DarkSide-50 recent results and future prospects

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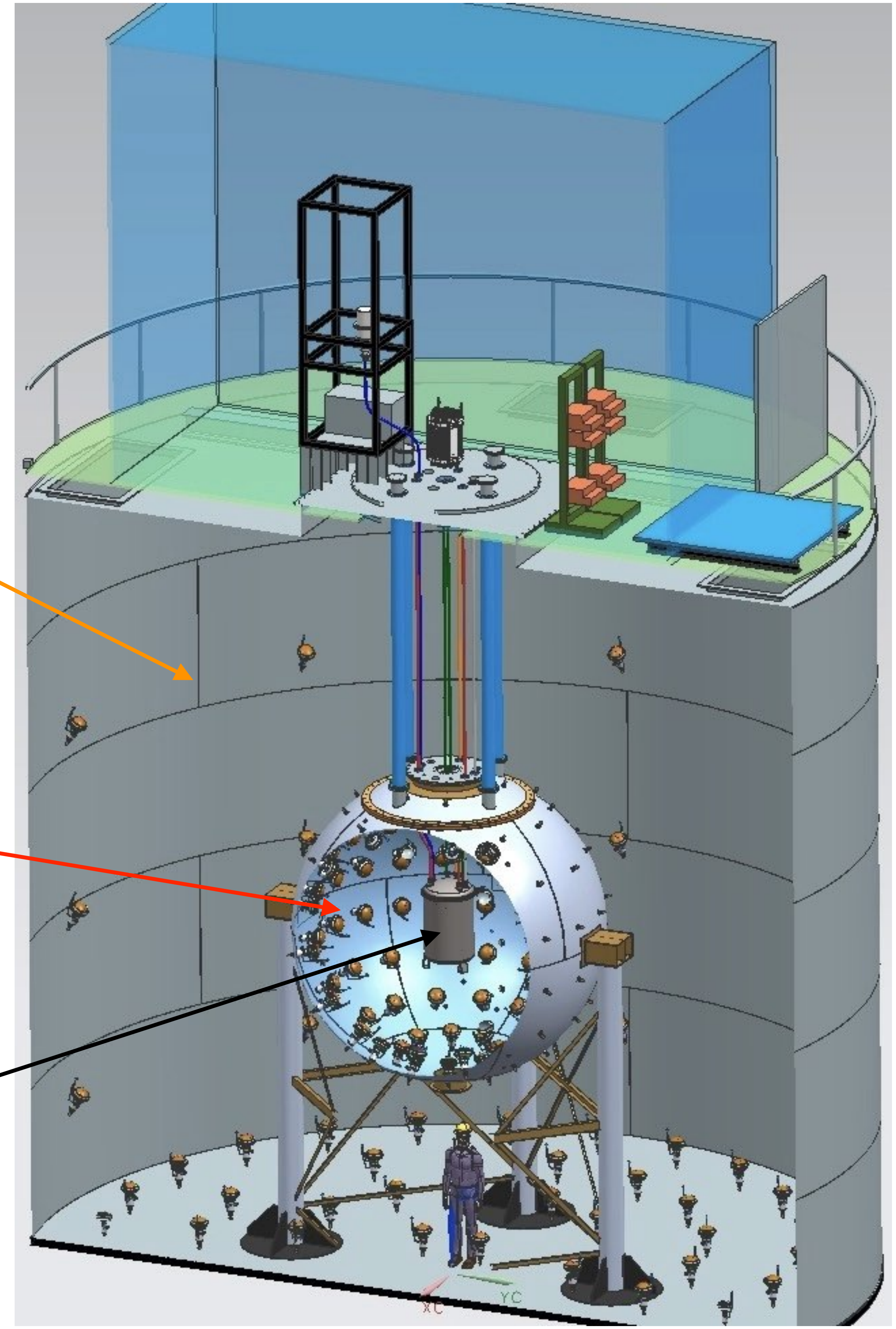
on the behalf of the DarkSide collaboration

WIN 2019, Bari - June, 7th 2019

DarkSide-50 @ LNGS detector overview

- **Water Cherenkov** detector (1,000 tons of ultra pure water): active veto for μ and passive shield for external radiation
- **Liquid scintillator** detector (30 tons of PC+PPO+TMB): active Ɣs and neutron detector thanks to ^{10}B loading
- **LAr TPC** detector (current phase ~50 kg of argon in the fiducial volume): inner detector for WIMP

