Low-mass dark matter and neutrino-less double beta decay searches with the DarkSide technology

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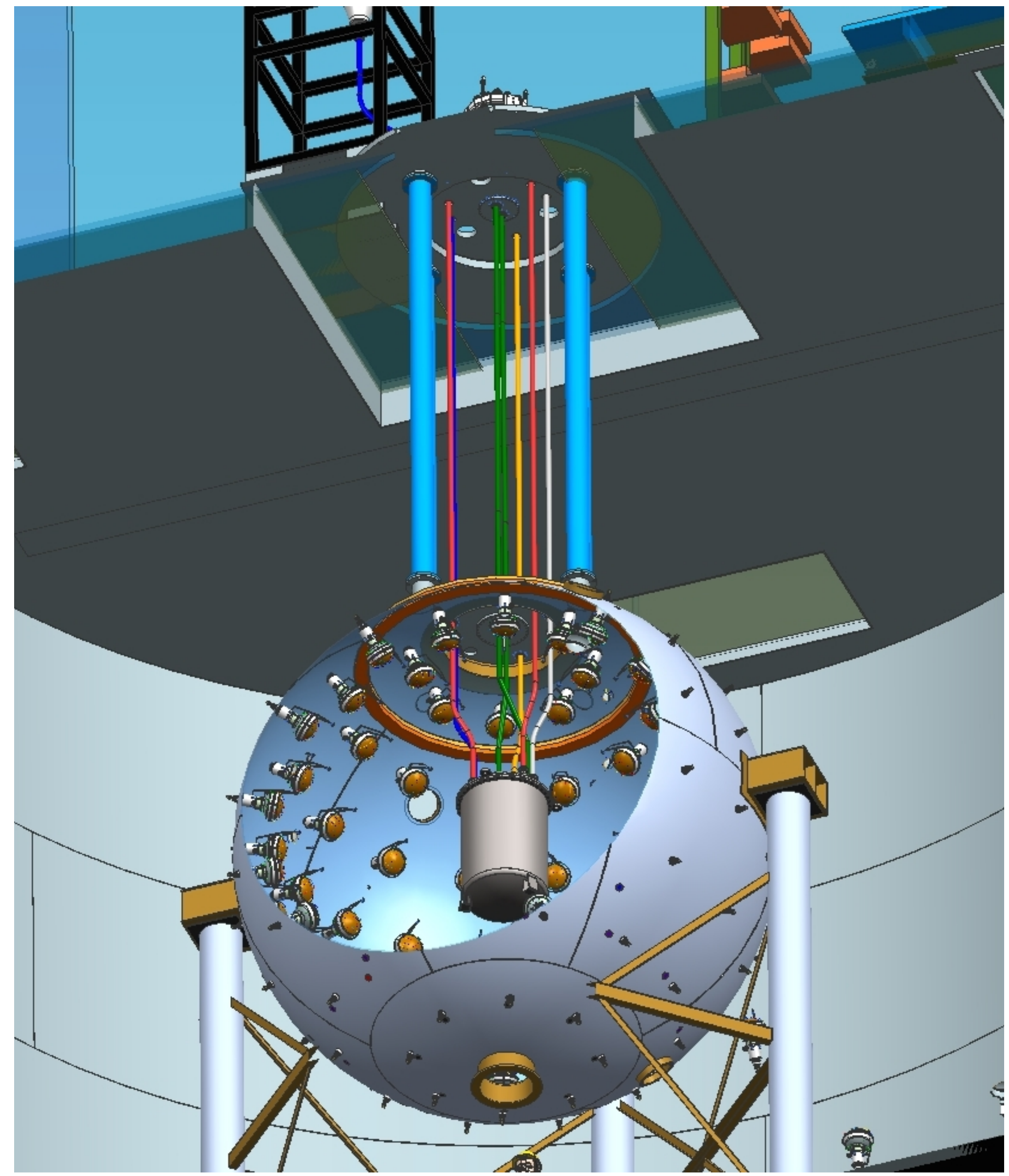
Outline

- **Low-mass dark matter search**
  - DarkSide-50 detector
  - Results of DarkSide-50
  - The future of the DarkSide program: DarkSide-20k
- **Neutrino-less double beta decay search**
  - LAr-LXe DarkSide detector

The DarkSide-50 Detector

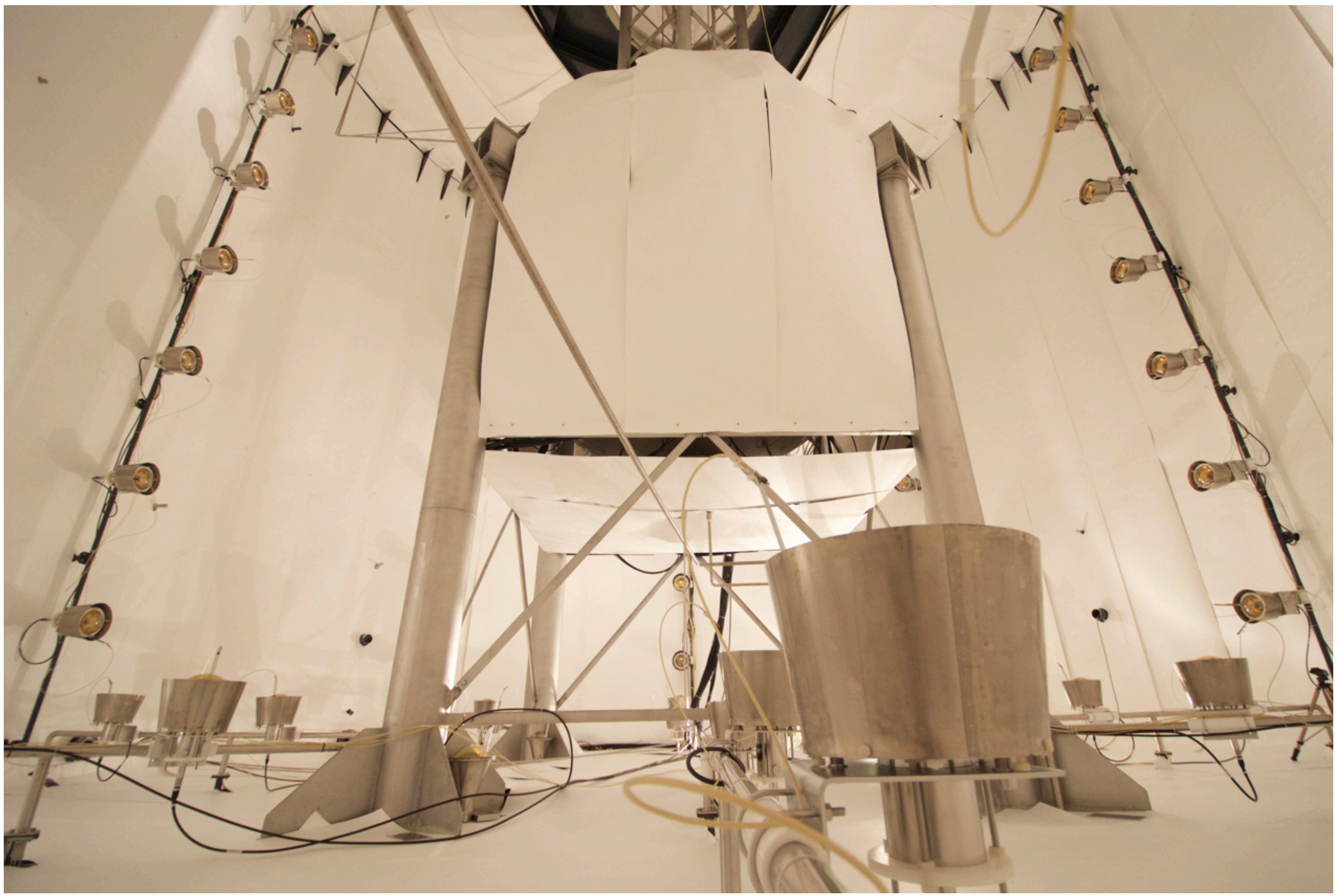
Situated in the Hall C of the Laboratori Nazionali del Gran Sasso, DarkSide-50 is constituted by three nested detectors:

- an external muon veto
- a neutron veto
- a two-phase time projection chamber (TPC) serving as the dark matter detector



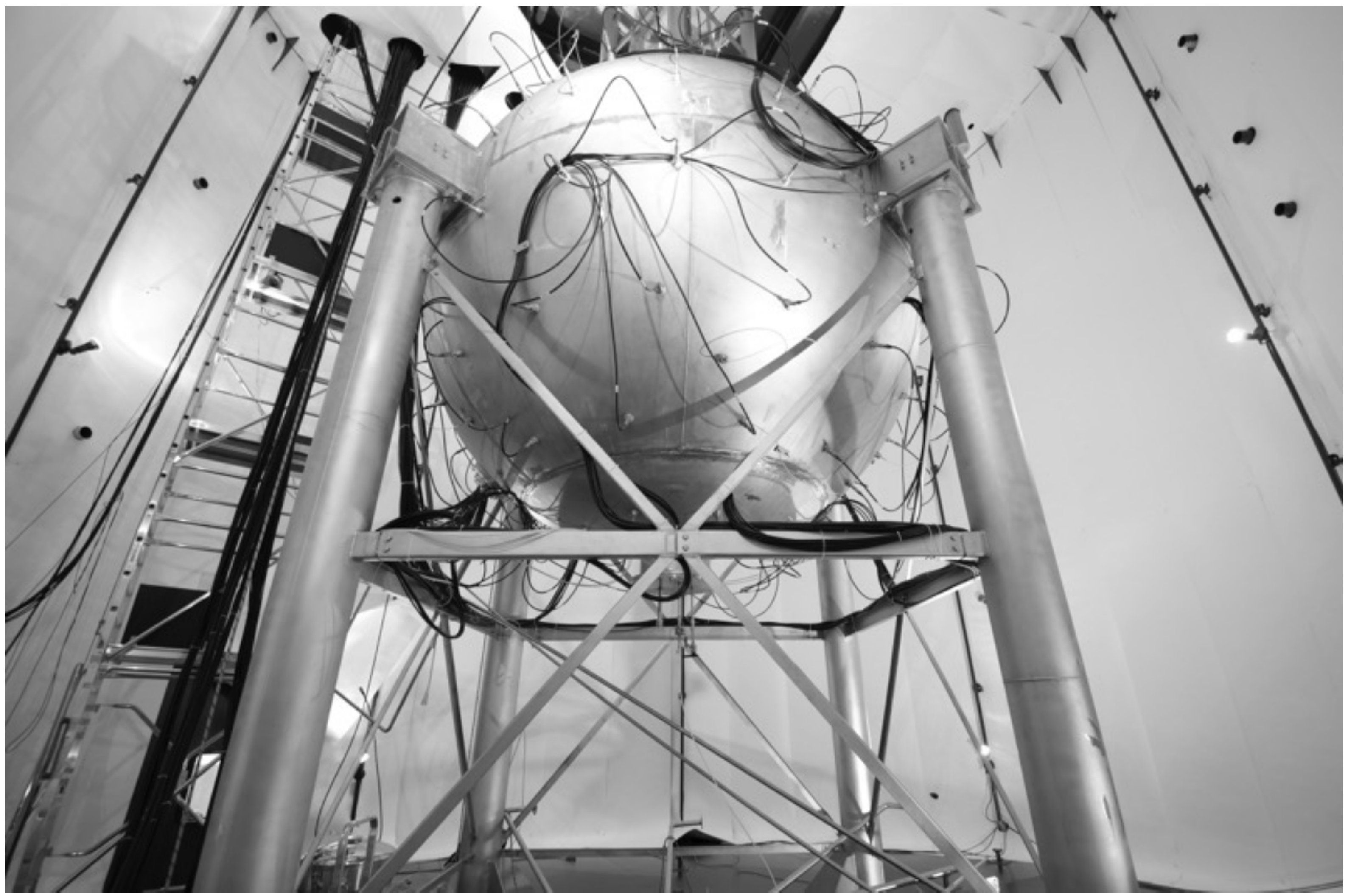
The Water Cherenkov Veto

A cylindrical water tank filled with ultra pure water
and instrumented by 80 photomultiplier tubes (PMTs)



The neutron veto

A stainless steel sphere filled with boron loaded scintillator and instrumented with 110 PMTs



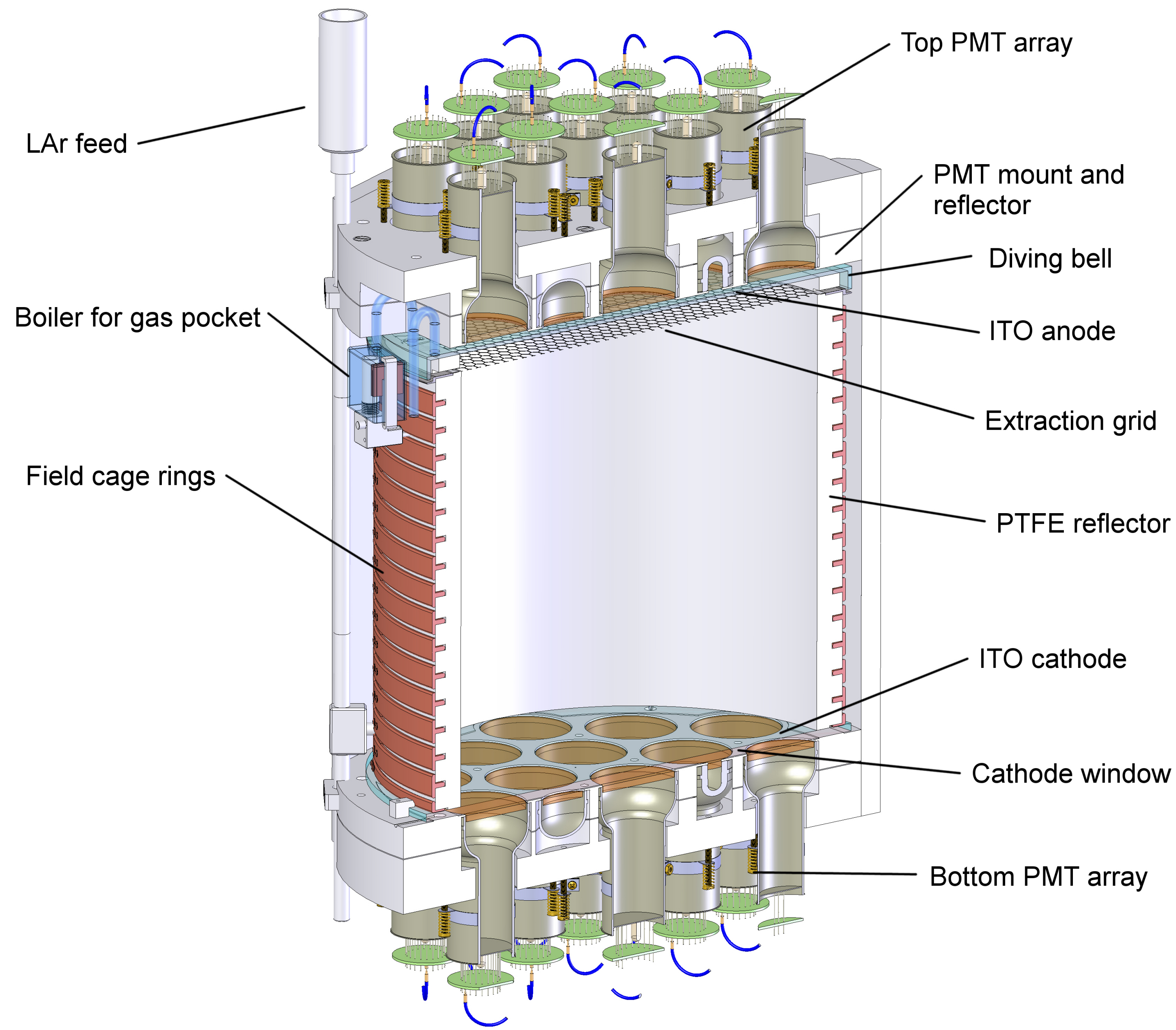
$$^{10}B + n \rightarrow^{7} Li(1015keV) + \alpha(1775keV)$$

