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Gd-PMMA

a novel neutron tagging technology for low background detectors

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On behalf of the DarkSide collaboration

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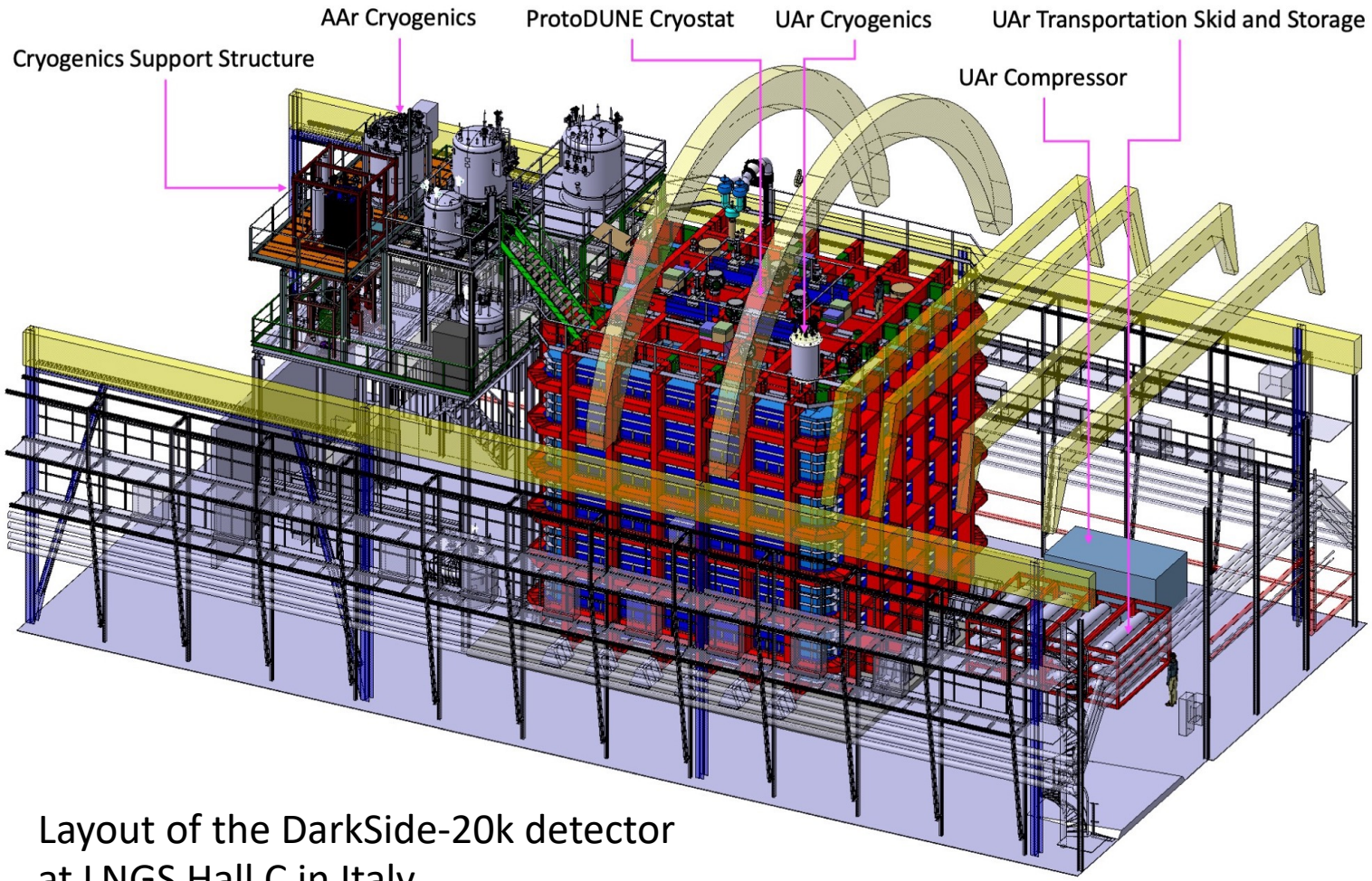
DarkSide-20k Overview

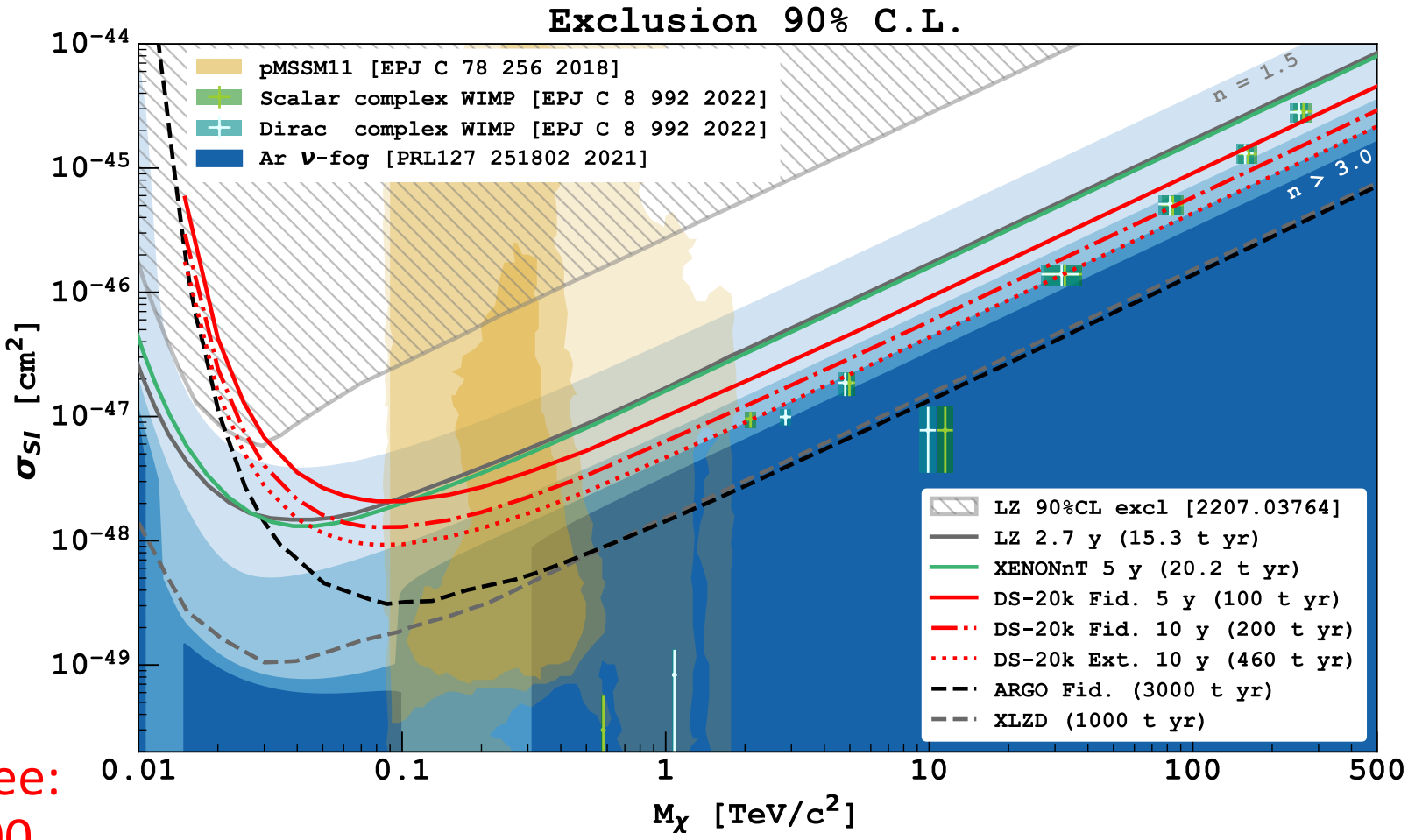
- DarkSide-20k:
  - Direct search for WIMP dark matter with argon;
  - Dual-phase argon time projection chamber (TPC).
- Newly designed active neutron veto as a solution for achieving instrumental background-free;
- New material proposed:
  Gadolinium doped acrylic (Gd-PMMA).



Layout of the DarkSide-20k detector at LNGS Hall C in Italy.