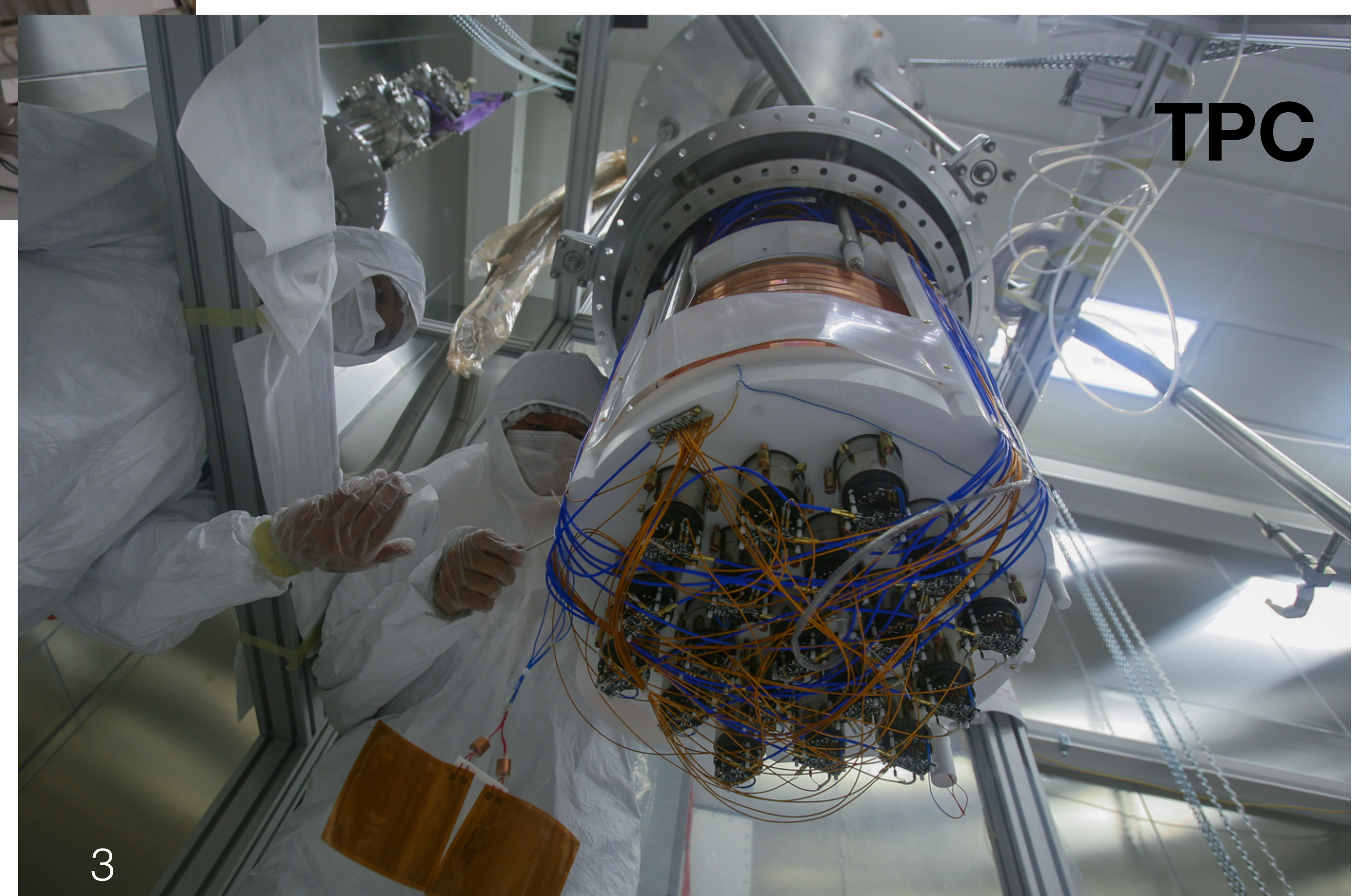


DarkSide-50

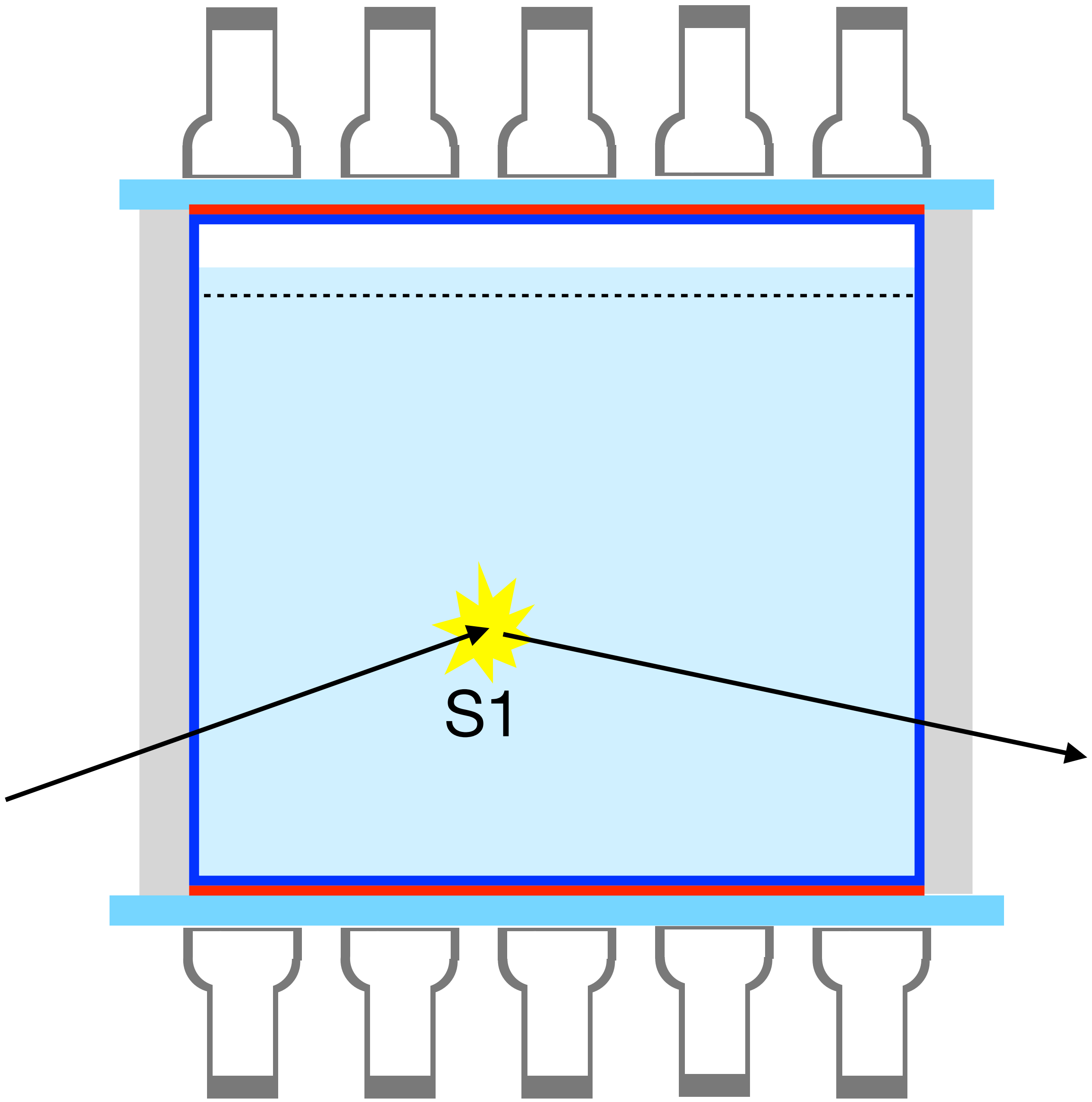

Water
Cherenkov


Liquid
scintillator

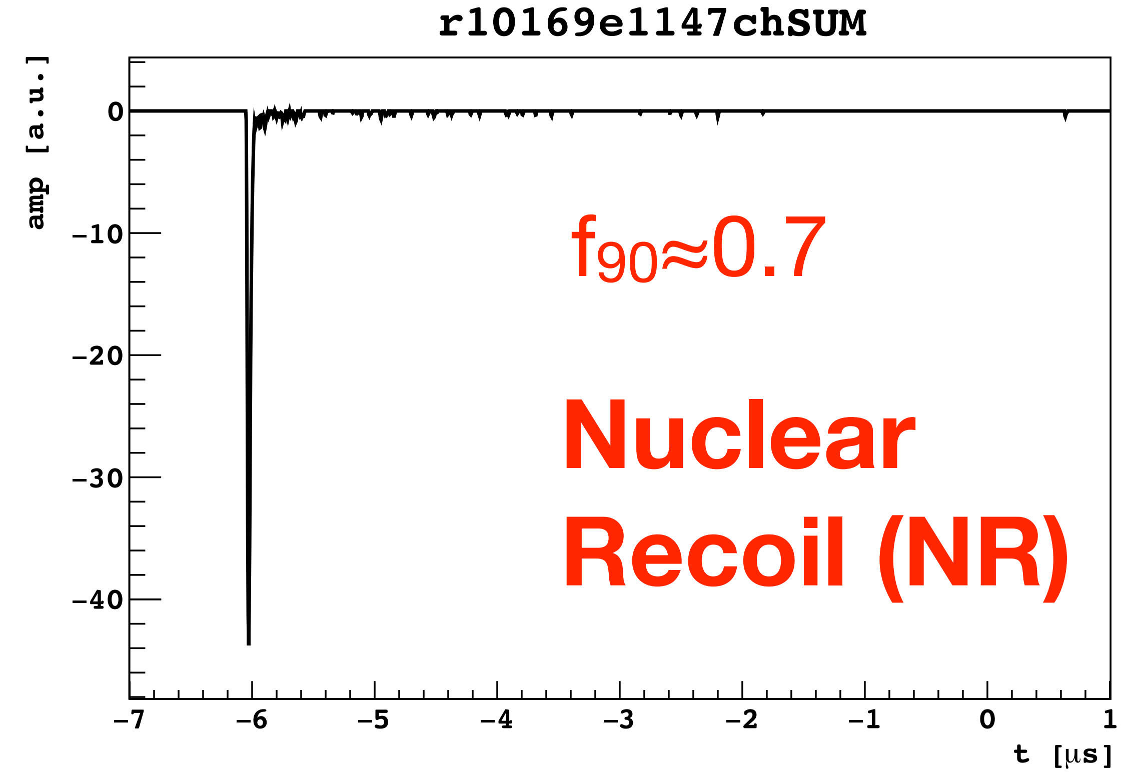

Cryogenic
amplifiers on PMTs

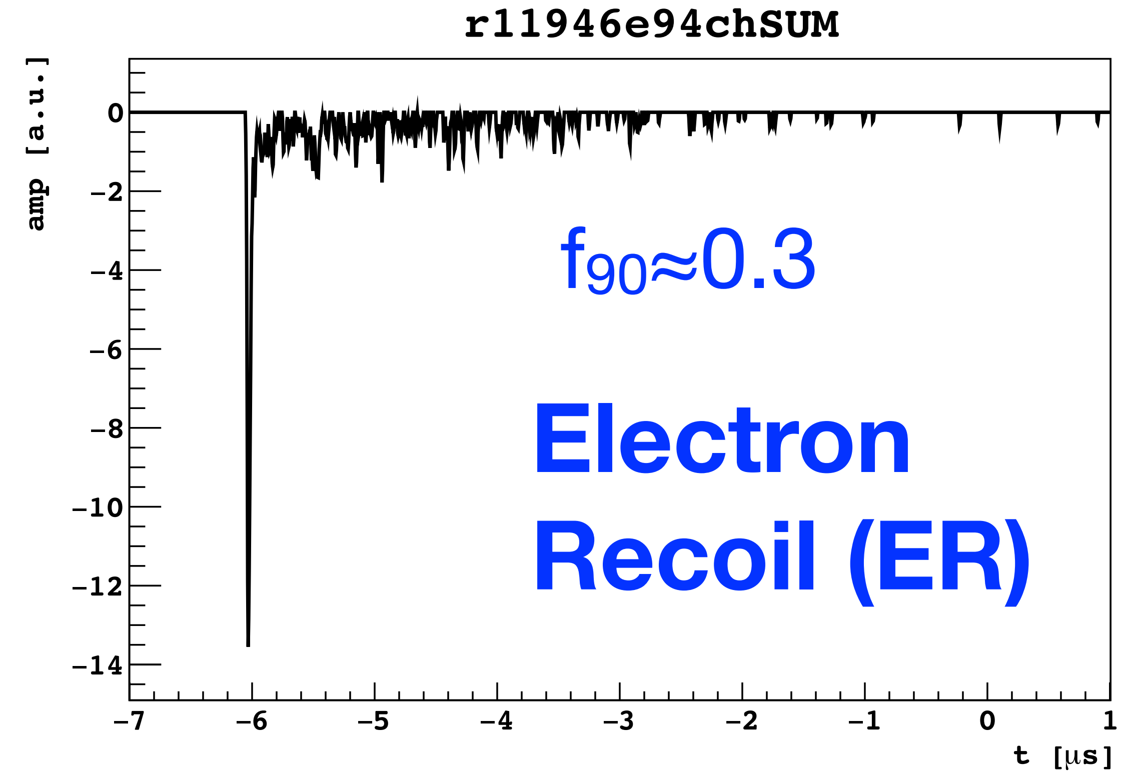

TPC

Dual phase TPC technology: S1

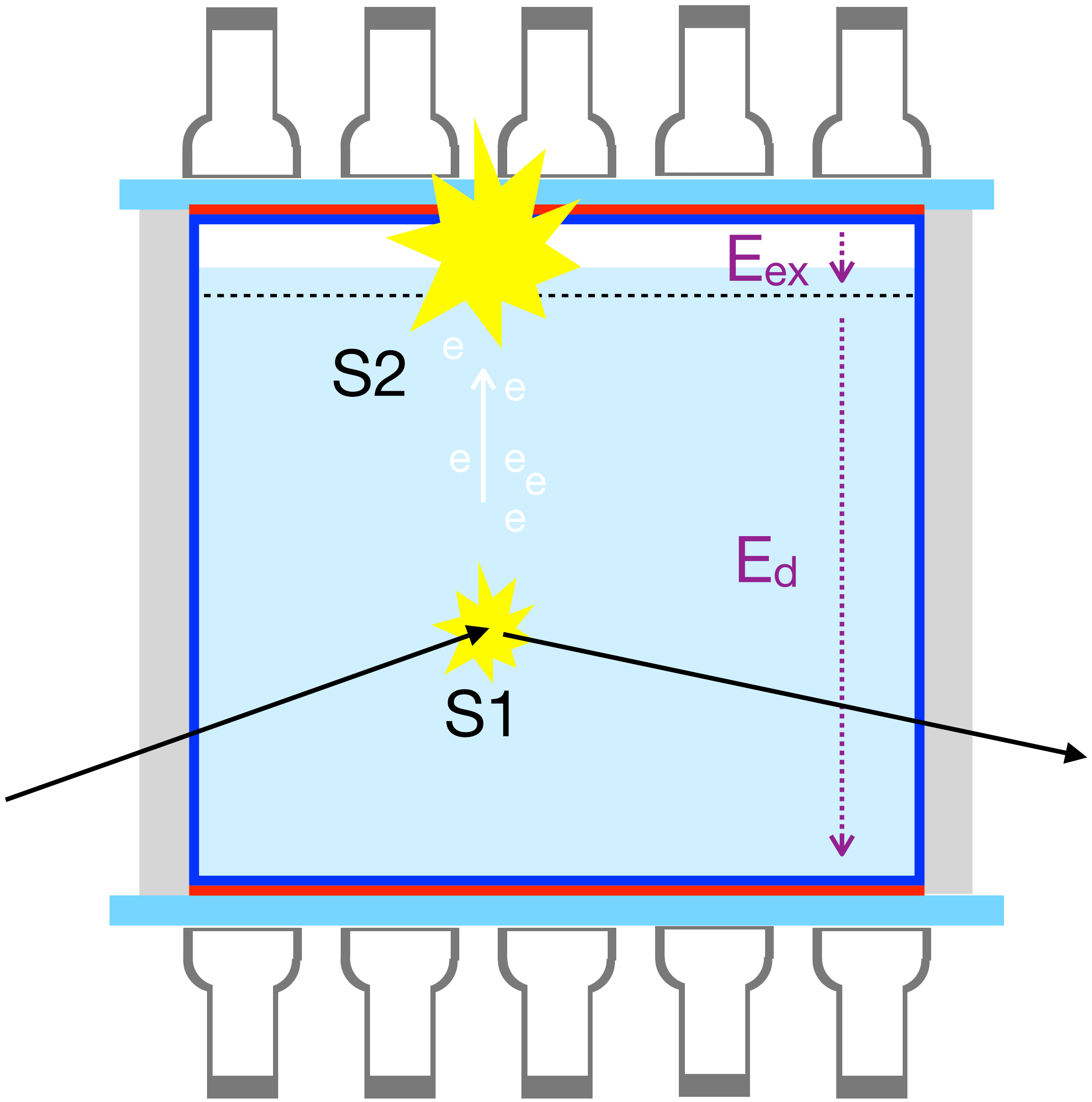


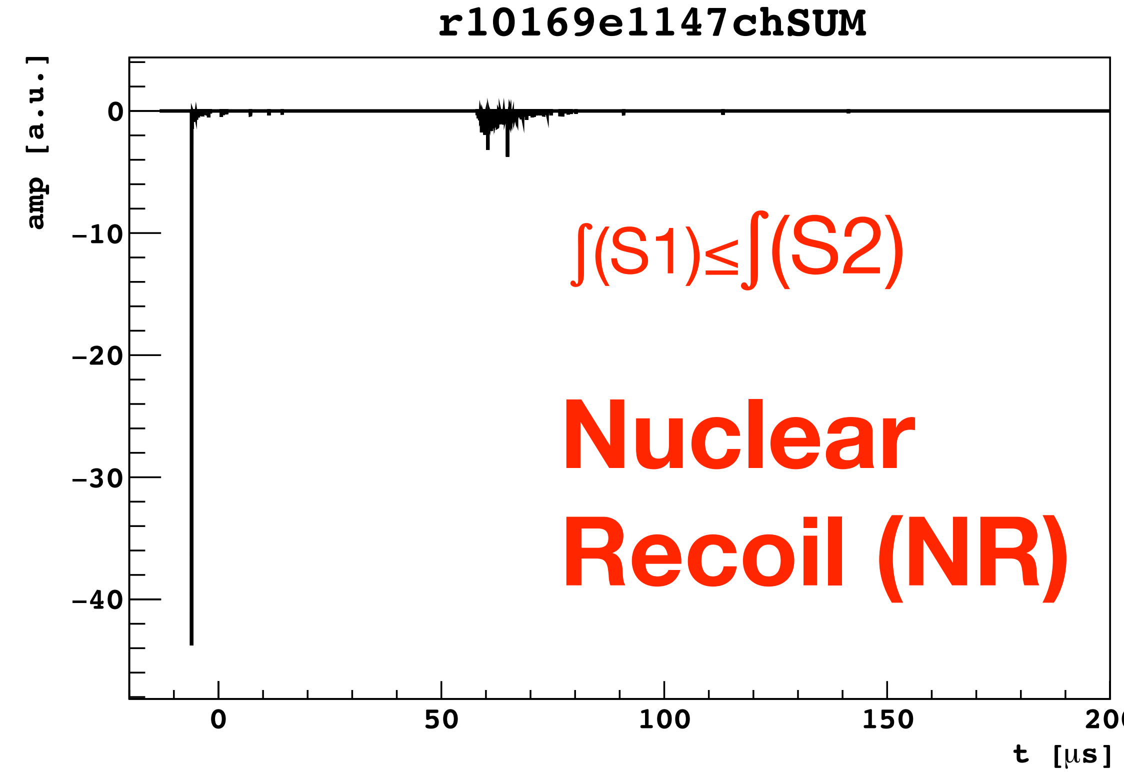
- **Light signal (S1)** time profile allows Pulse Shape Discrimination (PSD) thanks to f_{90} parameter (fraction of light in the first 90ns)

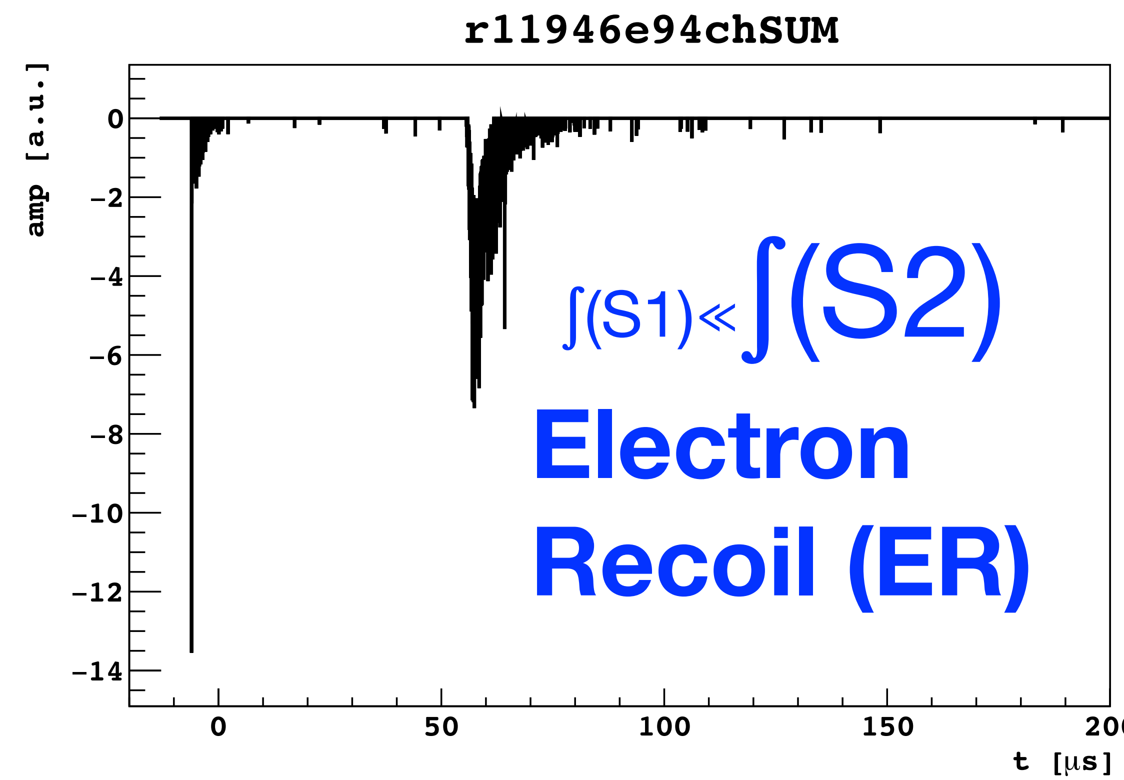




Dual phase TPC technology: S2







- **Electroluminescence/ionization signal (S2)** due to drifted electrons allows 3d position reconstruction, additional discrimination (S2/S1), and improved energy reconstruction

DarkSide-50 recent results

- High mass WIMP search (S1+S2)
  Physical Review D 98 (10), 102006 (2018)

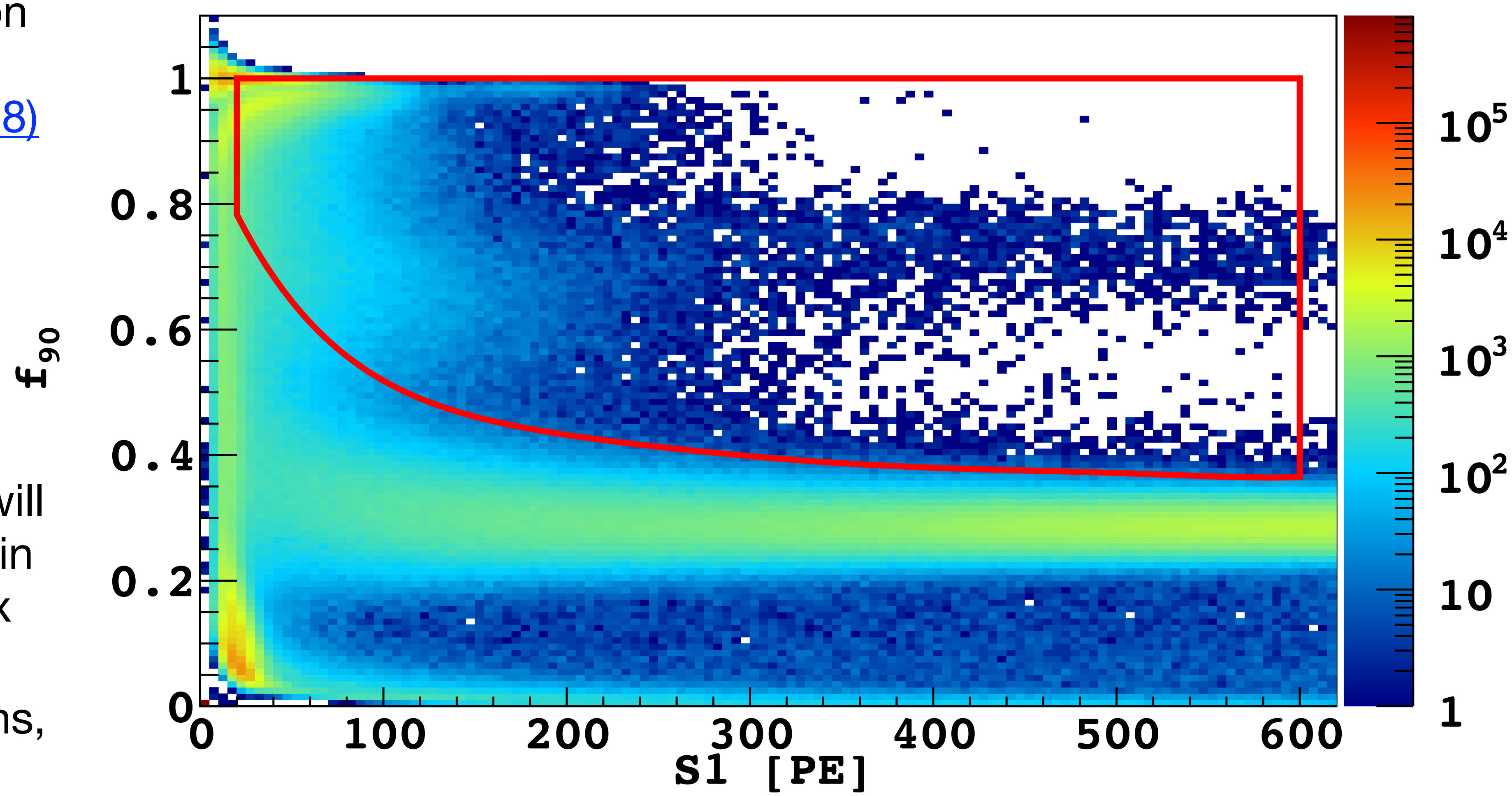
- Low mass WIMP searches:

  - S2-only
    Physical Review Letters 121 (8), 081307 (2018)

  - Sub-GeV
    Physical Review Letters 121 (11), 111303 (2018)

High mass WIMP search (S1+S2)

- A blind analysis of 532-days (16 660 kg d) exposure using a target of low-radioactivity argon extracted from underground sources: [PRD 98, 102006 (2018)]
- Blinding box (**red solid line**) drawn using early 71-days (2616 kg d) results [PRD 93, 081101(R) (2016)]
- Goal: design an analysis that will have <0.1 background events in the to-be-designed search box
- Backgrounds: β and γ, neutrons, surface α, and Cherenkov

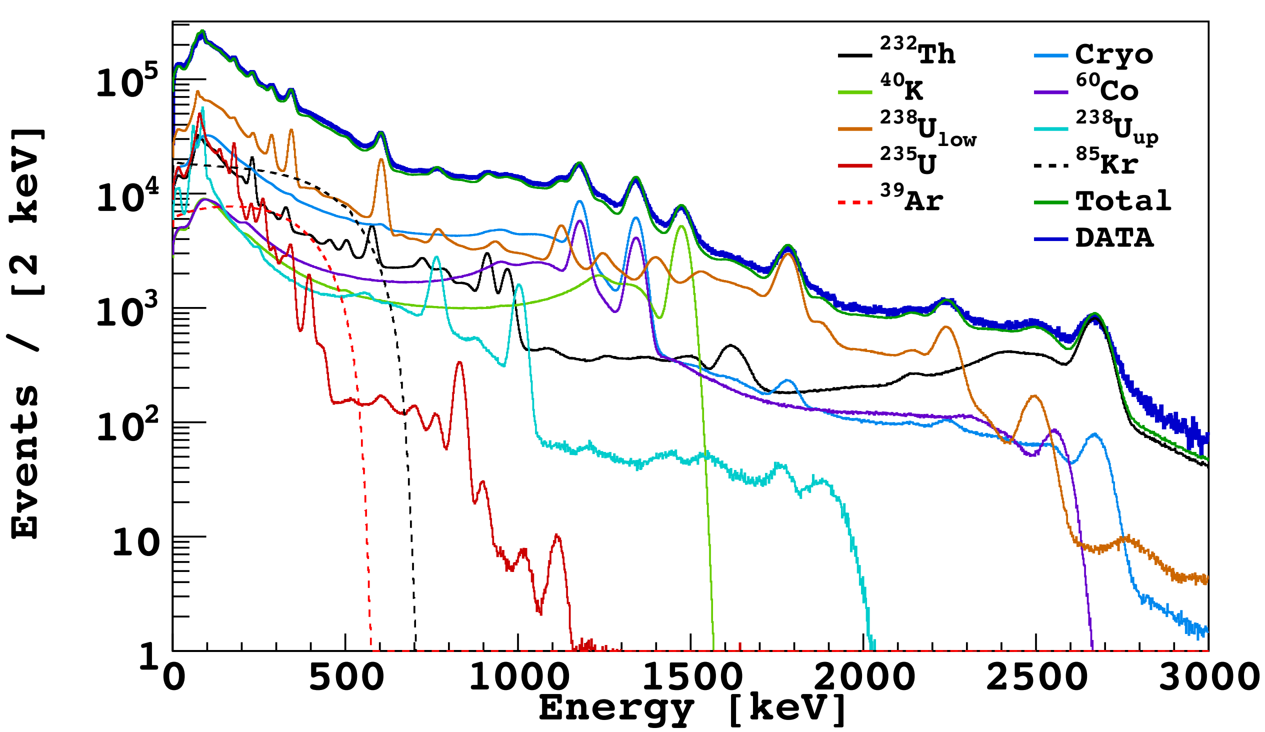


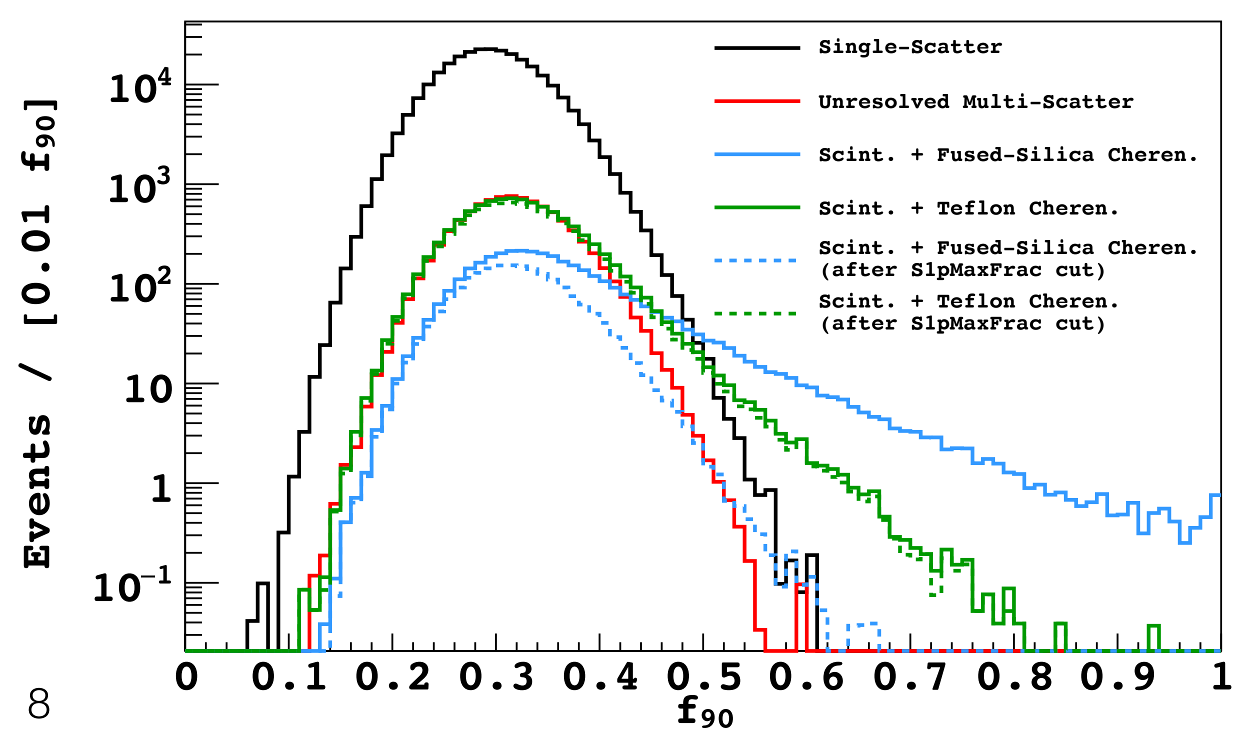
Background: ERs

- **β and γ:** External ɣs but mostly main source is internal (PMTs, cryostat, target itself). UAr has (0.73 ± 0.11) mBq/kg of ^{39}Ar, and (2.05 ± 0.13) mBq/kg of ^{85}Kr. Rejected by:
  - PSD rejection power in ROI is down to 6x10^{-8} for single-site ERs
  - WCD + LSV

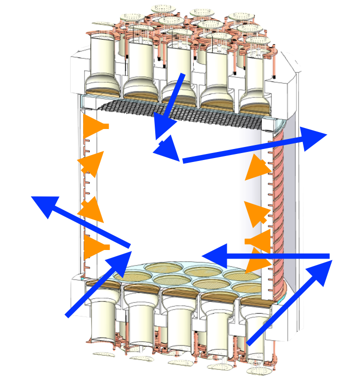
- **Cherenkov + scintillation:** ɣ multiple scatters in LAr and PTFE or fused-silica. Cherenkov (f_{90}≈1) moves regular scintillation into NR band. Rejected by:
  - light distribution in top PMTs
  - radial fiducialization

Results obtained thanks to intensive background modeling done with a data/MonteCarlo hybrid approach - JINST 12, P10015 (2017)