$$^{10}B + n \rightarrow^{7} Li* + \alpha(1471keV)$$

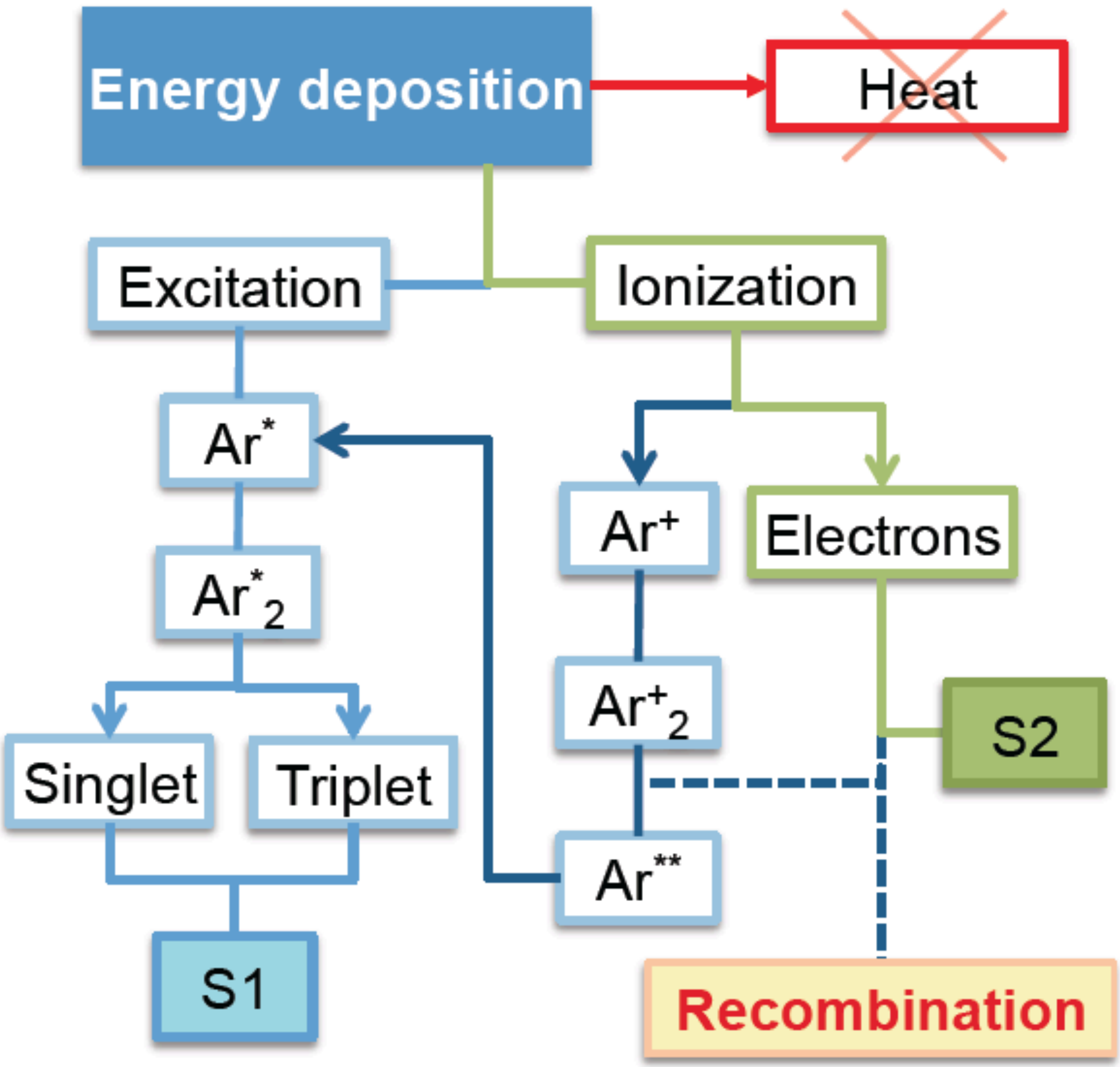
$$^{7}Li* \rightarrow^{7} Li(839keV) + \gamma(478keV)$$

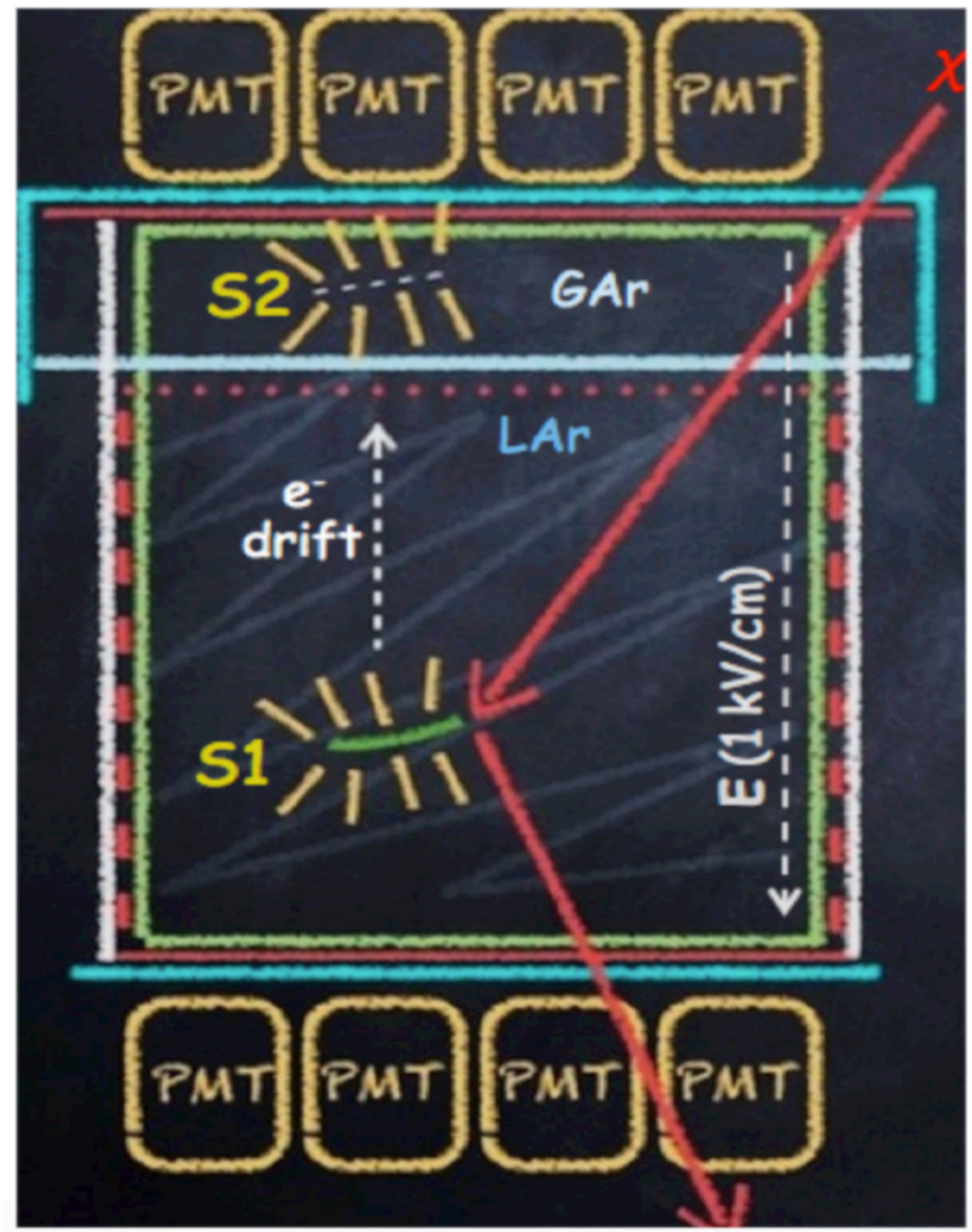
The Time Projection Chamber

- Filled with 50 kg of Underground Argon (UAr)
- Instrumented with 38 PMTs
- High reflectivity teflon walls
- Acrylic windows covered with ITO
- Uniformity of the drift field is established by the use of copper rings
- Inner surface coated with wavelength shifter