Physics Prospective of DarkSide-20k

- Sensitivity to Spin-Independent WIMPs;
- With nominal exposure 200 t-y (20 t x 10 years):
  - 90% C.L. exclusion: 6.3×10^{-48} cm^2 @1 TeV/c^2 ;
  - 5 σ discovery: 2.1×10^{-47} cm^2 @1 TeV/c^2 ;
  - 3.2 CEvNS events expected.



- Background goal:
  - Instrumental background-free: < 0.1 neutrons in RoI (30~200 keVnr) with 200 t-y exposure.

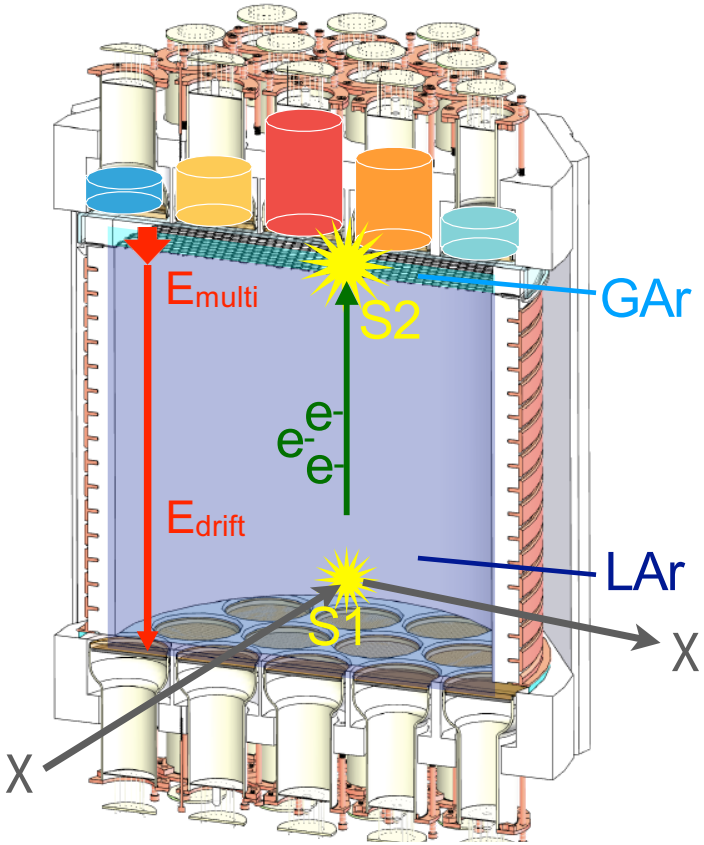
Background Mitigation Strategies

Goal: <0.1 neutron in RoI (30~200 keVnr) with 200 t-y exposure.

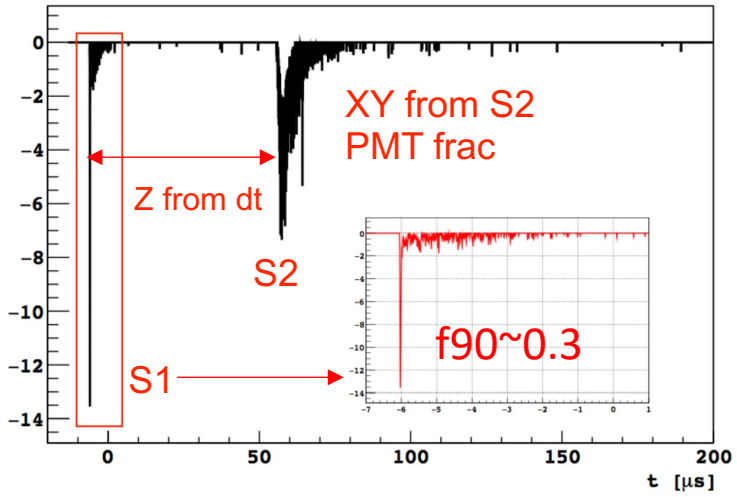
Source	Strategies & Tools
β/γ	UAr, PSD, material selection…
Radon progeny	Surface cleaning, Rn suppressed air…
Radiogenic neutron, mostly (α, n)	Neutron veto, fiducialization, material selection…
Cosmogenic neutron	Muon veto…
Neutrino induced NRs	irreducible

Fiducialization and PSD

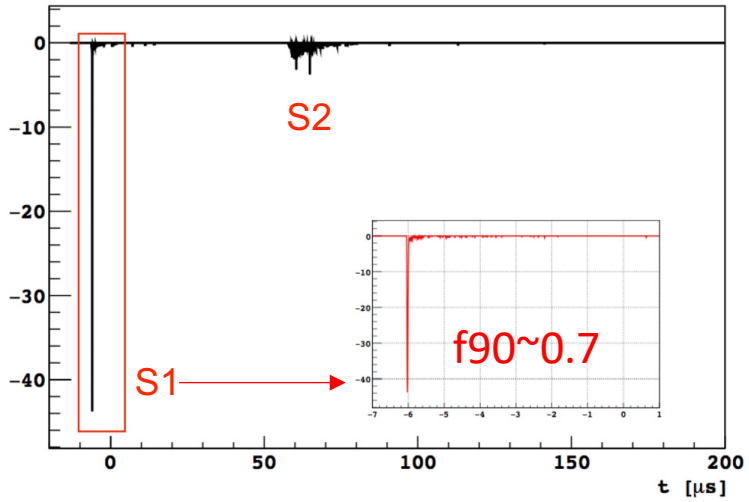
- TPC: Scintillation (S1) + Ionization (S2);
- 3D positioning using T_{drift} and S2 distributions;
- S1 Pulse shape discrimination (PSD):
  - De-excitation time: singlet 6 ns, triplet 1.5 us;
  - ER background rejection > $1x10^8$;
  - f90: ratio of light in the first 90 ns (S1).