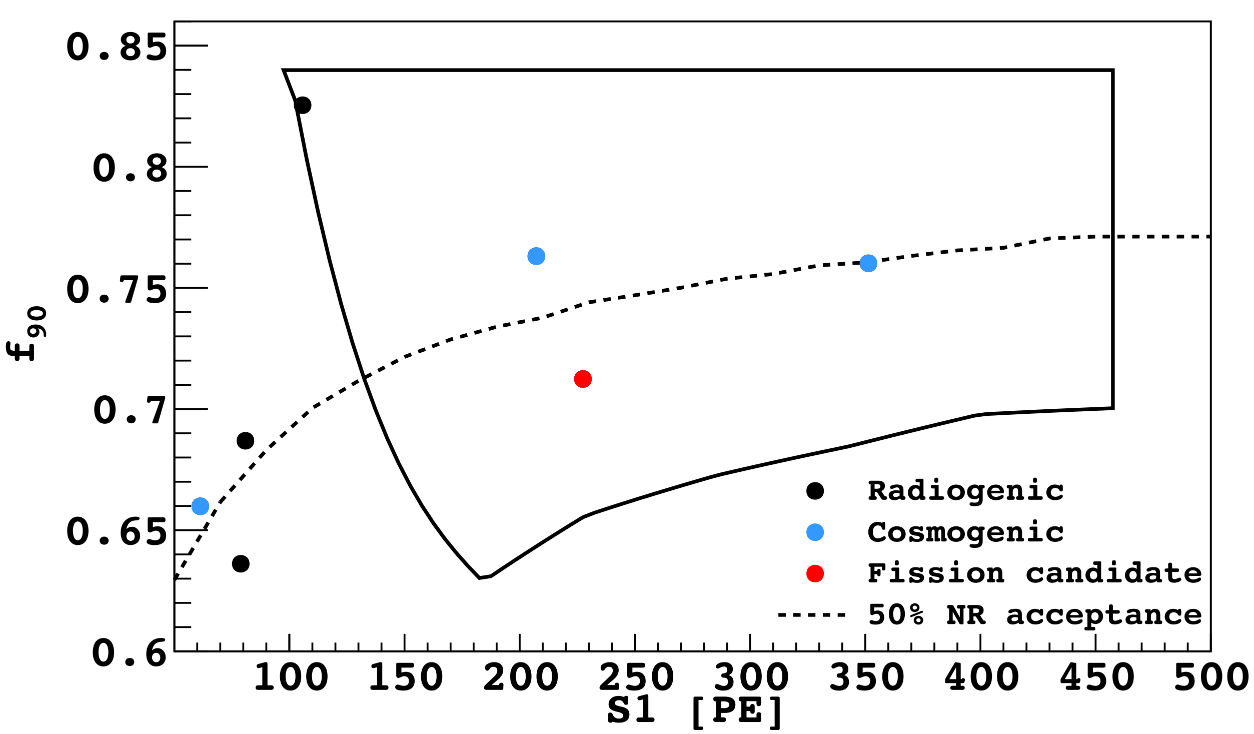
Background: NRs

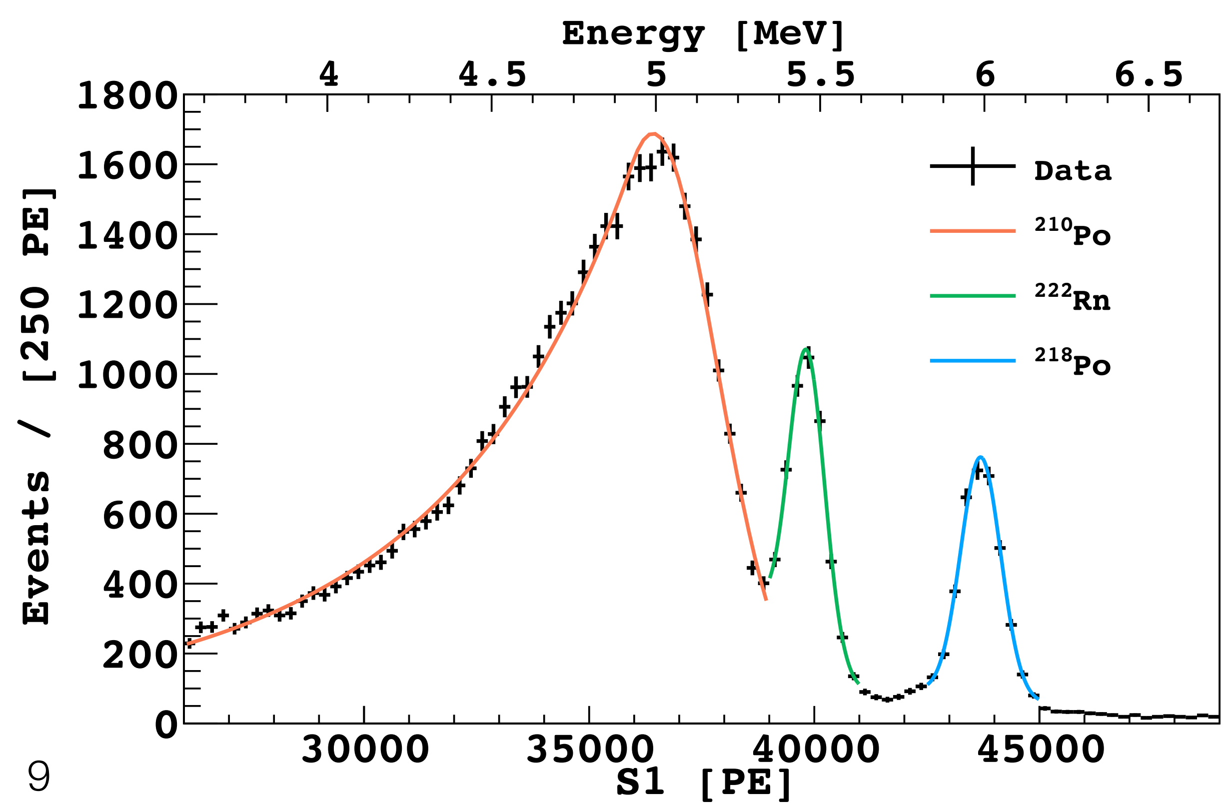


- **Neutrons:** cosmogenic (produced by muons interaction with surrounding materials) or spontaneous ^{238}U (α,n) reactions. **PMTs are the main source**. Rejected by:
  - Multiple scatter in TPC
  - Coincidence with LSV: measured efficiency with AmC 99.64±0.04% (fraction of event surviving veto cuts)
  - Coincidence with WCD

- **Alphas:** stringent radio pure material selection constrains α-emitters to Rn daughters on surfaces (fabrication/assembly process) or in LAr (recirculation).

- Degraded α can follow in NR band. Rejected by:
  - **Self-vetoing**:
    - Very small or absent S2
    - S2 has long scintillation tail due to TPB scintillation

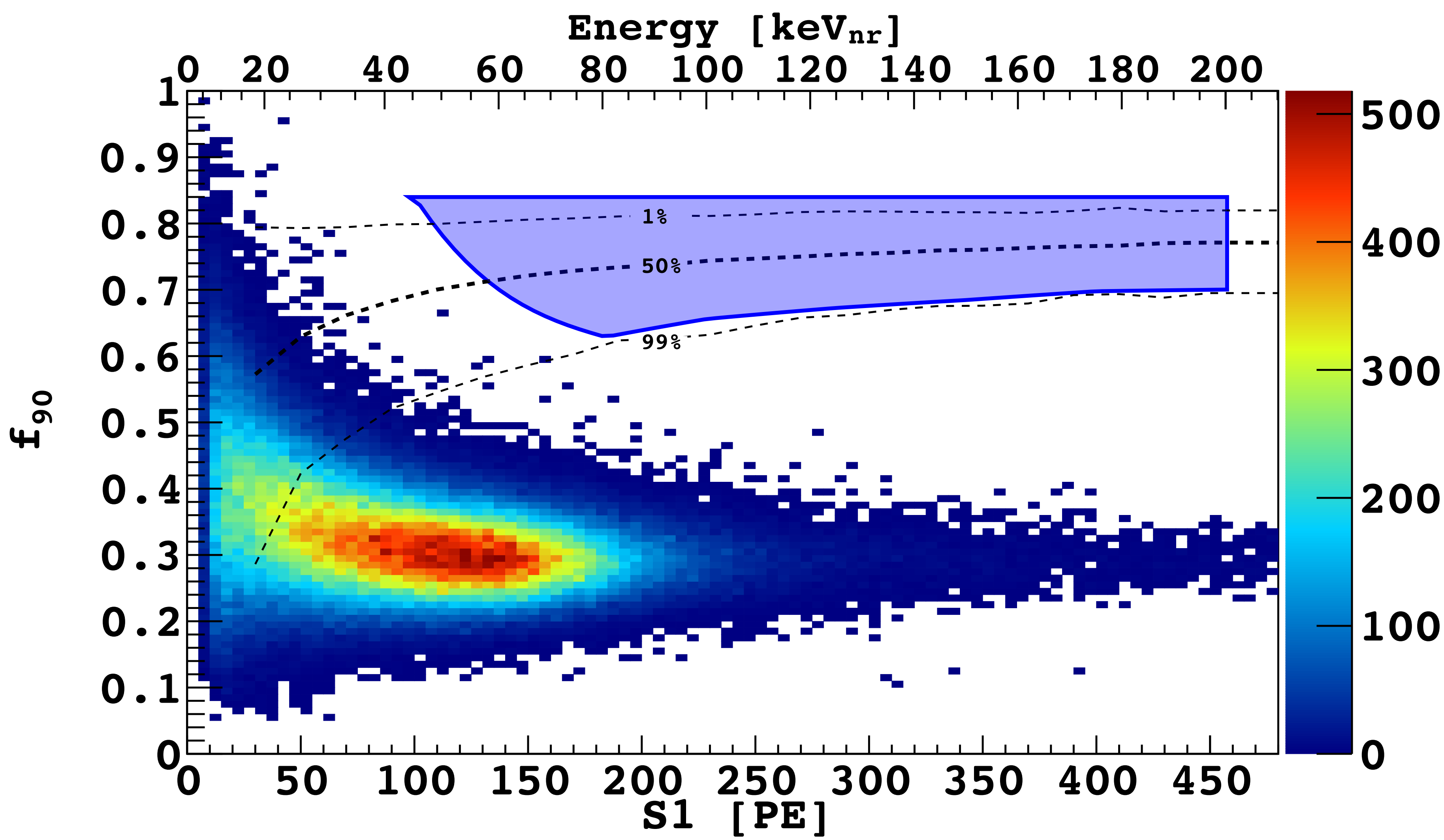




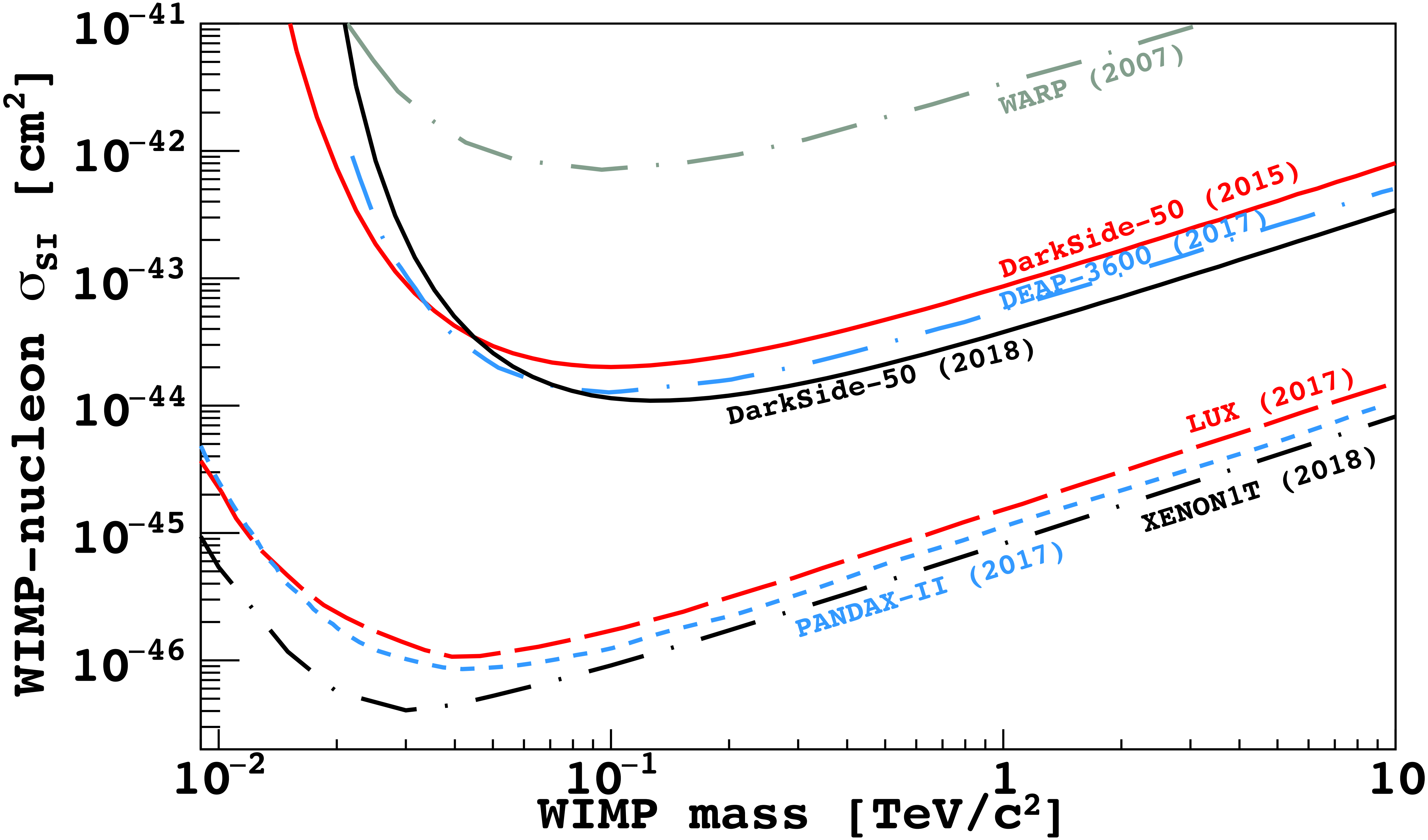
Final dataset and dark matter box

Background	Events surviving all the cuts
Cosmogenic neutrons	< 3×10^{-4}
Radiogenic neutrons	< 5×10^{-3}
Surface α	< 1×10^{-3}
Cherenkov + scintillation	0.08
Total	**0.09±0.04**

Goal of <0.1 background events achieve and **final dark matter search box** defined: **let's open the box!**



90% C.L. exclusion limit

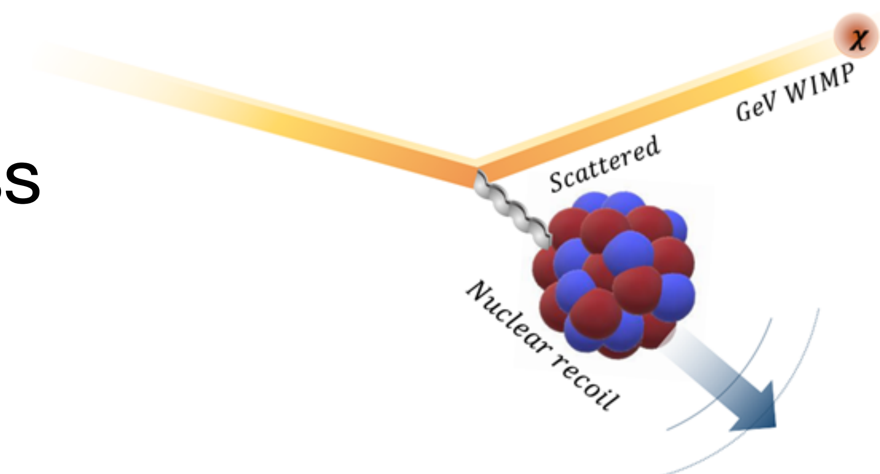


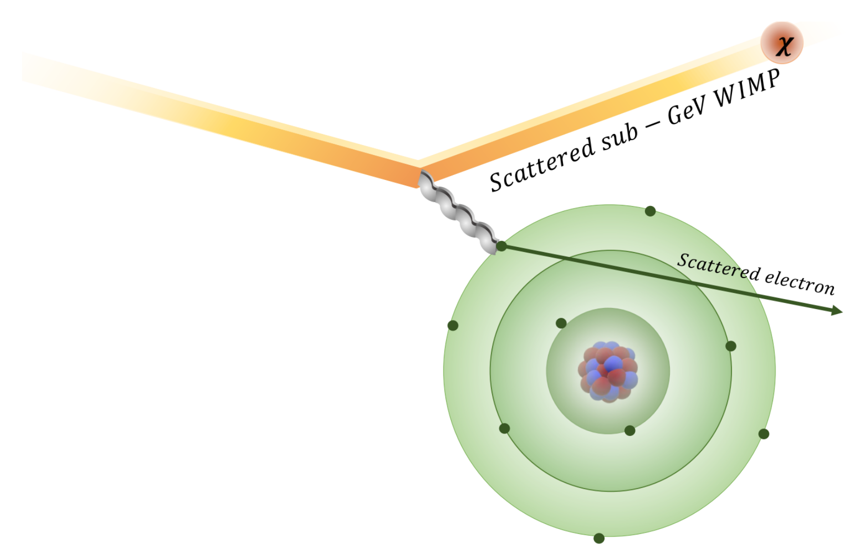
Low mass WIMP searches

- Trigger on S1 imposes a threshold of 13 keV_{nr}
  → limited sensitivity for WIMPs with mass <10GeV/c^2

- But if same threshold is applied to ionization signal S2 → E_{th}<0.6keV_{nr}
  allows to explore this parameter space!

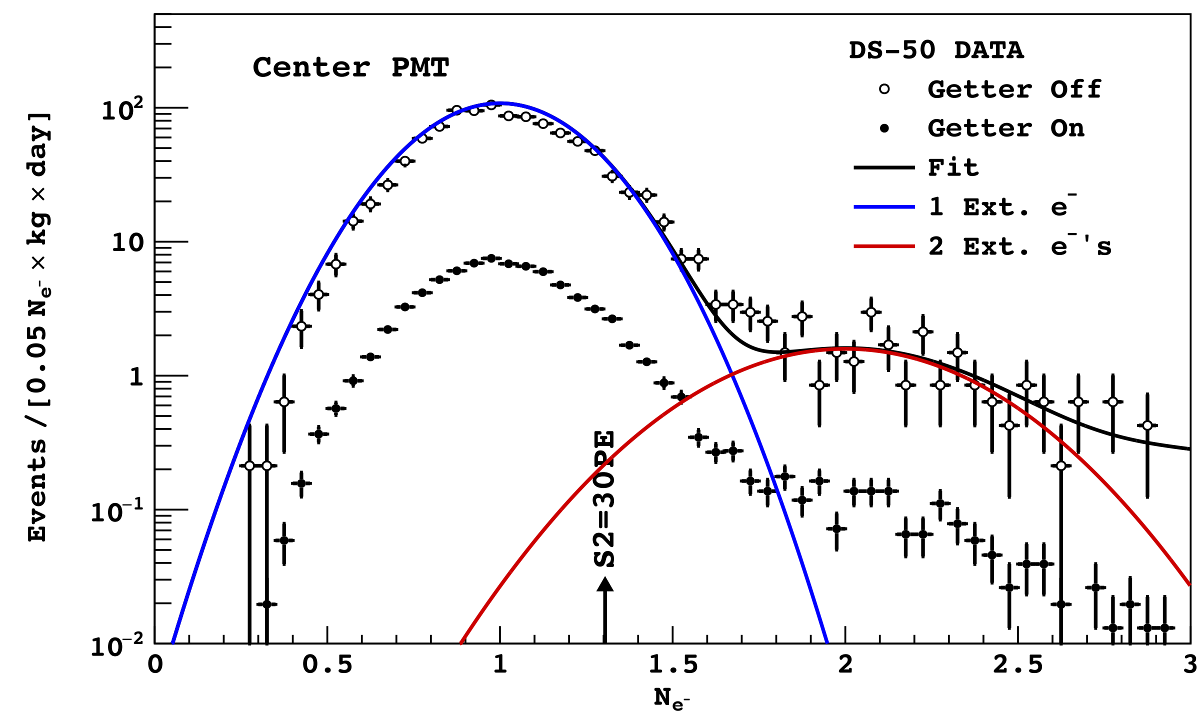
- Using S2-only events is possible to search for low mass WIMPs interacting both with **nuclei** or even with **electrons** (with background)



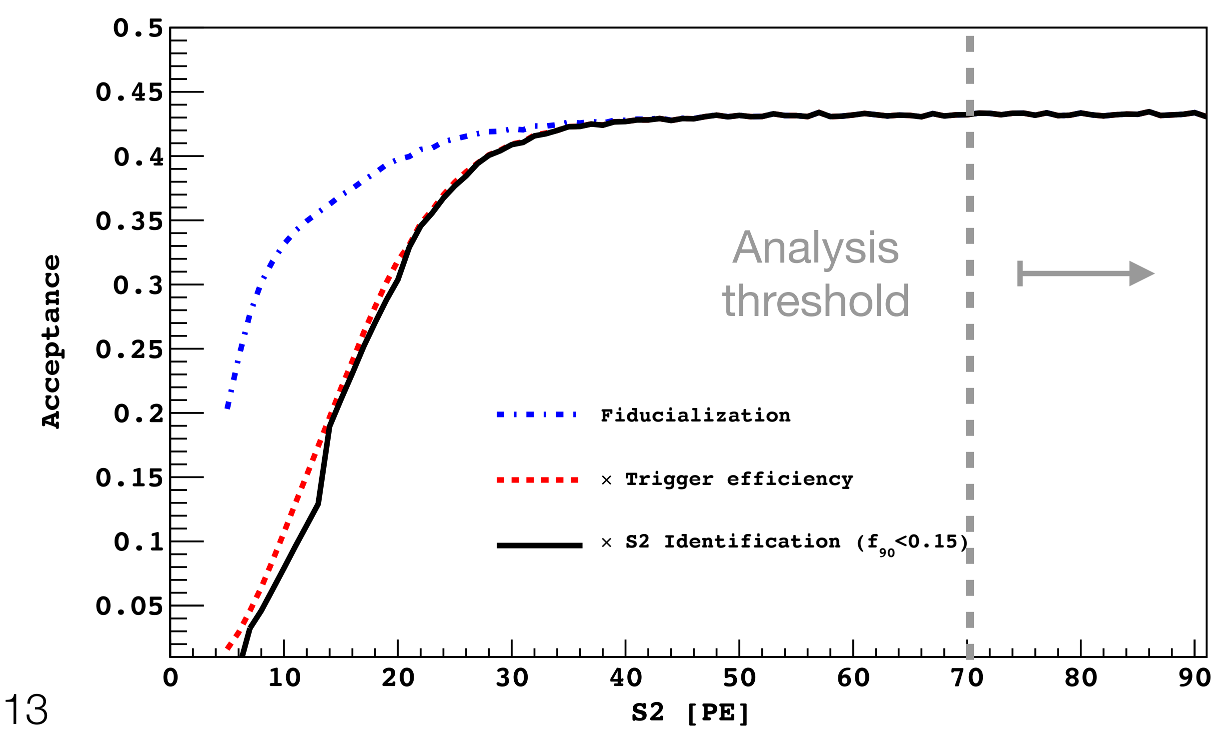


Low mass WIMP search (S2-only)

- S2-only signal:
  - Sensitive to single extracted electron
  - No need of PSD
- Acceptance: estimated by data+MC (MC reproduces both spatial and temporal distribution of S2 as measured in electron diffusion - see arXiv:1802.01427)
- Fiducialization: no xy available, but use volume under inner 7 PMTs (position assigned by PMT collecting the largest amount of light)