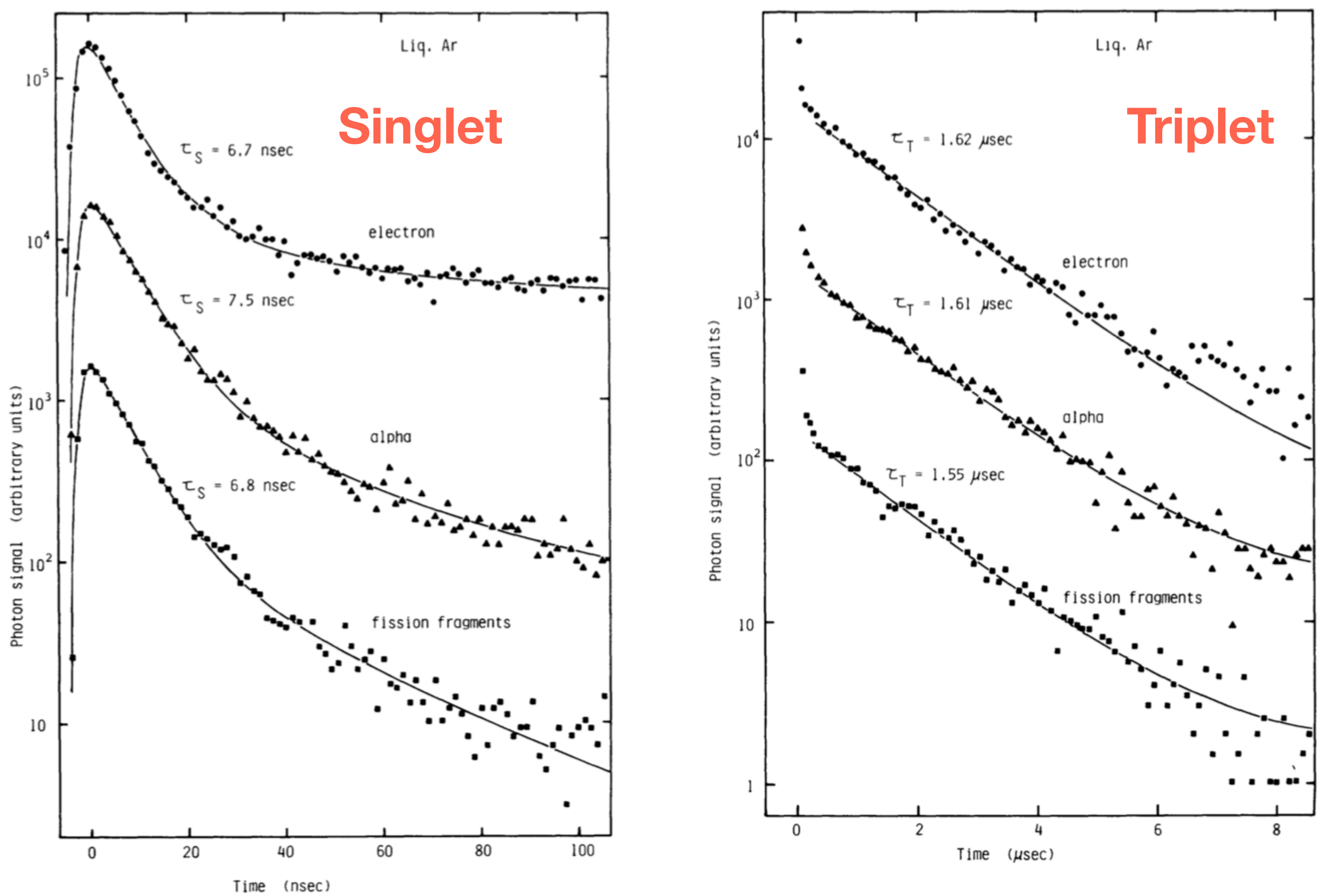


The Time Projection Chamber



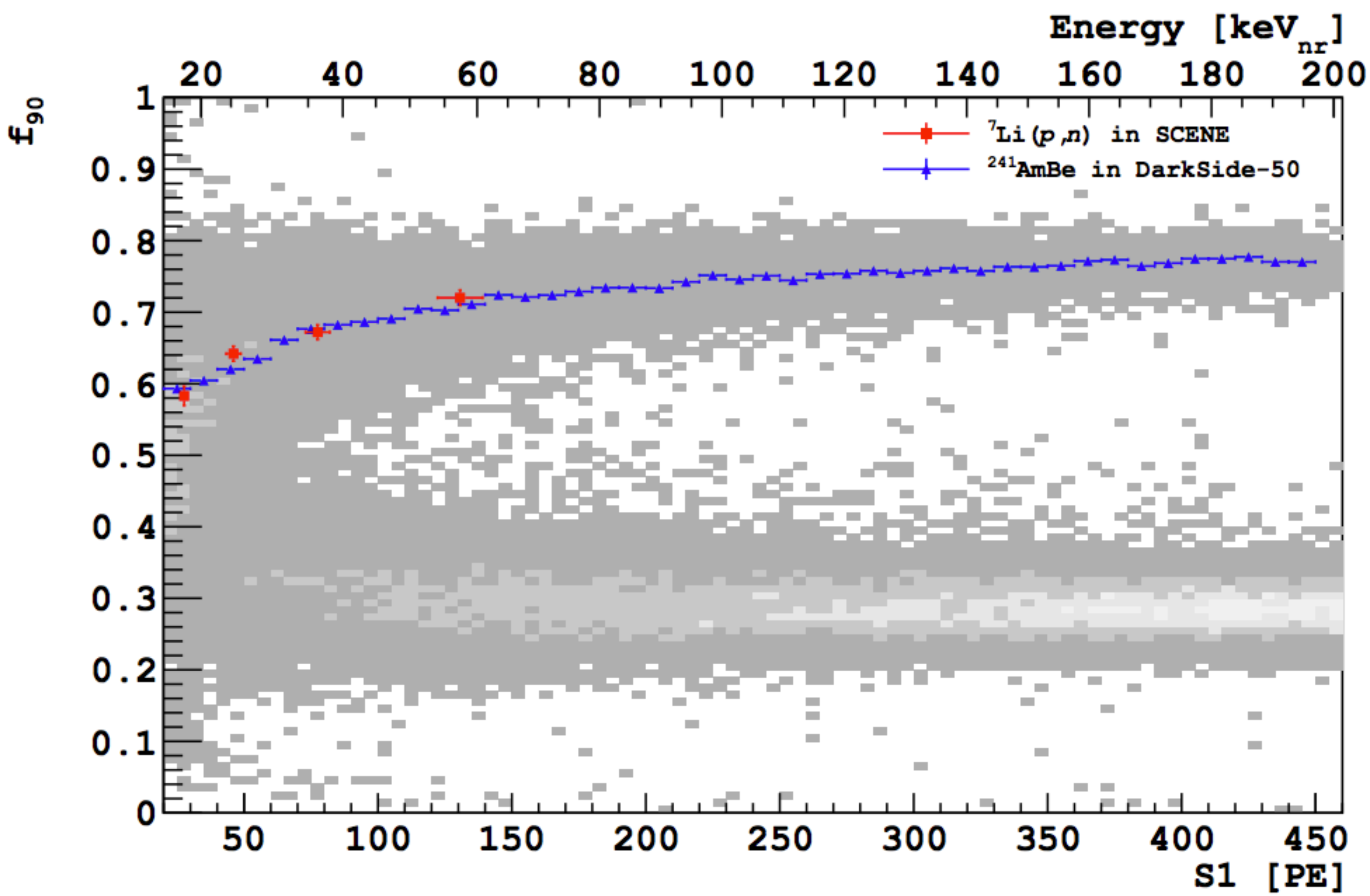


Pulse shape discrimination



$$f_{prompt} = \frac{\sum_i PE_{i,prompt}}{\sum_i PE_i}$$

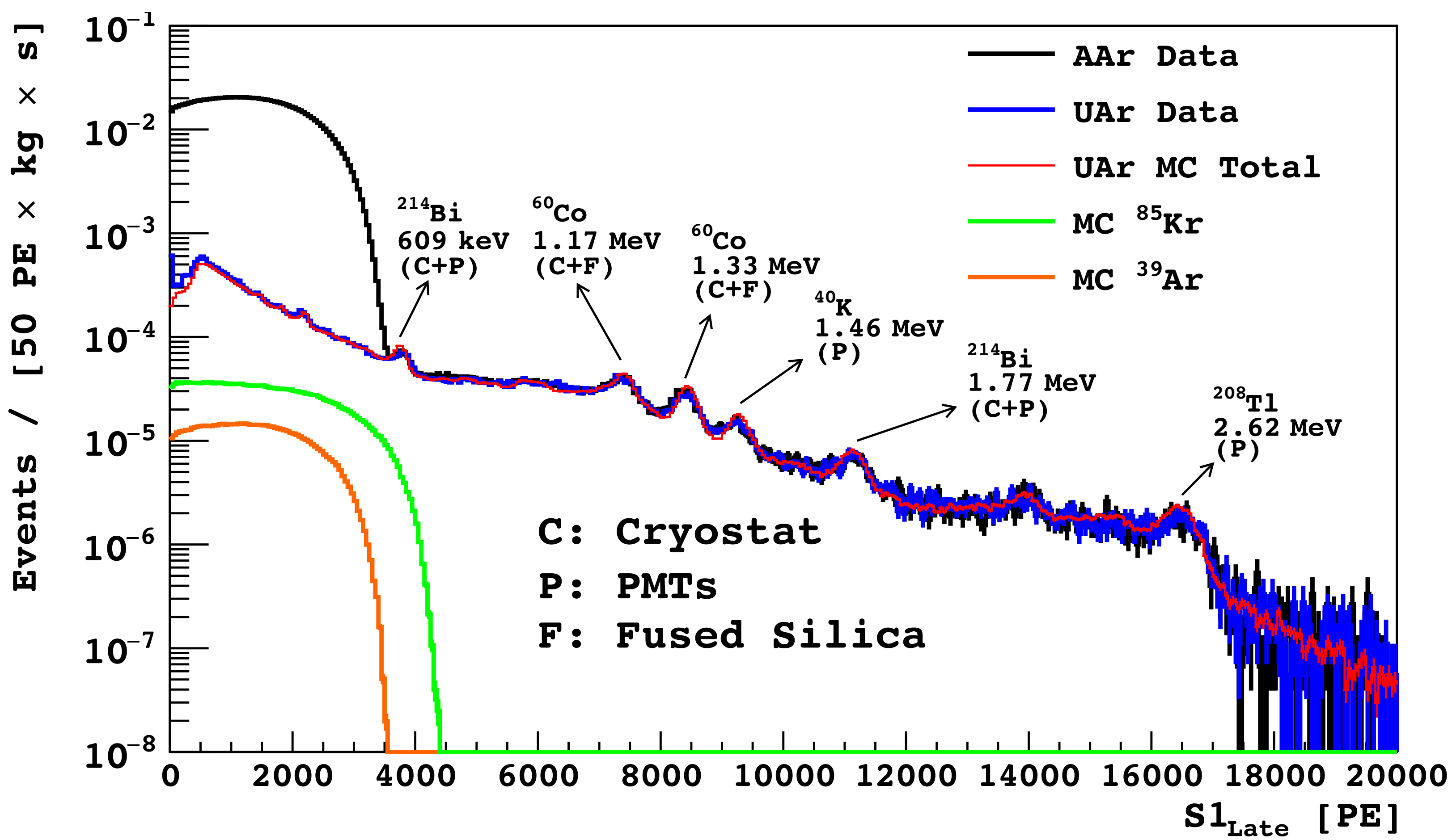
Pulse shape discrimination



The maximum separation is obtained in the first 90 ns of the prompt signal

The importance of underground Argon

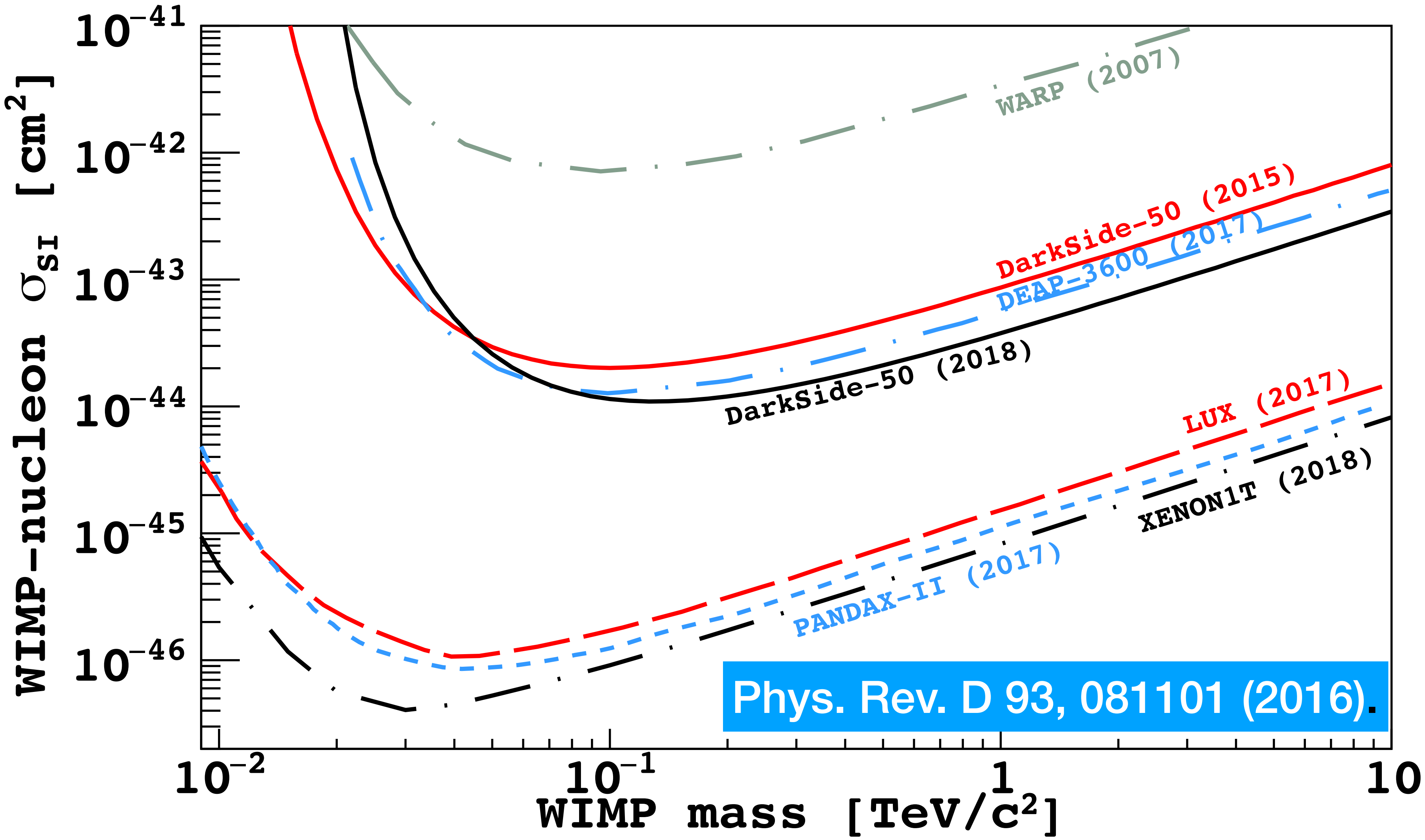
Sources of background are beta and gammas originated from the material of the TPC and from the decay of ^{39}Ar contained in atmospheric argon.



Comparison of the measured field off spectra for the UAr (blue) and AAr (black) targets normalised to exposure. Phys. Lett. B 743, 456 (2015).

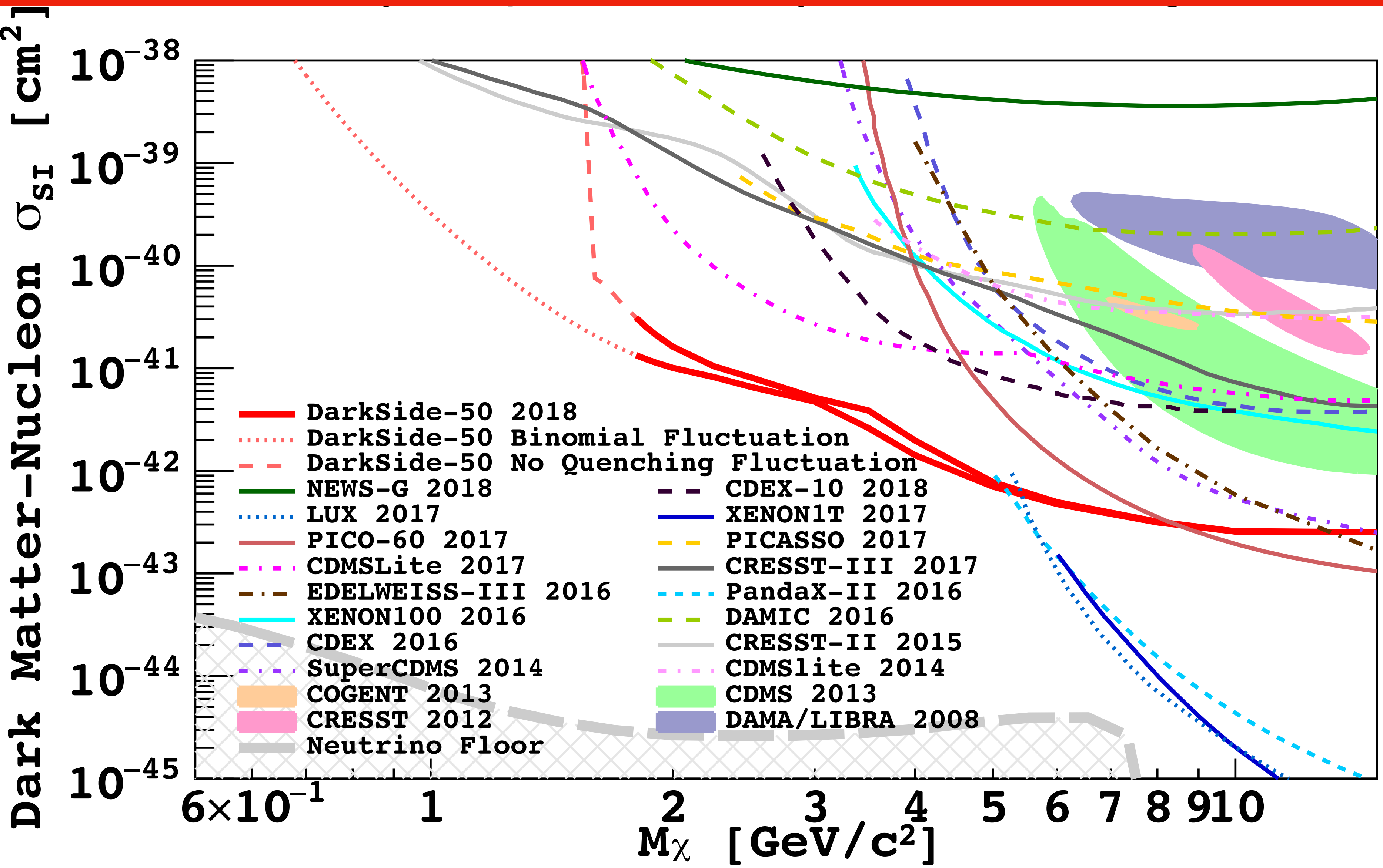
Latest result of DS-50

Spin-independent cross section exclusion limit (C.L. 90%) from the 532.4 live days campaign.



DS-50 and low mass dark matter

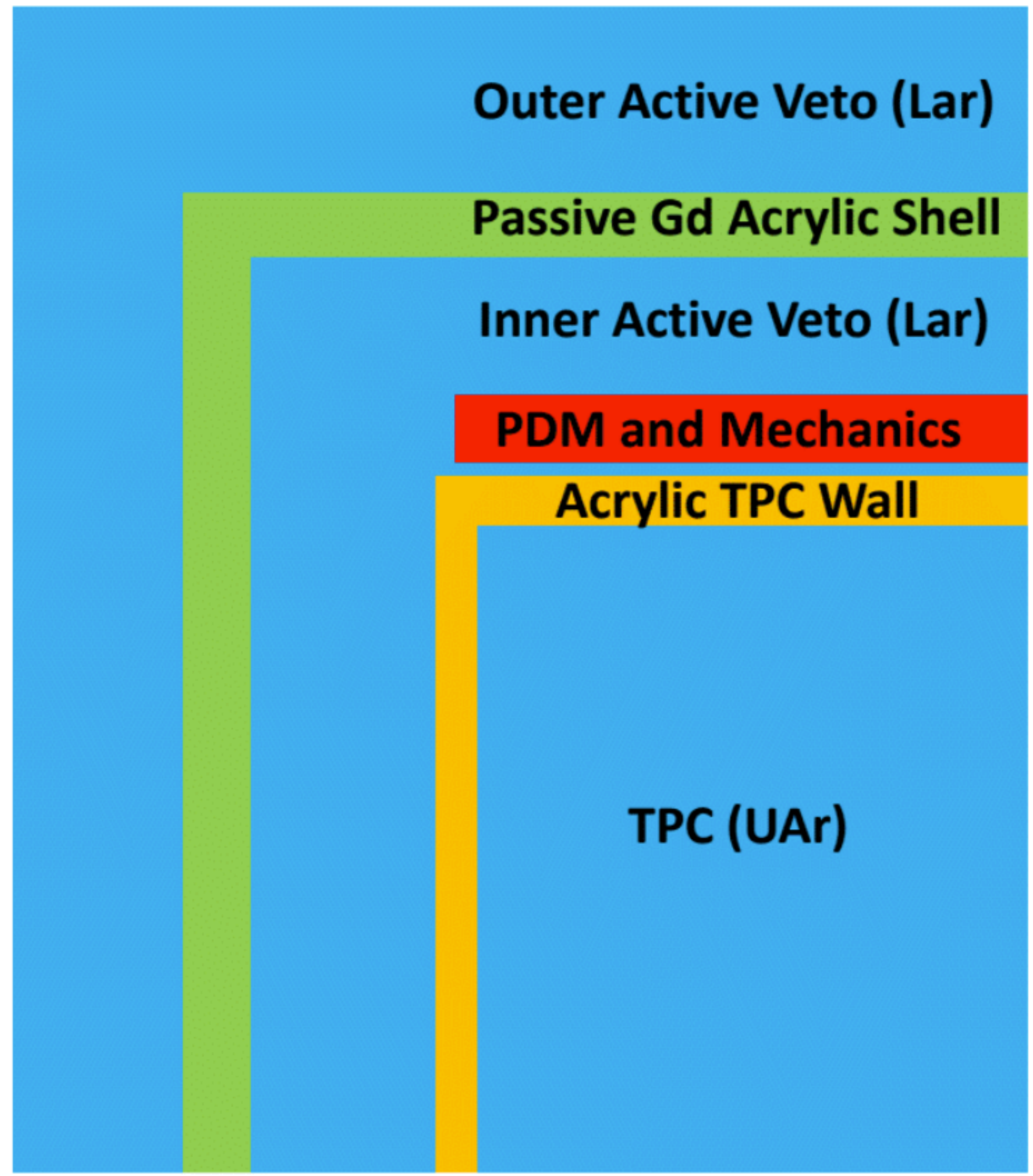
World best limit for low-mass dark matter search
in the mass range of 1.8 GeV/c^2 to 6.0 GeV/c^2



Phys. Rev. Lett. 121, 081307 (2018).

