# Cherenkov background in DS-20k

## DarkSide CPPM meeting

**From my master's thesis in Rome – Sapienza University (here)**

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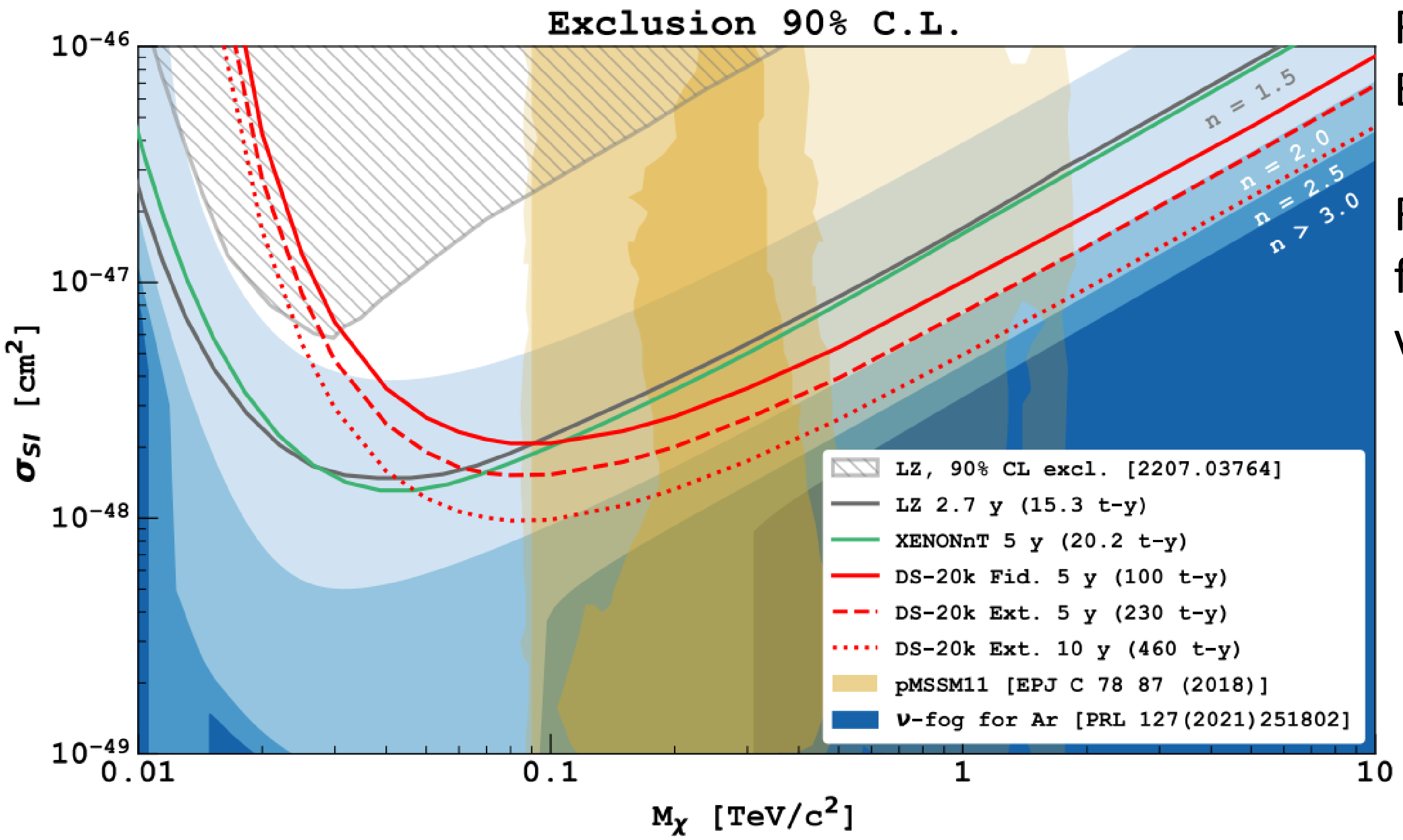
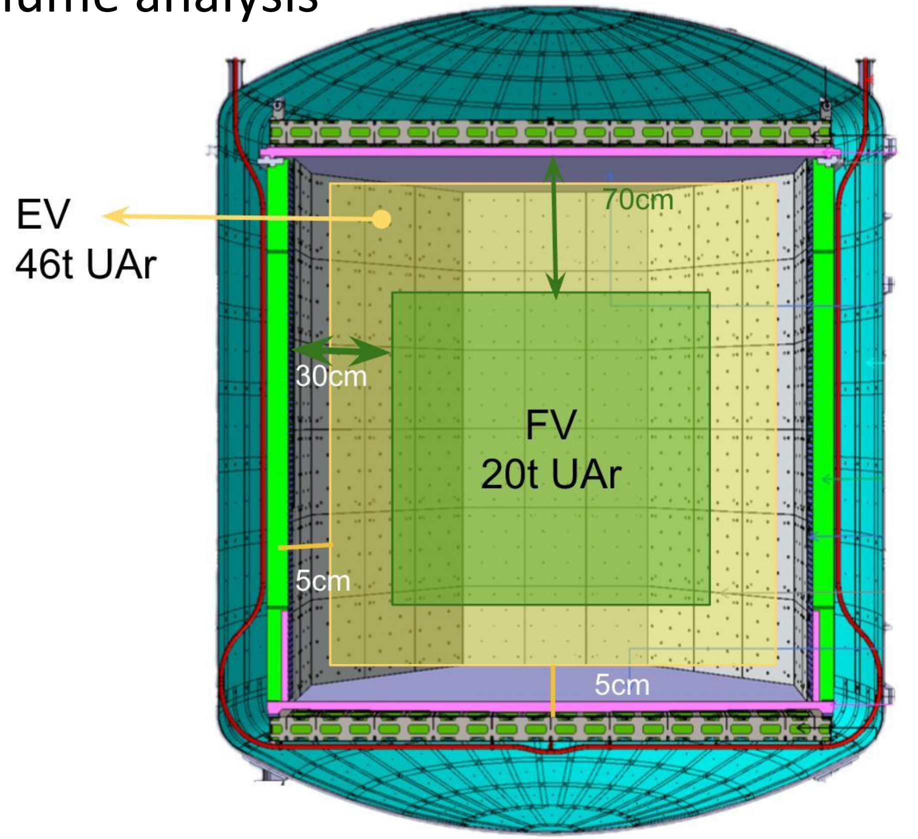
# DarkSide-20k high mass sensitivity




Fiducial volume: 20 tons

Extended volume: 46 tons

Fiducial volume analysis is “background-free” but less sensitive w.r.t. extended volume analysis



# Background

BACKGROUND SOURCES:

1. Nuclear recoils
   - Neutrons (radiogenic, cosmogenic or from $(\alpha, n)$ reactions)
   - Neutrinos (CEνNS from atmospheric $\nu$)
2. Electron recoils
   - γ-rays (from bulk of materials)
   - $^{39}\mathrm{Ar}$
3. **Outliers**
   - Random coincidence between $\alpha$ and unresolved S1+S2
   - **Cherenkov**

REJECTION TOOLS

Fiducialization

Irreducible bkg

PSD (see next slide)

PSD + use of UAr

Fiducialization + algorithms (?)

Fiducialization + algorithms (?)

Background budget:

- Fiducial volume: 0.1 n in 10 y (+ 3.2 $\nu$)
- Extended volume: 12.8 n in 10 y (+ 7.4 $\nu$)