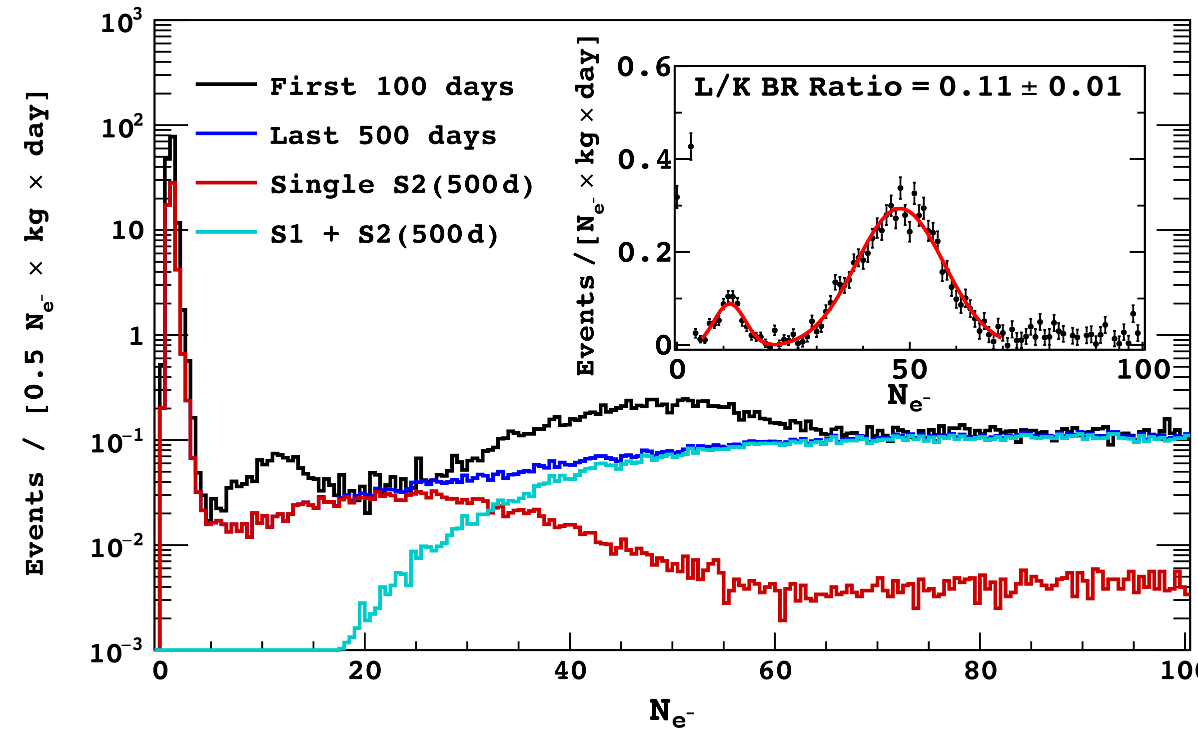


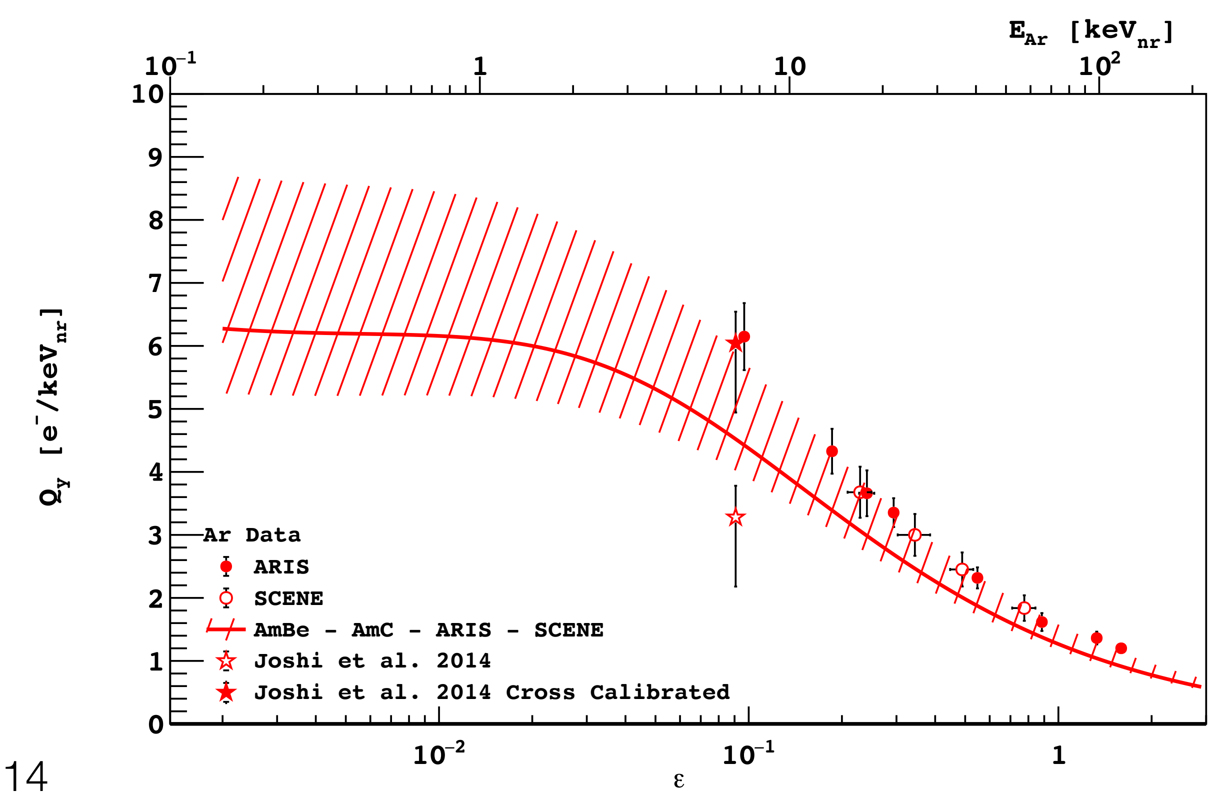
N_e=S2/**η** where **η**=(23±1)PE/e



Energy scale for ER and NR

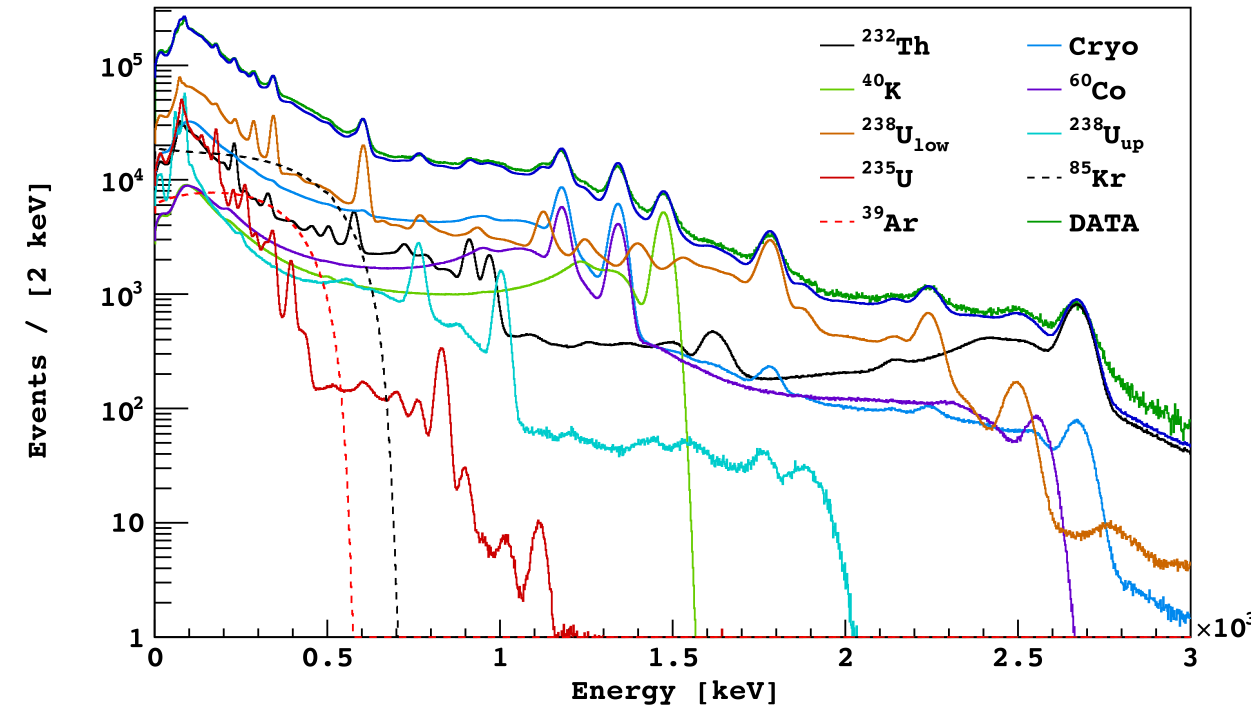
- ER energy scale obtained with ^{37}Ar
  - Provides 2 X-rays at 0.27 and 2.82 keV
  - Decayed with $t_{1/2}$ =35d and no remain in the last 500d data set (compare **black** and **blue** spectra)
- NR energy scale obtained with AmBe and AmC
  - Bezrukov model fitted on calibration data
  - Difference with other measured points taken as systematic
  - Conservative assumption - measured points are higher than fit: less ionization → less e^- → less sensitivity

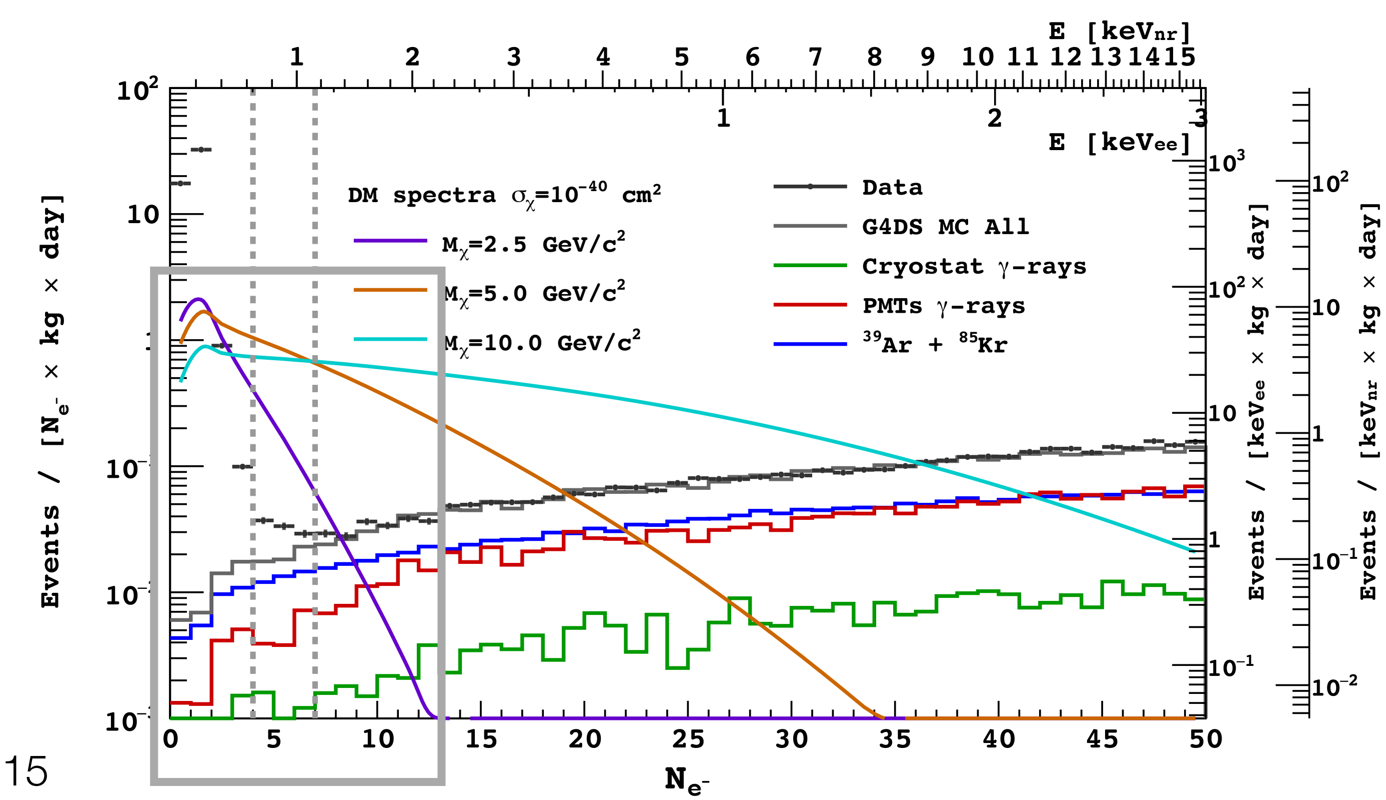




Background and WIMP signal

- Background is constrained in region of interest by extrapolating from high energy part of the spectrum
    - **At low energy, excess of events it is not understood**
- WIMP recoil energy spectra modeled using
    - Ionization, energy quenching and detector response

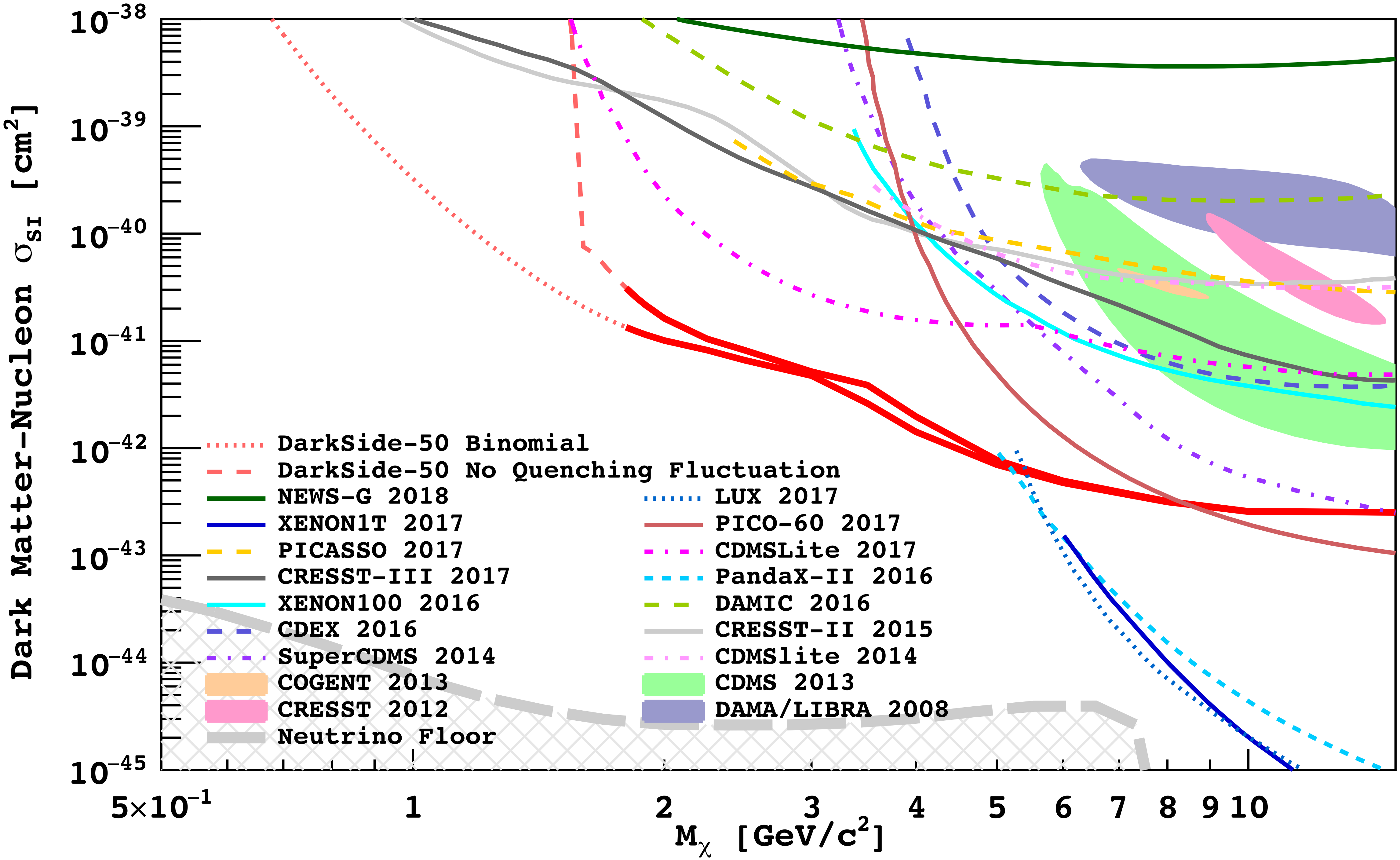




Profile likelihood method

- Upper limit σ_{SI} extracted observed N_e spectrum using binned profile likelihood (PL) method
- Two signal regions (N_e^{th} of 4 and $7e^-$) which covers WIMP masses in the range [1.8,10] GeV/c^2
- PL includes uncertainties both on WIMP signals (NR ionization, single electron yield) and background spectrum (rates, ER ionization yield)
- Average ionization yield dominates uncertainties! Due to lack of knowledge two assumptions about fluctuation at low recoil energy: no fluctuation and binomial