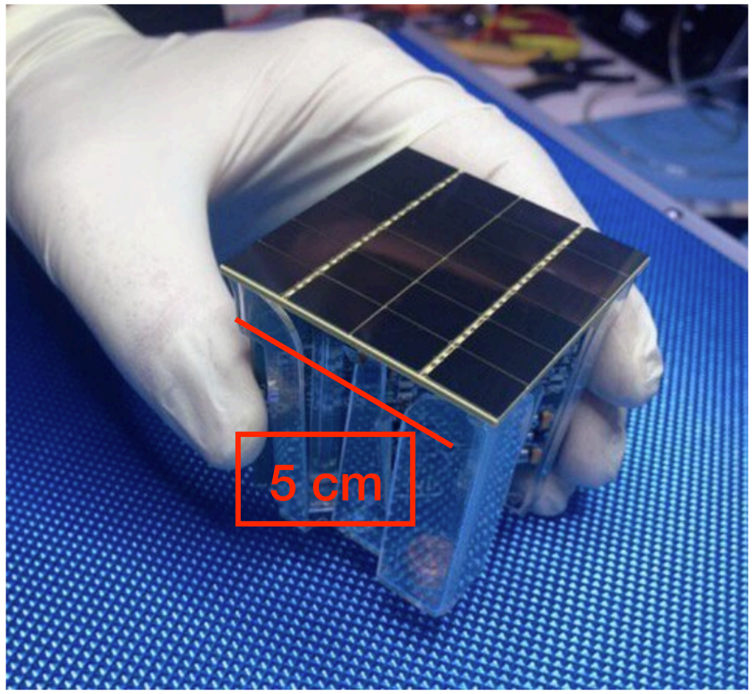
The future: DarkSide-20k

- Octagonal prism TPC contained in an ultra pure acrylic vessel (PMMA)
- Filled with 48 ton of active UAr
- The LSV will be replaced by Gd-loaded passive shield
- The 38 PMTs will be substituted by $\sim$ 8000 photodetector modules (PDMs)

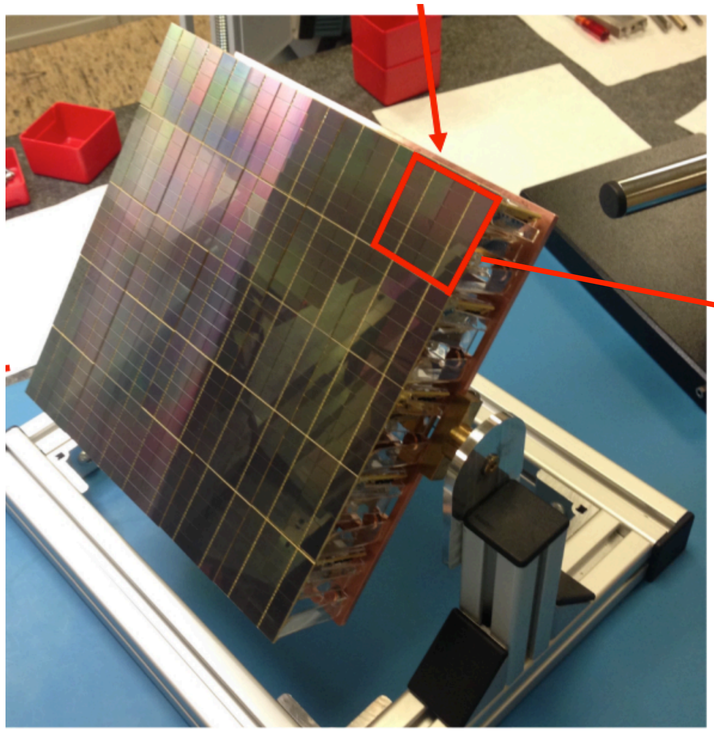


Tiling and packaging PDMs

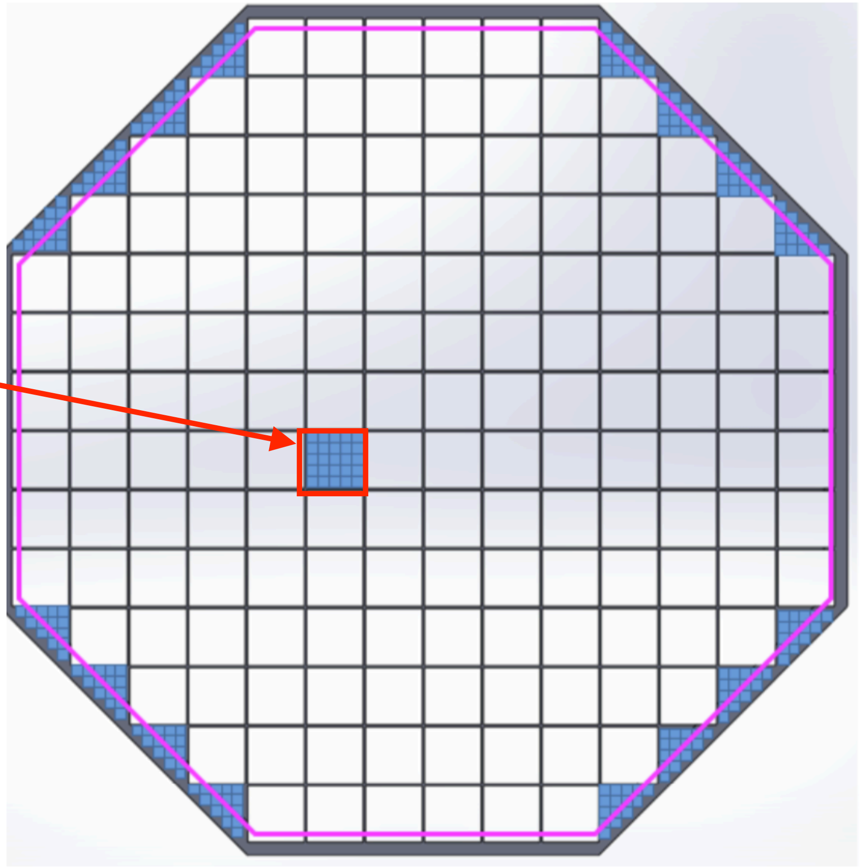
The PDM is the silicon-based equivalent of the PMT. Each PDM is formed by 24 SiPMs tile of size of 1 cm^2, read out as a single analog channel.



PDM, 24 SiPMs tiles,
5 cm x 5 cm x 5 cm



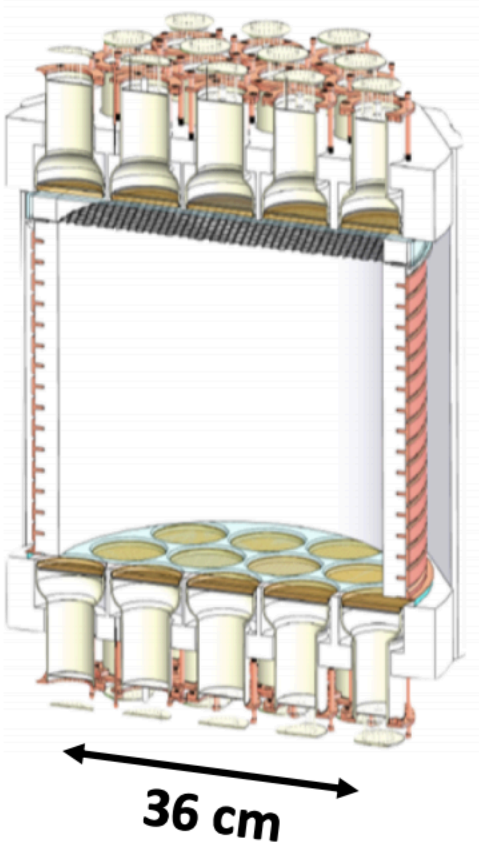
25 PDMs,
25 cm x 25 cm x 5 cm



Top/Bottom Photosensor array,
in total ~8000 PDMs

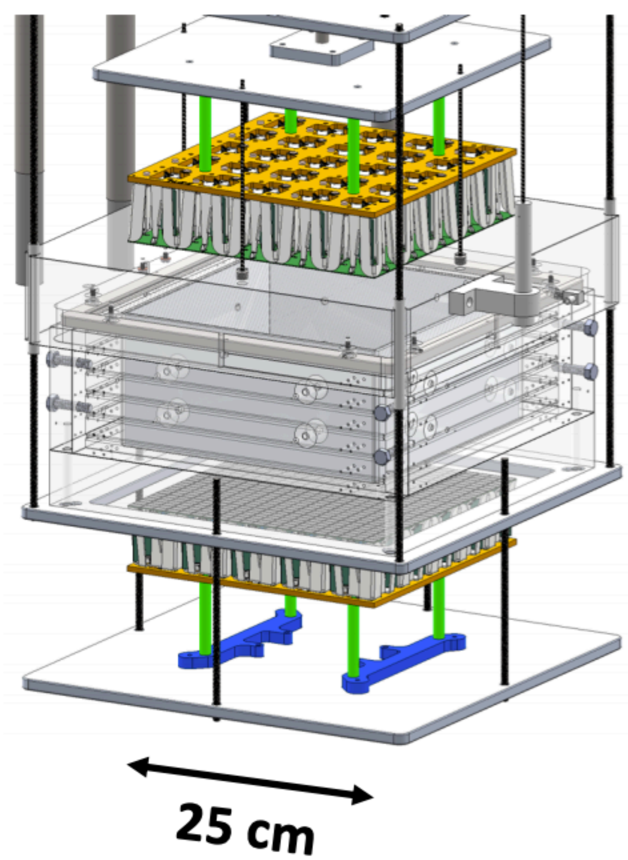
Evolution of DarkSide

38 PMTs



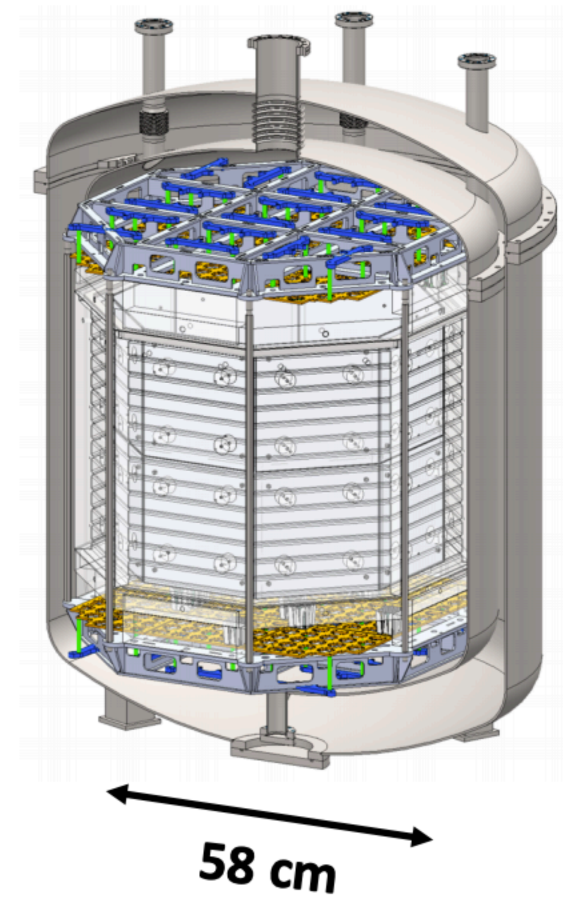
DS-50
(2014-present)
46 kg of UAr
Conventional TPC

50 PDMs



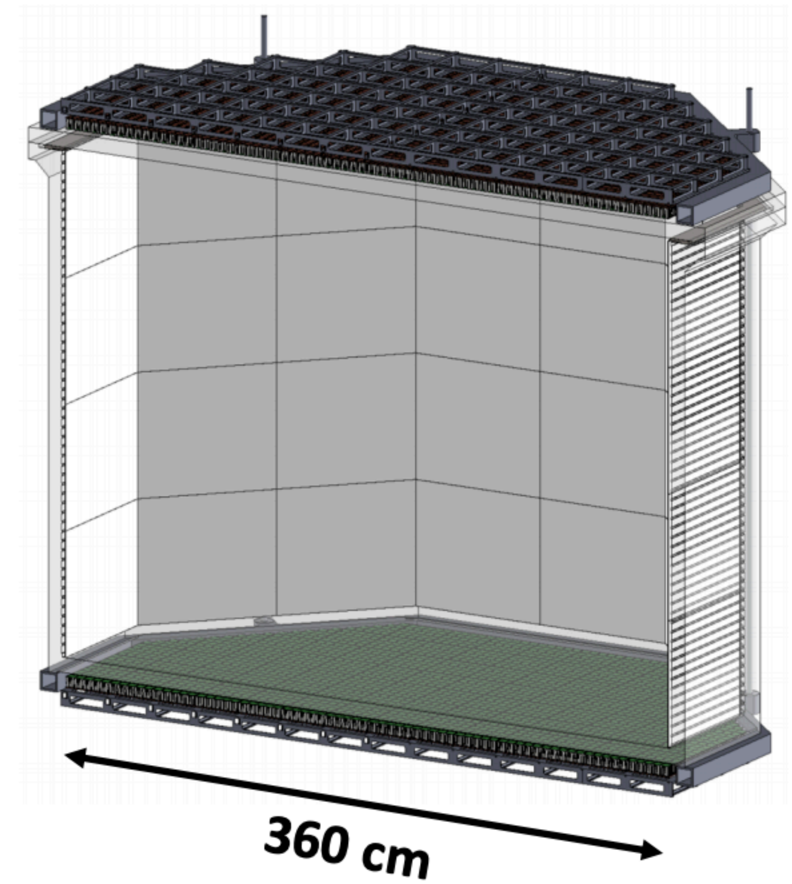
DS-Proto-0
(2019-2020)
10 kg of active UAr
Test bench

370 PDMs



DS-Proto-1
()
75 kg of active UAr.
Scale down version of DS-20k

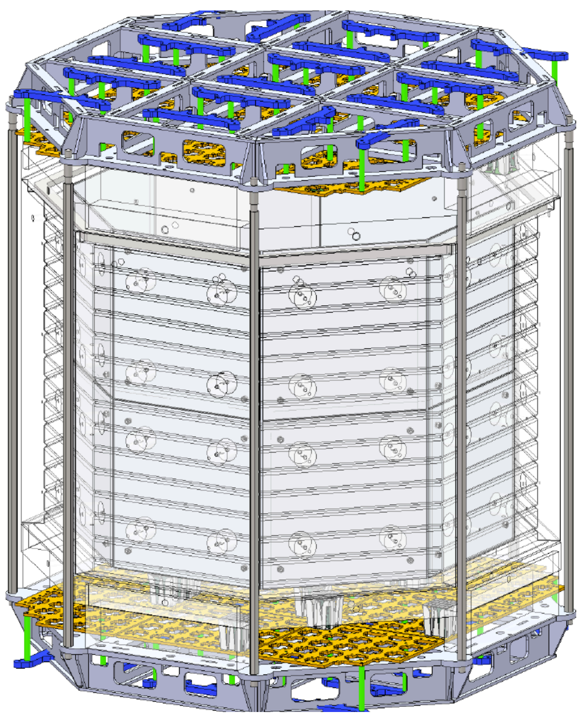
8280 PDMs

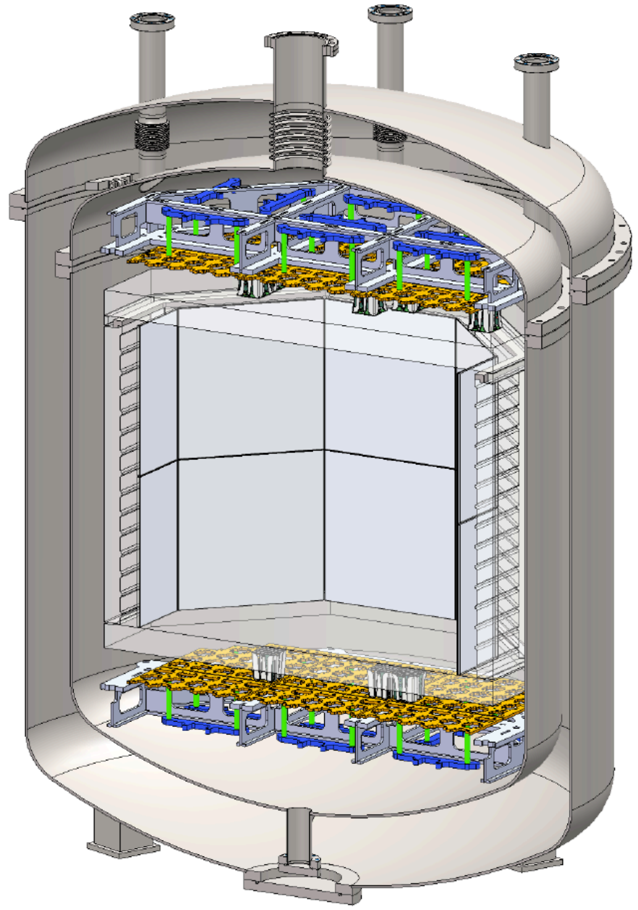


DS-20k
48 ton active UAr

DarkSide-Proto

- Octagonal prism LAr TPC
- Edge of 30 cm, height of 60 cm
- 185 PDMs on top and bottom of the TPC
- Drift field 200 V/cm
- Top and bottom boundaries of 5 cm thick PMMA, instead of acrylic as in DS-50
- Inside surface coated with a conductive polymer (no more ITO)
- Extraction and electroluminescence of 2.8 kV/cm and 4.2 kV/cm
- Gas pocket of 7 mm





DarkSide-Proto purpose

- Serving as prototype of intermediate dimension (~1 t) to validate DS-20K technologies
- TPC mechanics, all structural elements will be built as a scaled-down version of DS-20k detector.
- Dark matter search in the mass range of 0.6 GeV/c^2 to tens of GeV/c^2

Troubles in low mass dark matter region

- Efficiency for detecting S1 is low -> PSD is no more available

- The most significant background are gammas and betas

- Nuclear recoils below 10 keV_{nr}->efficiency in detecting S1 is very low

- Mechanisms producing neutrons are extremely rare

- Neutron veto loss its importance

Background sources

- **Internal backgrounds:** events due to radioactive elements dissolved in the active UAr target: $^{39}Ar, ^{37}Ar, ^{85}kr$

- **External background:** events originating from radioactivity in the construction materials of the LAr TPC and cryostat: $^{60}Co, ^{40}K, ^{232}Th, ^{238}U, ^{235}U$

- **Cosmogenic background:** events originating from the residual cosmic ray flux in the Hall C of LNGS.

Background simulations

This work intends to be a study of the possible geometries of a future detector featuring the DarkSide technology to optimize the sensitivity to low mass dark matter WIMP-like particles.