⚠ Factor $\sim$ 3 increase without Gd-PMMA

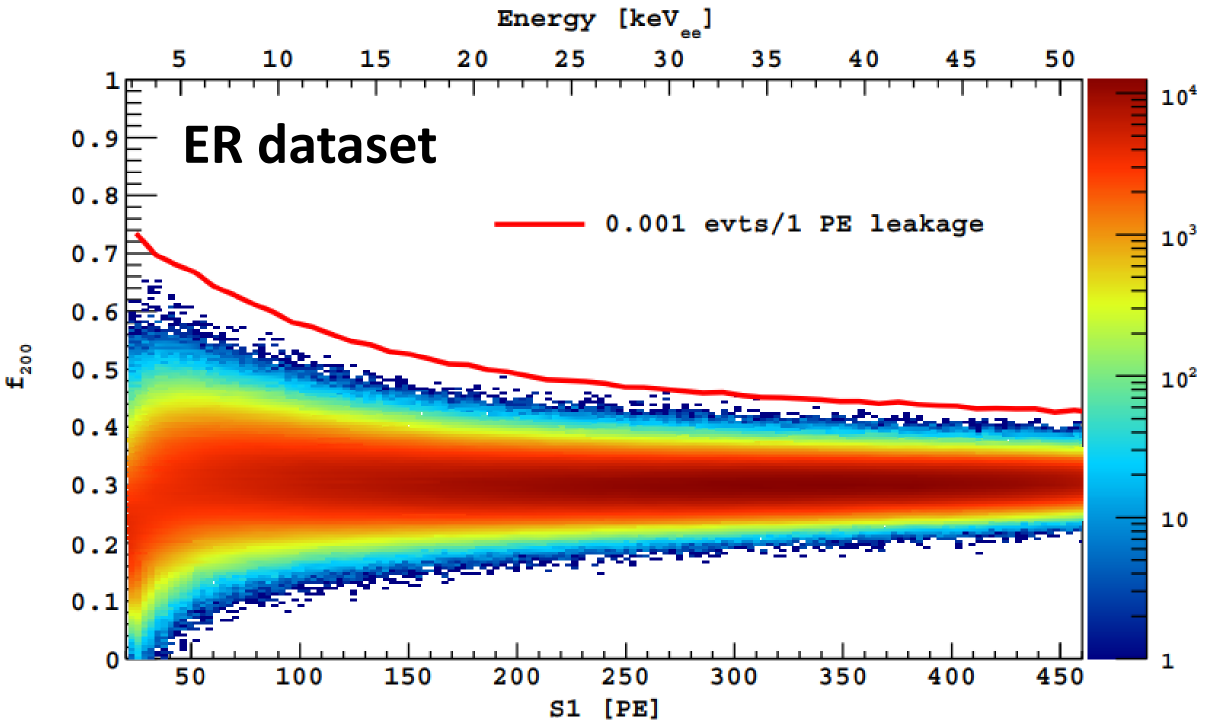
# Background rejection

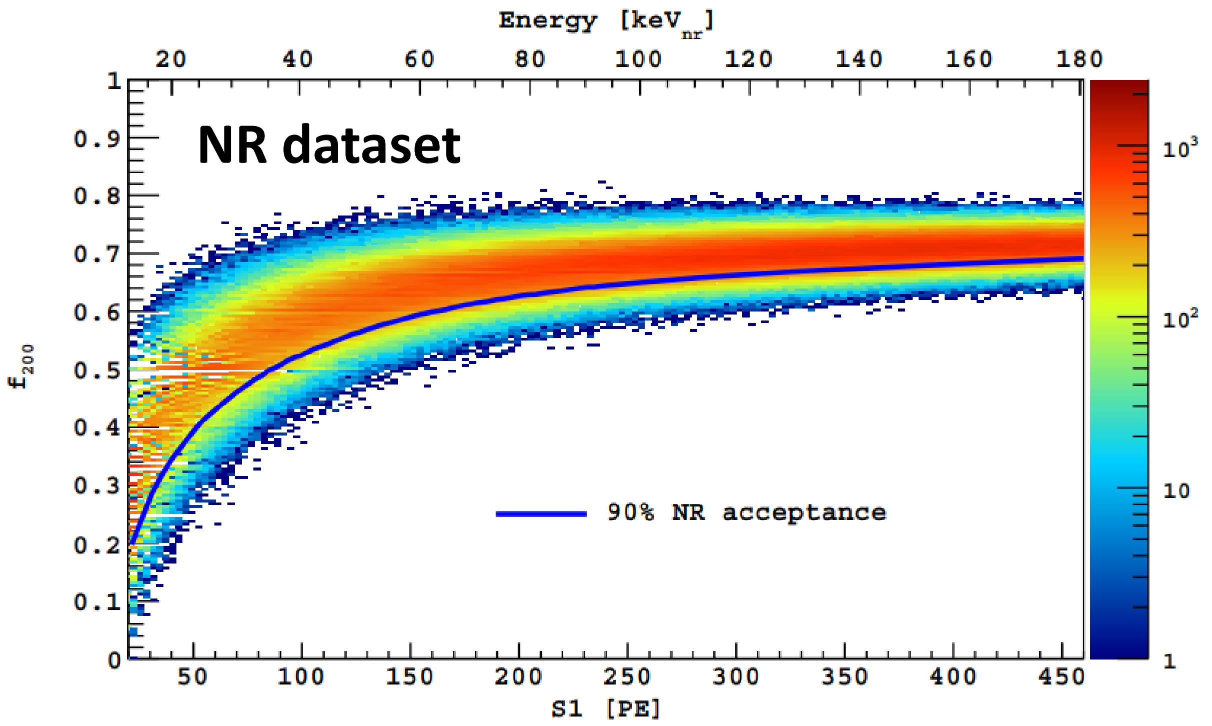
**Pulse Shape Discrimination (PSD):**

Singlet-to-triplet state ratio in excited dimer $Ar_2^*$ : 0.7 for NRs and 0.3 for ERs.

PSD variable: $f_{200} = \frac{\text{S1 in 200 ns}}{\text{S1}}$

Rejection power $10^9$

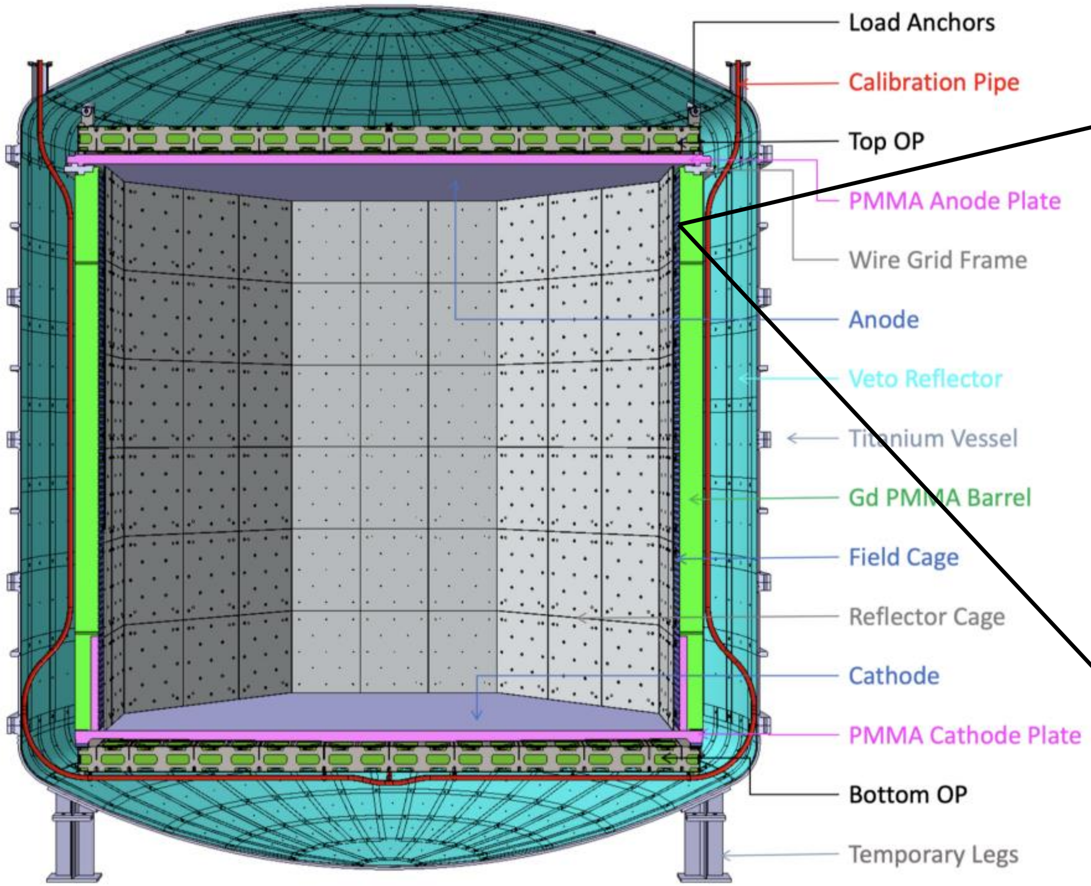



PE = photoelectron

Light yield: 10 PE/keVee released

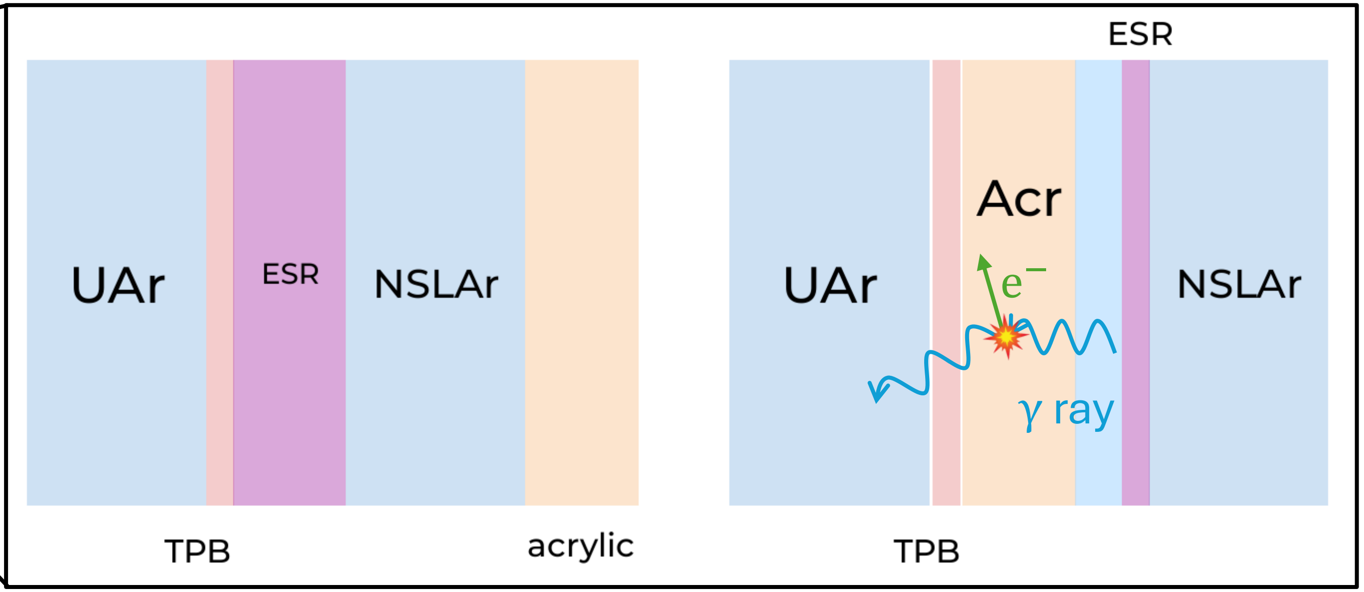
# TPC walls




Major activities from Gd-PMMA and SiPMs

Baseline configuration (current design)