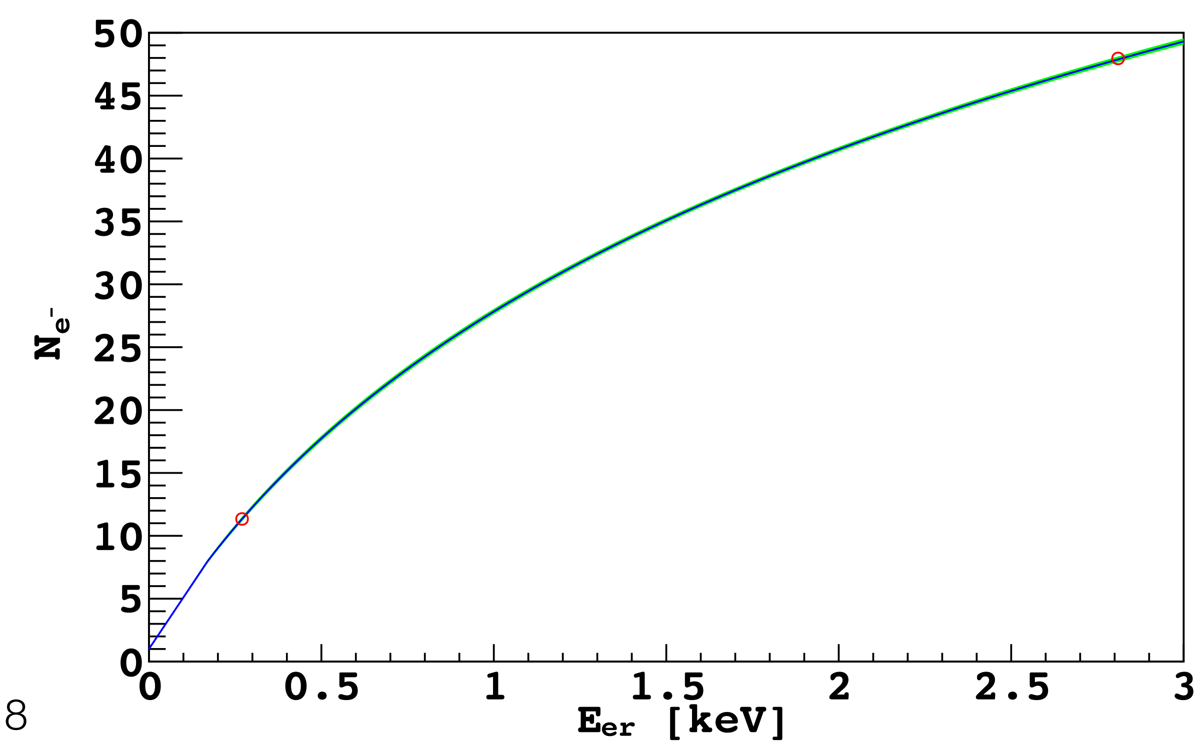
90% C.L. Exclusion limit



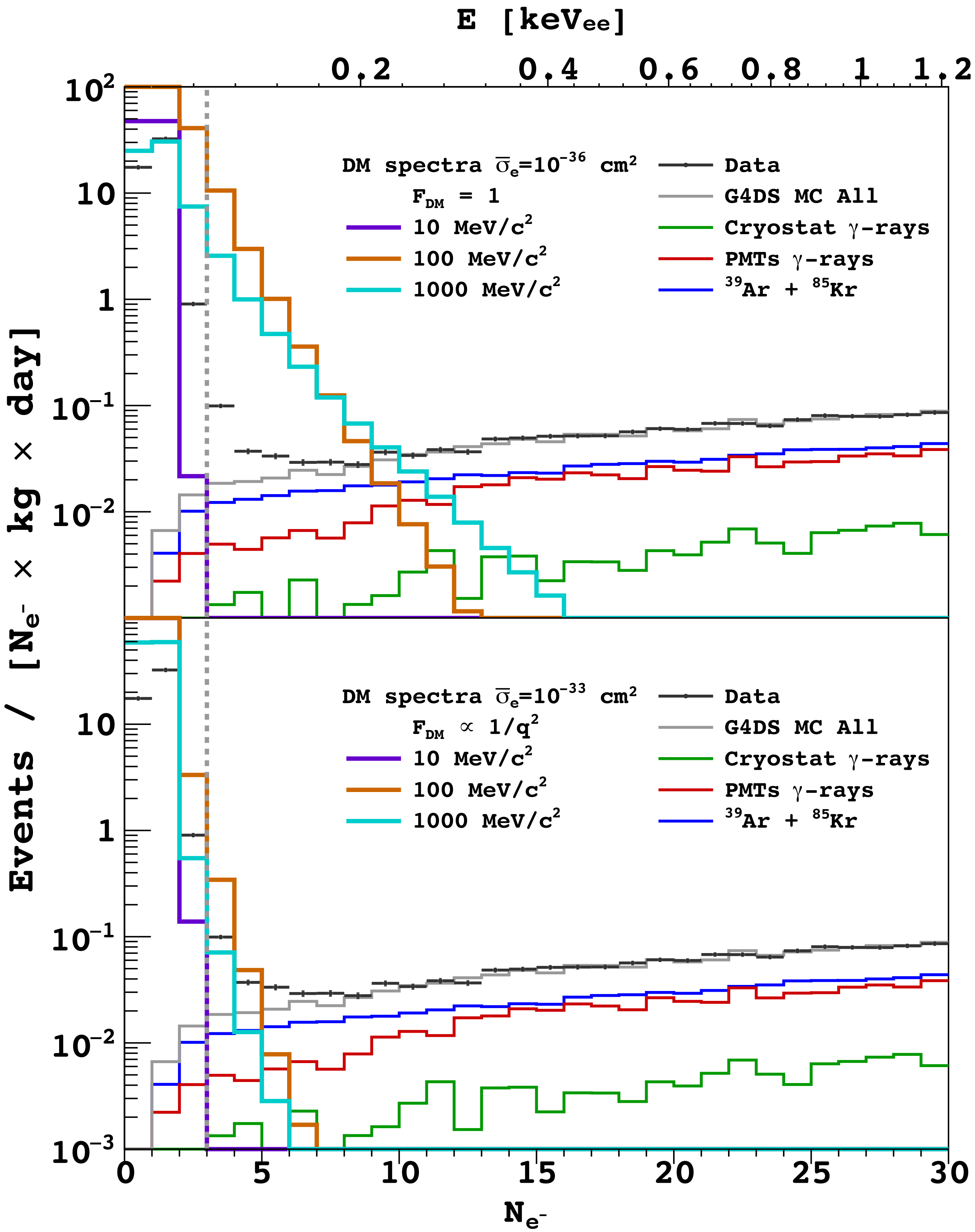
Sub-GeV dark matter search

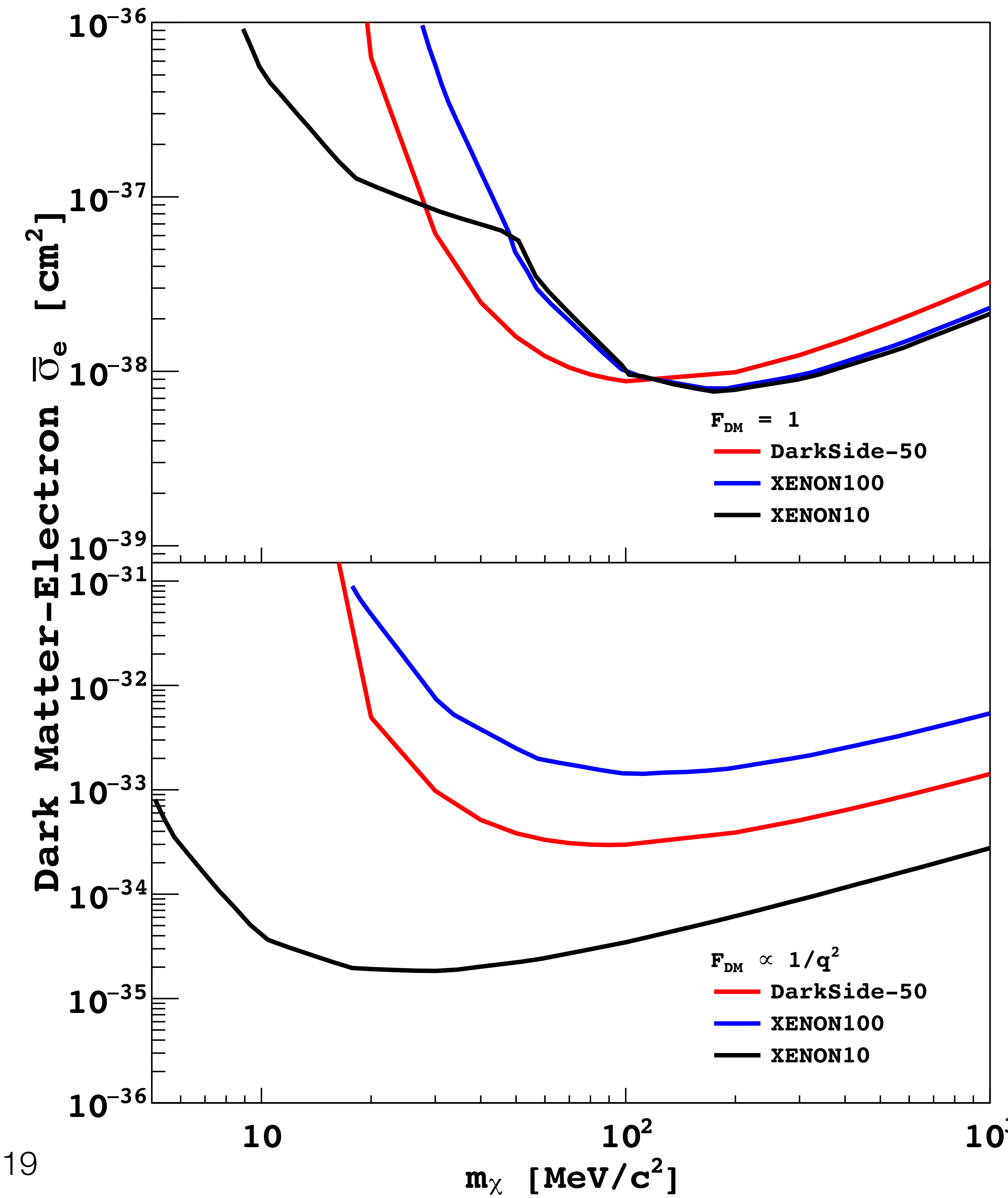
- WIMP-electron interaction parametrized by form factor $F_{DM} = F_{DM}(q)$ which, depending on the mass of the mediator ($m_{A'}$) has different asymptotic momentum (q) dependence:
  - $F_{DM} \approx 1$ (heavy mediator)
  - $F_{DM} \approx 1/q^2$ (light mediator)

- ^{37}Ar X-rays are used to convert electron recoil spectra to ionization spectra:
  - L-shell: 0.27 keV
  - K-shell: 2.82 keV



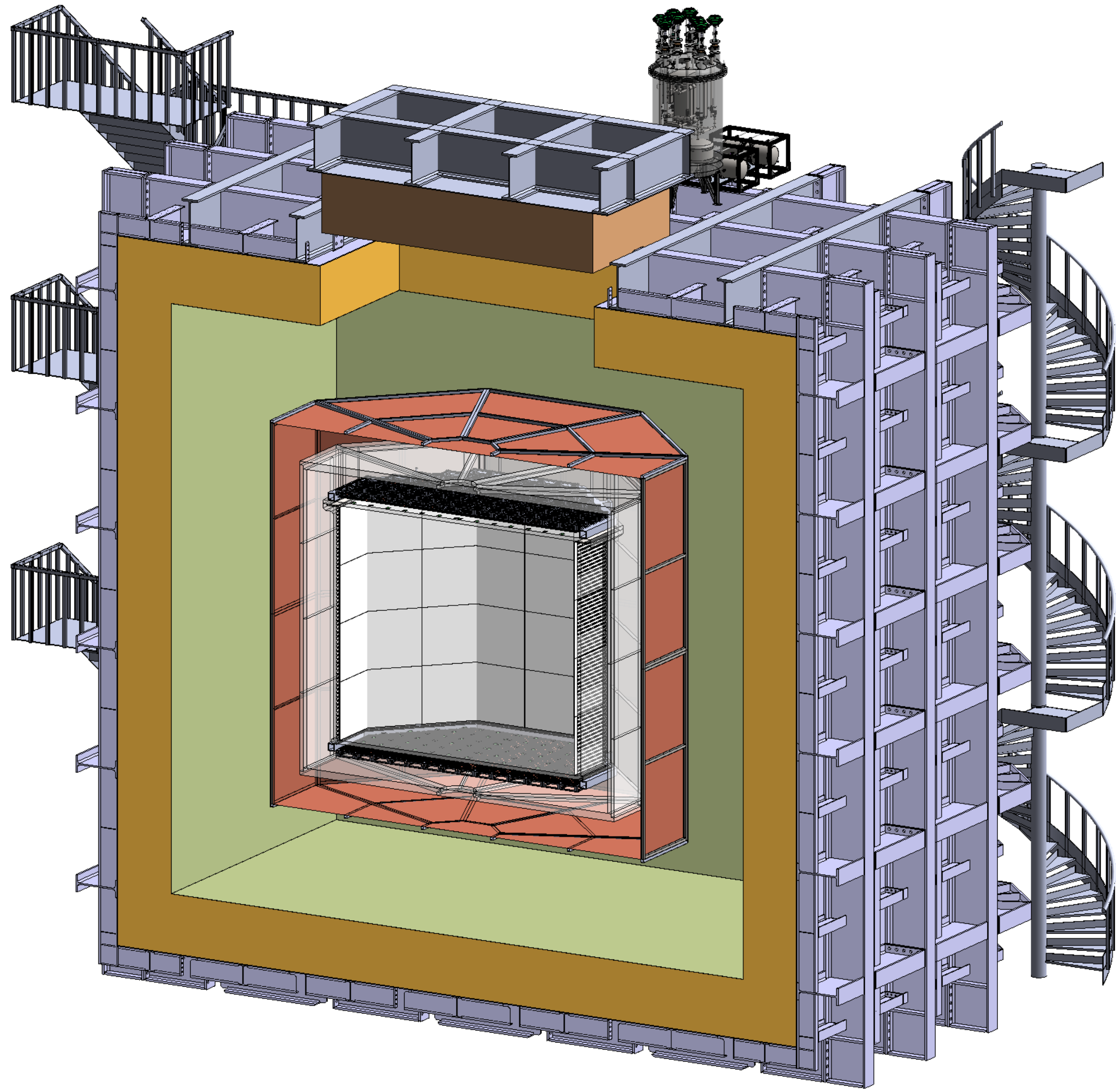
Sub-GeV dark matter search





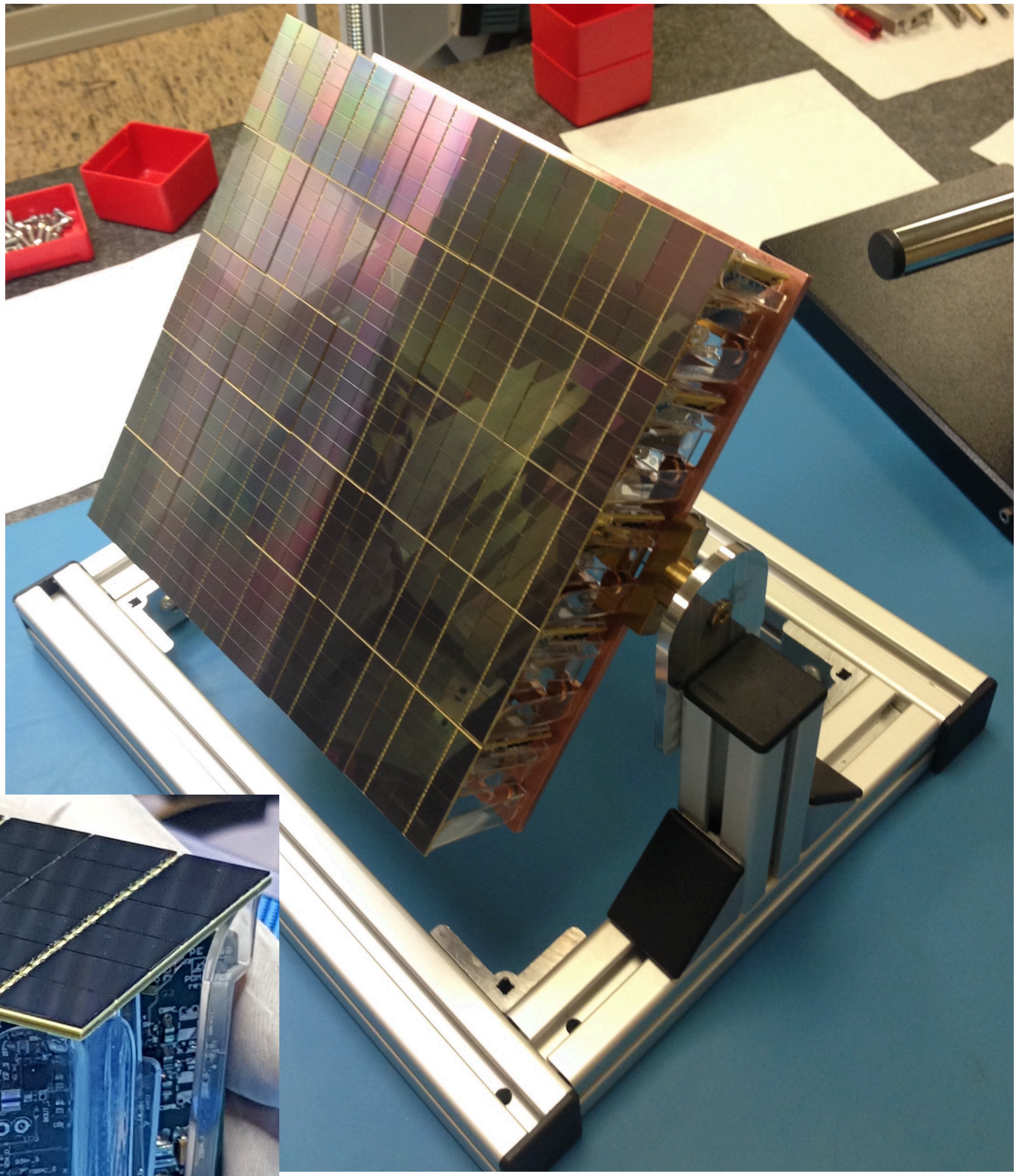
DarkSide program: what's next?

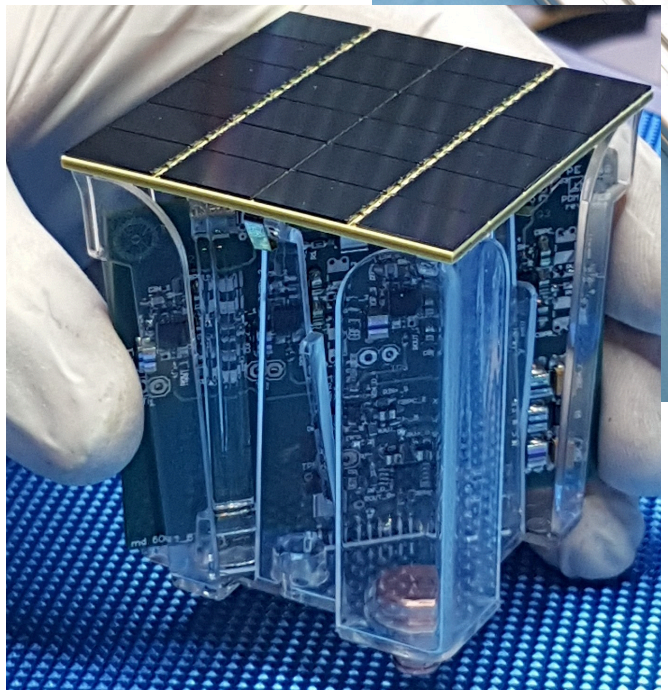
- DarkSide-20k @ LNGS
- Sealed acrylic TPC containing 50 tonnes of UAr in a ProtoDUNE-like cryostat filled with ~700 tonnes of AAr
- 30 m^2 SiPMs as photosensors (8280 channels for TPC and ~3000 channels for Veto)
- Gd-doped acrylic panels as neutron veto



SiPMs to replace PMTs

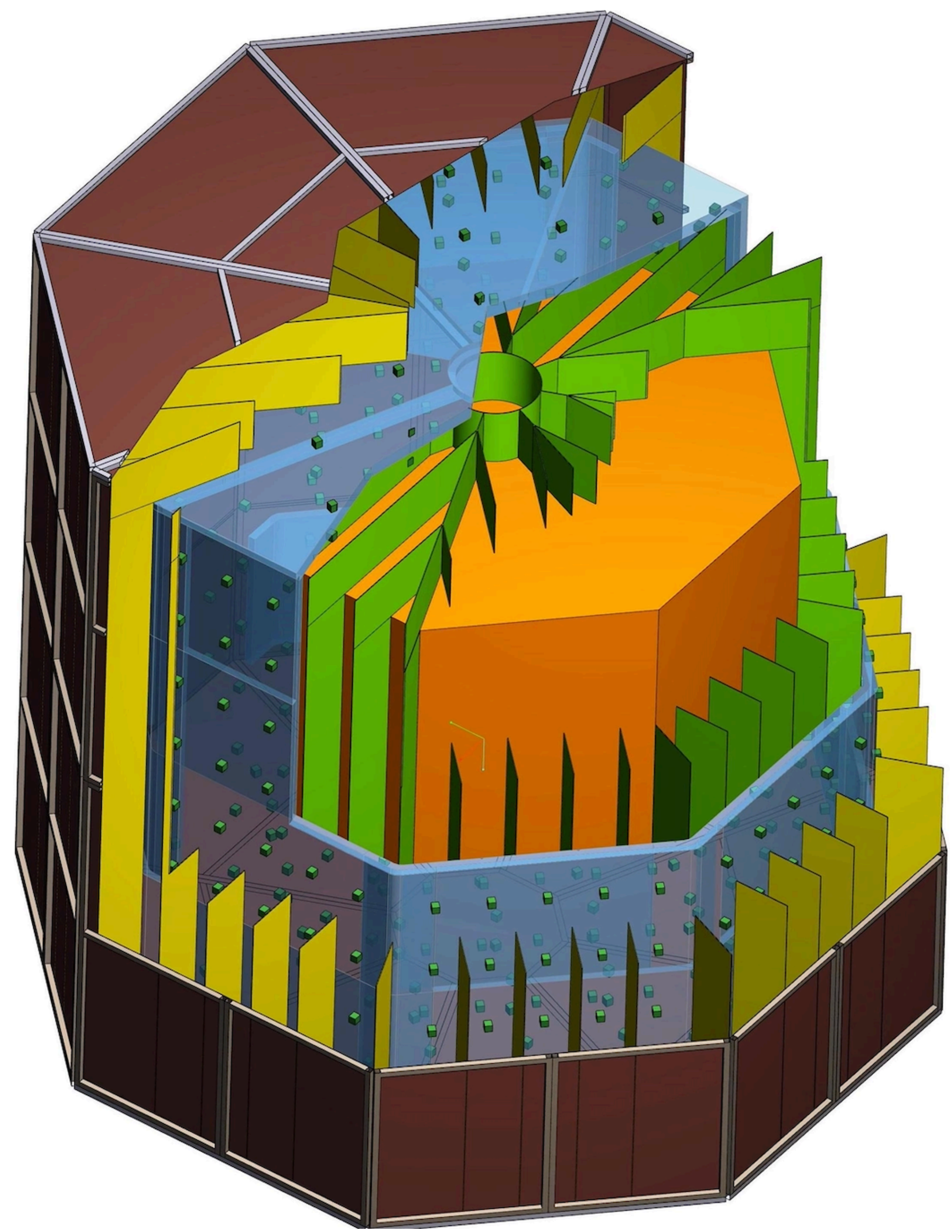
- Developed for LAr by a combined effort between DarkSide and FBK
- Compact and high coverage
- High S/N (>8)
- High PDE (~50%)
- SiPMs mass production by LFoundry and packaging of PDM and in NOA, L'Aquila
- Full production chain largely funded by Regione Abruzzo, Italy