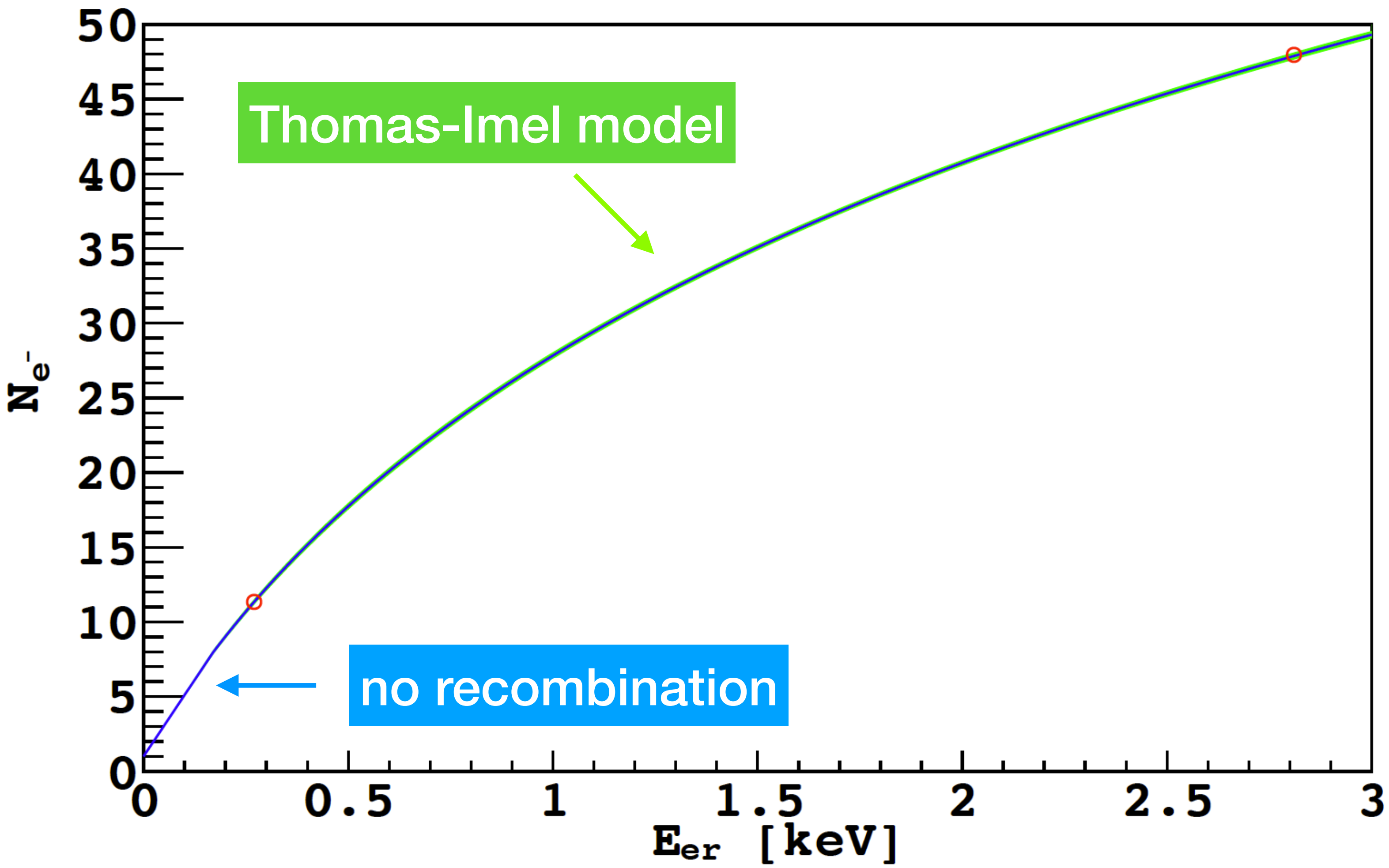
The principle steps of the study are:

- Simulation of nuclear decays of the radioisotope mentioned in every detector component with G4DS toolkit
- Spectrum of ionization electrons generated by background events
- Comparison of background spectra and the one expected for WIMP interaction-> sensitivity of the detector.

Background simulations

- We define a cluster as one or more energy deposits which occur at a distance greater than of 2 mm on z-axis and within a time window of 2 μs -> position and energy of the cluster

- Need to convert energy cluster in number of electrons that will produce by electroluminescence the S2 light signal



- Finite resolution of the detector is reproduced by a gaussian smearing on x-y position reconstruction via S2 signal ~2 cm.

Background simulation: cuts

To further remove background events:

- **Single scatter cut**: all events with more than one interaction in the active volume are rejected
- **Fiducial cut**: we remove events near the walls of the TPC, with a distance greater than 5 cm.

Fiducial volume: 267 kg.

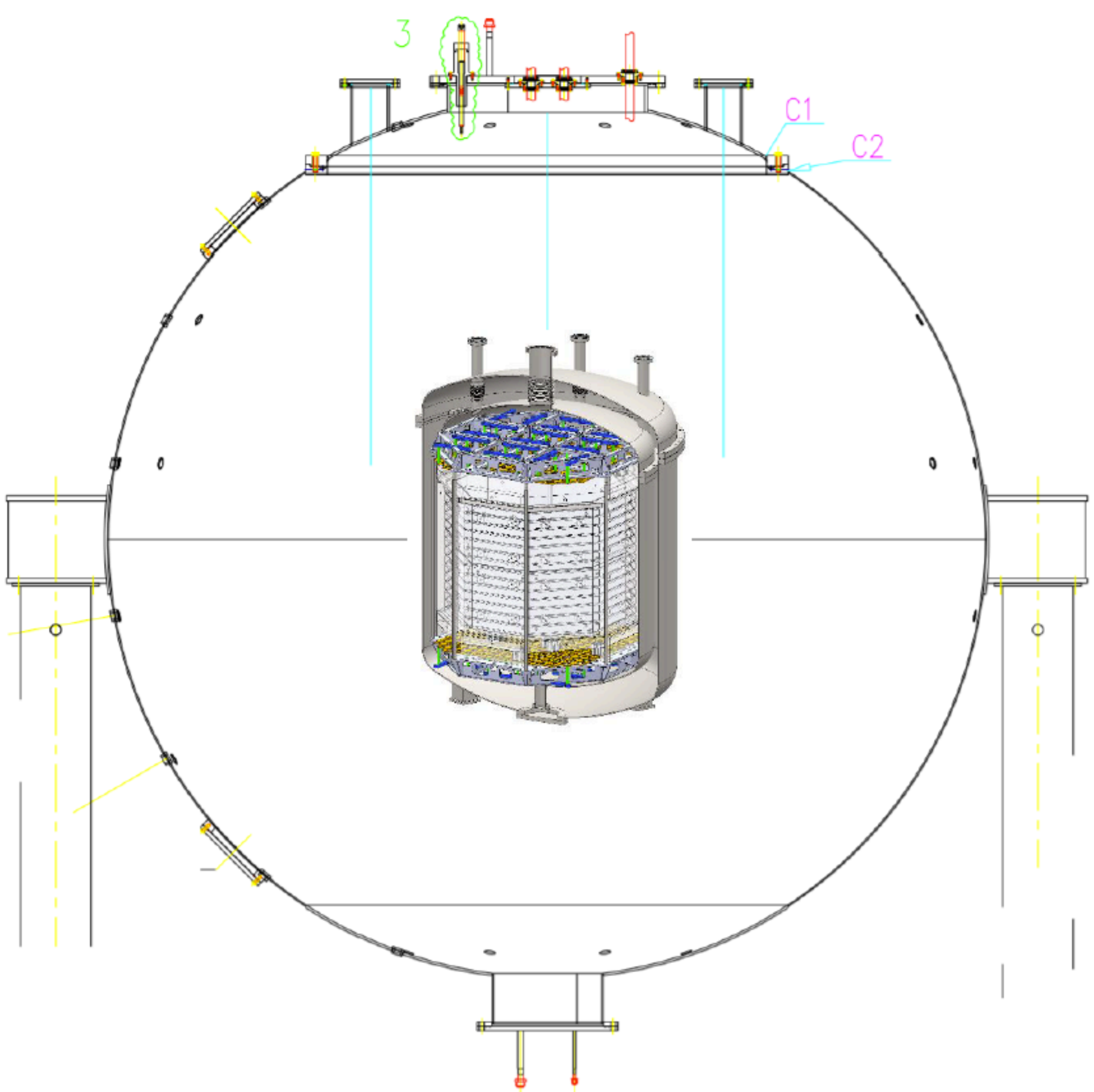
Detector configurations

- **First configuration**: DS-Proto is inside the LSV filled with ultra-pure water. The TPC is installed in a double wall stainless steel cryostat vessel (1.25 cm and 1.75 cm internal and external wall thickness). Electrodes of PMMA of 5 cm thick.

- **Second configuration**: Removing LSV and inserting the LAr-TPC at the centre of a huge cryostat of 5 m diameter and 6 m height filled with liquified AAr. I will name this geometry as DarkSide-LowMass.

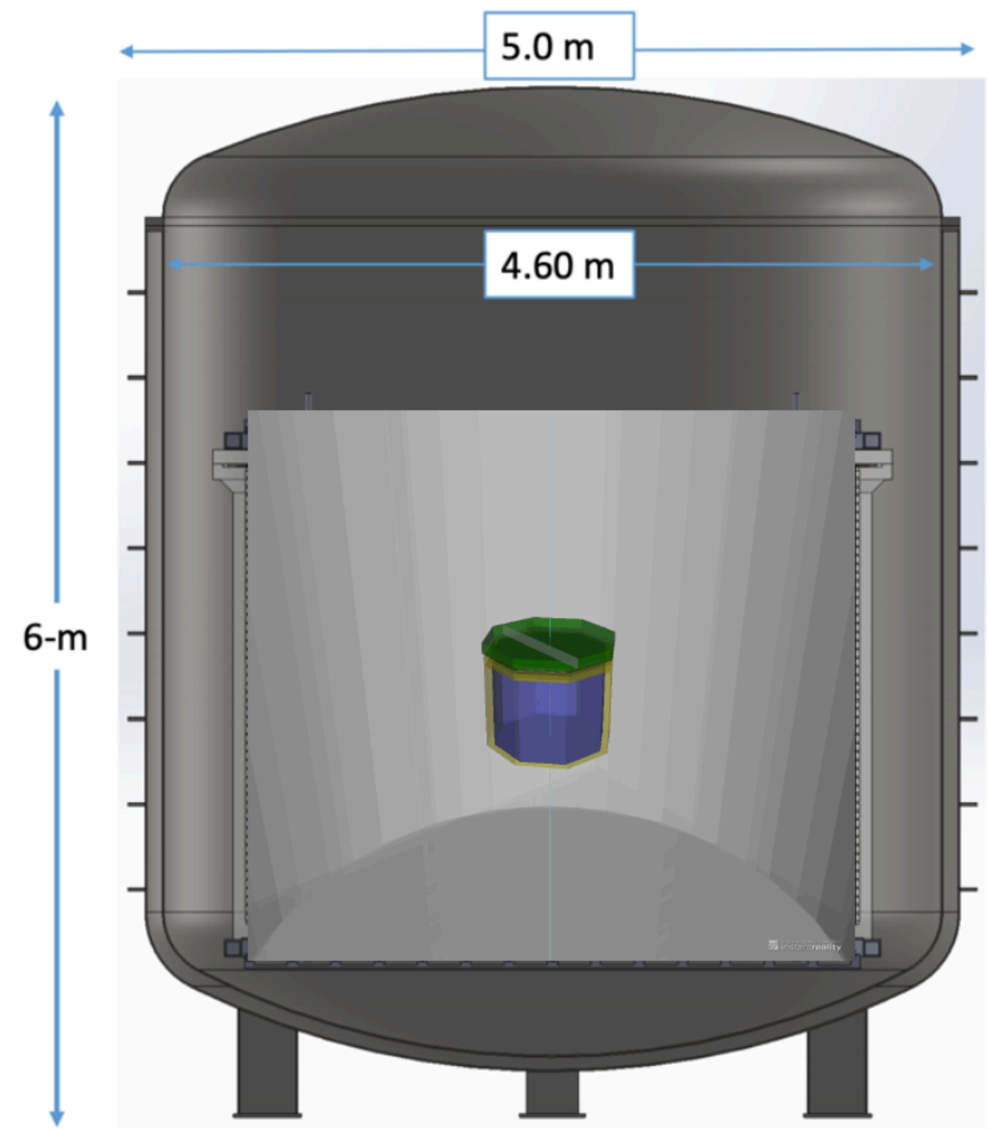
Detector configurations

First Configuration



DS-Proto

Second Configuration



DS-LowMass

DS-Proto first configuration: components and materials

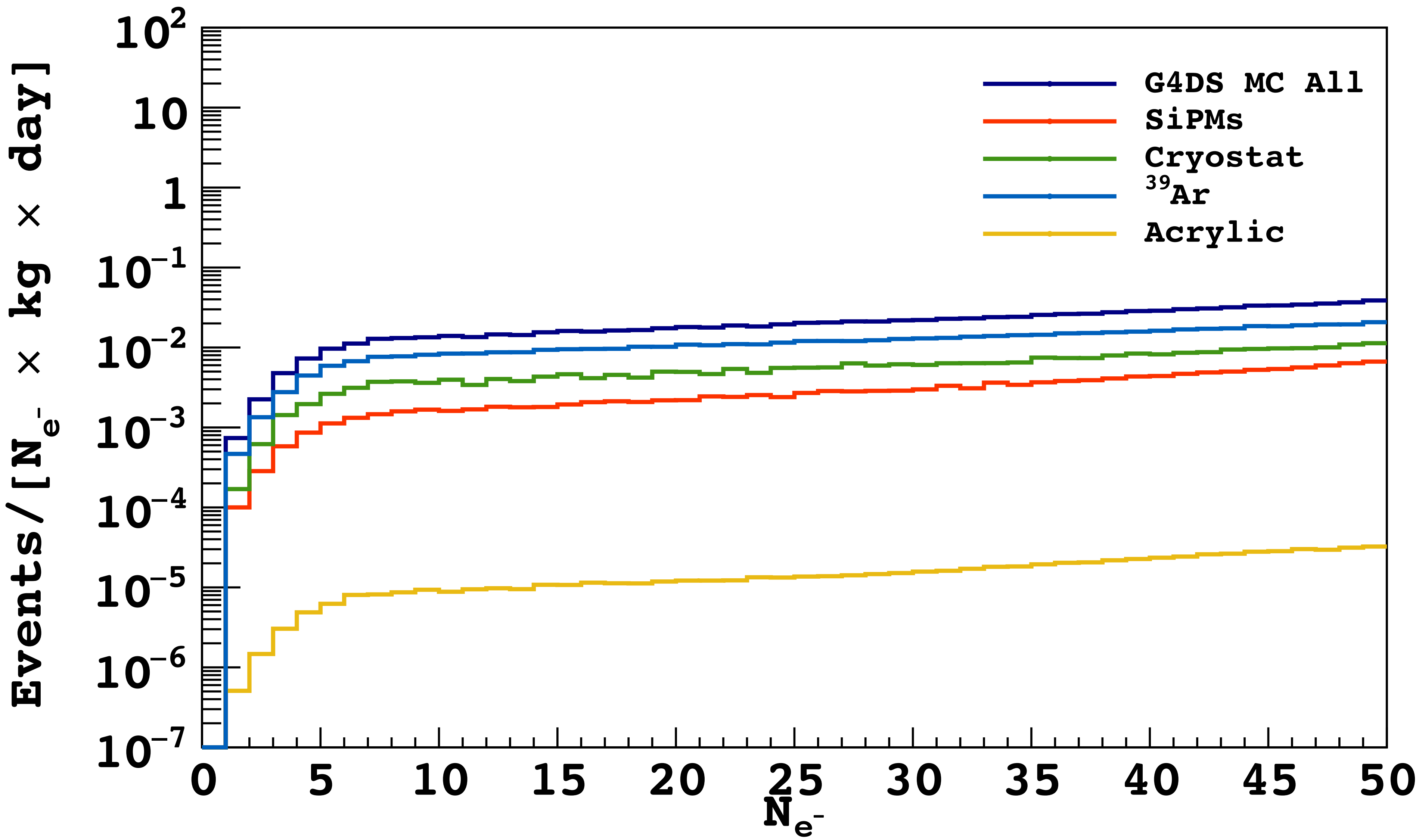
Components	Material	Mass (kg)
Cryostat	Stainless steel	2300
Reflector	PMMA	89
Windows	PMMA	67
PDMs	Various	370
Target	UAr	260

DS-Proto first configuration: activities

μBq/kg or μBq/PDM

Material	^{238}U	^{226}Rn	^{235}U	^{232}Th	^{40}K	^{60}Co	^{39}Ar
Stainless steel	2600	2600	26	1400	<3700	<650	0
PMMA	120	120	1.2	41	0	0	0
PDMs	4200	4400	0	3400	<1900	<82	0
UAr	0	0	0	0	0	0	730