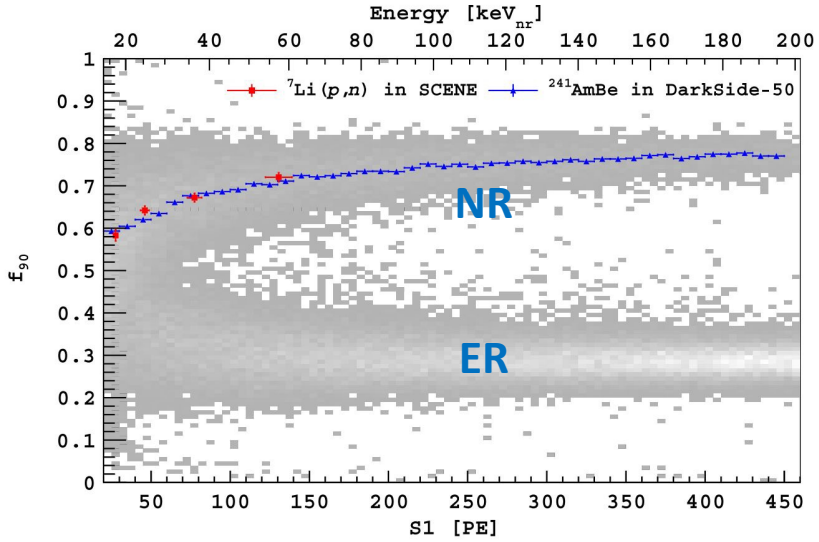


Electron Recoil



Nuclear Recoil





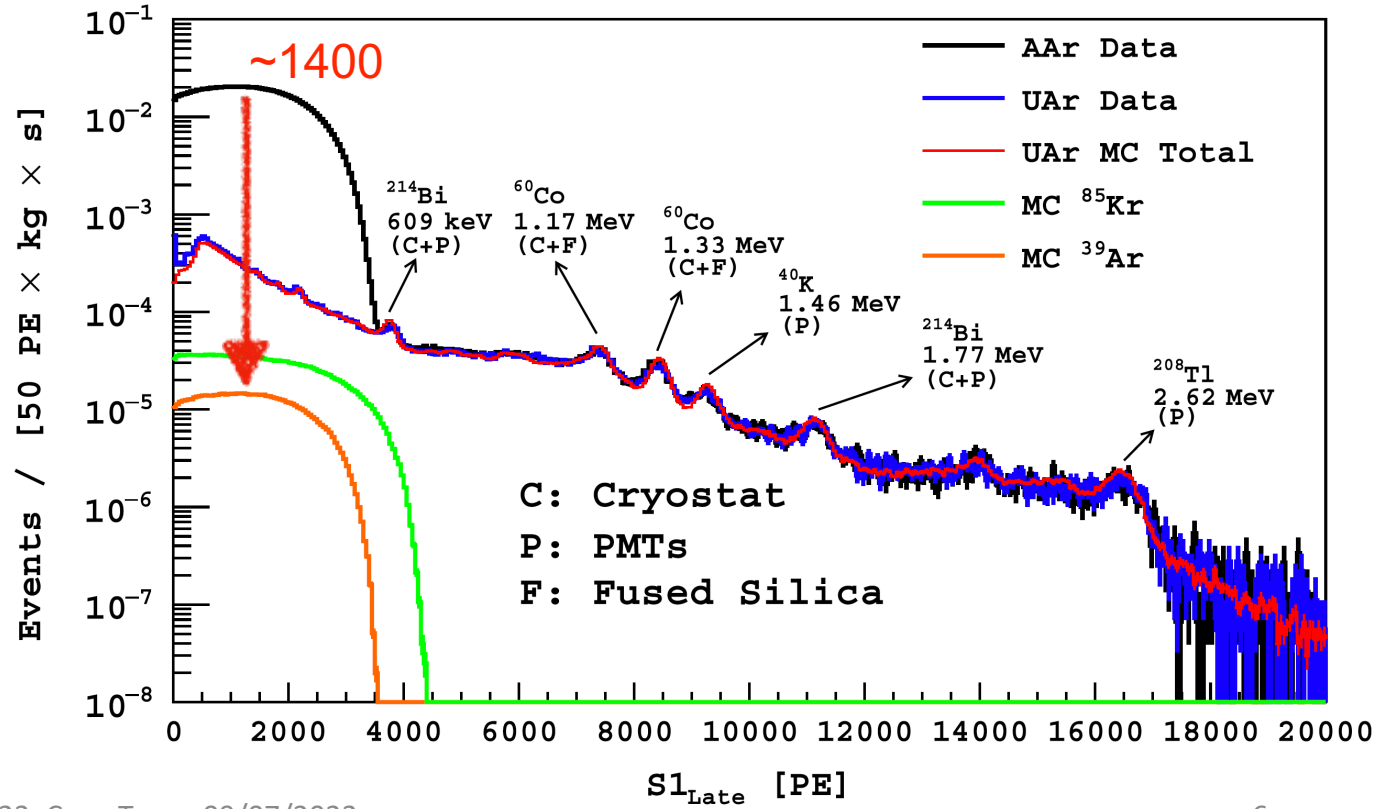
Using Underground Argon

See Roberto Santorelli's talk on Wednesday!!

- 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.

- 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;
- 120 tonnes UAr to be extracted and purified for DarkSide-20k.

Phys. Rev. D 93, 081101 (2016)



The DarkSide-20k Detector

Membrane "ProtoDUNE-like" cryostat

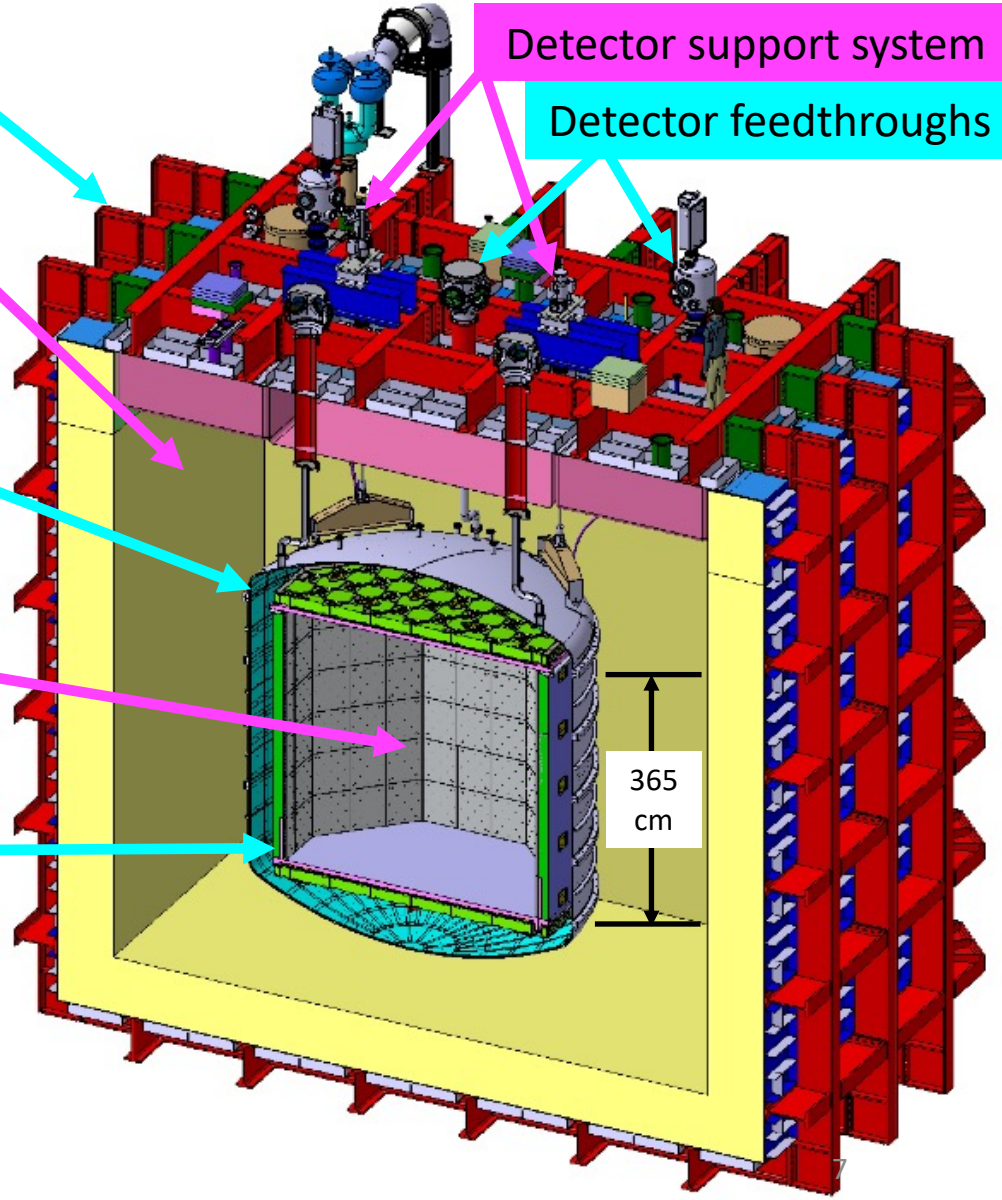
Atmospheric argon (AAr) volume (≈700 t)

Vacuum vessel containing UAr and TPC/veto

Underground argon (UAr) volume (≈100 t)