Alternative configuration **(this simulation)**

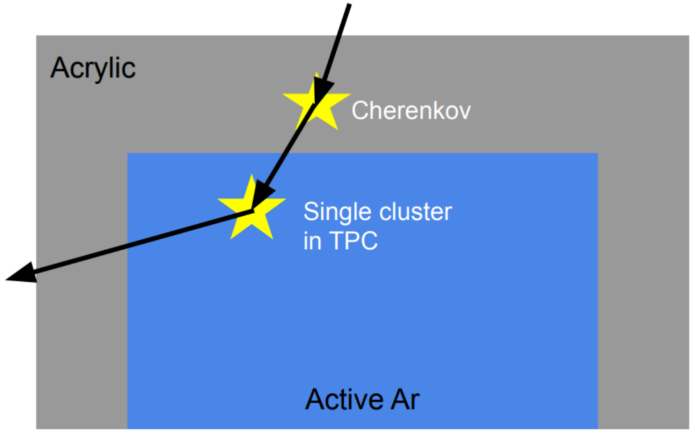



This design may suffer from **α emissions** due to Rn decay products depositing on ESR

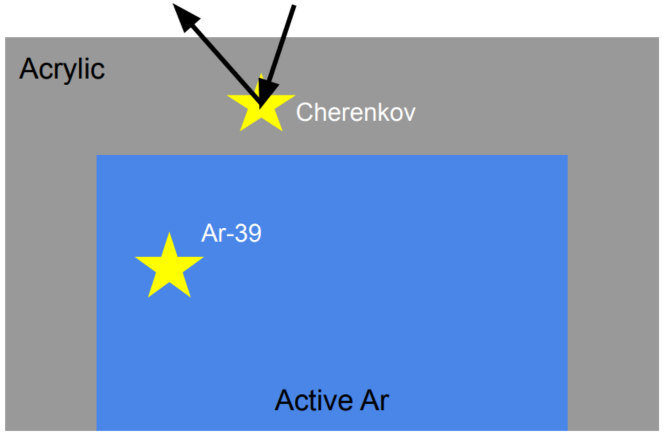
Swap ESR and acrylic to reduce α emissions. γ rays scattering on acrylic produce fast electrons that produce **Cherenkov**

# Cherenkov background in DarkSide-20k

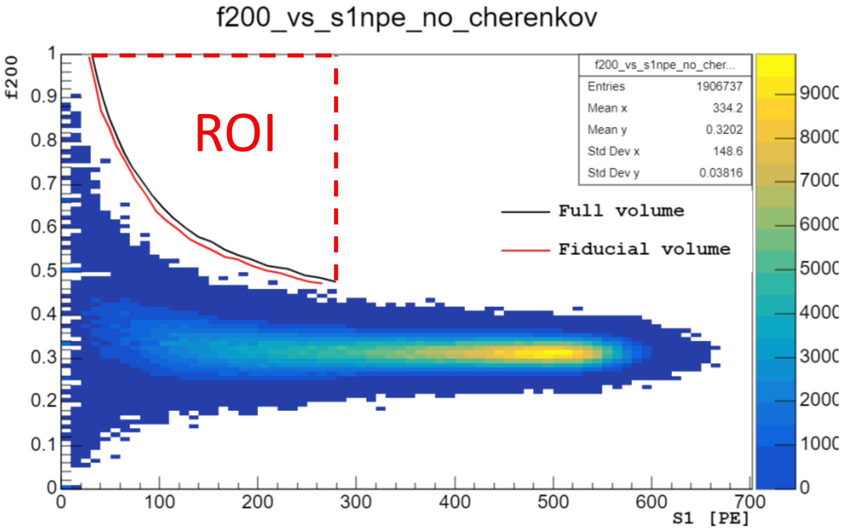
## 1. Cherenkov + single cluster

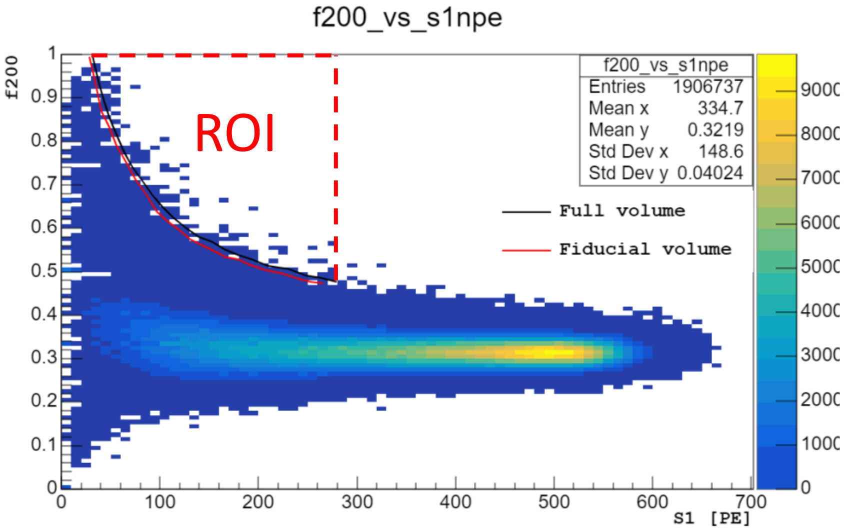



## 2. Cherenkov + $^{39}Ar$ pile-up




Dangerous background only if the electron emits Cherenkov radiation in the acrylic;
In LAr it would lose all its energy, leaving a signal too large for a WIMP




Leakage curves built with a **pure scintillation dataset** of $^{39}Ar$

Plot for single cluster topology

**ER events surpassing PSD due to Cherenkov boost to $f_{200}$**

# Background estimate from MonteCarlo

Bigger Cherenkov contributors due to high-energy γ rate and overall activity: $^{232}\mathrm{Th}$ and $^{40}\mathrm{K}$

1. SINGLE CLUSTER TOPOLOGY

   ROI events predicted (conservative estimate) in 10 y for fiducial volume analysis:

   - $^{232}\mathrm{Th}$: $(2.4 \pm 1.2) \times 10^{-3}$
   - $^{40}\mathrm{K}$: $(7.7 \pm 8.6) \times 10^{-4}$

   **Negligible w.r.t. neutrons**

   ROI events predicted (from MC counting) in 10 y for extended volume analysis:

   - $^{232}\mathrm{Th}$: $29.0 \pm 20.5$
   - $^{40}\mathrm{K}$: $0.56 \pm 0.72$

   **Comparable with neutrons**

⚠ g4ds10 data (old detector configuration)

2. PILE-UP TOPOLOGY

   ROI events predicted (from MC counting) in 10 y for $^{232}\mathrm{Th}$ :

   - Fiducial volume: $(8.53 \pm 0.58) \times 10^{-3}$
   - Extended volume: $(5.67 \pm 0.48) \times 10^{-2}$

   **Negligible w.r.t. neutrons**

# Mitigation strategy

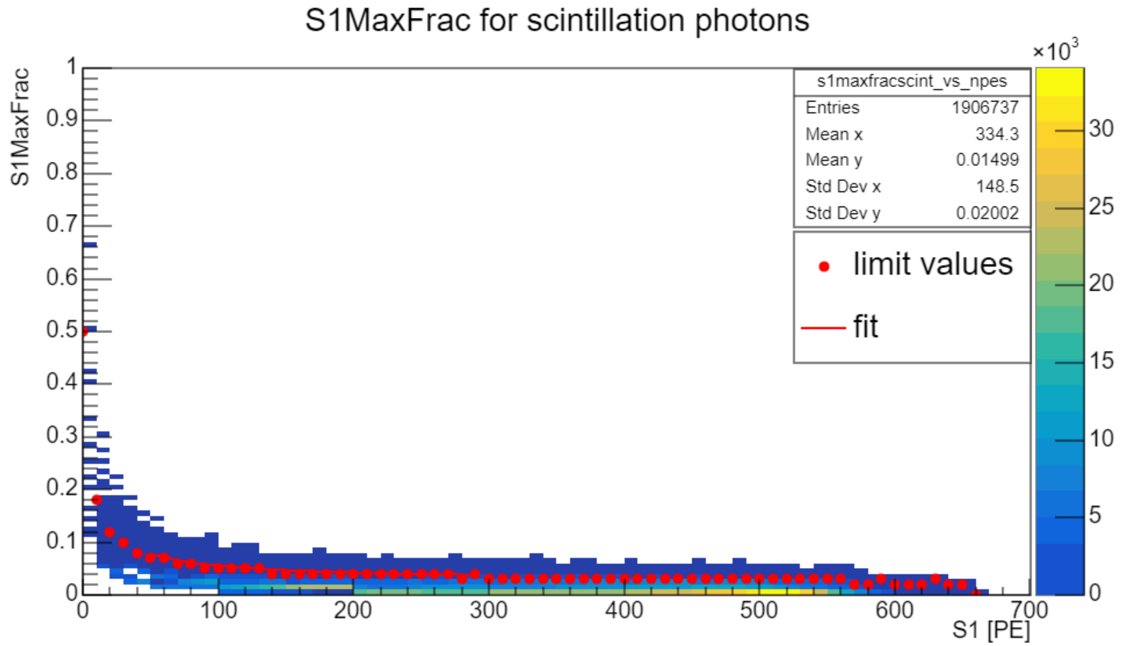
Cherenkov photons are emitted in a cone of light, whereas scintillation photons are emitted isotropically.
The presence of clusters can be described by:

$$\text{S1MaxFrac} = \frac{\text{PEs in the most hit channel}}{\text{PEs total}}$$