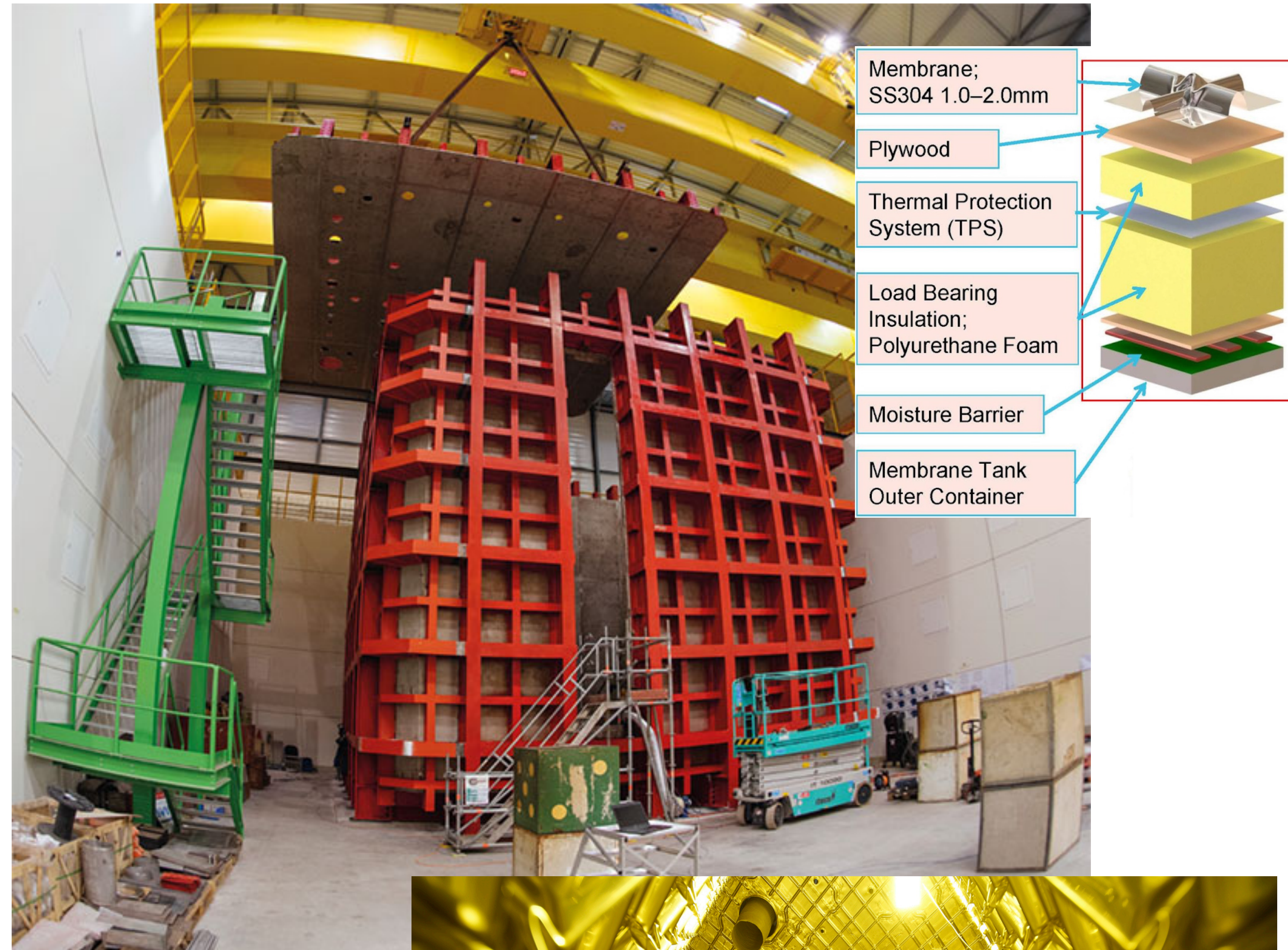
A new neutron veto concept

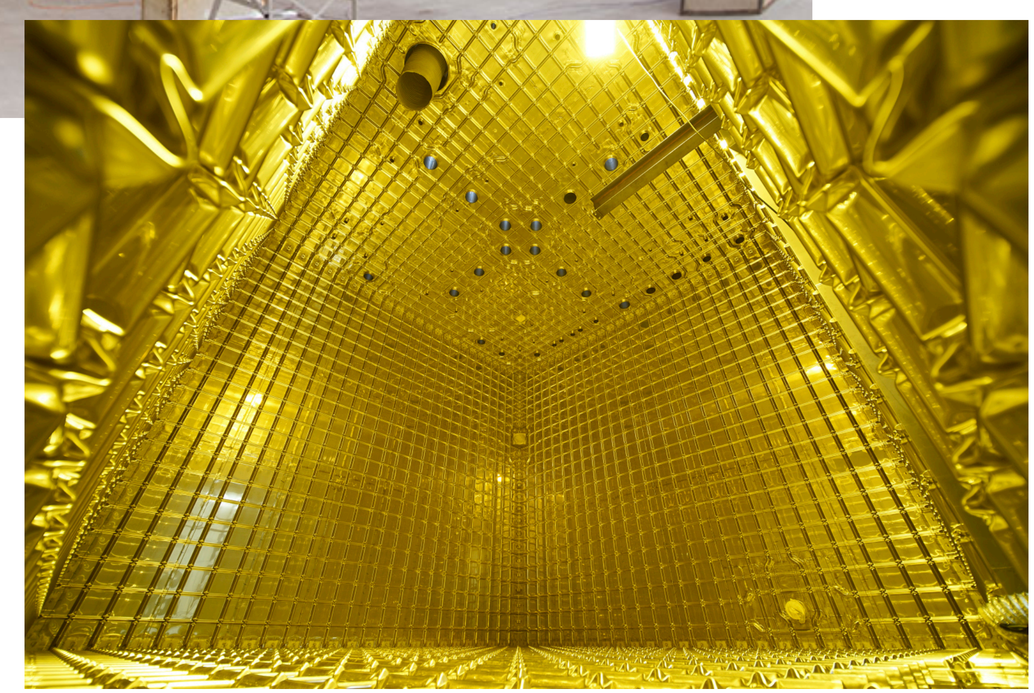
- 4π coverage
- 10cm thick passive Gd-loaded acrylic shell to moderate and capture neutrons
- 40cm thick inner and outer active liquid AAr volumes to detect gamma cascade due to neutron captured on Gd
- Faraday cage to optically and electrically isolate both veto and TPC
- Vertical segmentations to reduce pile-up rate of ^{39}Ar (1Bq/kg in AAr) event from AAr and ESR foil as reflector to maximize light collection
- All internal surface of each sector coated with TPB as wavelength shifter



ProtoDUNE-like cryostat

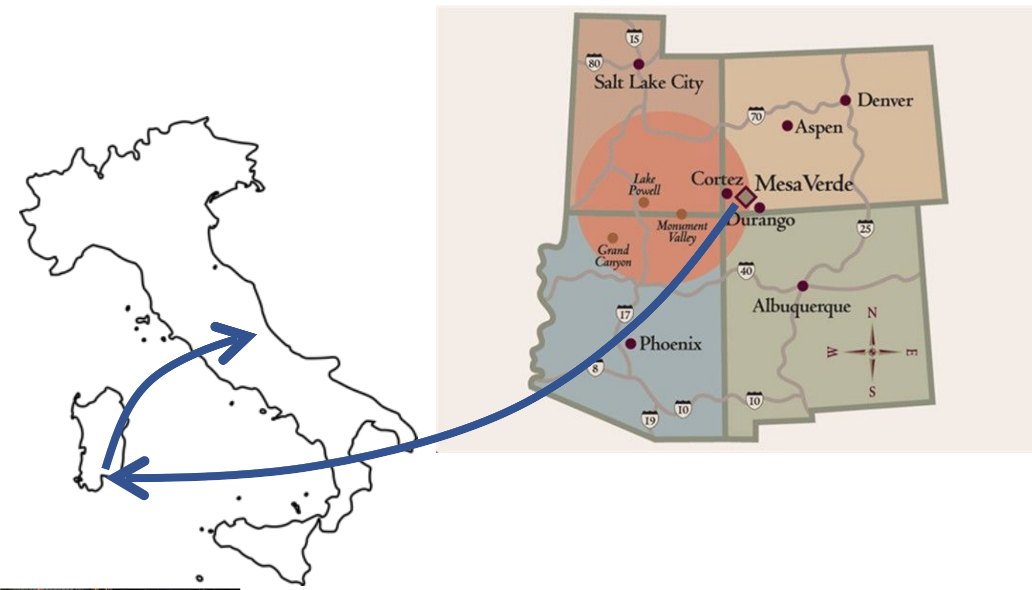
- Technology developed at CERN for ProtoDUNE experiment
- Membrane + passive thermal insulation
- Matured technique adopted from the Liquified Natural Gas carriers and vessels
- Access and support of TPC and Veto from top roof





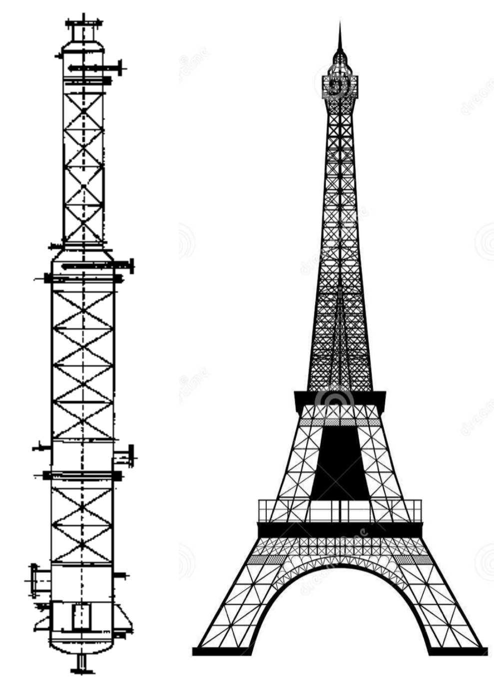
Low-radioactive argon procurement and purification

- **Urania:** procurement of at least 60 tonnes of UAr from Colorado, USA (same as DS50) withe extraction rate of 250 kg/day, with 99.9% purity



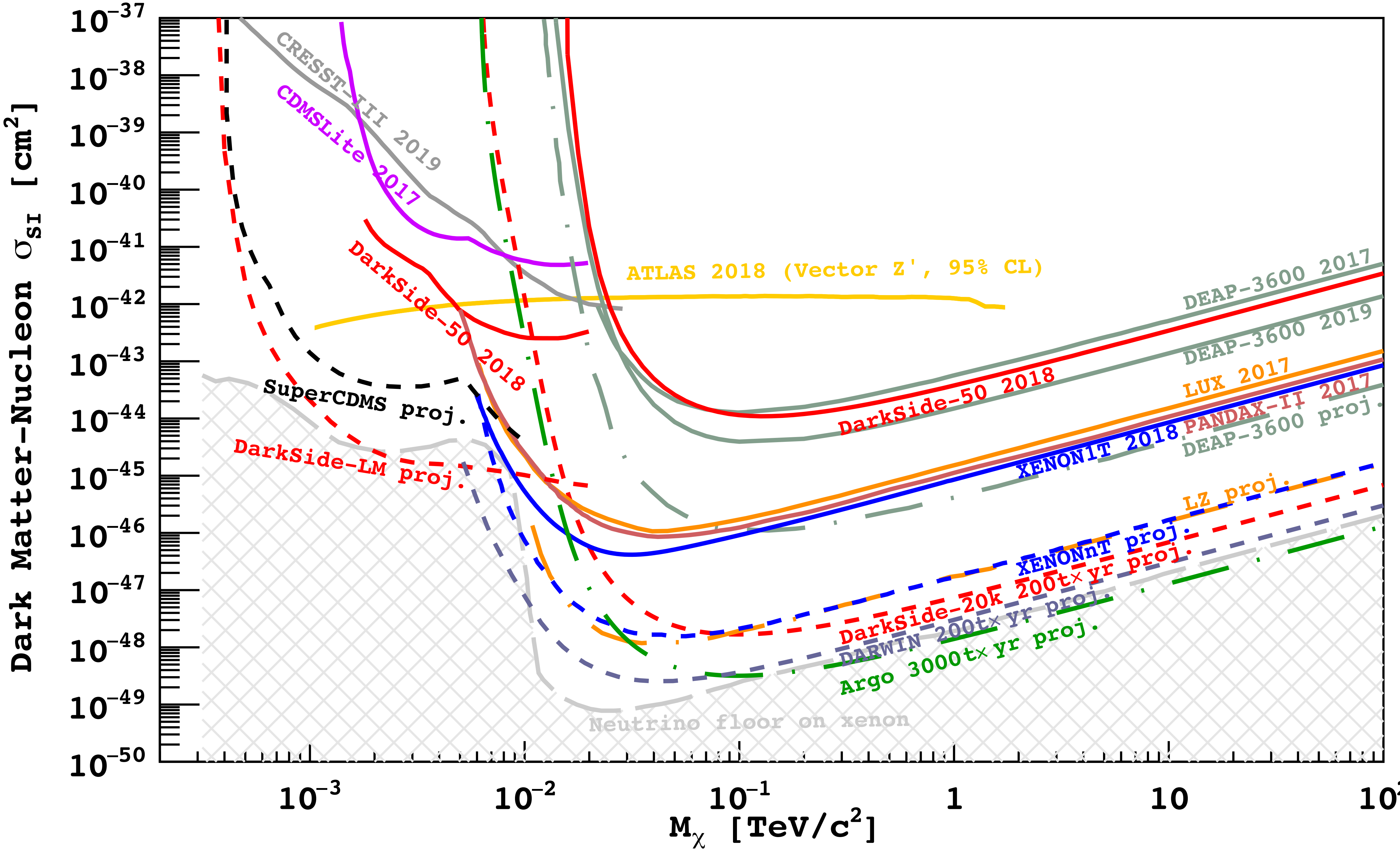
- **Aria:** UAr transported to Sardinia, Italy for final chemical purification via a 350m tall cryogenic distillation column in Seruci, Sardinia, Italy
    - Process ~1 tonne/day with 1000 reduction of all chemical impurities and isotopically separate ^{39}Ar from ^{40}Ar

Seruci-0 - prototype



Seruci-I and II

Projected sensitivity



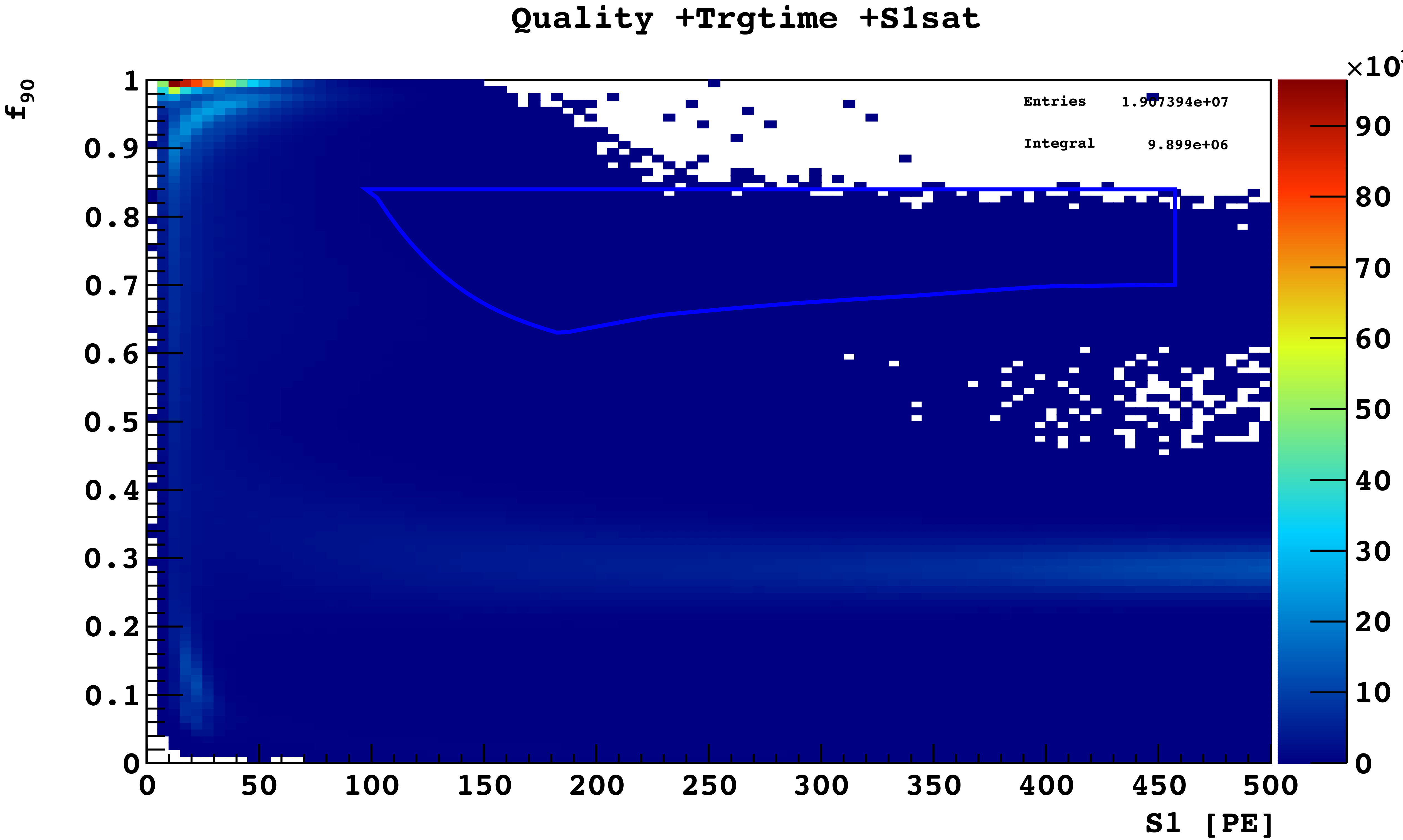
Conclusions

- DarkSide-50 results proved LAr technology is competitive both for high- (background free) and low-mass (best sensitivity for 1.8-5.5 GeV) WIMP searches

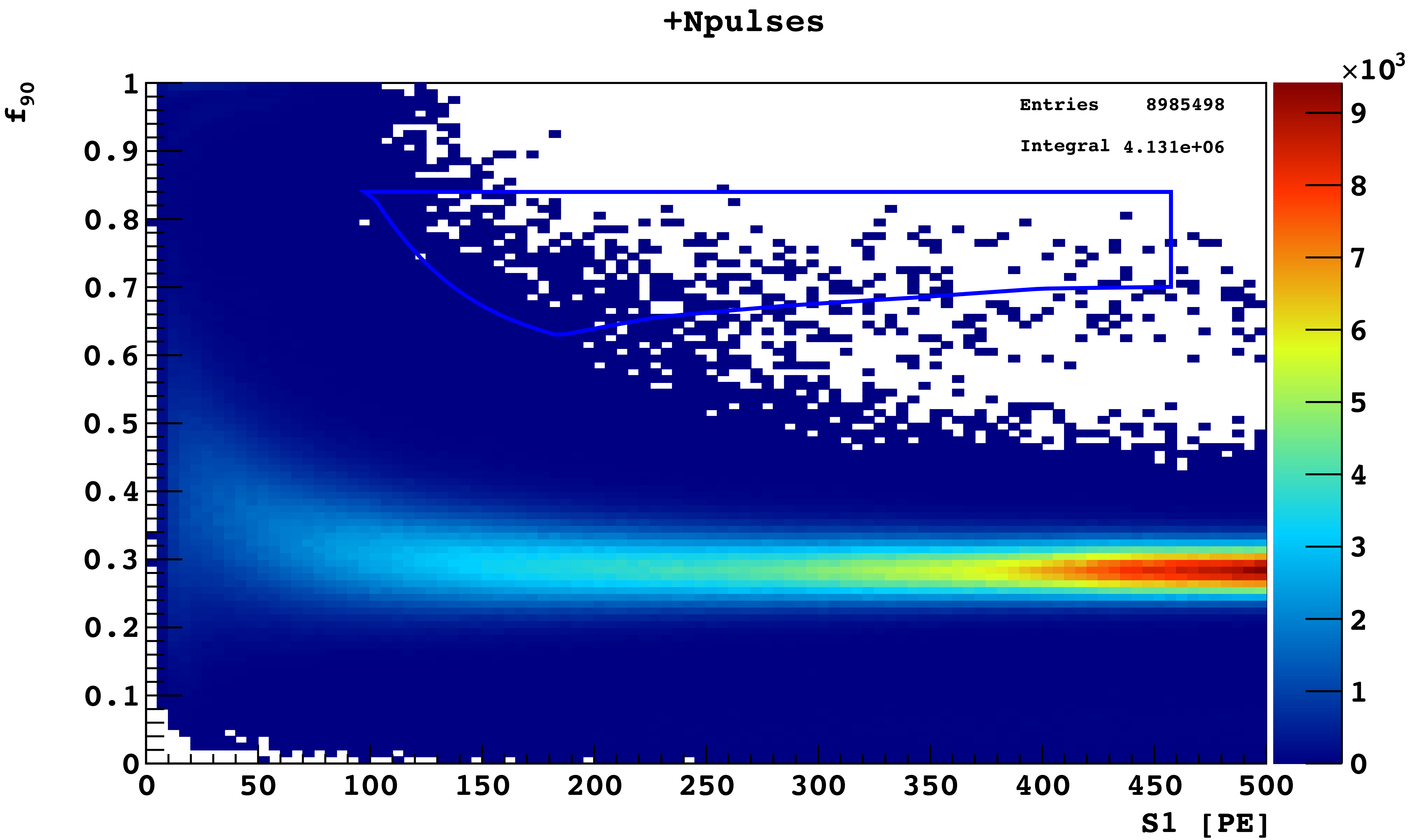
- Ambitious dark matter search program with DarkSide-20k which is developing essential technologies on several fronts