DS-Proto first configuration: background spectrum



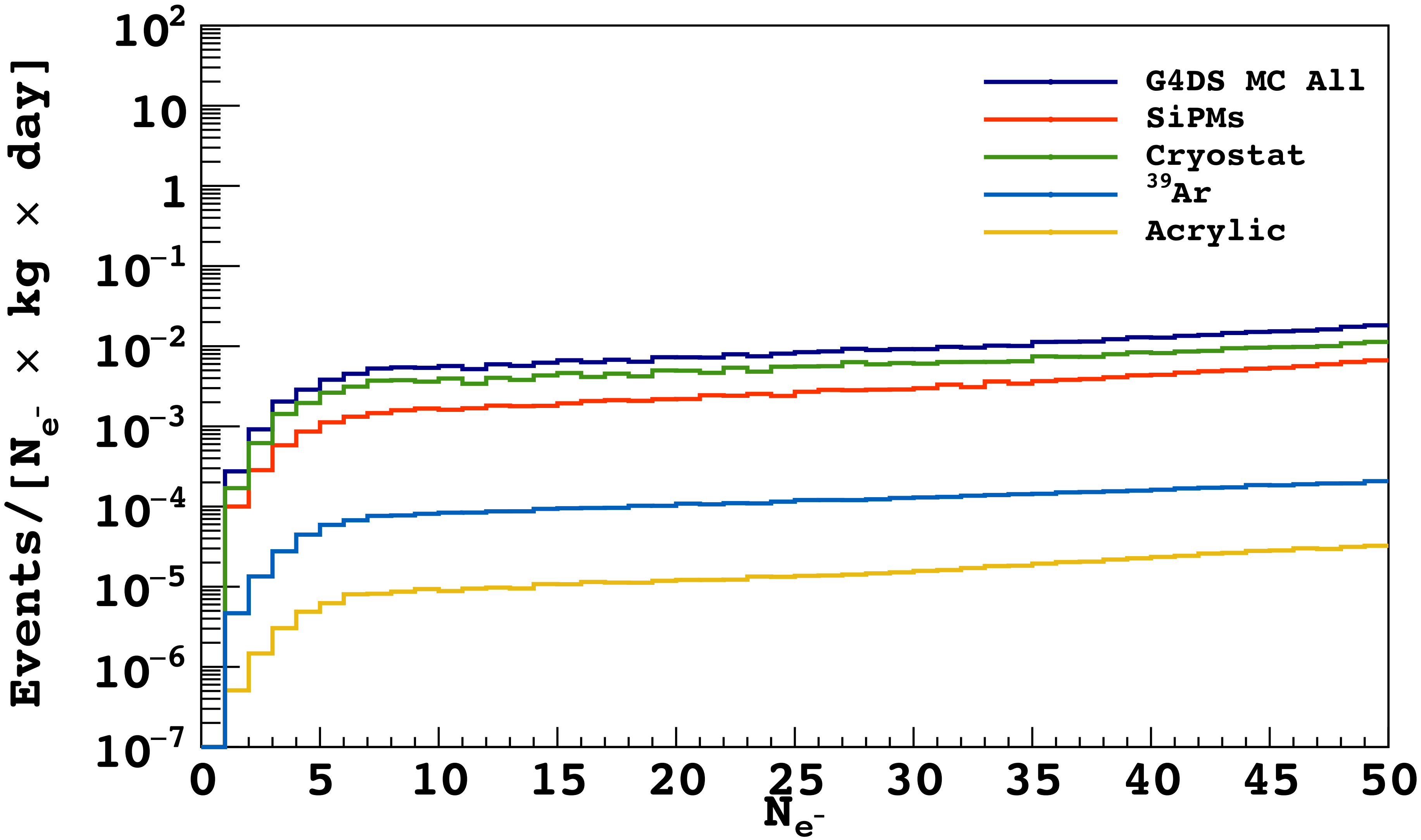
The major contribution to background comes from the activity of ^{39}Ar of the UAr target

DS-Proto second configuration: activities

μBq/kg or μBq/PDM

Material	^{238}U	^{226}Rn	^{235}U	^{232}Th	^{40}K	^{60}Co	^{39}Ar
Stainless steel	2600	2600	26	1400	<3700	<650	0
PMMA	120	120	1.2	41	0	0	0
PDMs	4200	4400	0	3400	<1900	<82	0
UAr	0	0	0	0	0	0	7.3 ↓

DS-Proto second configuration: background spectrum



Having suppressed the activity of ^{39}Ar the leading background becomes the activity of stainless steel

DS-LowMass first configuration: materials and components

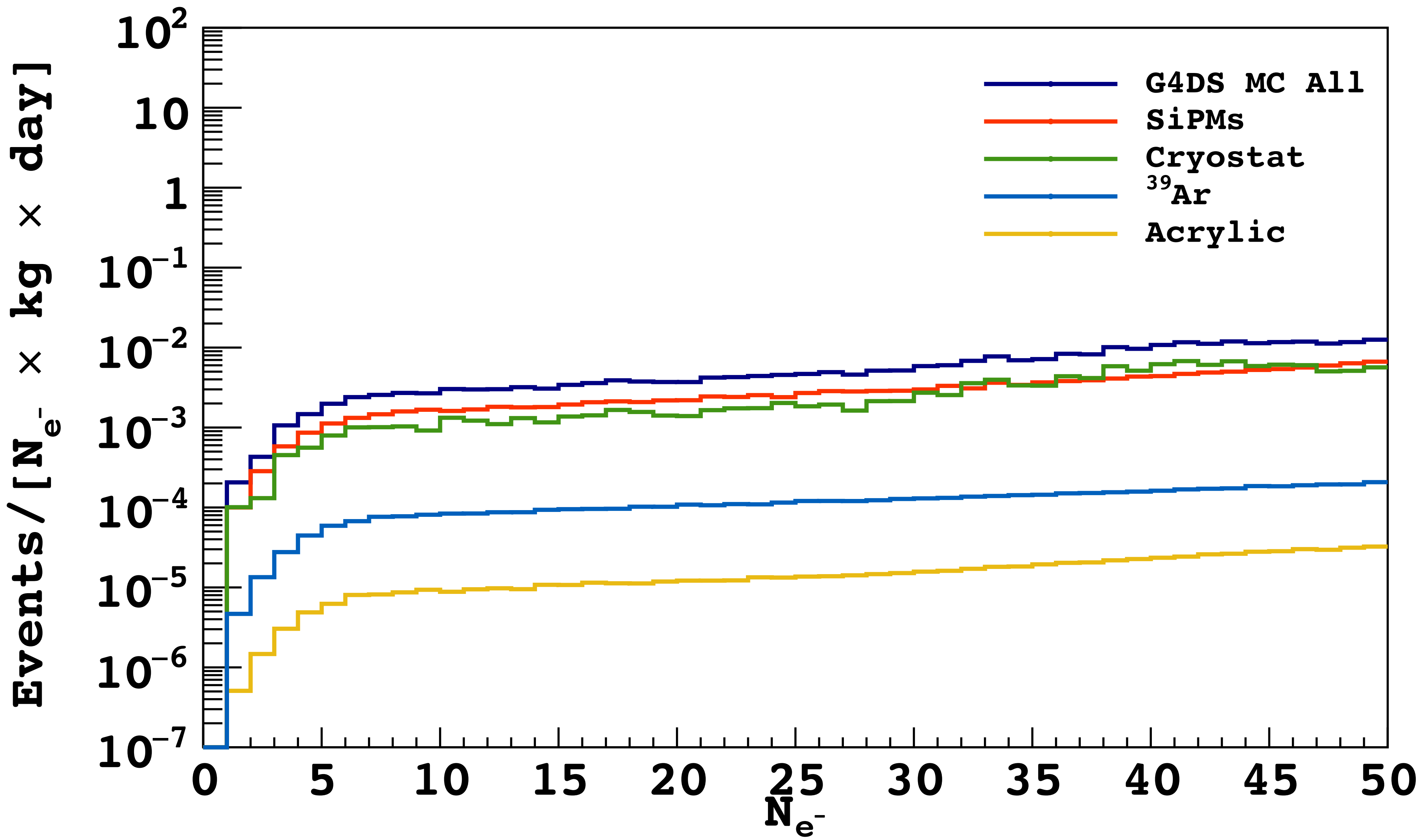
Components	Material	Mass (kg)
Cryostat	Stainless steel	13000
Reflector	PMMA	89
Windows	PMMA	67
PDMs	Various	370
Target	UAr	260

DS-LowMass first configuration: activities

μBq/kg or μBq/PDM

Material	^{238}U	^{226}Rn	^{235}U	^{232}Th	^{40}K	^{60}Co	^{39}Ar
Stainless steel	2600	2600	26	1400	<3700	<650	0
PMMA	120	120	1.2	41	0	0	0
PDMs	4200	4400	0	3400	<1900	<82	0
UAr	0	0	0	0	0	0	7.3

DS-LowMass first configuration: background spectrum



DS-LowMass second configuration: what's new

- Stainless steel cryostat -> DUNE cryostat, so no background from stainless steel.

- Reduction of number of divider chain resistors from 52 to 8 per PDM; reduction of the masses of 2 order of magnitude ->strong R&D effort ongoing at LNGS

- High purity PMMA->ultra pure PMMA developed for JUNO detector

- Increase of PMMA thickness from 5 cm to 15 cm->shield against anode PDMs radioactivity

DS-LowMass second configuration: materials and components

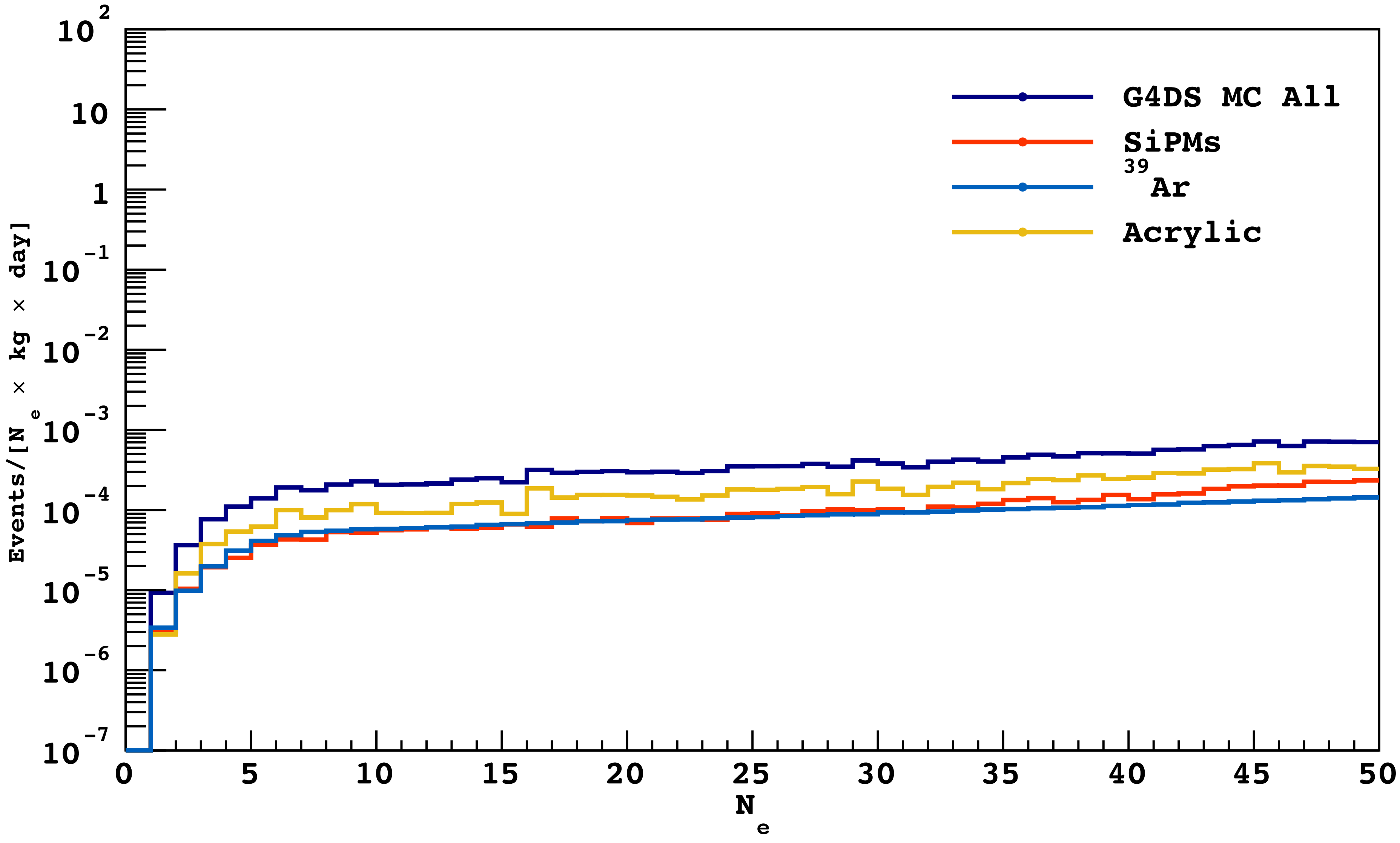
Components	Material	Mass (kg)
Reflector	PMMA	300
Windows	PMMA	310
PDMs	Various	370
Target	UAr	260

DS-LowMass second configuration: activities

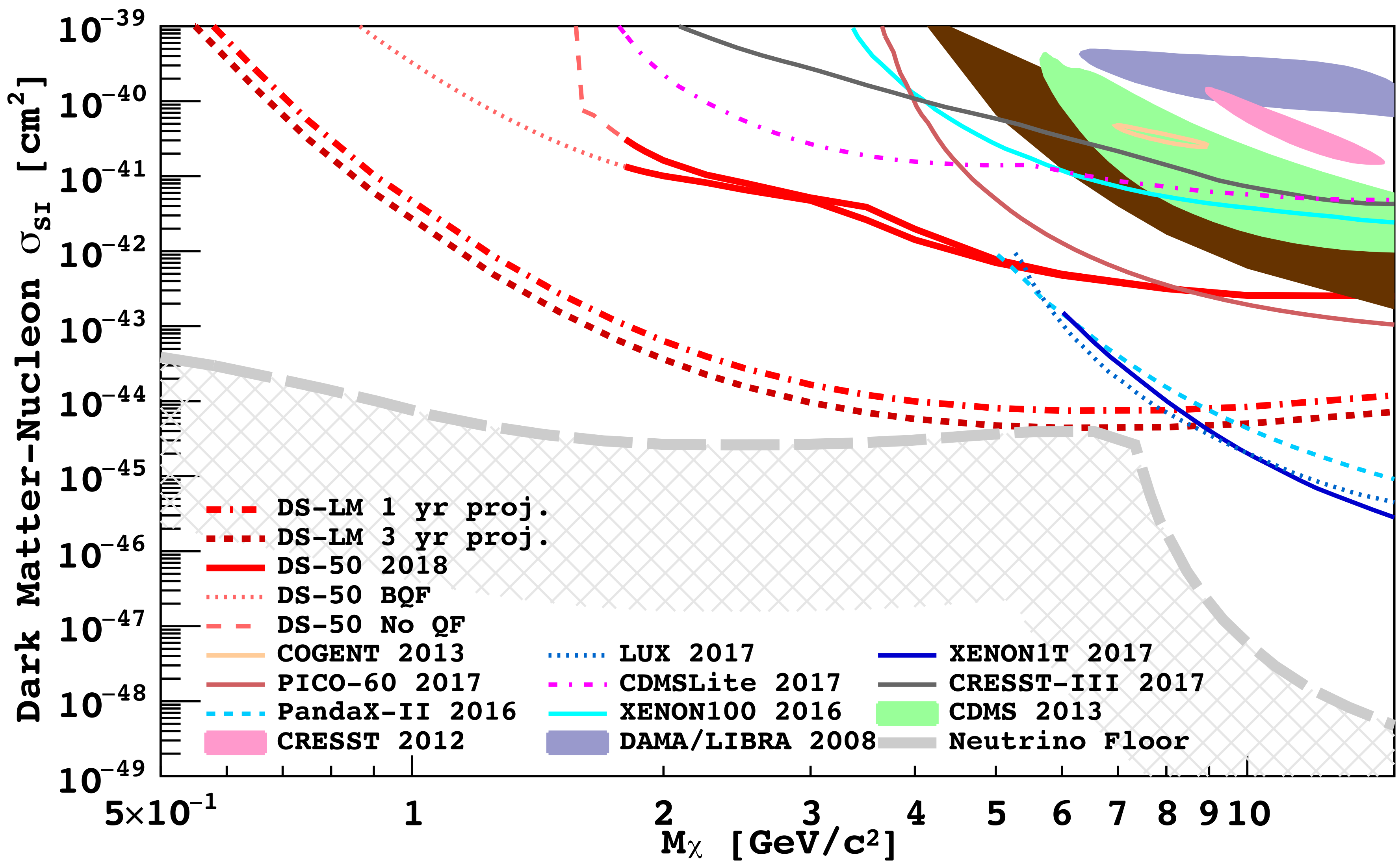
μBq/kg or μBq/PDM

Material	^{238}U	^{226}Rn	^{235}U	^{232}Th	^{40}K	^{60}Co	^{39}Ar
PMMA	3.7	3.7	0	5.3	<2600	0	0
PDMs	570	170	20	140	<360	<22	0
UAr	0	0	0	0	0	0	7.3

DS-LowMass second configuration: background spectrum



DS-LowMass sensitivity



90% C.L exclusion curves projected for 1 and 3 years of exposure. For masses below 8 GeV/c^2 can increase of about two order of magnitude the sensitivity of DS-50.