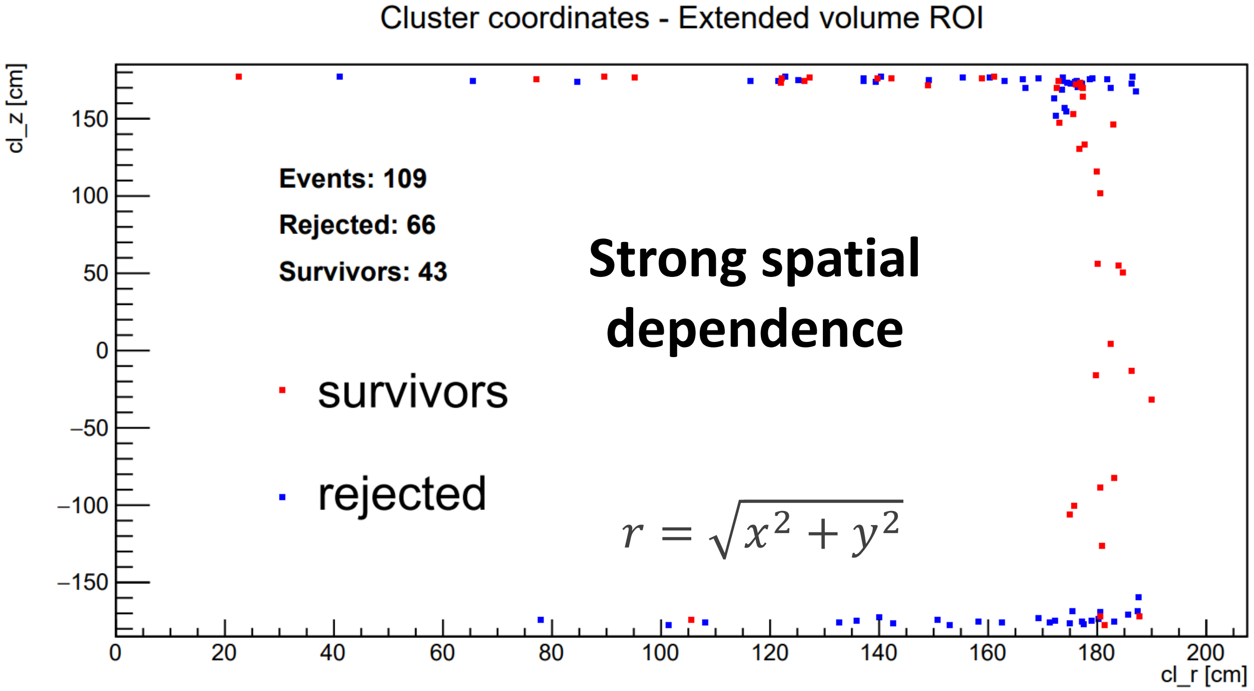
Already used in DS-50!

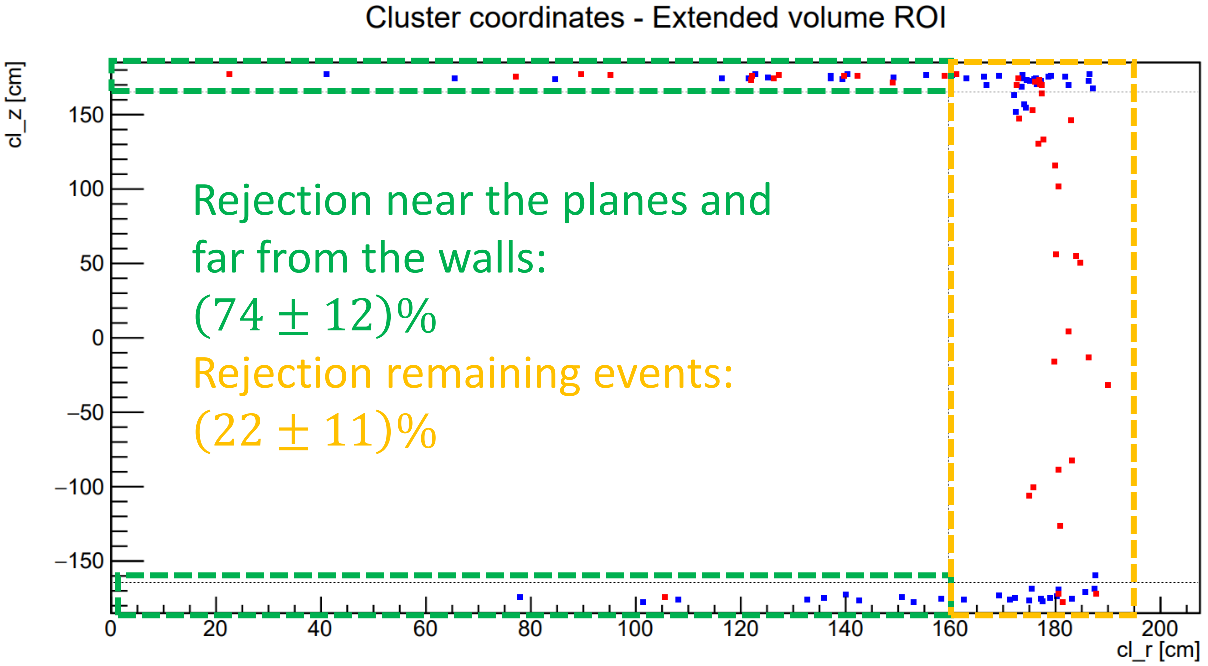
Strategy:

1. Build S1MaxFrac vs S1 without Cherenkov
2. For each S1 bin, determine the S1MaxFrac limit value that contains 99% of the signal
3. Hyperbolic fit: $f_{th}(S1) = \frac{p_0}{S1+p_1} + p_2$ in the range 50 PE < S1 < 290 PE
4. Events with S1MaxFrac > $f_{th}(S1)$ are rejected

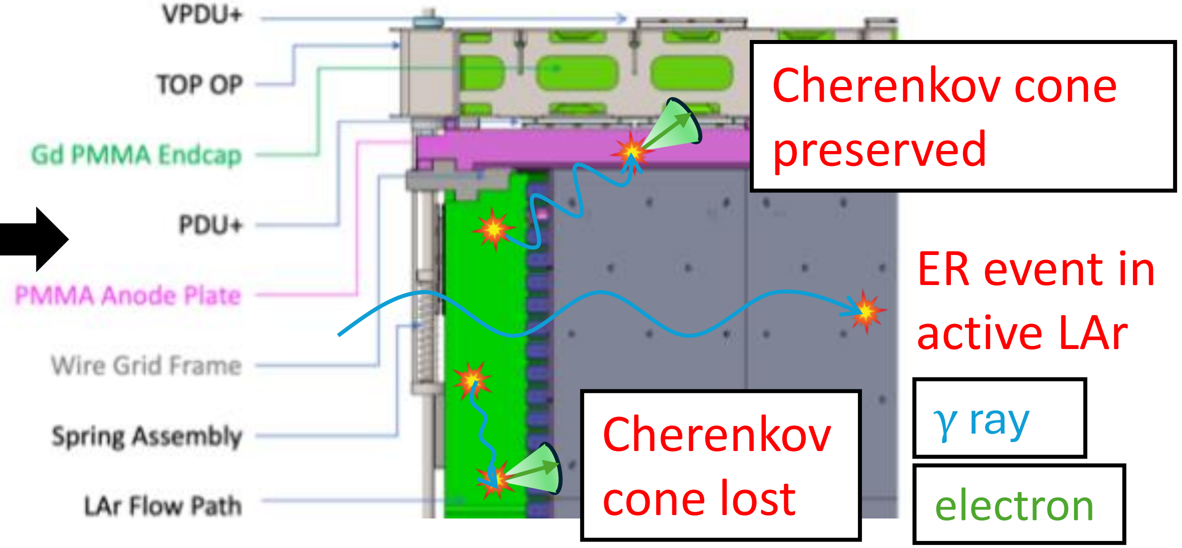


# Rejection results (1/2)




Rejection favoured when Cherenkov cone is emitted towards SiPMs → geometrical constraint on $\gamma$



# Rejection results (2/2)

Fraction of rejected events (after PSD):

- Fiducial volume analysis: $(59.1 \pm 7.6)\%$ for single cluster, $(92.2 \pm 9.0)\%$ for $^{39}$Ar pile-up
- Extended volume analysis: $(\mathbf{60.5 \pm 9.4})\%$ for single cluster, $(\mathbf{93.4 \pm 11.7})\%$ for $^{39}$Ar pile-up

Background events after PSD and S1MaxFrac cut:

**Fiducial volume $(\mathbf{1.7 \pm 0.9}) \times \mathbf{10^{-3}}$ events in 10 years**

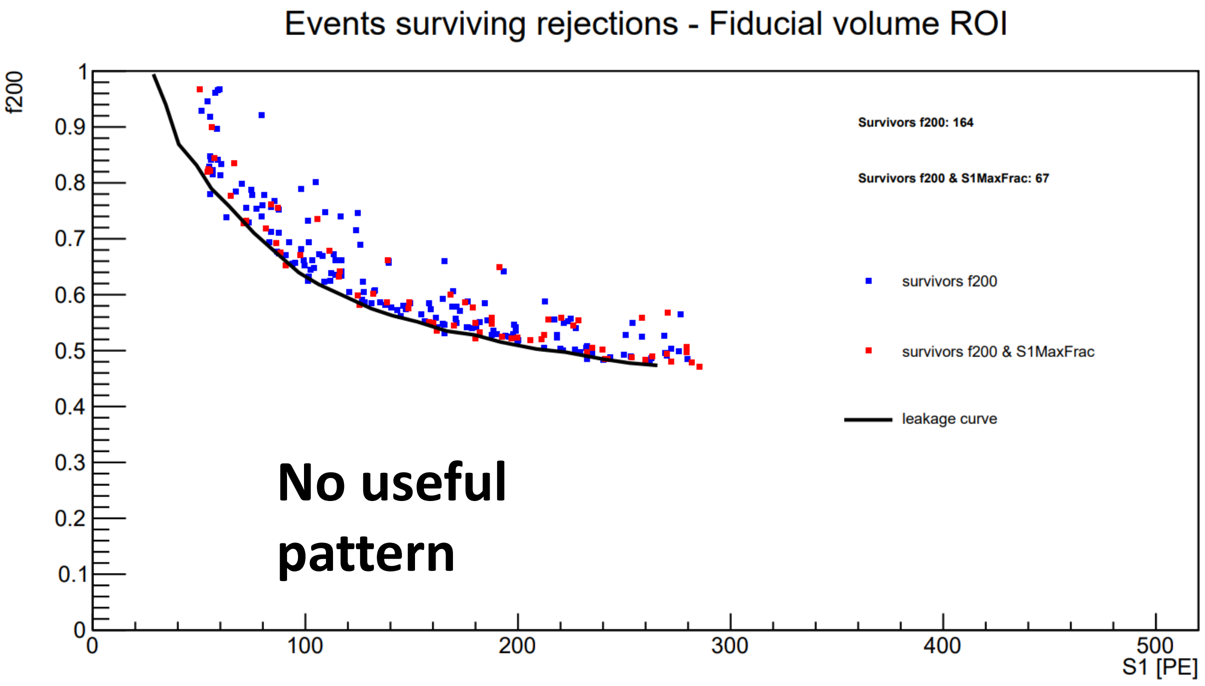
**Extended volume $(\mathbf{11.5 \pm 8.5})$ events in 10 years**

REJECTION NOT SUFFICIENT

Baseline configuration

Redefinition of extended volume?