- LAr technology is very promising to lead the path towards the neutrino floor in both high- and low-mass WIMP regions

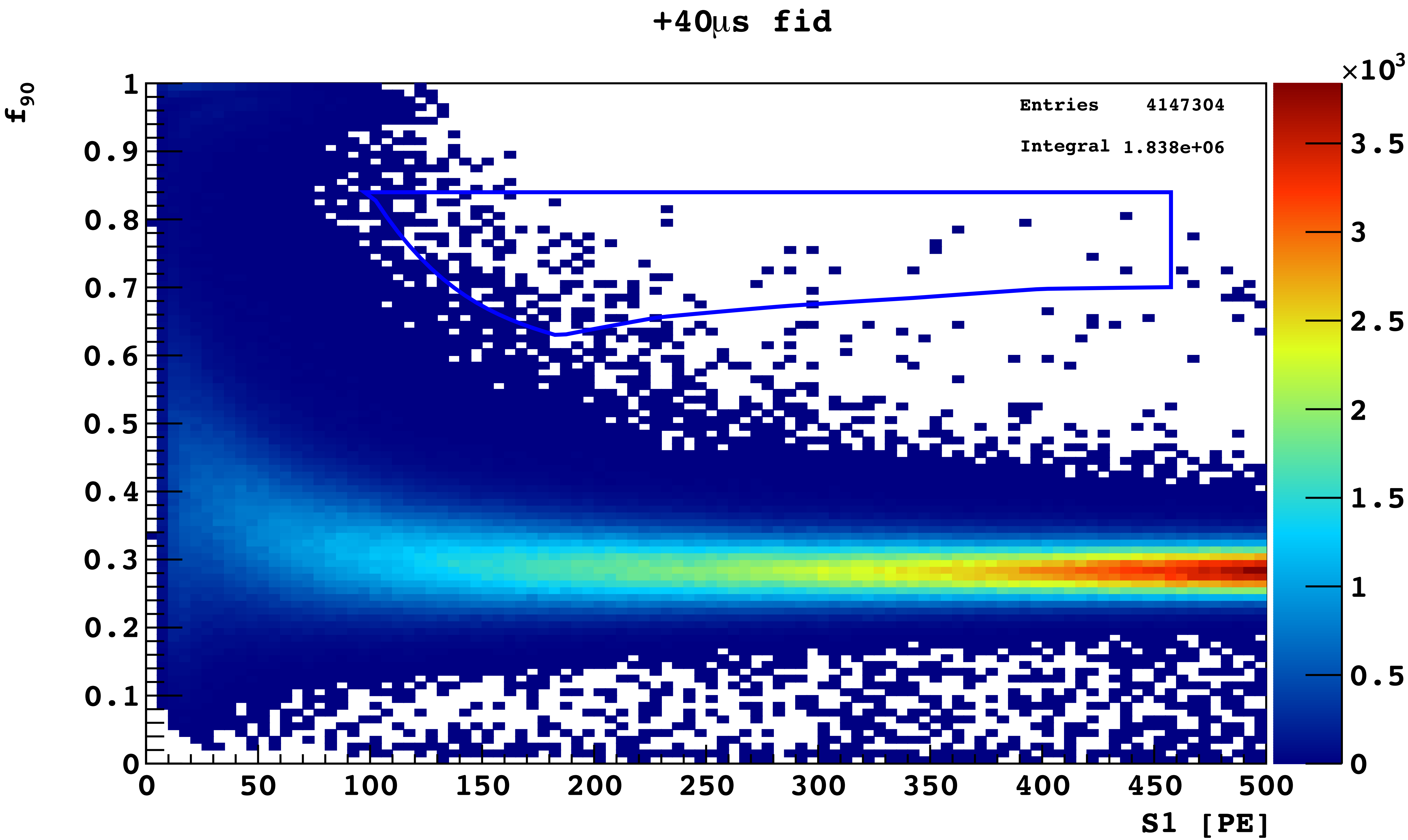
Backups



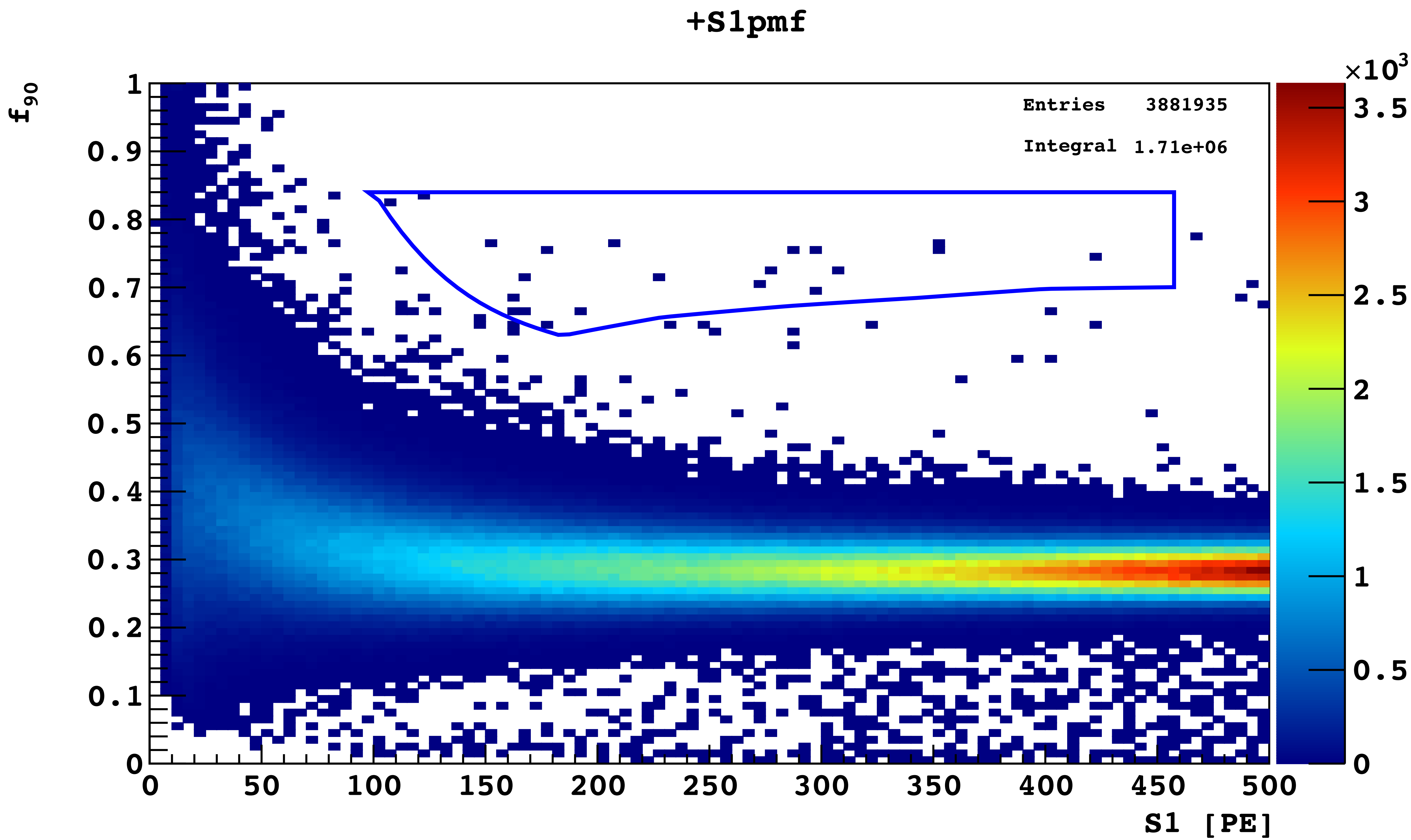
- Trigtime: the first pulse is within expected trigger time window
- S1sat: S1 pulse is not saturated



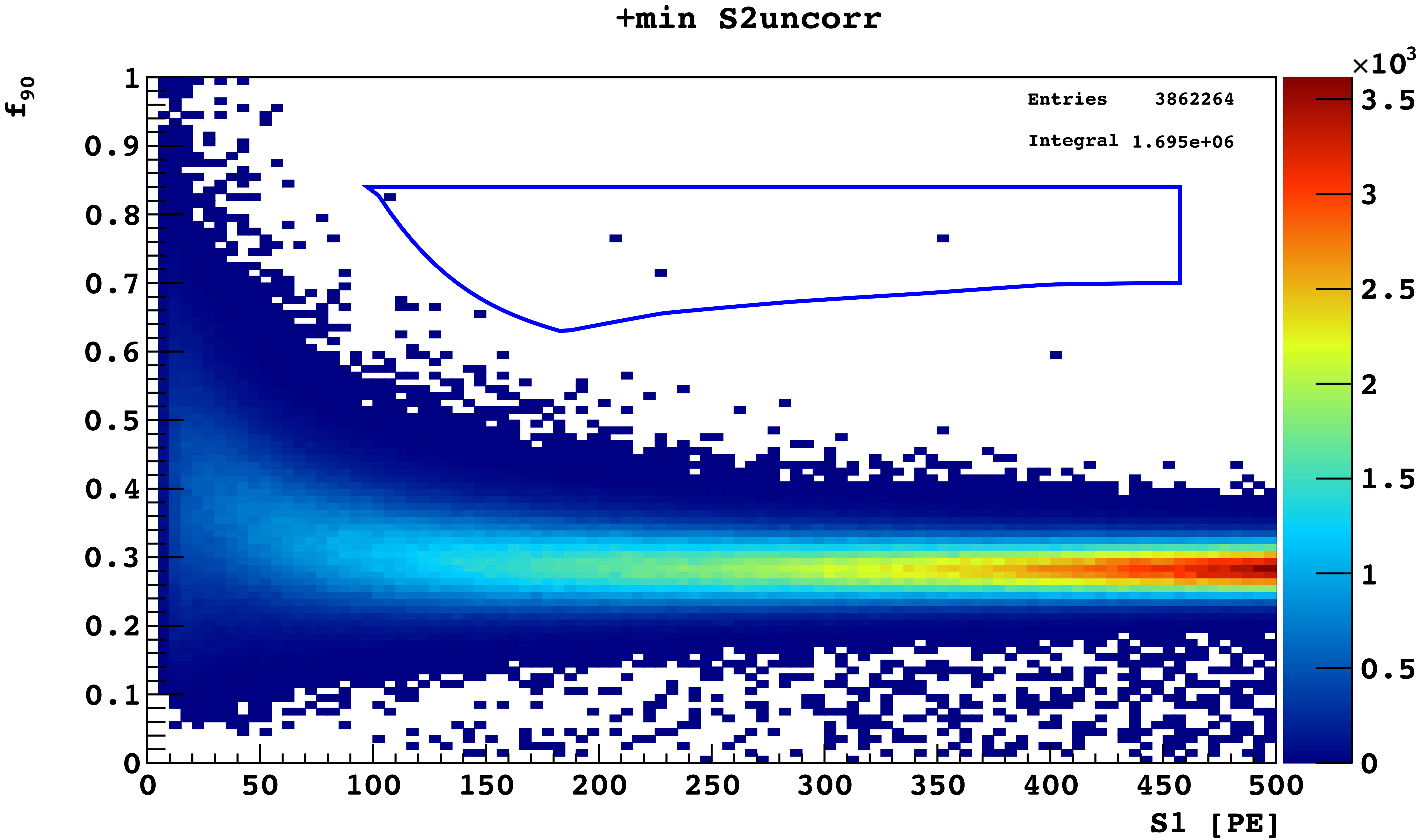
- Npulses: number of pulse is 2 or 3 if there is S3 (echo of S2)
- Most of surface events are gone



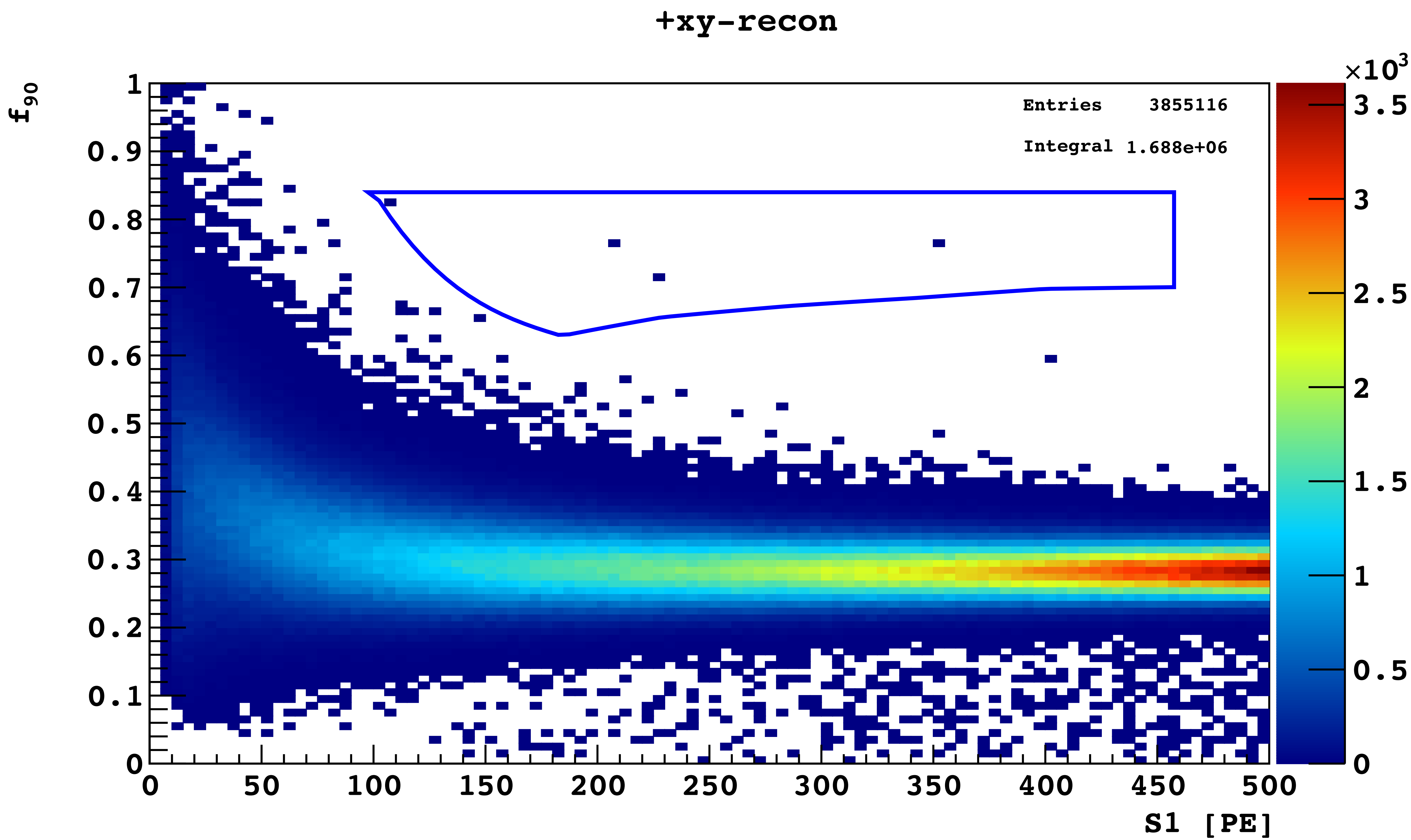
- 40μs fid: remove 40μs from top and bottom in t_drift
- Lots of ɣs from PMTs, unresolved S1+S2 events, and surface close to top are removed



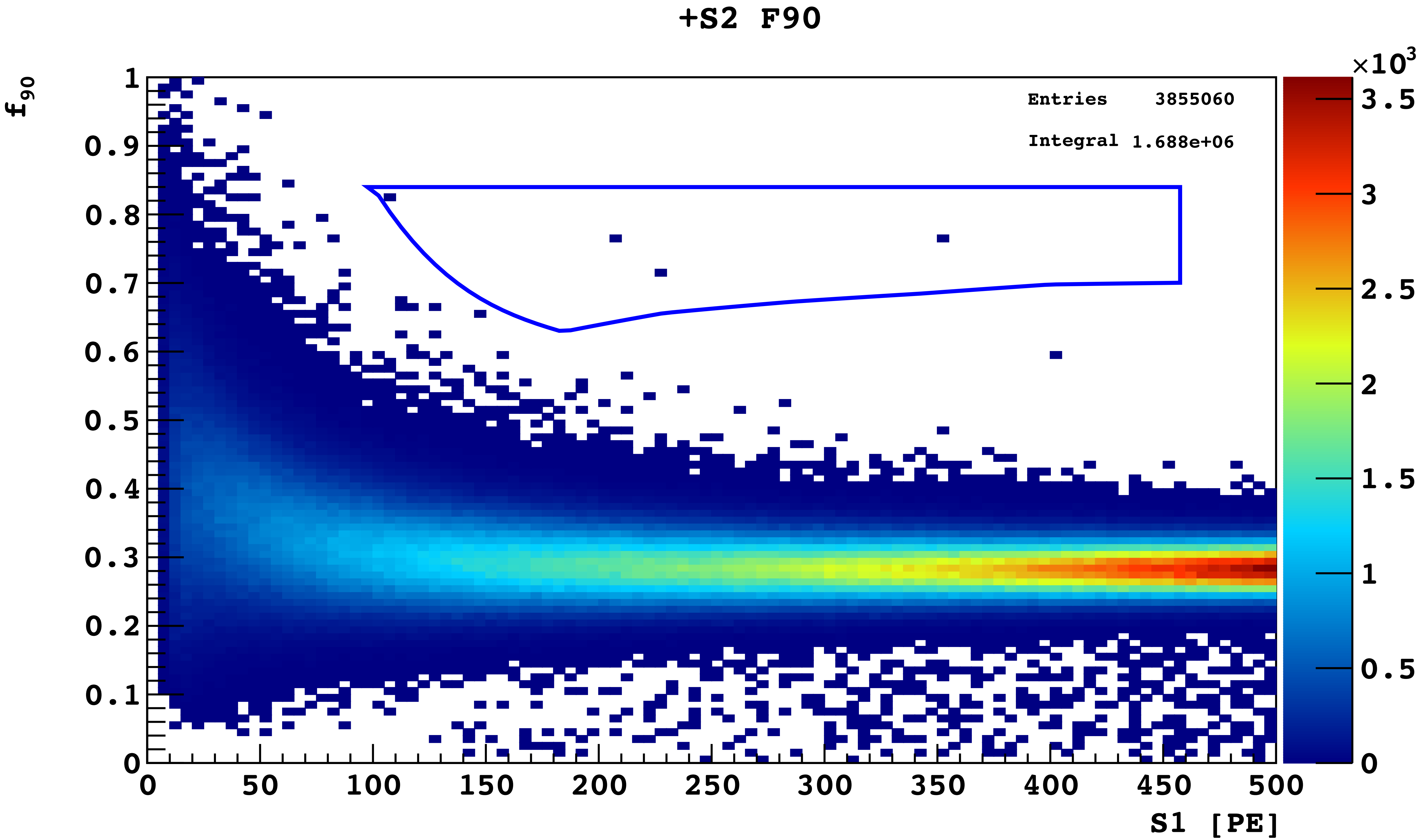
- S1pmf: fraction of prompt light in the maximum PMT is less than a threshold, which is a function of t_drift and S1
- Remove S1+Cherenkov events from fused silica windows