Darkside technology for neutrino-less double beta decay search

DarkNoon conceptual geometry

- The TPC LAr is an octagonal prism, 670 cm height and 175 cm side, contained in a ultra pure PMMA vessel. The thickness of PMMA is 25 cm in all directions.

- The cryostat is a DUNE-like cryostat of infinite dimensions->external background is negligible

- TPC is filled with a mixture of LAr and LXe enriched in ^{136}Xe at the level of 90%. The detector is an idealised study with a LXe mass fraction of 45%

DarkNoon materials and components

Components	Material	Mass (kg)
Vessel	PMMA	36703.8
PDMs	Various	8280
Target	^{136}Xe	74600
Target	other Xe	82888.9
Target	UAr	20000

DarkNoon activities

Material	^{238}U	^{226}Rn	^{235}U	^{232}Th	^{40}K	^{60}Co	^{39}Ar
PMMA	0.4	0.4	0	0.5	<250	0	0
PDMs	6	2	0.2	1	<4	<0.2	0
UAr	0	0	0	0	0	0	7.3

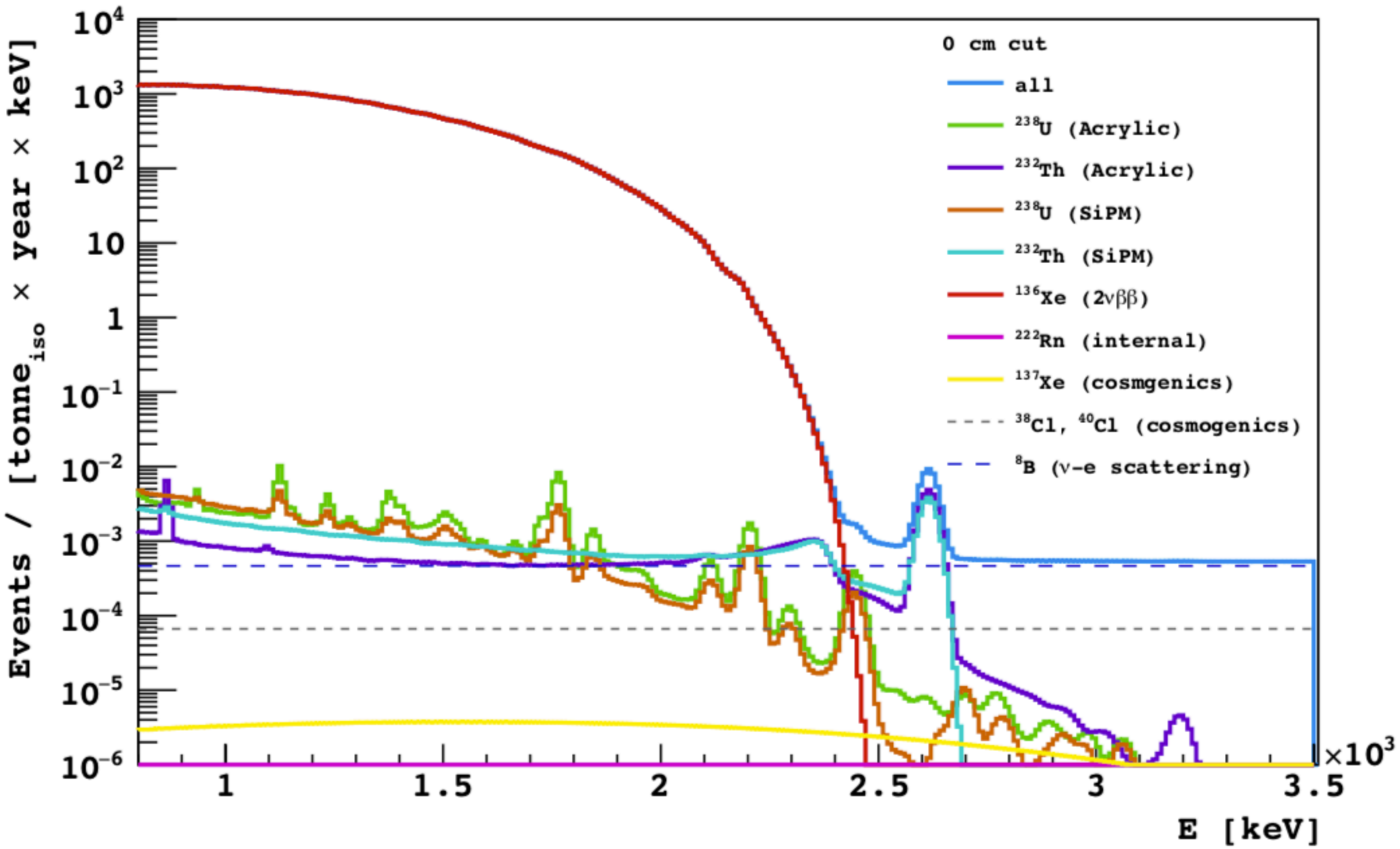
Background sources

- **Long lived nuclides**: radionuclides coming from decay chain of ^{238}U and ^{232}Th, but I considered only ^{214}Bi an ^{208}Tl
- **Cosmogenically created radionuclides**: activation of ^{137}Xe. I considered the estimation made by nEXO Collaboration at SNOLAB depth: $2.2 \times 10^{-3}/(kg\ d)$
- **Neutrino induced background**: solar neutrinos coming from 8B reaction chain produce a continuous spectrum covering the full energy range of interest.

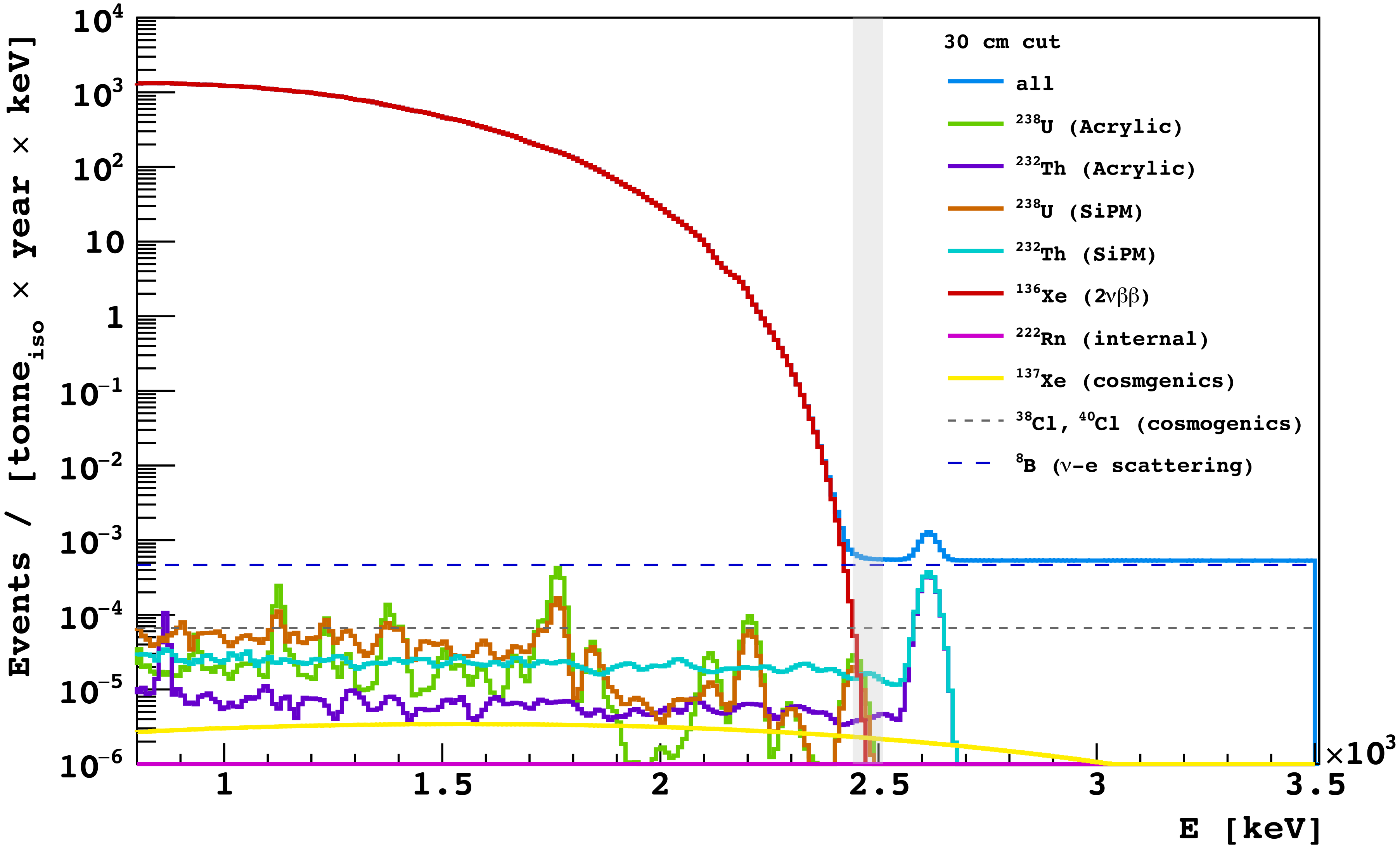
Background simulation

- Event reconstruction as for DarkSide low mass
- Application of cuts:
  - Single scatter cut
  - Fiducial cut: no fiducial cut, 30 cm, 50 cm
  - Consistency cut

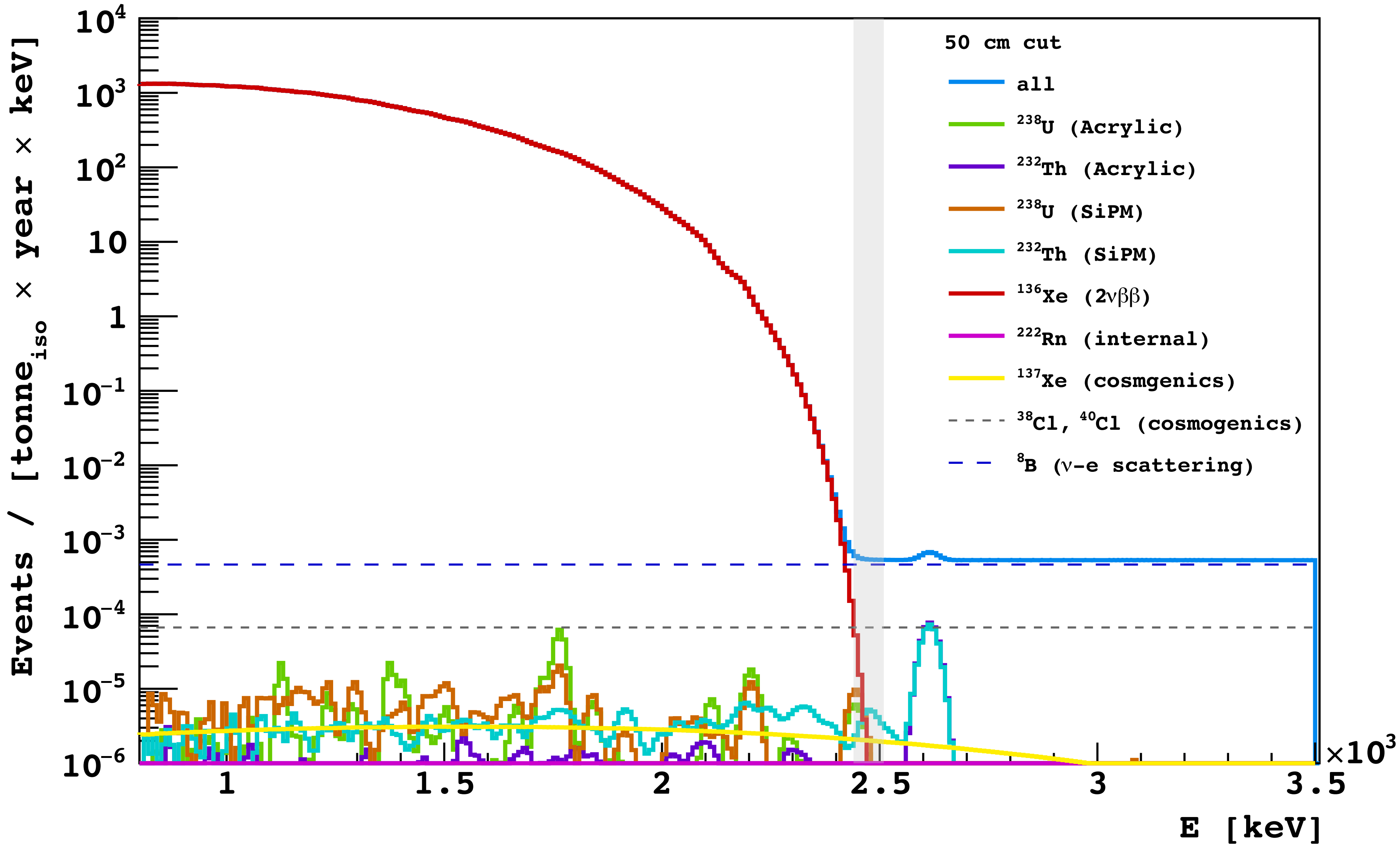
Background spectrum



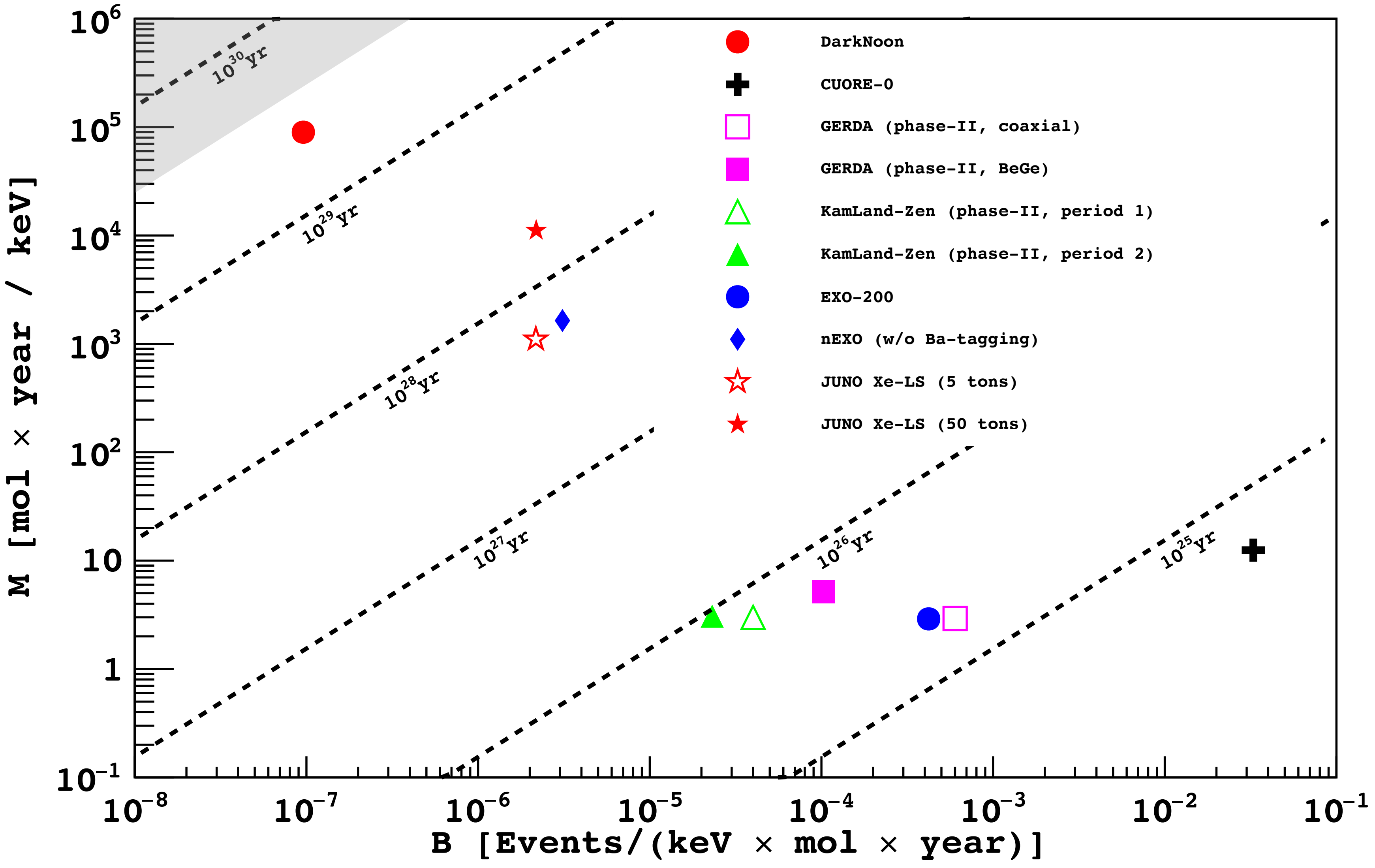
Background spectrum



Background spectrum



Physics potential



$$\left(\frac{T_{1/2}^{0\nu\beta\beta}\cdot\alpha}{ln2\cdot N_A}\right)=\frac{M_{norm}}{B_I},$$

$$B_I=\frac{b}{(M\epsilon\eta\cdot t/m_{iso})\cdot \mathrm{ROI}};\ M_{norm}=\frac{M\epsilon\eta\cdot t}{ROI\cdot M_{isotope}}$$

