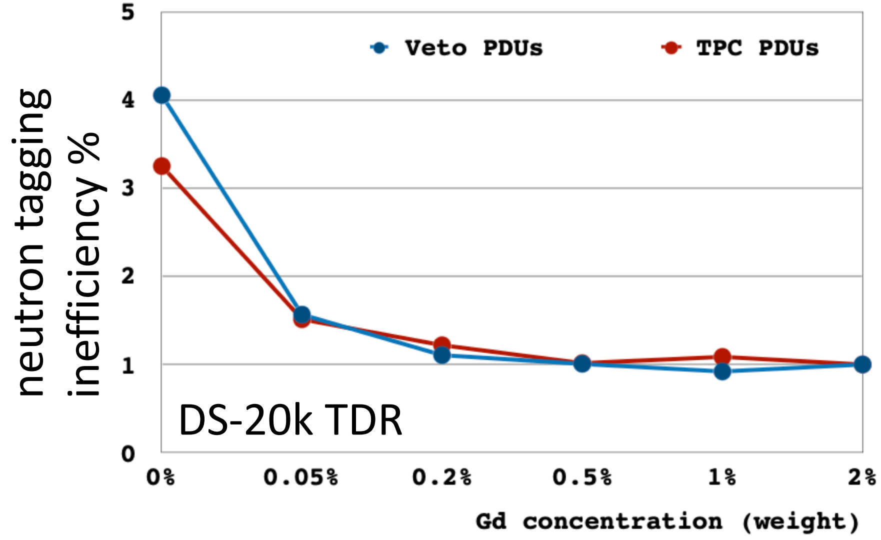
Wavelength Shifter	λ_{em} [nm]	PLQY @ 128 nm	τ [ns]	n	p_{sat} [mbar]	T_m [°C]	Comment
TPB	430	0.6 [25]–2 [26]	2	1.7	10^{-11}	204	
p-Terphenyl	350	0.82 [27]	1	1.65		213	PLQY @ 254 nm
bis-MSB	440	0.75–1 [28,29]	1.5	1.7		180	PLQY rel. to TPB
pyrene	470	0.64 [30]	155	1.8	$6 \cdot 10^{-6}$	150	PLQY @ 260 nm
PEN	420	0.4–0.8 [31]	20	1.75	–	270	PLQY rel. to TPB

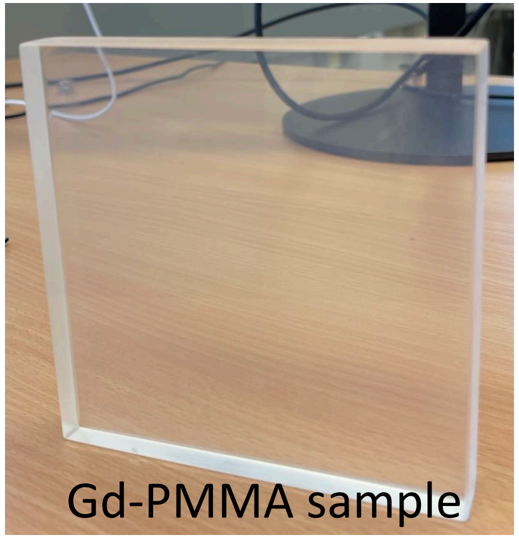
Kuzniak, M.; Szelc, A.M. Instruments 2021, 5, 4.

The Inner Detector - n veto

- Acrylic (Hydrogen) + Gadolinium + Argon
  - ➢Gd-PMMA (1 wt%), 15 cm thick;
  - →4π coverage: TPC walls, top & bottom endcaps;
  - ➢40 cm thick UAr buffer + UAr in TPC;
- Produced γ rays interact in UAr in both buffer and TPC;
- ESR as reflector and PEN as wavelength shifter;
- Scintillation lights detected by SiPMs in both buffer and TPC.