Redefinition of leakage curves?



# Next steps

**Future simulations are needed** to update the sensitivity curve. They should have:

- **More statistics** to reduce fluctuations and to build signal efficiency vs rejection power curves (here the signal efficiency was fixed to 99%)
- **Updated geometry** (baseline configuration for the TPC walls to decrease significantly Cherenkov background and g4ds11 update)
- Other **major Cherenkov sources**, such as SiPMs
- Readout planes **noise effects**

# Thanks for your attention

# BACKUP SLIDES

# WIMPs search

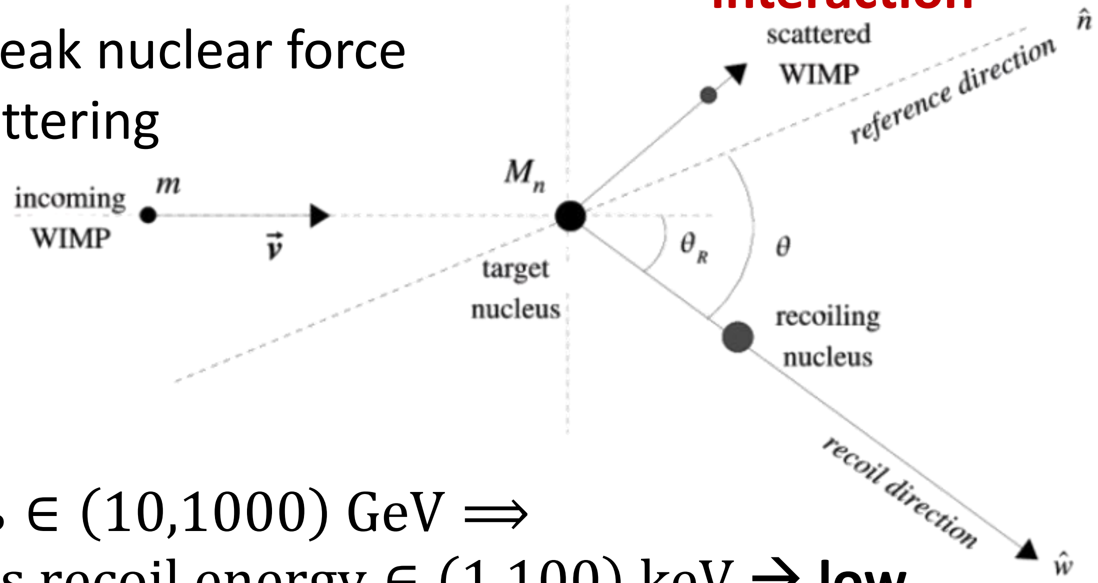


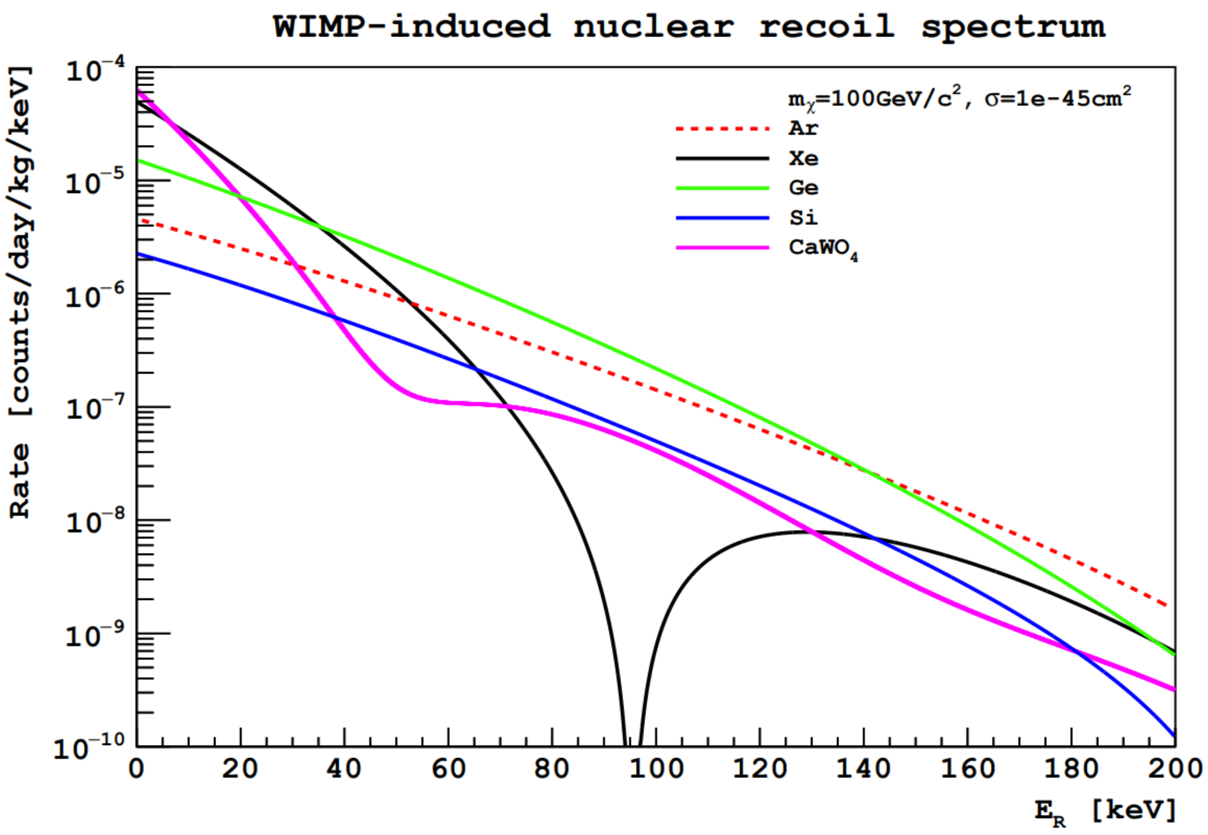
Several DM evidences: rotation curves of spiral galaxies, Bullet Cluster, CMB's power spectrum etc.

**Weakly Interacting Massive Particles (WIMPs):** One of main DM particle candidates

- Broad mass range: sub-GeV to tens of TeV
- Interactions: gravity and any as weak (or weaker) than weak nuclear force
- Direct detection: WIMP-OM nucleus coherent elastic scattering

**WIMP-nucleus interaction**



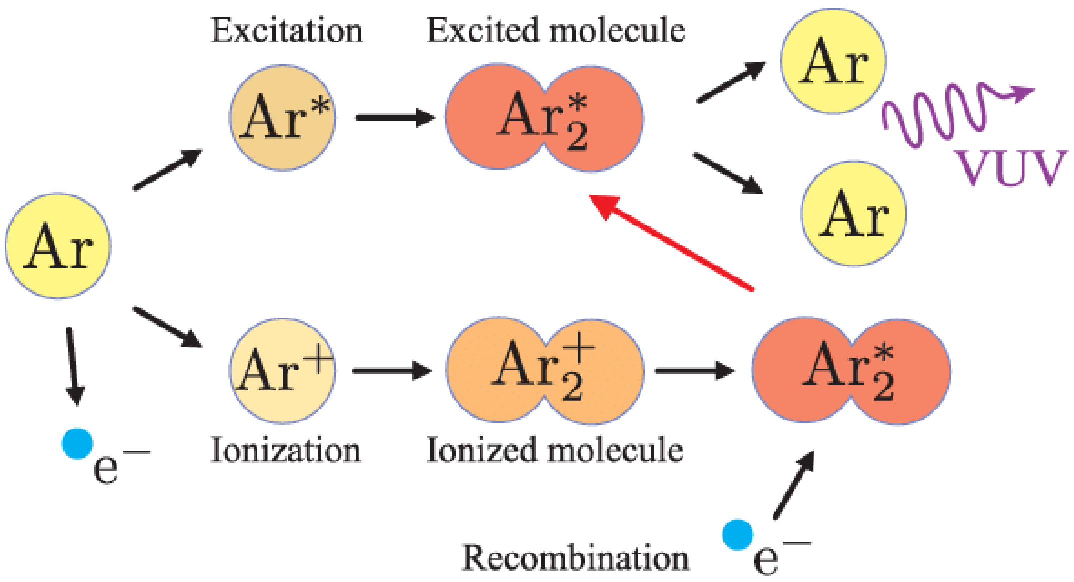




$m_{WIMP} \in (10,1000)$ GeV $\Longrightarrow$
nucleus recoil energy $\in (1,100)$ keV → **low energy threshold needed!**

Low rate → **low background needed!**

Rate depending on the WIMP velocity distribution (plot based on Standard Halo Model)