Cherenkov effect as background strategy

- Irriducible background due to ^{8}B neutrinos
- Single electron of double beta decay of ^{136}Xe in the ROI

↓

Cherenkov effect

Cherenkov effect as background strategy

- Cherenkov light has UV to visible photon emission
- Directionality correlated to the direction of the primary beta track
- Photon number proportional to the primary beta track length

Simulation strategy

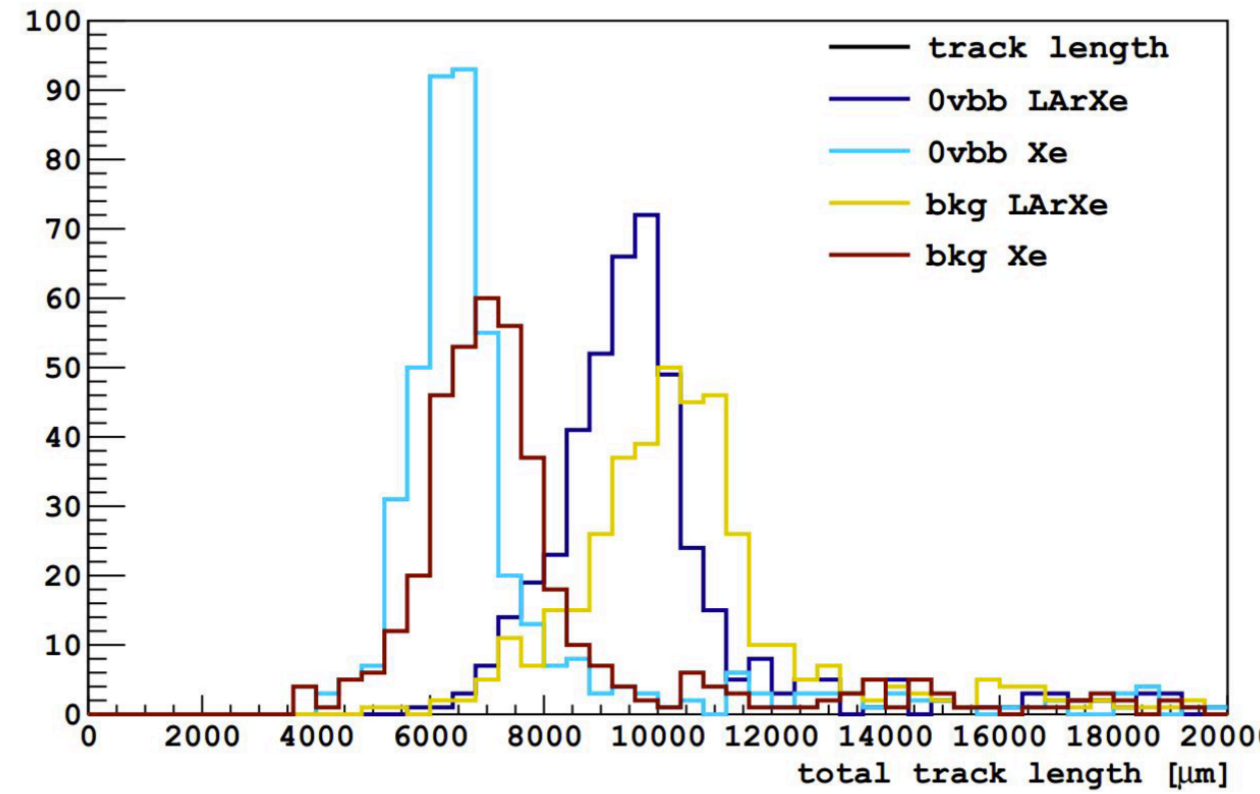
1. Single beta events of energy of 2.5 MeV and 0nubb of ^{136}Xe are produced in the mixture of LAr-LXe (80%-20% molar mass) and in pure LXe

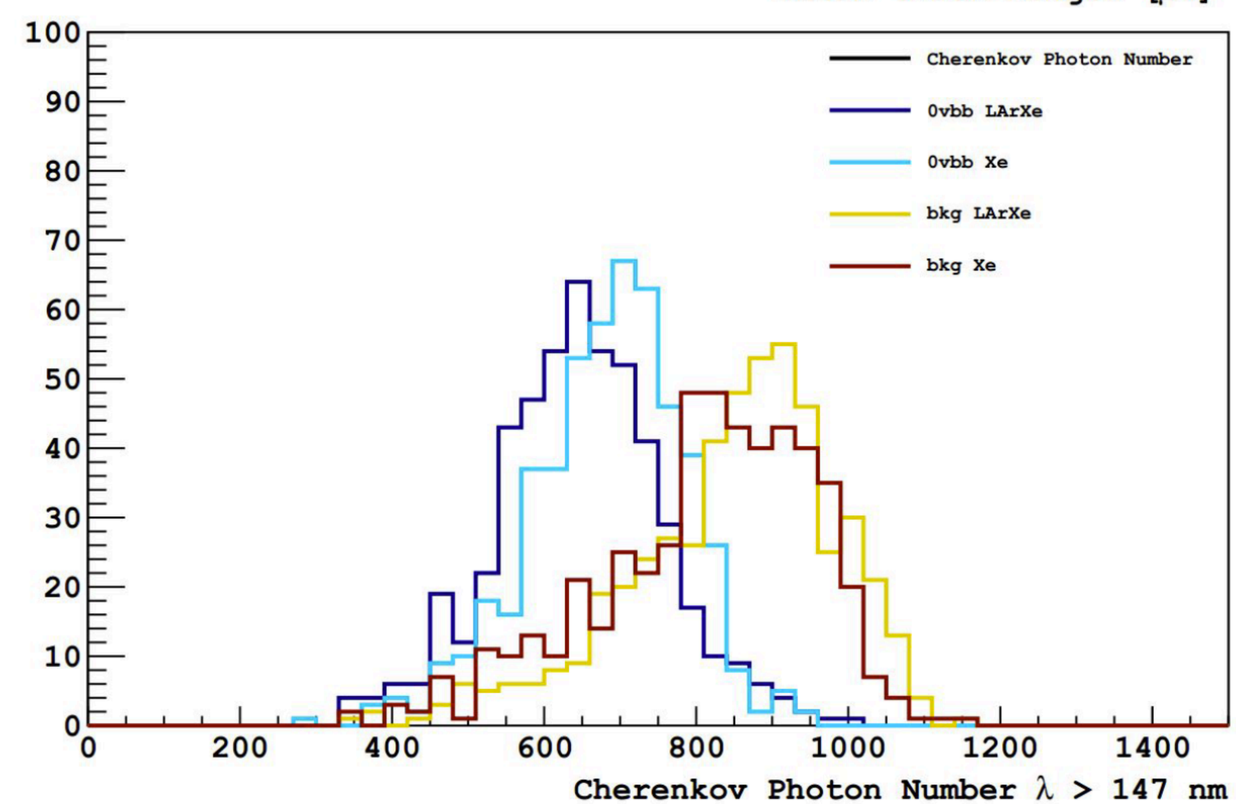
2. Starting from the generated electrons I generate photons according to $\frac{d^2E}{dxd\omega} = \frac{q^2}{4\pi}\mu(\omega)\omega\left(1 - \frac{c^2}{v^2n^2(\omega)}\right)$

3. I assume that the refractive index is constant from 200 to 800 nm

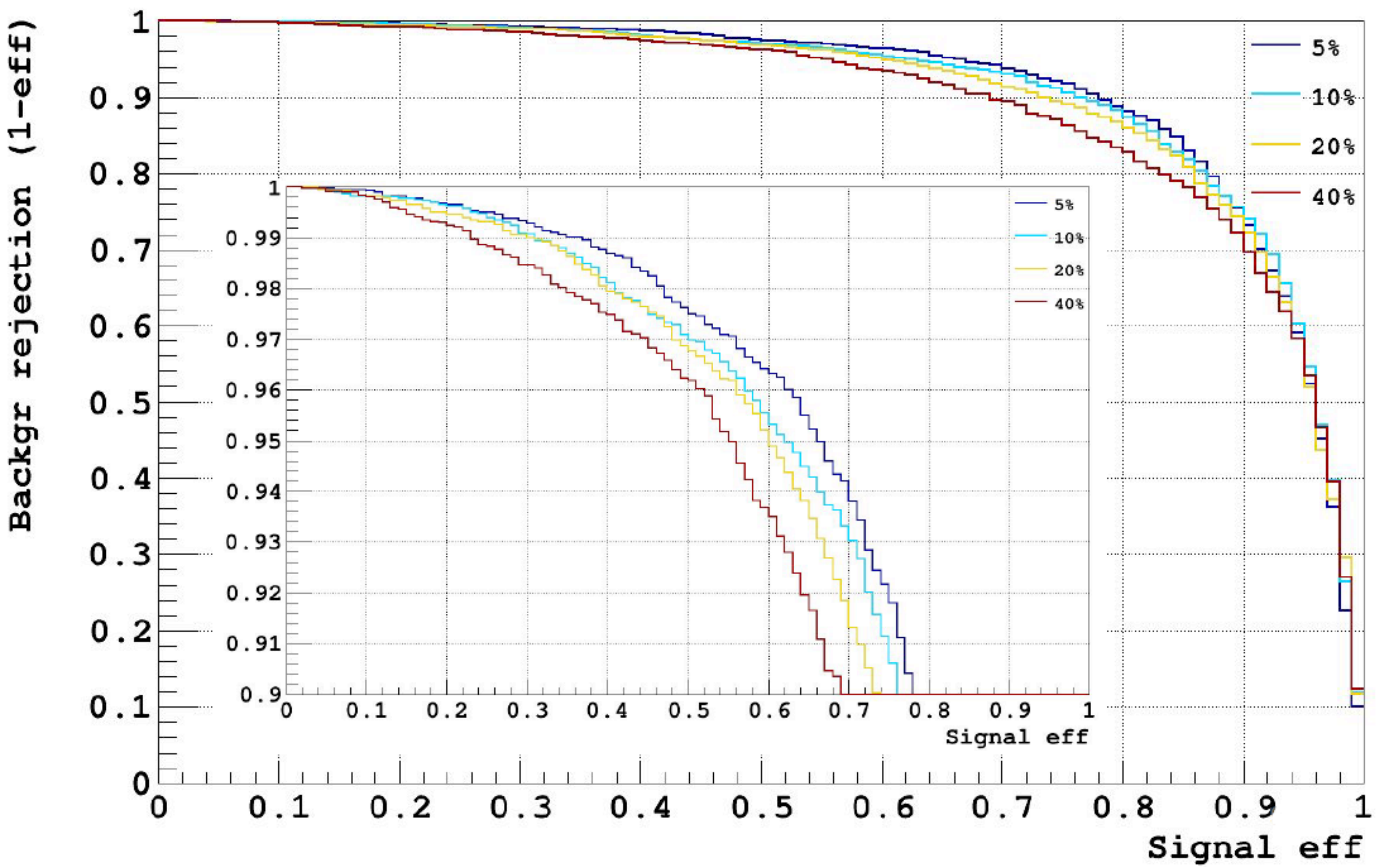
Simulation results

- The track length of single and double beta particles in pure LXe is shorter than in the mixture of LAr-LXe.
- The LAr-LXe mixture gives a better discrimination in Cherenkov photon number.



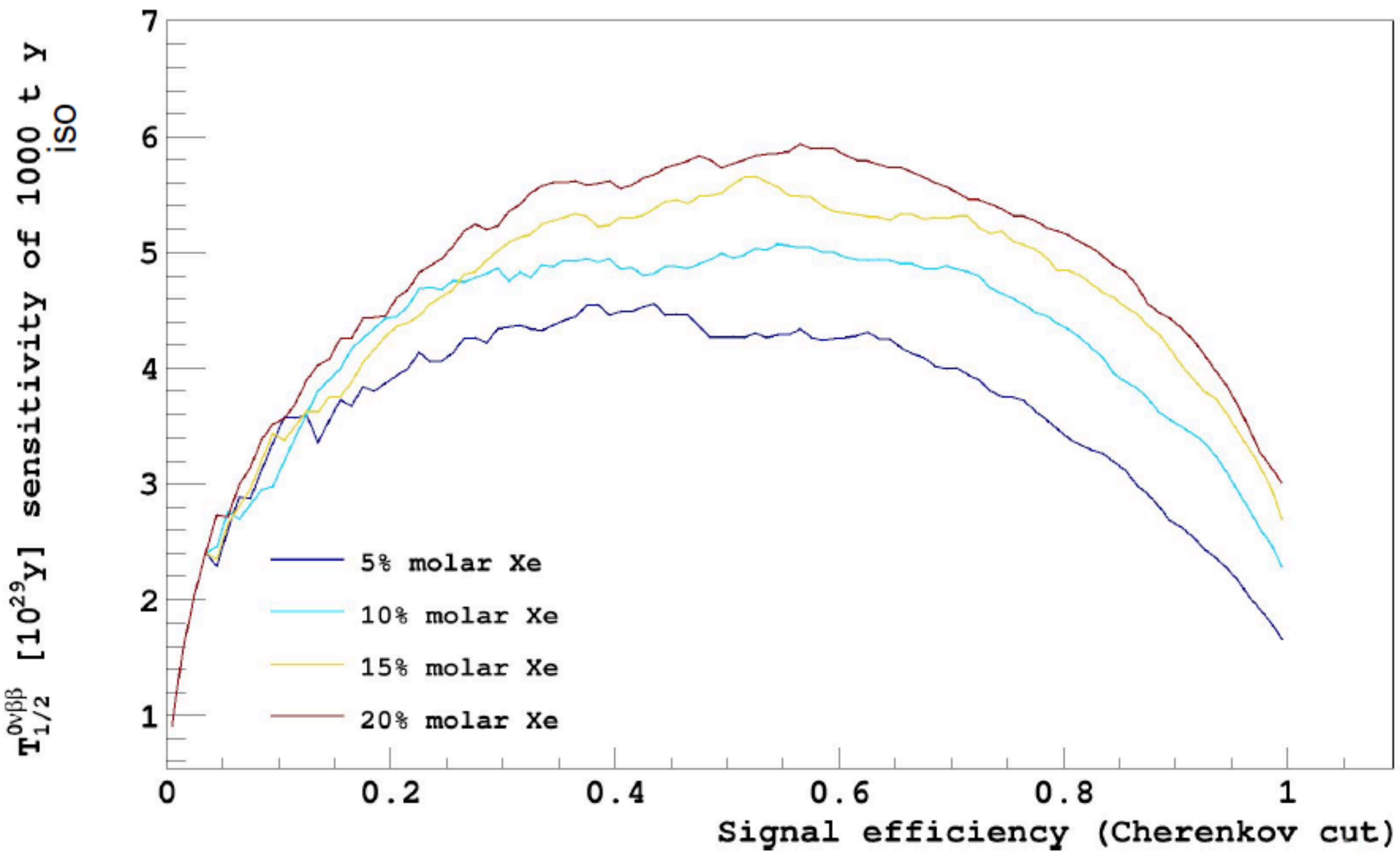


Cut efficiency at different Xe concentration in LAr-LXe



A 5% concentration of Xe in the mixture of LAr-LXe performs the best signal efficiency and rejection background

The sensitivity vs Efficiency of Cherenkov cut



Maximum sensitivity at 20% molar Xe, but also a 15% molar mass of Xe is comparable

Result

Taking into account the reached sensitivity and imagining to increase the exposure to 1000 $tonne_{iso}$ y