"Inner detectors", TPC and neutron veto

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



The Inner Detector

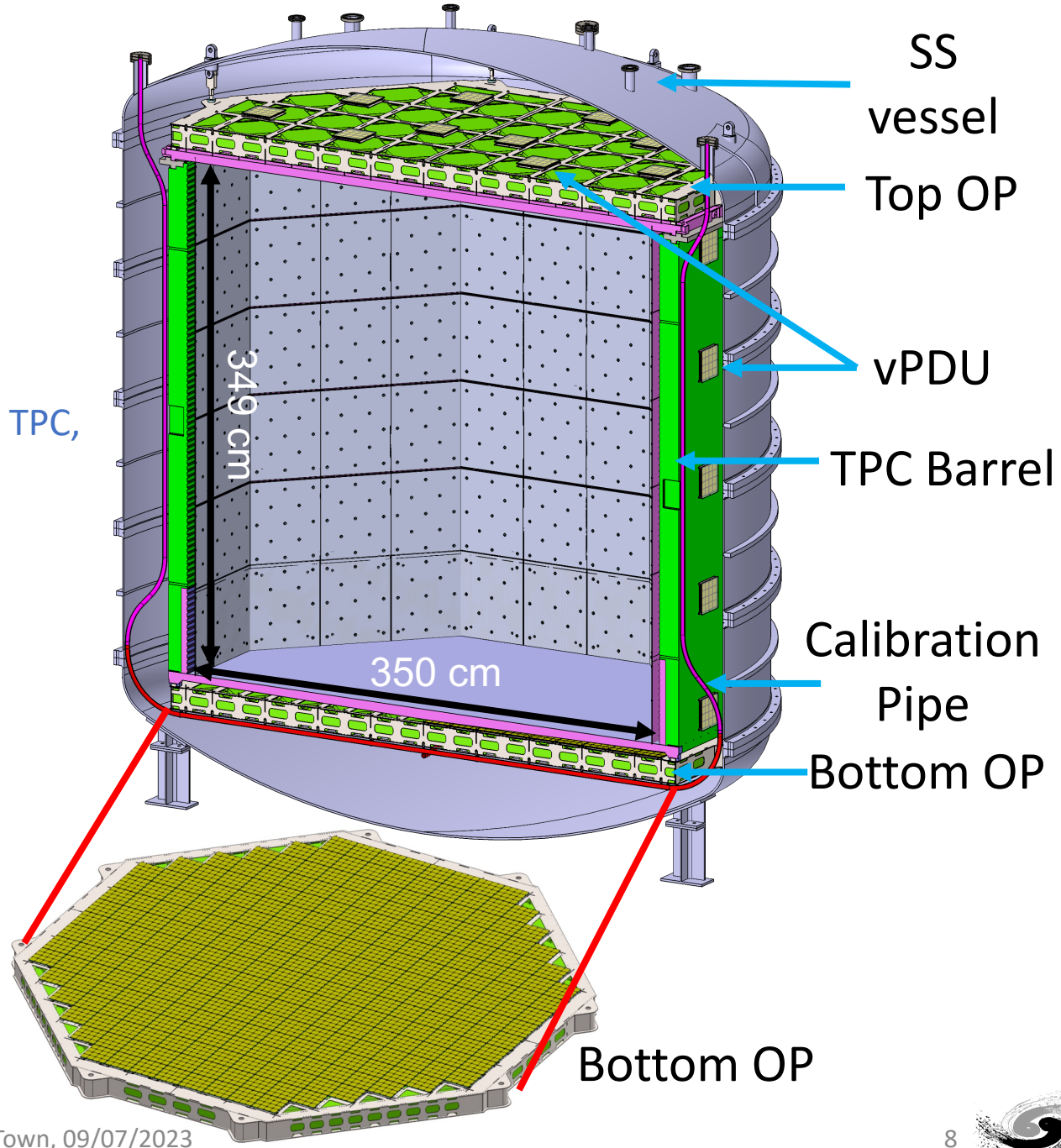
- TPC + neutron veto;
- Octagonal shape dual phase argon TPC:
  - Active UAr mass: 49.7 tonnes;

About high voltage of the DarkSide-20k TPC, see Tyler Erjavec's talk on Wednesday!!

- Neutron veto:
  - Active UAr mass: 32 tonnes.

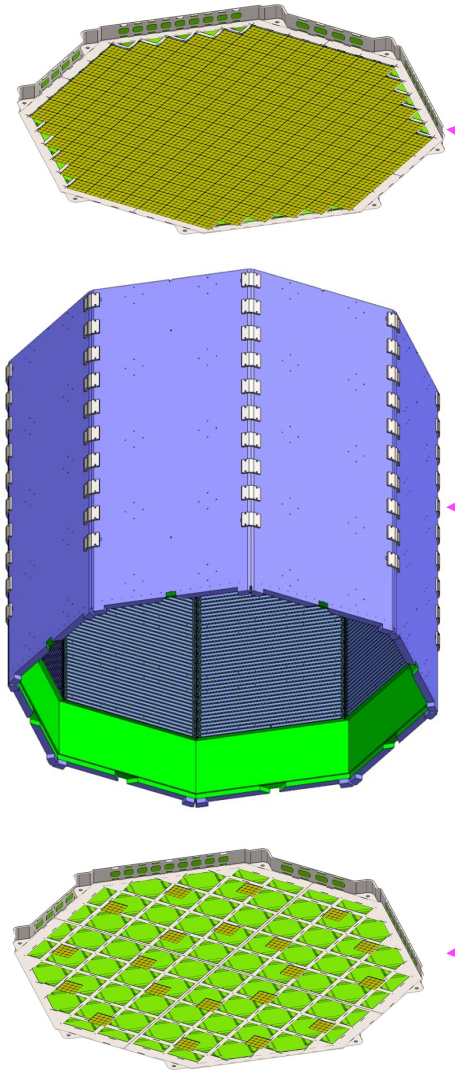
- SiPM as the photosensor;
- TPC: 2112 channels:
- Veto: 480 channels.

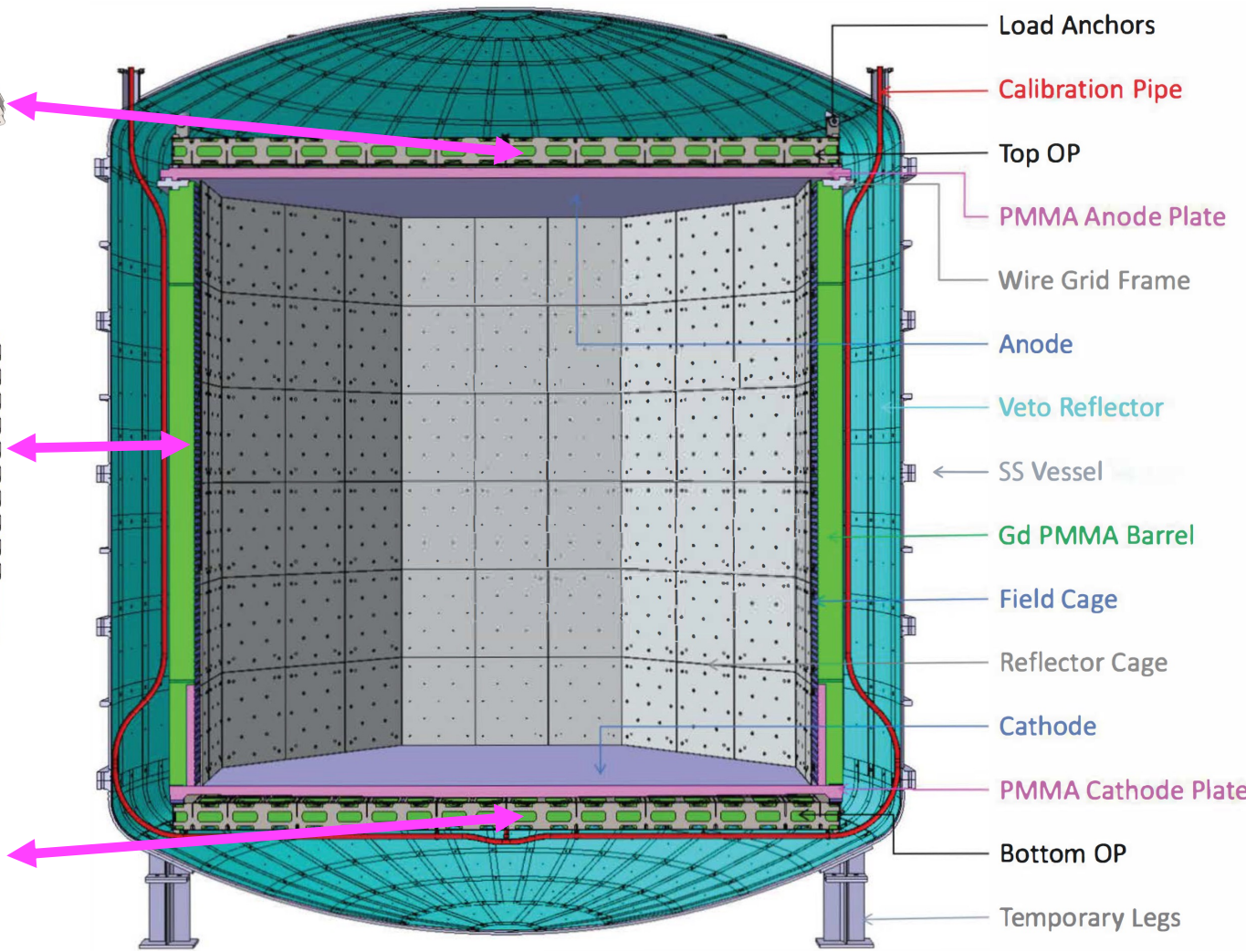
More details about the SiPM for DarkSide-20k, see Francesco Di Capua's talk!!