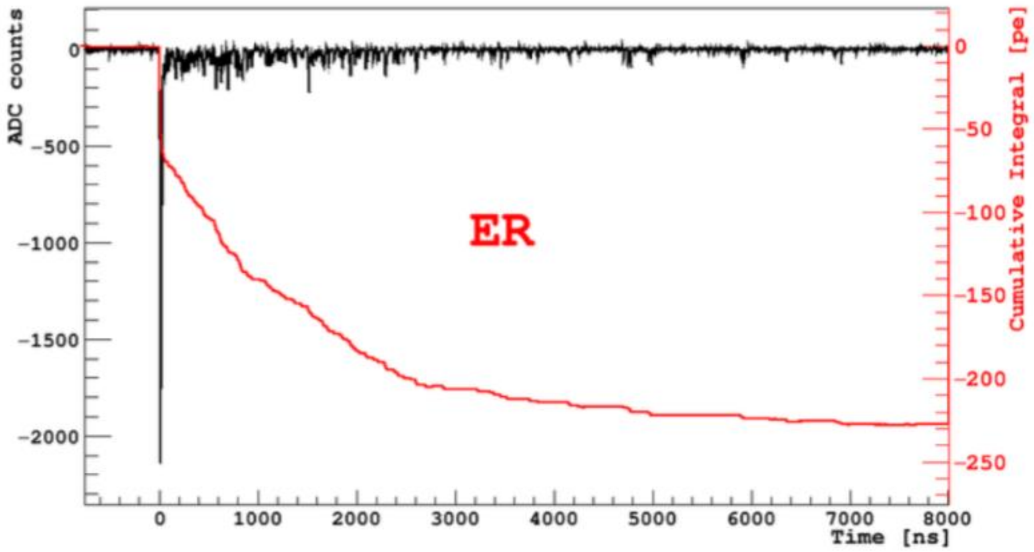
# Liquid argon properties

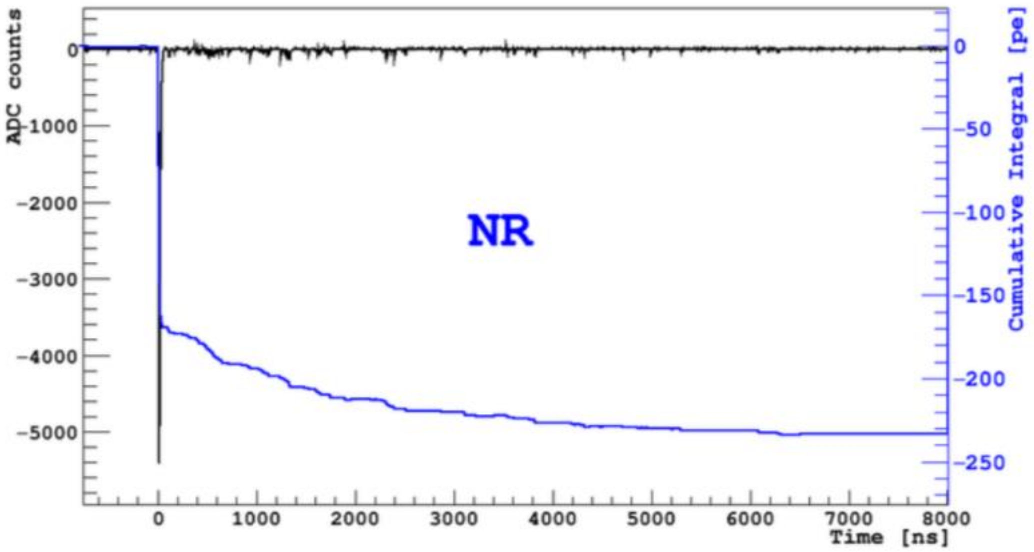



The excited dimer $Ar_2^*$ exists in 2 states:

- Singlet $^1\Sigma_u^1$ state, $\tau \simeq 7$ ns
- Triplet $^3\Sigma_u^1$ state, $\tau \simeq 1.3$ μs

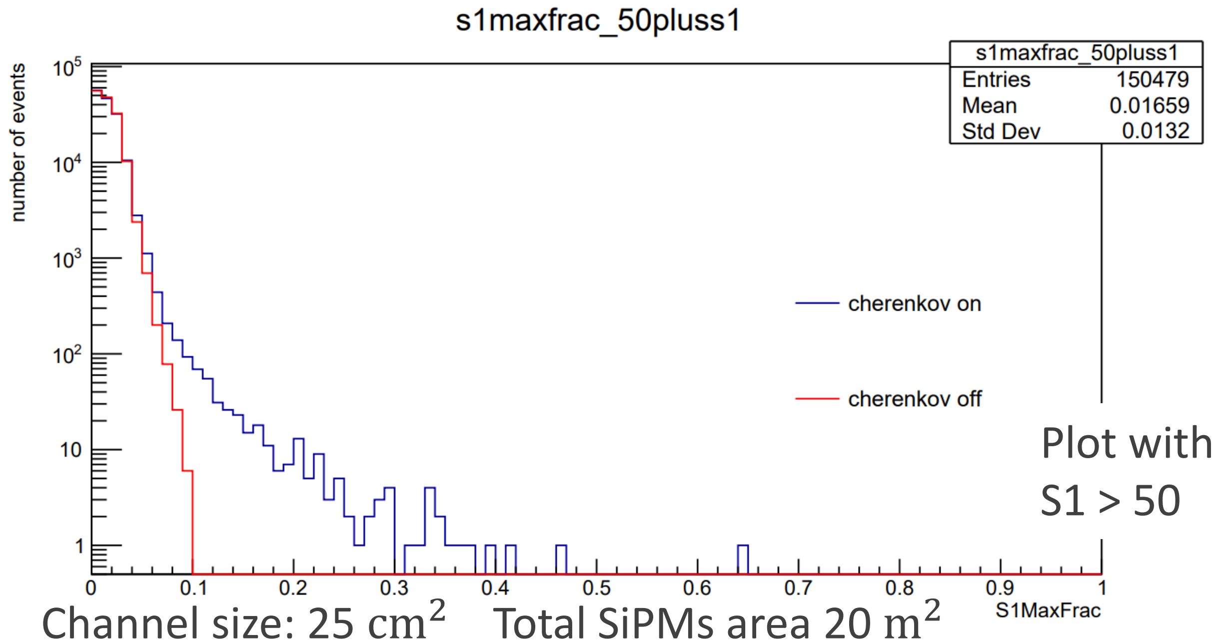
Singlet-to-triplet ratio: $\sim 0.7$ for NRs and $\sim 0.3$ ERs
It allows **Pulse Shape Discrimination** (PSD)



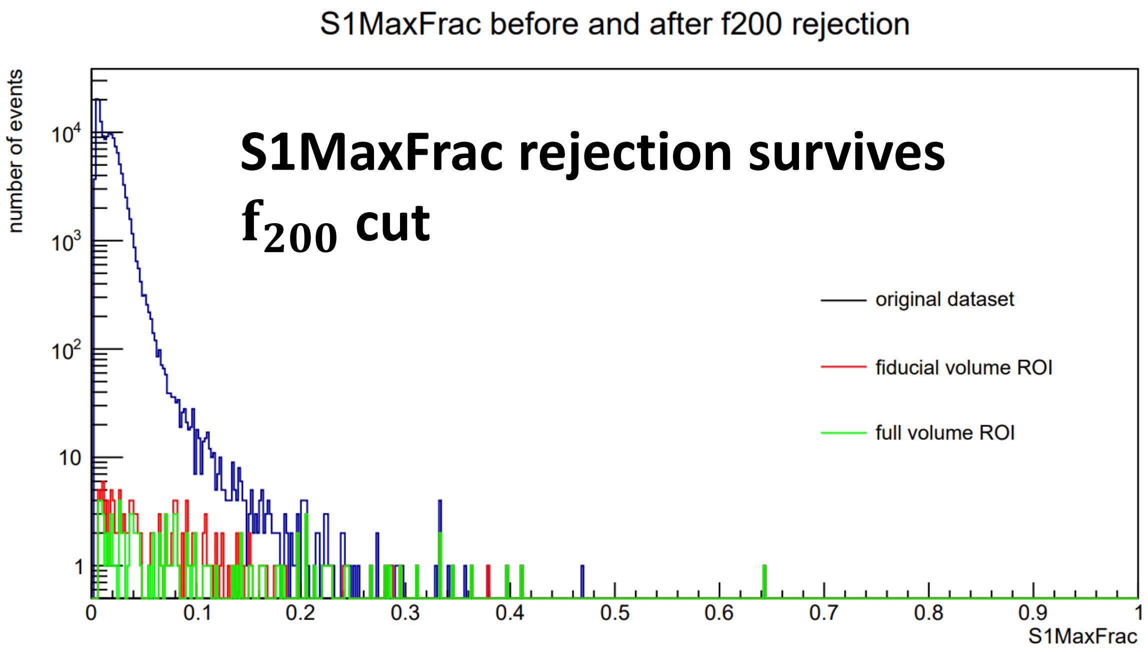

Scintillation waveforms in LAr for nuclear and electron recoils. The solid colored lines represent the cumulative integral