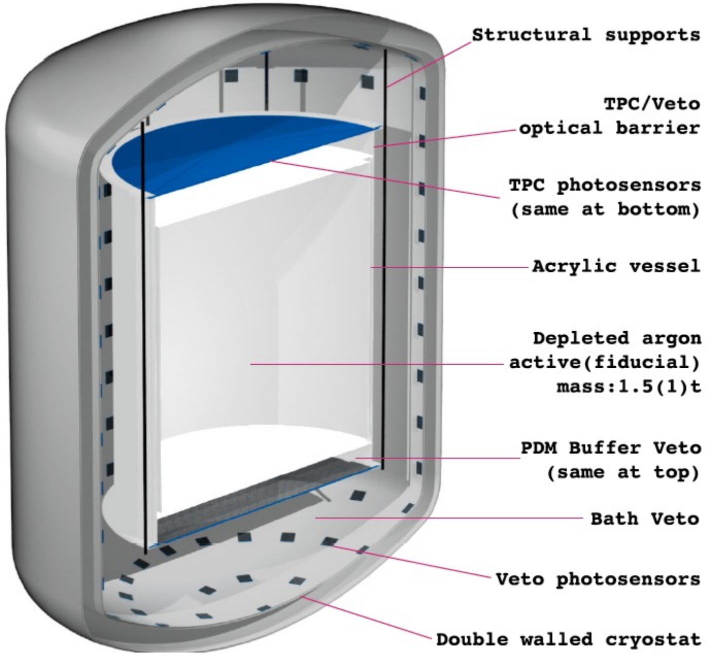




DarkSide-LowMass

- Dedicate to WIMP mass < 10 GeV/c^2.
- A tonne-scale dual phase Ar TPC,
- Candidate lab: CJPL-II in Sichuan, China.
- A factor of 10~100 lower ^{39}Ar than UAr:
  - ^{39}Ar 7.3~73 μBq/kg;
  - ^{85}Kr 0 μBq/kg.
- Low impurity:
  - Good electron lifetime;
  - Low rate of the single electron events;
  - Ultra-pure photosensor;
  - Radiopure cryostat (e.g. Ti);
- Low threshold:
  - High electric field to increase g2;
  - Xe doping.

See Masato Kimura's talk.



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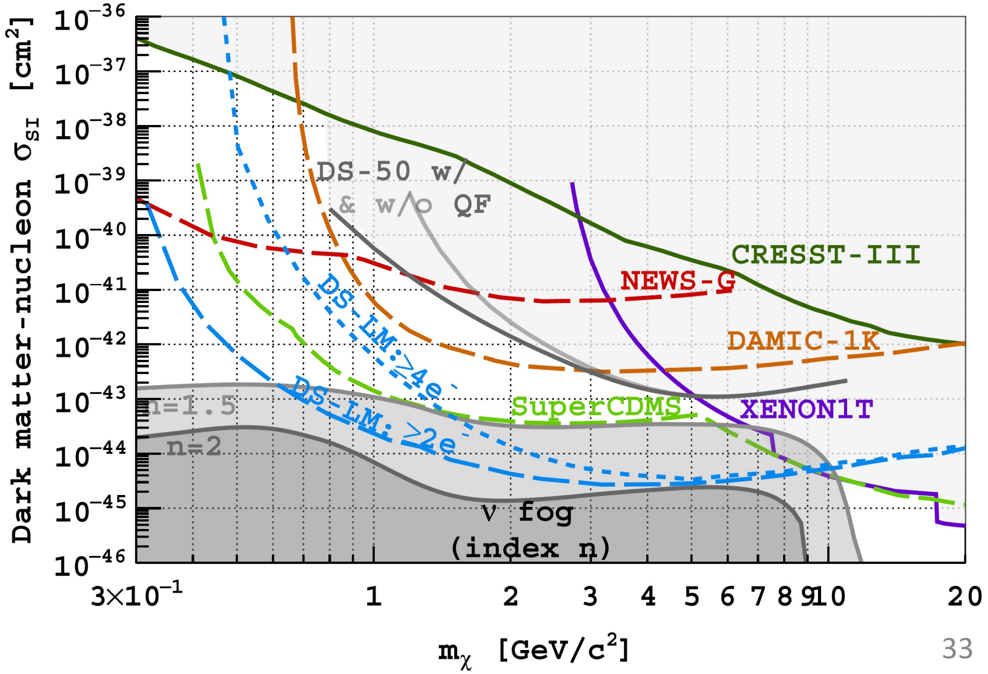

Summary

- DarkSide-50 demonstrated the dual-phase argon TPC, achieving instrumental background-free high-mass WIMP results, as well as world-leading low-mass WIMP results;
- DarkSide-20k, as the next-generation experiment, is set to construct a TPC ~1000x larger than DarkSide-50;
- A batch of R&D has been conducted for the DarkSide-20k detector:
  - Clevis, Wire grid, Gd-PMMA, Cable-like feedthrough…
- DarkSide-20k is currently in the construction phase, with commissioning expected to start in late 2026;
- DarkSide-LowMass is currently under preparation, TDR will be released soon.