Active Neutron Veto

- Gd-PMMA parts:
  - ➢TPC wall, 8 pieces
  - ➢Many Gd-PMMA bricks embedded in the top and bottom supporting structures (optical planes);
- Active volume is 4π covered by Gd-PMMA;
- 40 cm thick UAr buffer in the veto volume;
- UAr in the TPC.

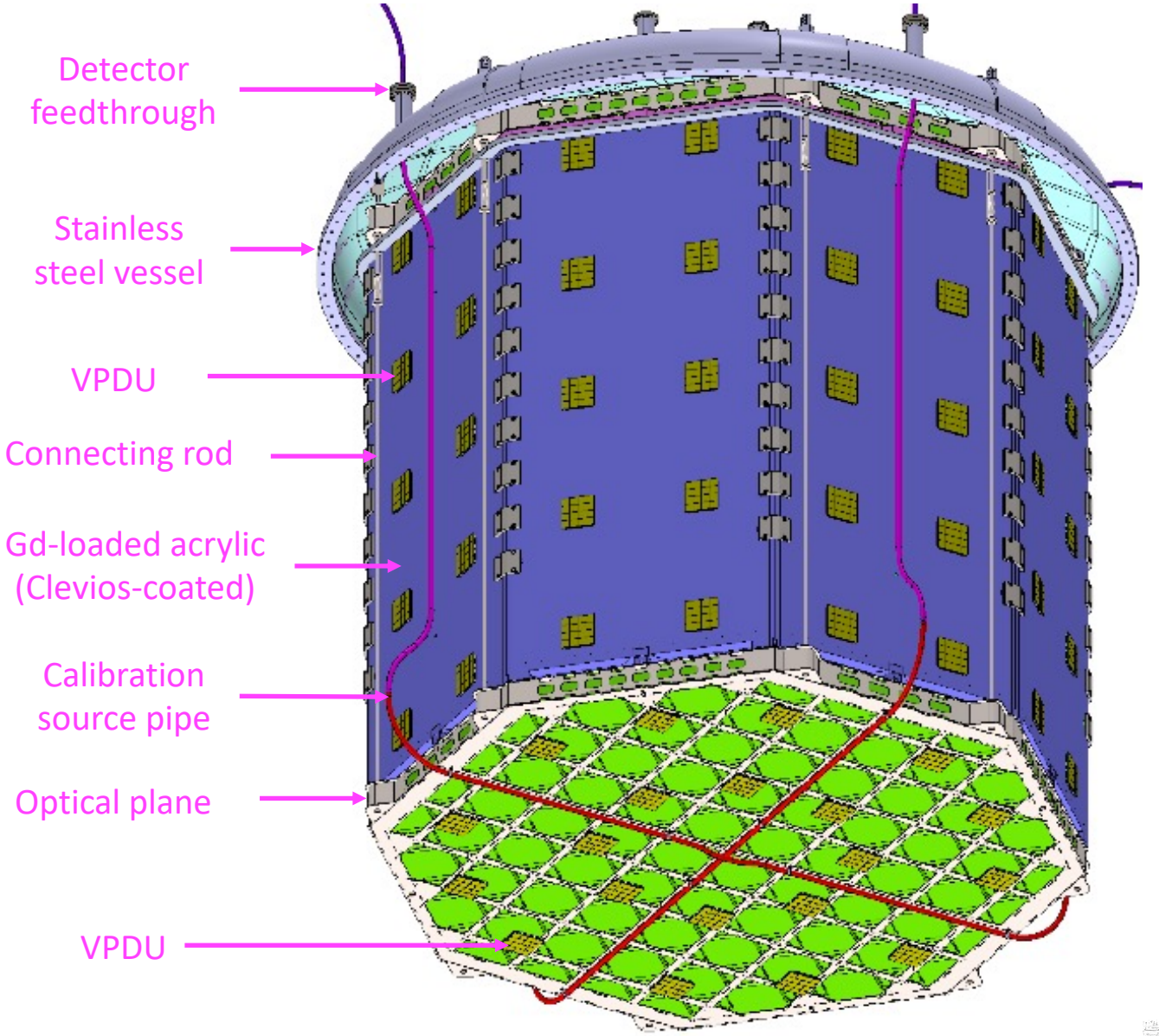




Active Neutron Veto

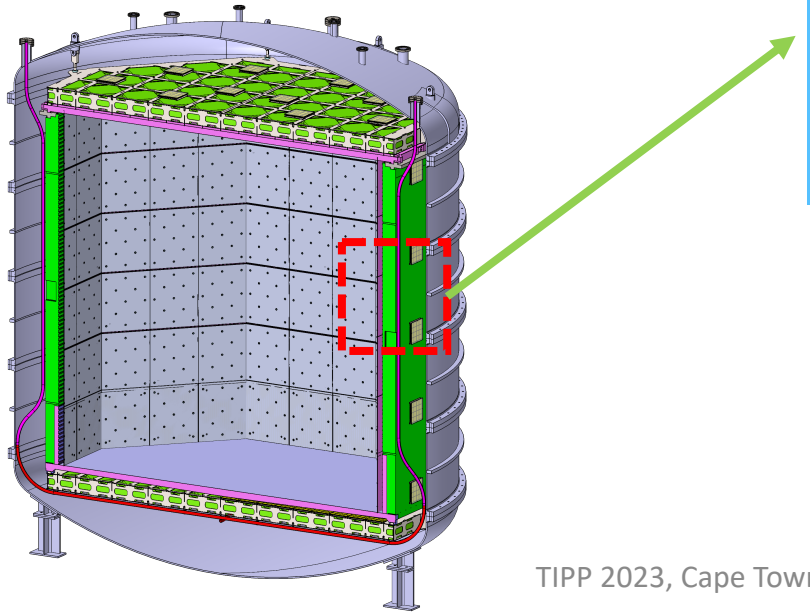
- 120 veto Photo Detection Units (vPDU) for the UAr veto buffer;
- 480 readout channels in total.

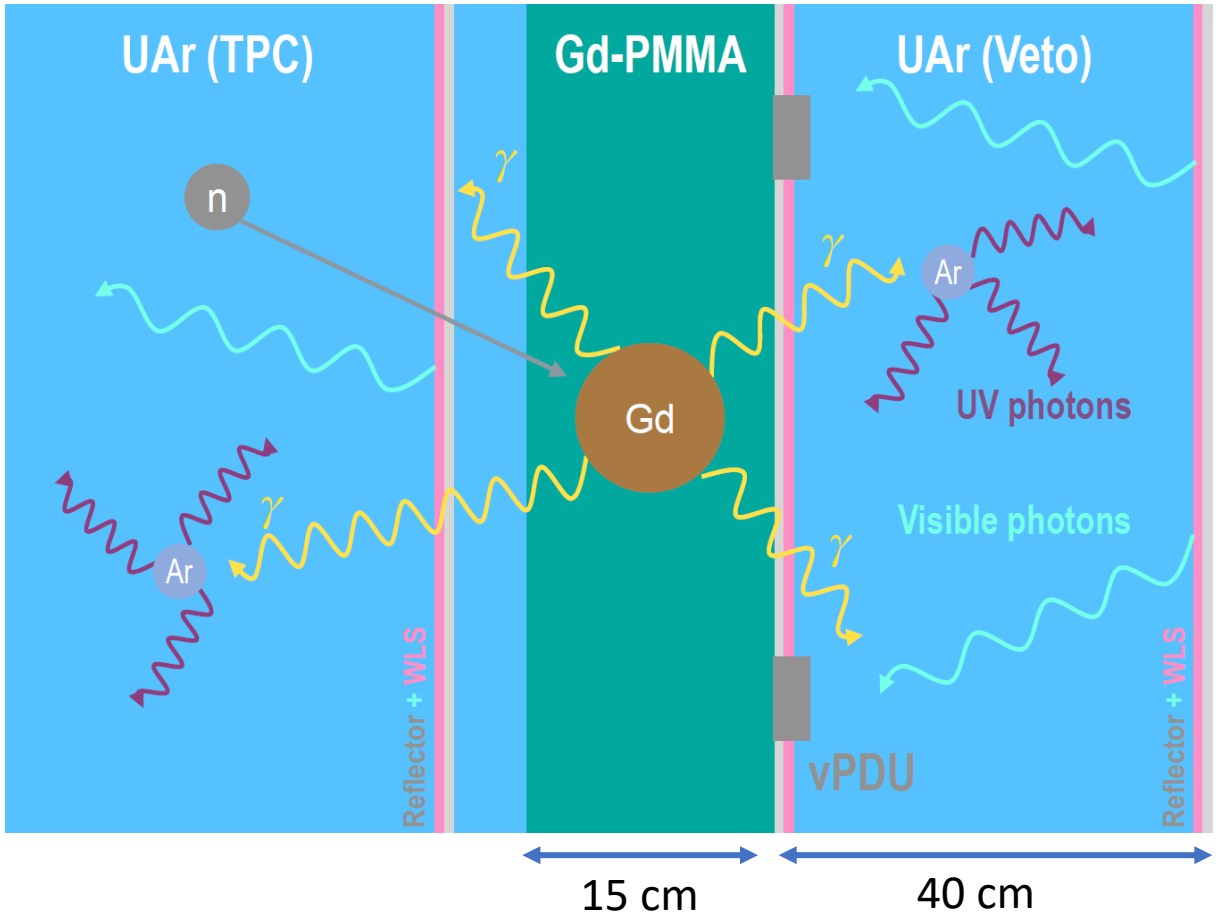
- Reflectors:
  - Enhanced Specular Reflector (ESR) for both veto and TPC;
- Wavelength shifters:
  - TPB for TPC;
  - PEN for veto.