# S1MaxFrac plots




Plot with S1 > 50

Channel size: 25 $cm^2$ Total SiPMs area 20 $m^2$



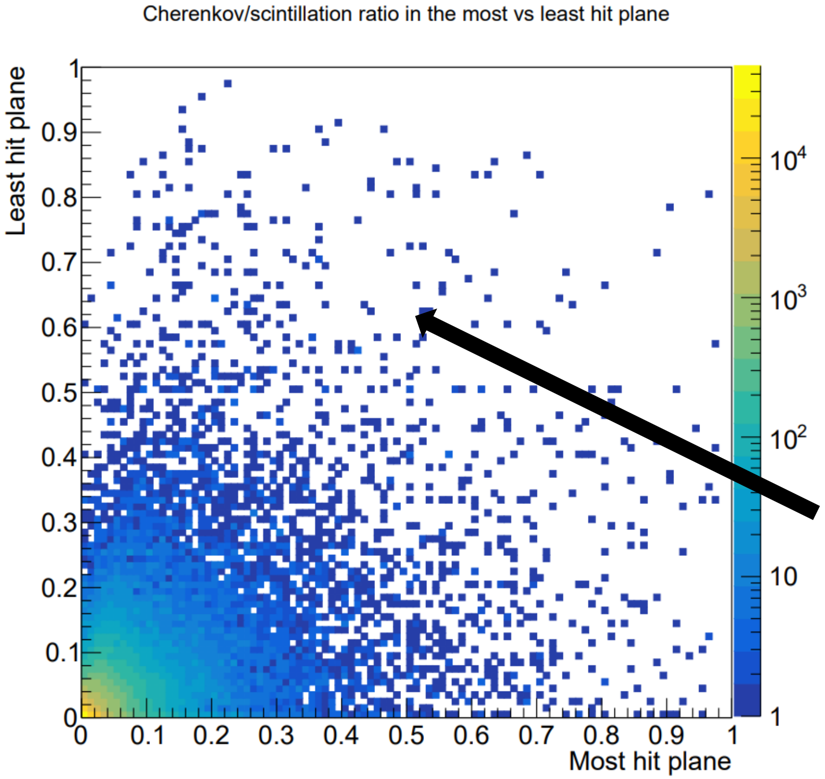

**S1MaxFrac rejection survives $f_{200}$ cut**

# Efforts for improvement (1/2)

**1. Distinguish the optical planes**:

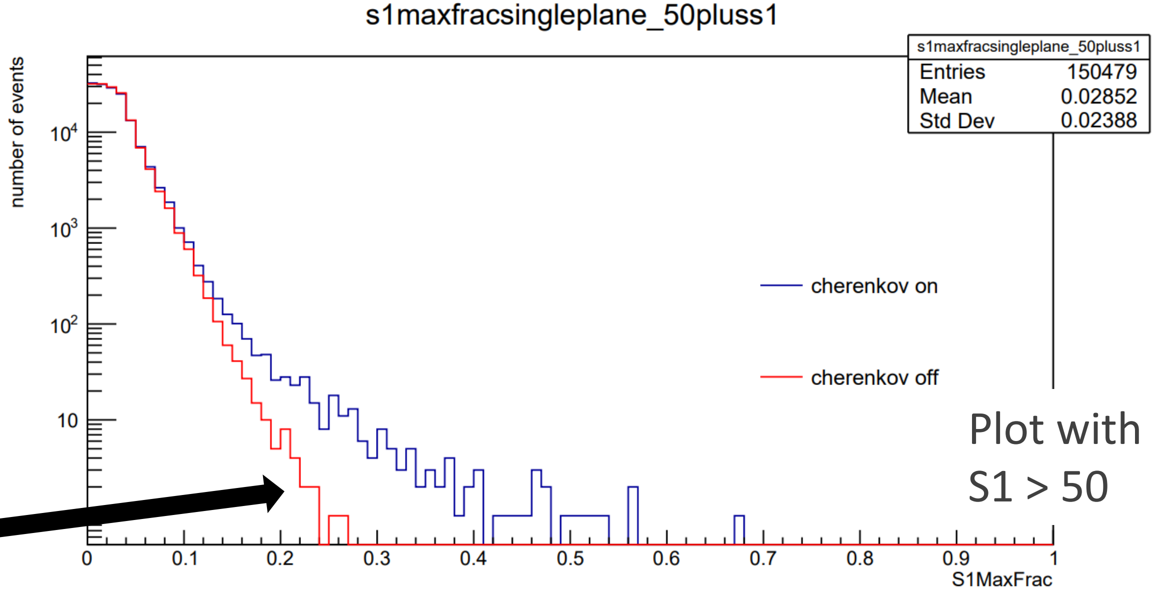
I tried to restrict S1MaxFrac to top and bottom planes without results. I have also tried

$$\mathrm{S1MaxFracSinglePlane} = \frac{\text{S1 in the channel with highest hits}}{\text{S1 in the plane with highest hits}}$$

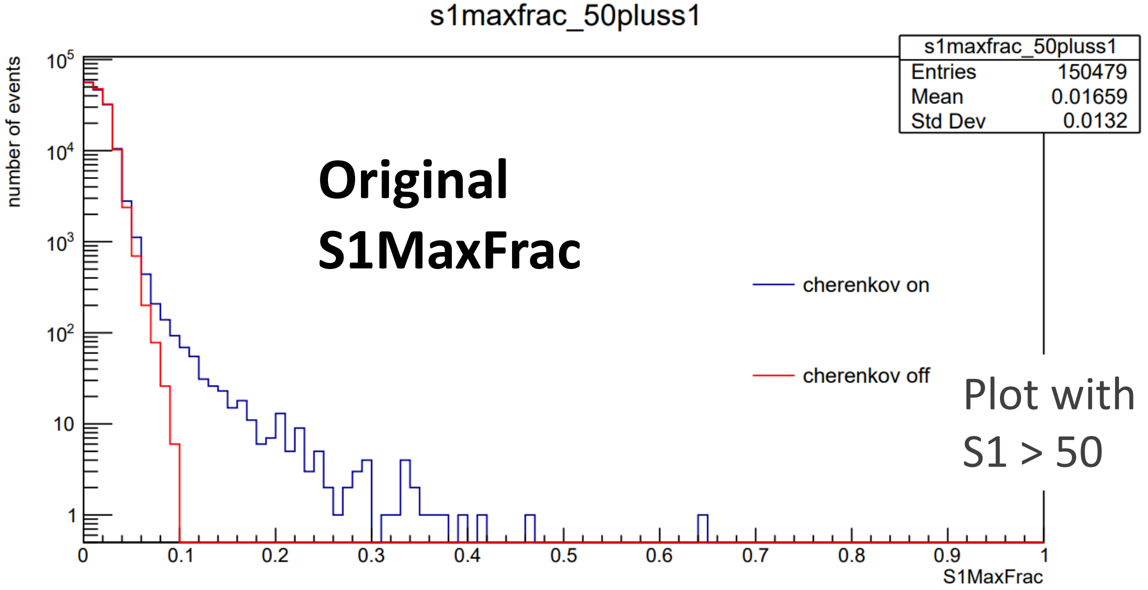



The red histogram has a bigger tail w.r.t. the original S1MaxFrac

Cherenkov/Scintillation ratio not negligible in the other plane




Plot with S1 > 50




**Original S1MaxFrac**

Plot with S1 > 50

# Efforts for improvement (2/2)

**2. Temporal information**:

Cherenkov photons tend to reach the optical plane before scintillation photons → consider only early photons $\text{S1MaxFracEarly} = \text{S1MaxFrac}|_{\text{for the first 30\% photons}}$

**Strong improvement in rejection power**, e.g. for fiducial volume analysis:

- From $(59.1 \pm 7.6)\%$ to $(76.2 \pm 9.0)\%$ for single cluster topology
- From $(92.2 \pm 9.0)\%$ to $(93.2 \pm 9.1)\%$ for pile-up topology

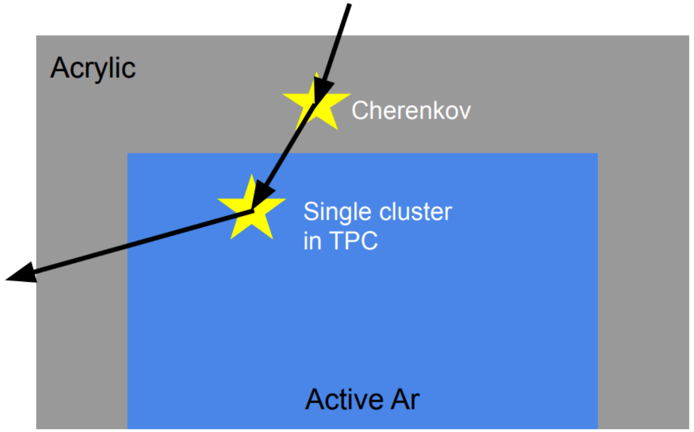
No significant evidence of differences varying the cut-off fraction between 10% and 40%, due to large statistical errors.

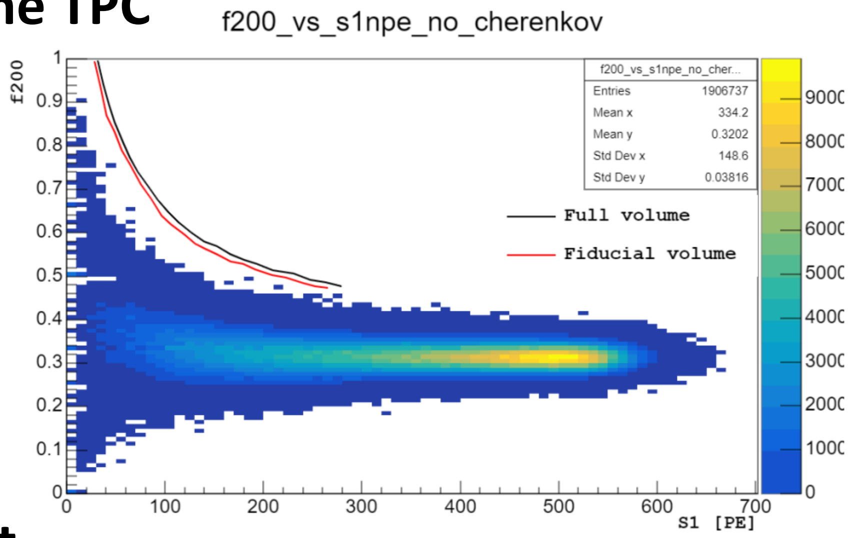
The introduction of a gaussian smearing of order 10 ns to emulate **time resolution leads to a dramatic decline in rejection power** for the single cluster topology: from $(76.2 \pm 9.0)\%$ to $(37.8 \pm 5.6)\%$, worse than original S1MaxFrac.