Active Neutron Veto

- Gd-PMMA -> Hydrogen + Gadolinium:
  - ➢Hydrogen -> single γ ~2.2 MeV;
  - ➢Gadolinium -> multiple γ upto 8 MeV.
- Produced γ rays interact in UAr in both veto buffer and TPC;
- Scintillation lights detected by SiPMs in both veto buffer and TPC.





Neutron Tagging Inefficiency

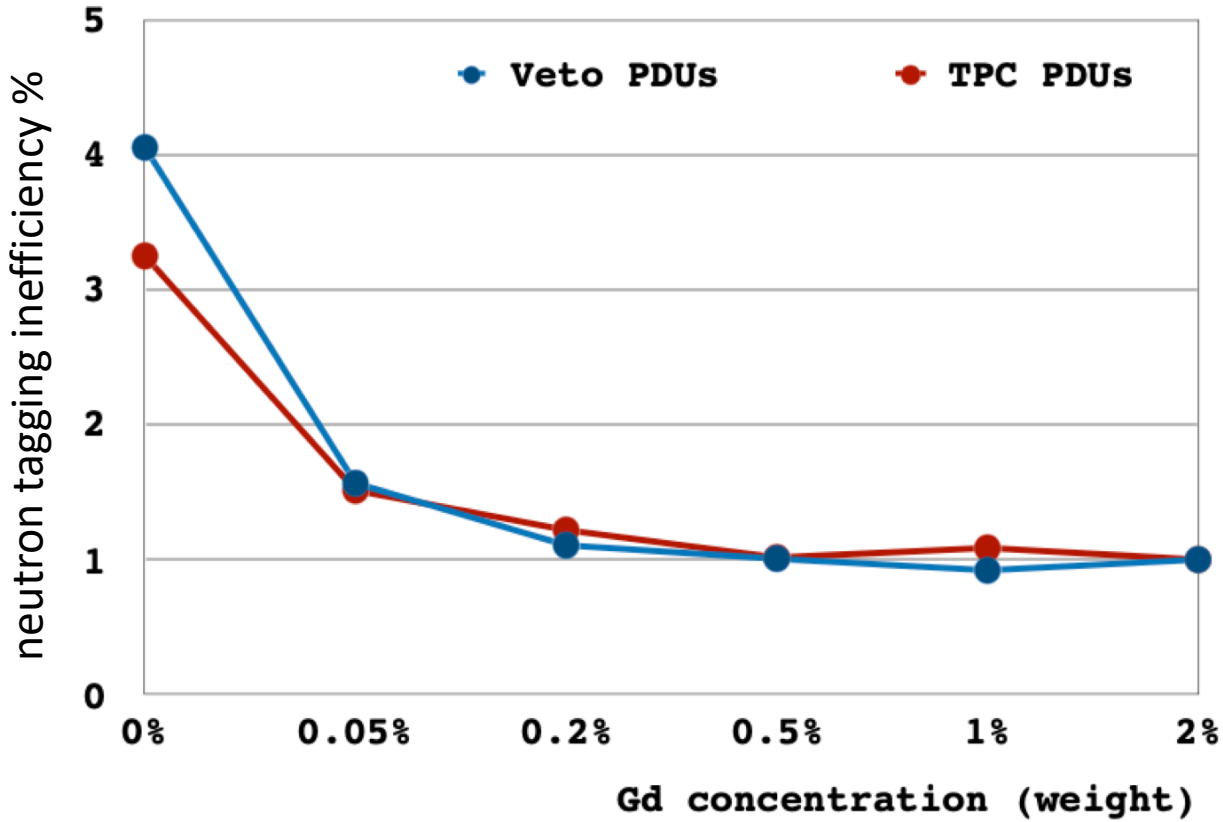
- Optimizing the gadolinium concentration and the thickness of Gd-PMMA for enhanced neutron efficiency.

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

- Gd concentration: 1 wt%;
- Thickness of Gd-PMMA: ≥ 15 cm;

➢Neutron tagging inefficiency ~1%;

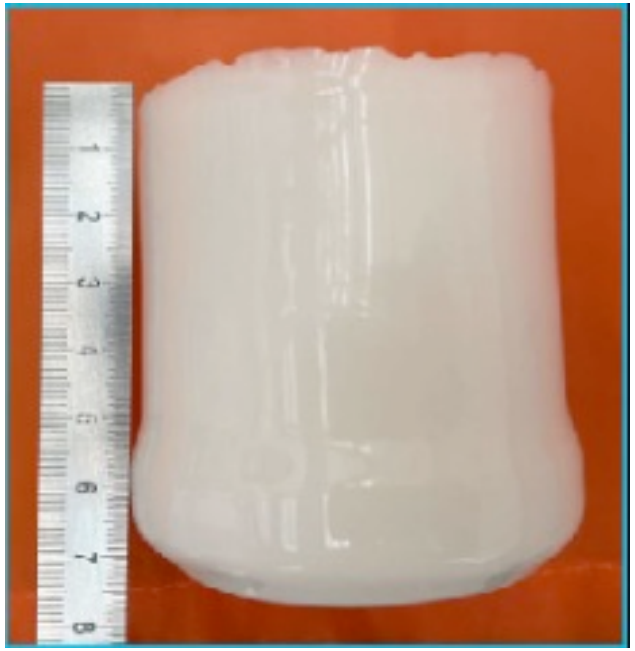
- < 0.1 n in RoI with 200 ty exposure.



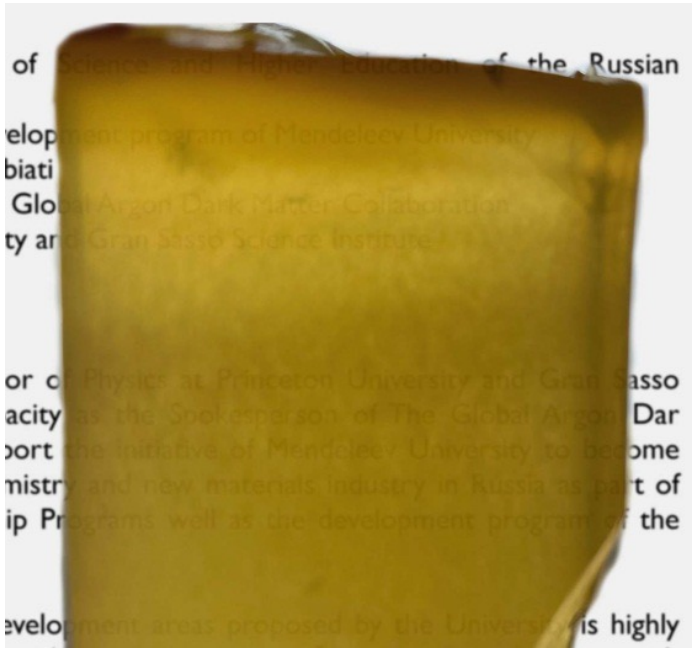
Development of Gd-PMMA

- Three approaches have been developed for Gd-PMMA:
  - Gd2O3 recipe: mechanically mix Gd2O3 nano grain with MMA for polymerization;
  - Gd(acac)3 recipe: “directly” dissolve Gd(acac)3 into MMA for polymerization;
  - Gd(MAA)3 recipe: “indirectly” dissolve Gd(MAA)3 into MMA for polymerization.