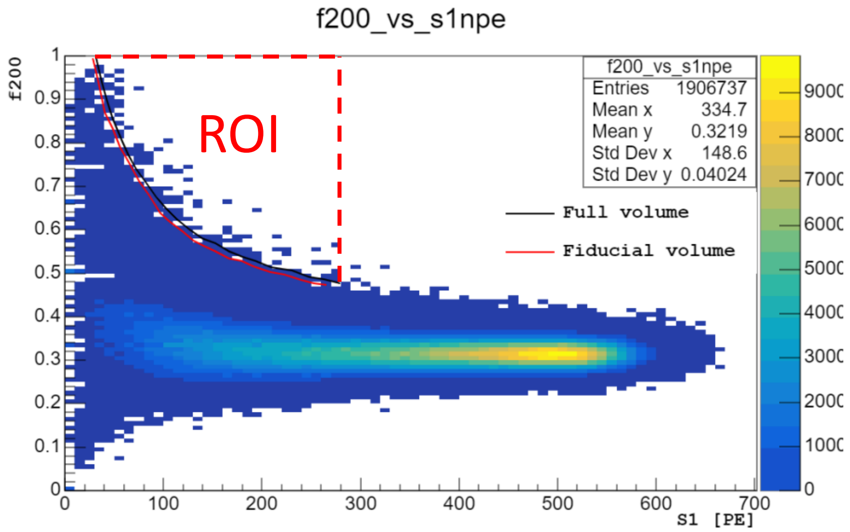
Alternative version where the time cutoff is fixed: $\text{S1MaxFracPrompt200} = \text{S1MaxFrac}|_{\text{for time} < 200\text{ ns}}$
After time resolution, results are still worse than original S1MaxFrac

# Cherenkov background in DarkSide-20k

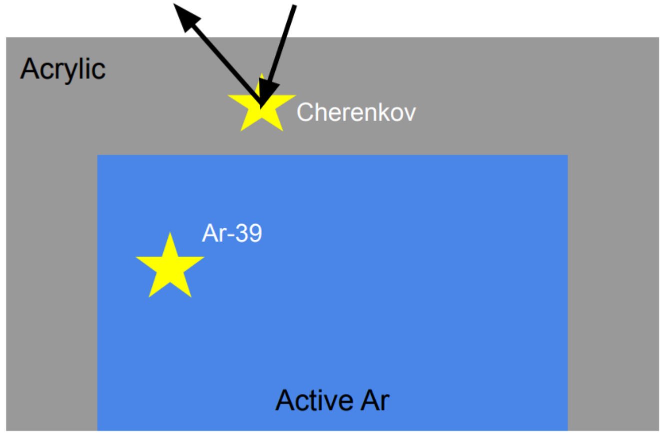
## 1. Cherenkov + single cluster in the TPC

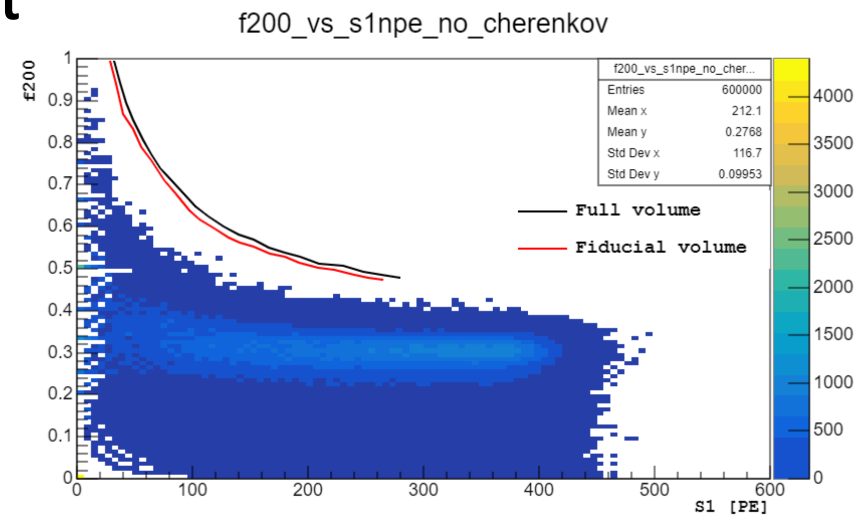


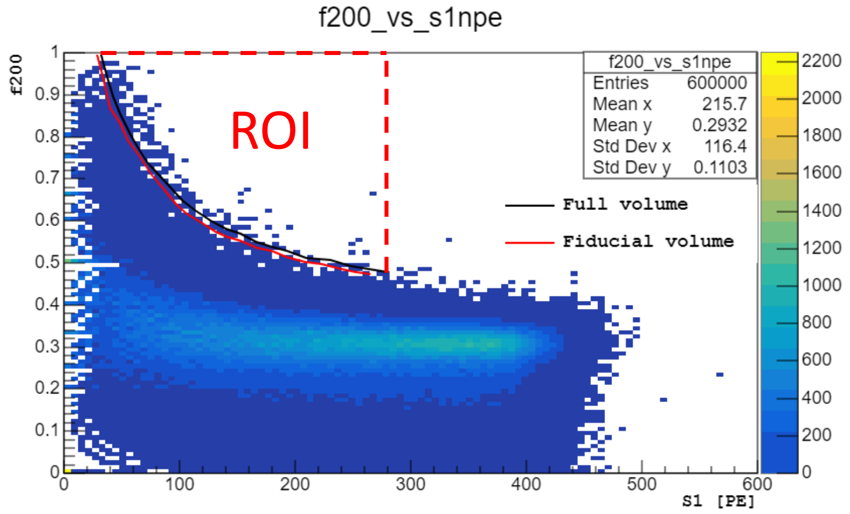




## 2. Cherenkov + $^{39}$Ar pile-up event




**ER events surpassing PSD due to Cherenkov boost to $f_{200}$**

# Cherenkov + single cluster in the TPC

Number of decays in 10 y ✖ Probability to induce a single scatter ✖ Probability to shift the event in the NR band (push-up probability)

- $^{40}$K rate: 100 Bq → $3.2 \times 10^{10}$ decays in 10 y
- $^{232}$Th rate: 4.4 Bq → $1.4 \times 10^{9}$ decays in 10 y

- Fiducial volume: $(2 \pm 1) \times 10^{-8}$
- Extended volume: $(5.7 \pm 0.6) \times 10^{-5}$

Computed from simulation.
No fiducialization applied

**Conservative estimate**: PSD survival probability anticorrelated with probability γ reaching inner region

| | Fiducial volume analysis $^{232}$Th | Fiducial volume analysis $^{40}$K | Extended volume analysis $^{232}$Th | Extended volume analysis $^{40}$K |
|---|---|---|---|---|
| Single cluster MC events | $(1.907 \pm 0.001) \times 10^6$ | $(8.676 \pm 0.009) \times 10^5$ | $(1.907 \pm 0.001) \times 10^6$ | $(8.676 \pm 0.009) \times 10^5$ |
| MC ROI events (w/o fid.) | $164 \pm 10$ | $1 \pm 1$ | $109 \pm 10$ | $1 \pm 1$ |
| MC ROI events (w/ fid.) | 0 | 0 | $2.0 \pm 1.4$ | $0.018 \pm 0.023$ |
| Push-up probability | $(8.60 \pm 0.67) \times 10^{-5}$ | $(1.2 \pm 1.2) \times 10^{-6}$ | $(5.72 \pm 0.55) \times 10^{-5}$ | $(1.2 \pm 1.2) \times 10^{-6}$ |
| ROI events predicted in 10 y | $(2.4 \pm 1.2) \times 10^{-3}$ | $(7.7 \pm 8.6) \times 10^{-4}$ | $4.56 \pm 0.65$ | $2.2 \pm 2.2$ |
| ROI events expected in 10 y | / | / | $29.0 \pm 20.5$ | $0.56 \pm 0.72$ |

# Cherenkov + $^{39}$Ar pile-up event

Probability of random coincidence ✖ Probability of $^{232}$Th decay without cluster + Cherenkov in acrylic ✖ Push-up probability ✖ Number of $^{39}$Ar events

Probability of random coincidence → Dependence on decay rate and time window:
$1 - e^{-44\ \mathrm{Bq} \times 400\ \mathrm{ns}} = 1.76 \times 10^{-5}$

Probability of $^{232}$Th decay without cluster + Cherenkov in acrylic → From the simulation:
$4.3 \times 10^{-3}$

Push-up probability → From the simulation. No fiducialization applied

Number of $^{39}$Ar events → **FV:** $4.6 \times 10^{9} \times 0.068 = 3.13 \times 10^{8}$
**EV:** $\frac{5}{2}\mathrm{FV} + 7.7\ \mathrm{Hz} \times 10\ \mathrm{y} = 3.21 \times 10^{9}$

| $^{232}$Th dataset | Fiducial volume analysis | Extended volume analysis |
|---|---|---|
| $^{39}$Ar MC events | $(6.00 \pm 0.08) \times 10^{5}$ | $(6.00 \pm 0.08) \times 10^{5}$ |
| MC ROI events | $216 \pm 14$ | $140 \pm 12$ |
| MC ROI events with fiducialization | $87 \pm 9$ | $128 \pm 11$ |
| Push-up probability | $(3.60 \pm 0.24) \times 10^{-4}$ | $(2.33 \pm 0.20) \times 10^{-4}$ |
| ROI events predicted in 10 y | $(8.53 \pm 0.58) \times 10^{-3}$ | $(5.67 \pm 0.48) \times 10^{-2}$ |