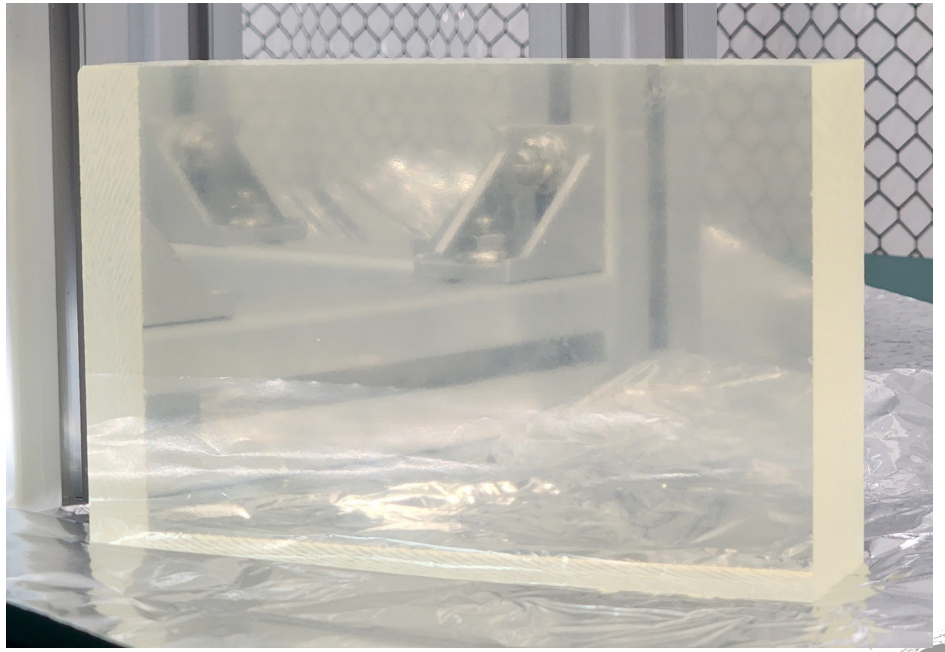
Gd2O3 recipe



Gd(acac)3 recipe

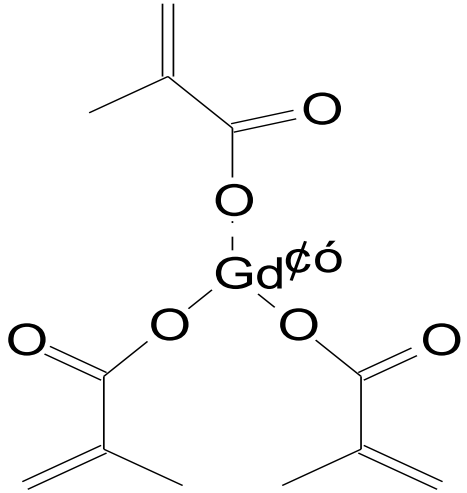


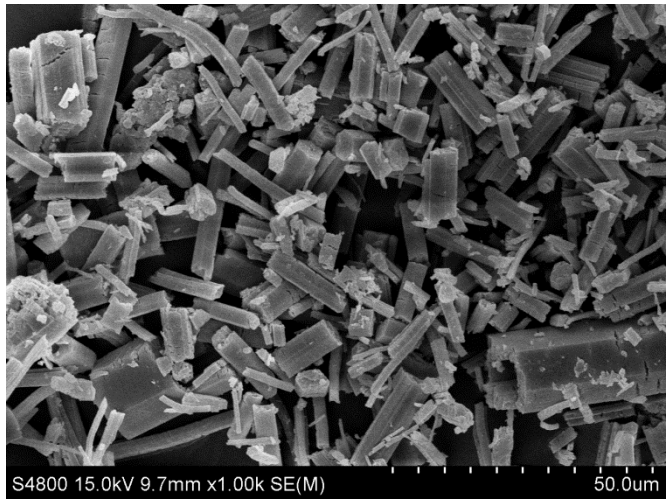
Gd(MAA)3 recipe



Gd(MAA)3

- Gadolinium methacrylate;
- It can be dissolved in liquid MMA monomer using a dedicated dissolving recipe;
- Good chemical stability due to the molecular connection between Gd(MAA)3 and MMA;
- Max. ~25% Gd(MAA)3 can be dissolved in liquid MAA (~10% Gd by mass fraction).



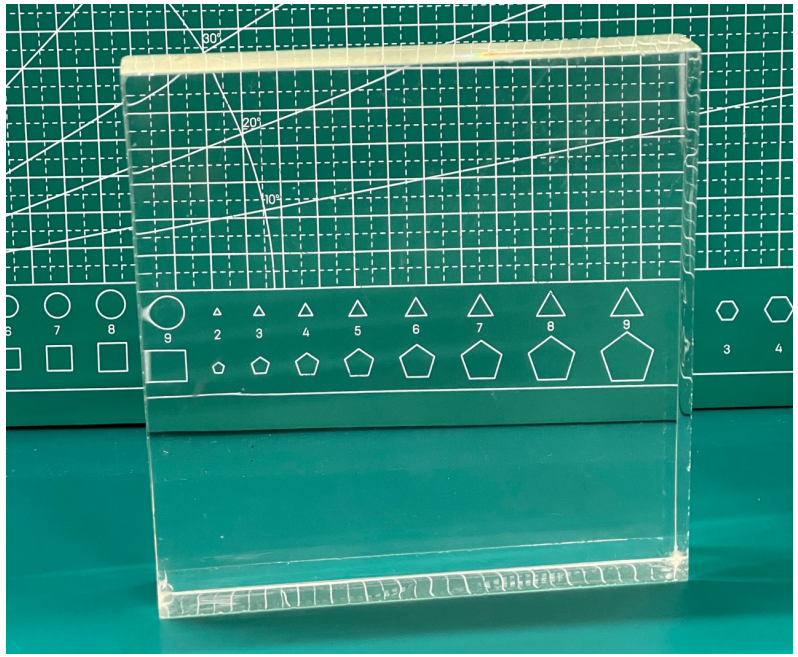


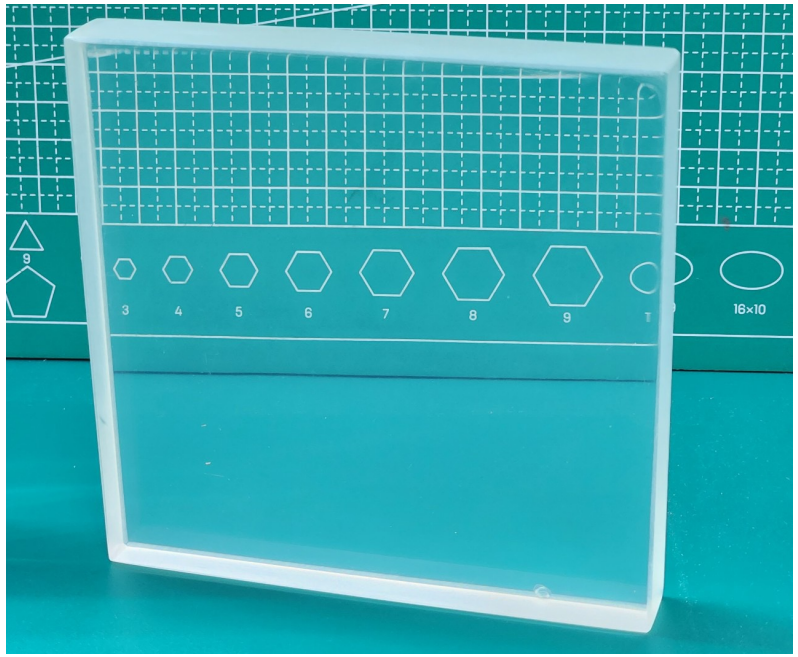
The dissolving recipe was developed by Yangzhou University:

揚州大學 YANGZHOU UNIVERSITY

Gd-PMMA

- Polymerization of Gd(MAA)3 doped liquid MMA;
- A dedicated initiator recipe was developed by Donchamp to prevent self-inhibition and implosion during polymerization;
- Another recipe has been developed for applications requiring high transparency.





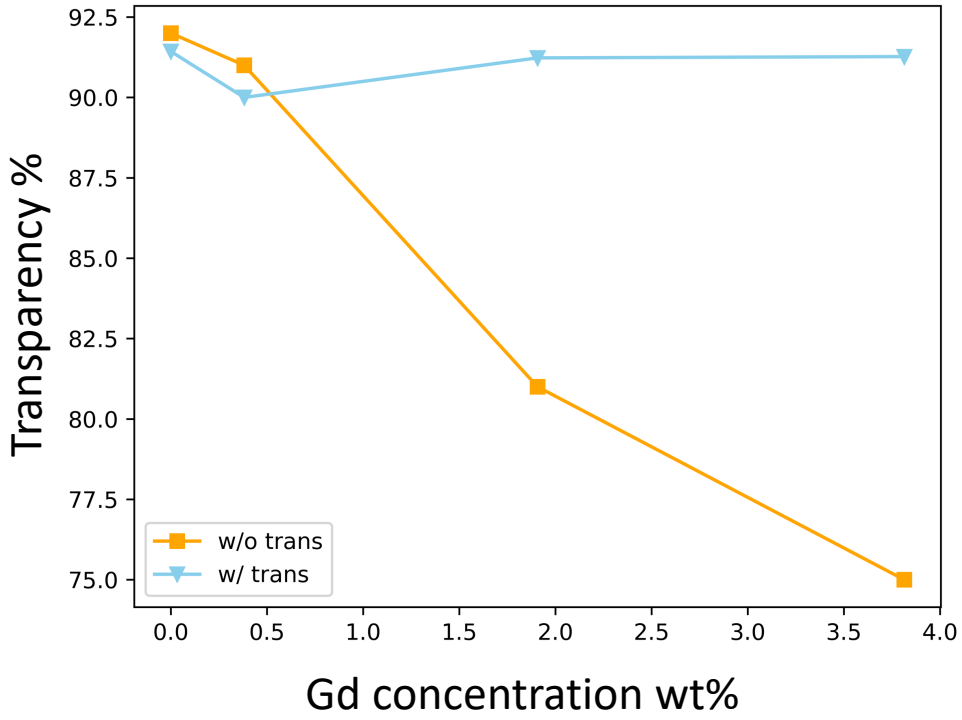
Some Properties of Gd-PMMA

Mechanical properties (Gd 1 wt%):

	Data from Yangzhou University	Data from Donchamp	Pure acrylic
Young's modulus	2-3 GPa	2.15 GPa	1.8-3.1 GPa [2]
Impact strength	14-19 KJ/m^2	15 KJ/m^2	16-20 KJ/m^2 [a]
Tensile strength		61 MPa	48-76 MPa [2]

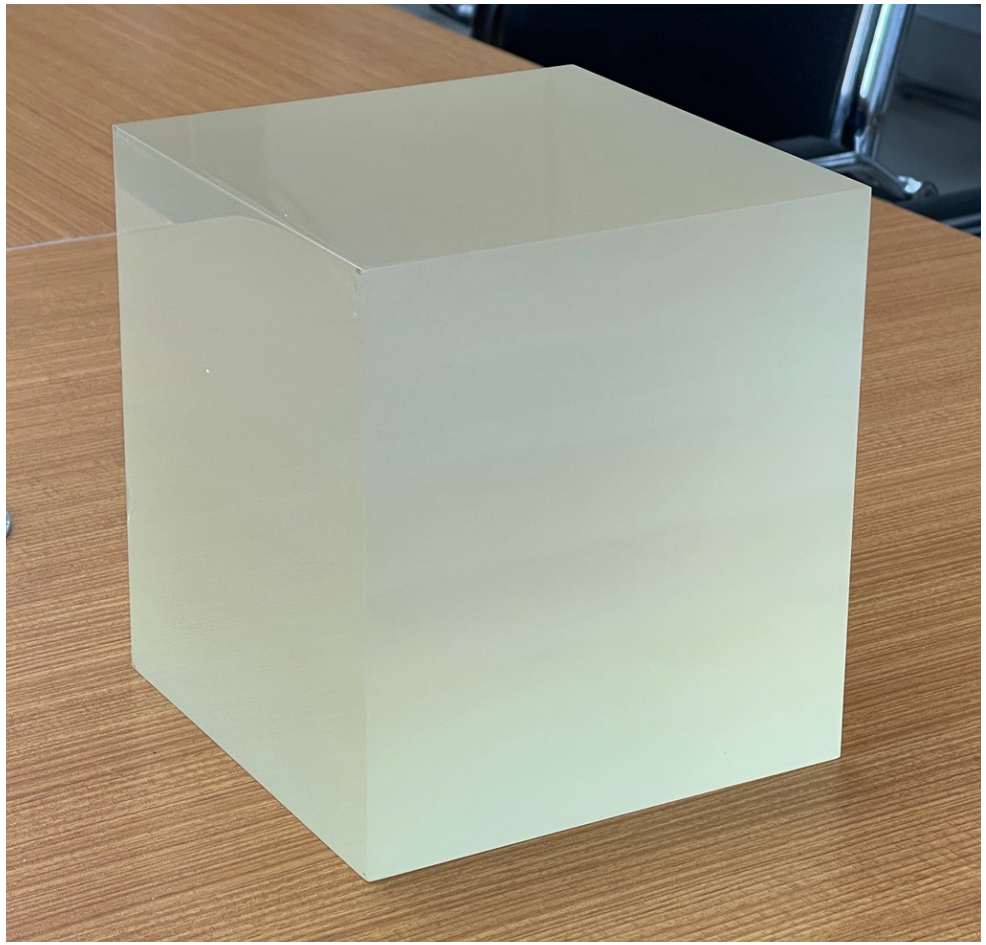
[a]Data from the Donchamp database.

Transparency measurement on samples produced using both the nominal transparency recipe and the high transparency recipe, with 405 nm light.



Gd-PMMA for DS-20k

- No transparency requirement;
- 25~30 tonnes of Gd-PMMA panels are required.
- Challenge of producing large panels:
  - Thickness requirement: ~17 cm;
  - Stable production yield;
- Solution:
  - Multi-layer lamination to reach the required thickness;
  - The cooling test, in which a 17 cm laminated sample (consisting of 6 layers), was slowly immersed in liquid argon, was successful.



Radiopurity Control

- 5N Gd2O3 from ShinEtsu is selected for Gd-PMMA production for DarkSide-20k;
- The Gd-PMMA panels will be produced in the radiopure line at Donchamp constructed by the JUNO experiment.

ShinEtsu 5N Gd2O3

Isotopes	mBq/kg
Th232_Ra228	< 0.5
Th232_Th228	0.4±0.1
U238_Ra226	0.5±0.1
U238_Th234	< 33
U238_Pa234m	< 7.4
U235	< 0.31
K40	4±1
Cs137	< 0.079

JUNO PMMA

Isotopes	mBq/kg
Th232_Ra228	< 0.14
Th232_Th228	< 0.078
U238_Ra226	0.05±0.02
U238_Th234	< 2.1
U238_Pa234m	< 1.8
U235	< 0.07
K40	< 0.41
Cs137	< 0.025

Gd-PMMA (under validation)

Isotopes	mBq/kg
Th232_Ra228	< 0.33
Th232_Th228	< 1
U238_Ra226	< 1.3
U238_Th234	< 8.3
U238_Pa234m	< 49
U235	< 0.54
K40	< 11
Cs137	< 0.12

Radiopurity assay at LNGS.

Summary

- DarkSide-20k uses liquid argon for dark matter detection.
- A novel active neutron veto detector with Gd-PMMA is designed.
- Gd-PMMA based on the Gd(MAA)3 recipe is developed.
- Gd-PMMA panel production for DarkSide-20k is under preparation.

Beyond Gd-PMMA:

Lead-doped acrylic: successfully developed!

Boron-doped acrylic: development in progress…

Boron-doped plastic scintillator: development in progress…

For more information, please contact wangyi90@ihep.ac.cn.