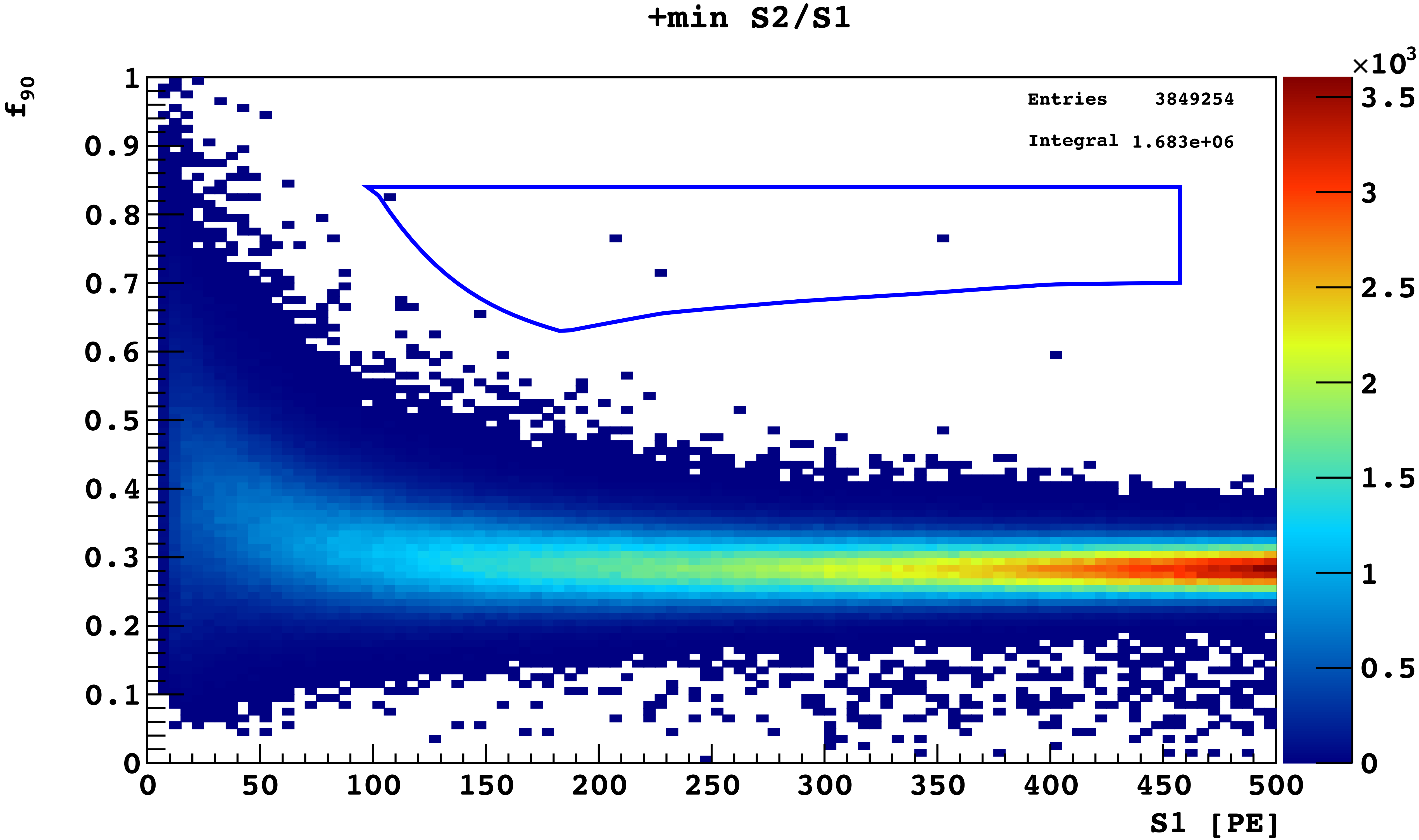
- min S2uncorr: S2≥200 PE
- This is more like quality cut, but remove surface events, which number of electrons are reduced by the surface effect



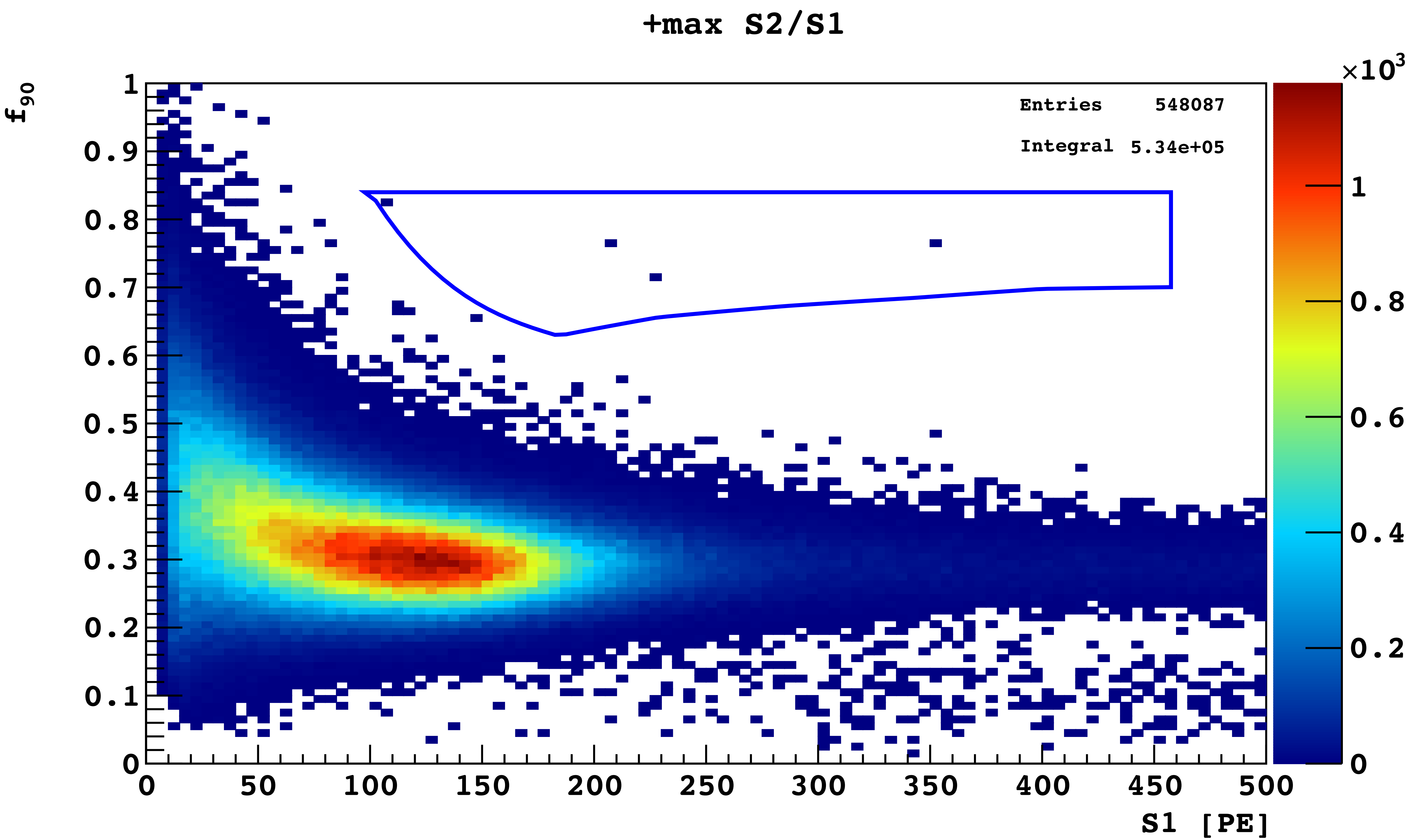
- xy-recon: reasonable x-y reconstructed values



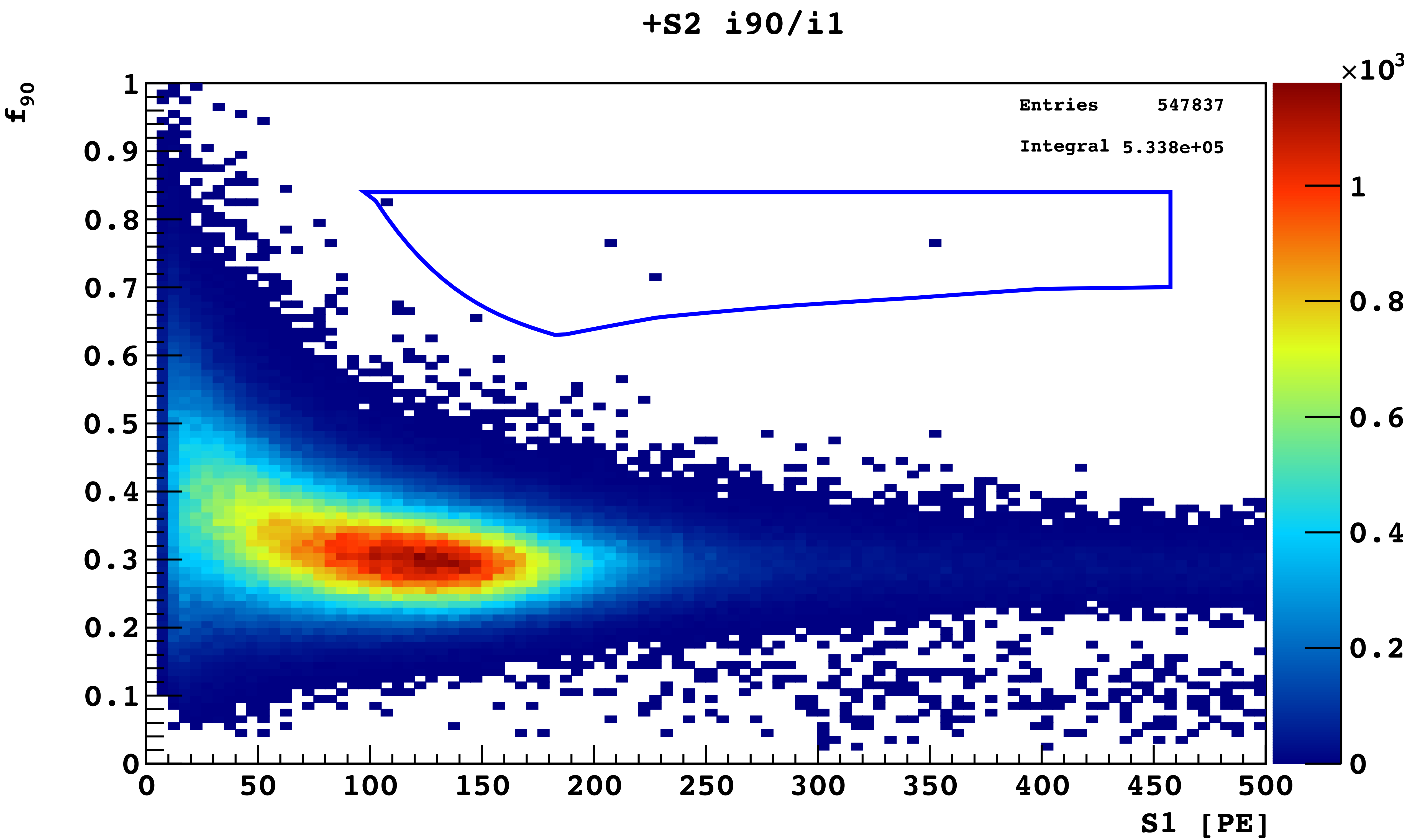
- S2 f90: f90 of S2 pulse <0.20
- Remove S1+S1 pileup events



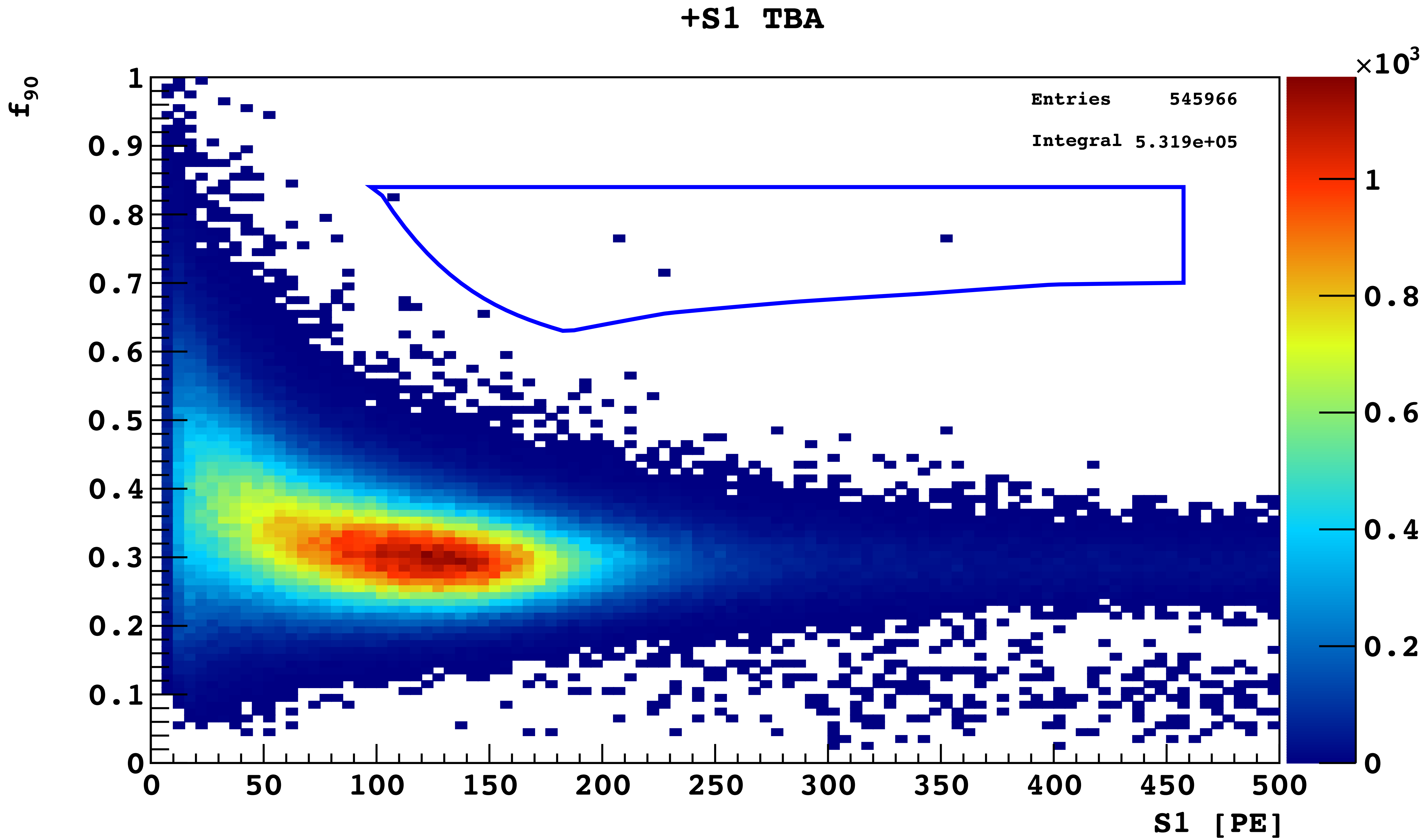
- min S2/S1: S2/S1 need to be above threshold, which is a function of S1
- Remove strangely small S2 events, like surface events



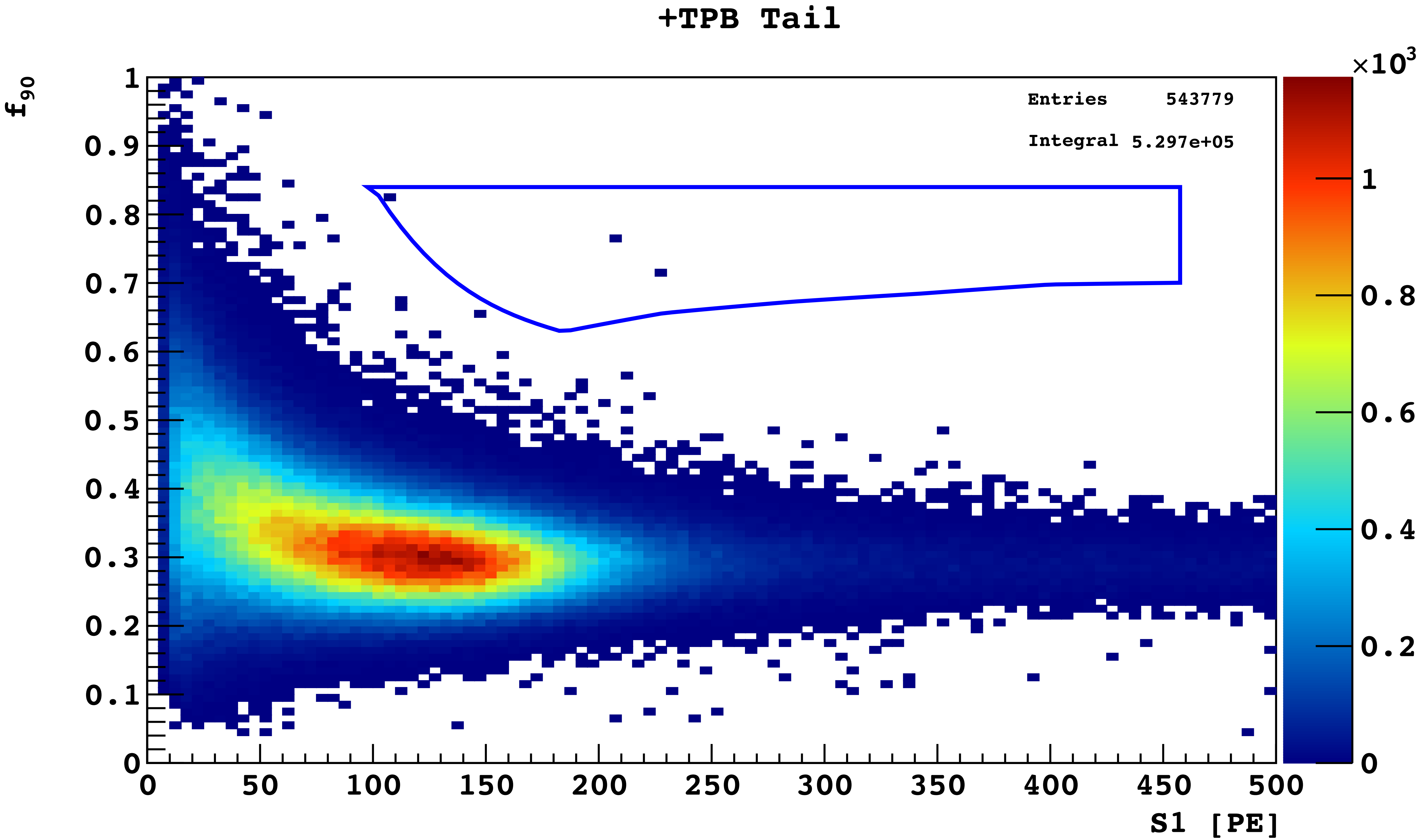
- max S2/S1: S2/S1 need to be below threshold, which is a function of S1
- Remove strangely large S2 events, which we don't expect, but applied as a safety net



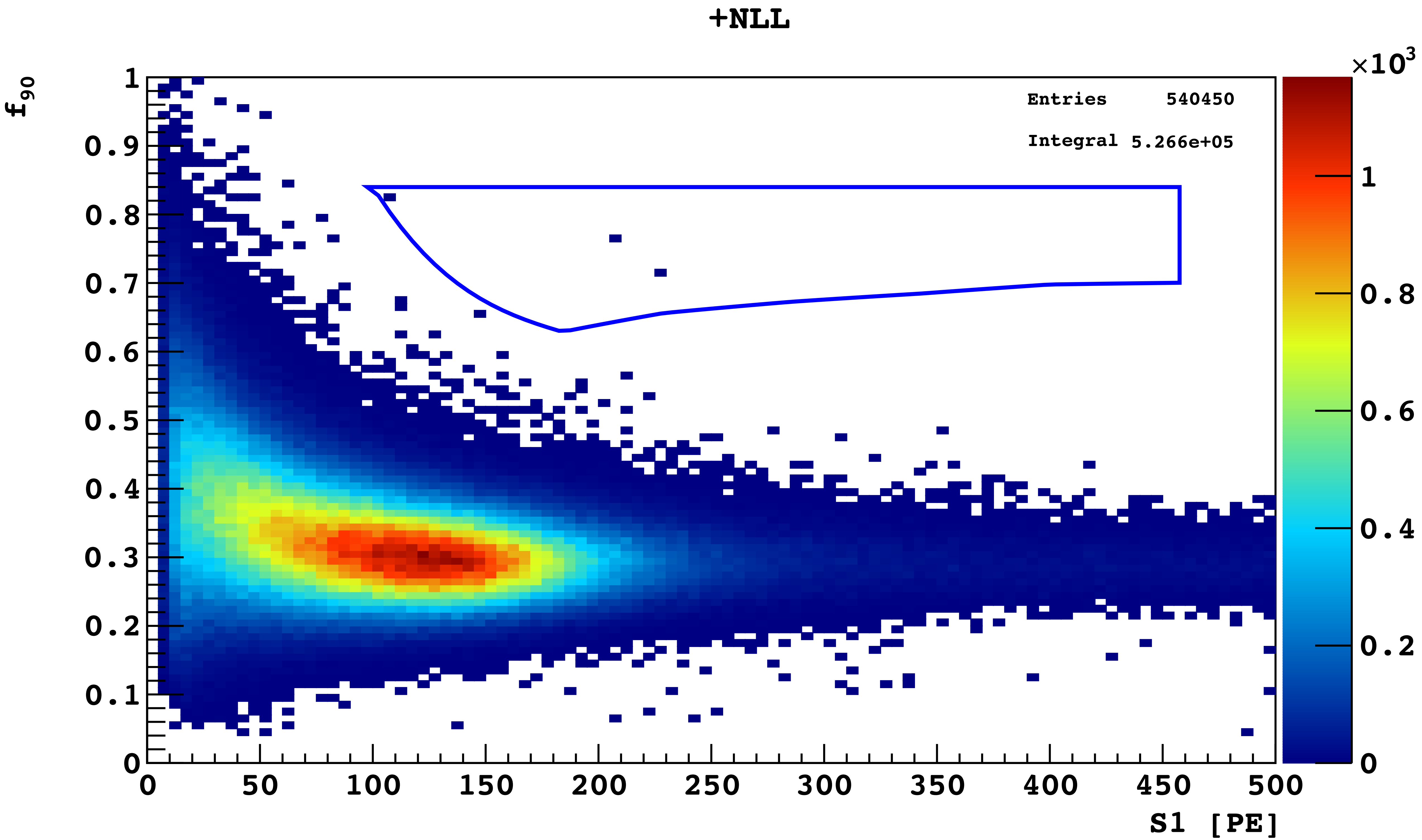
- S2 i90/i1: S2 have reasonable rise time
- Remove events in which S2 is actually S1+S2 pulses



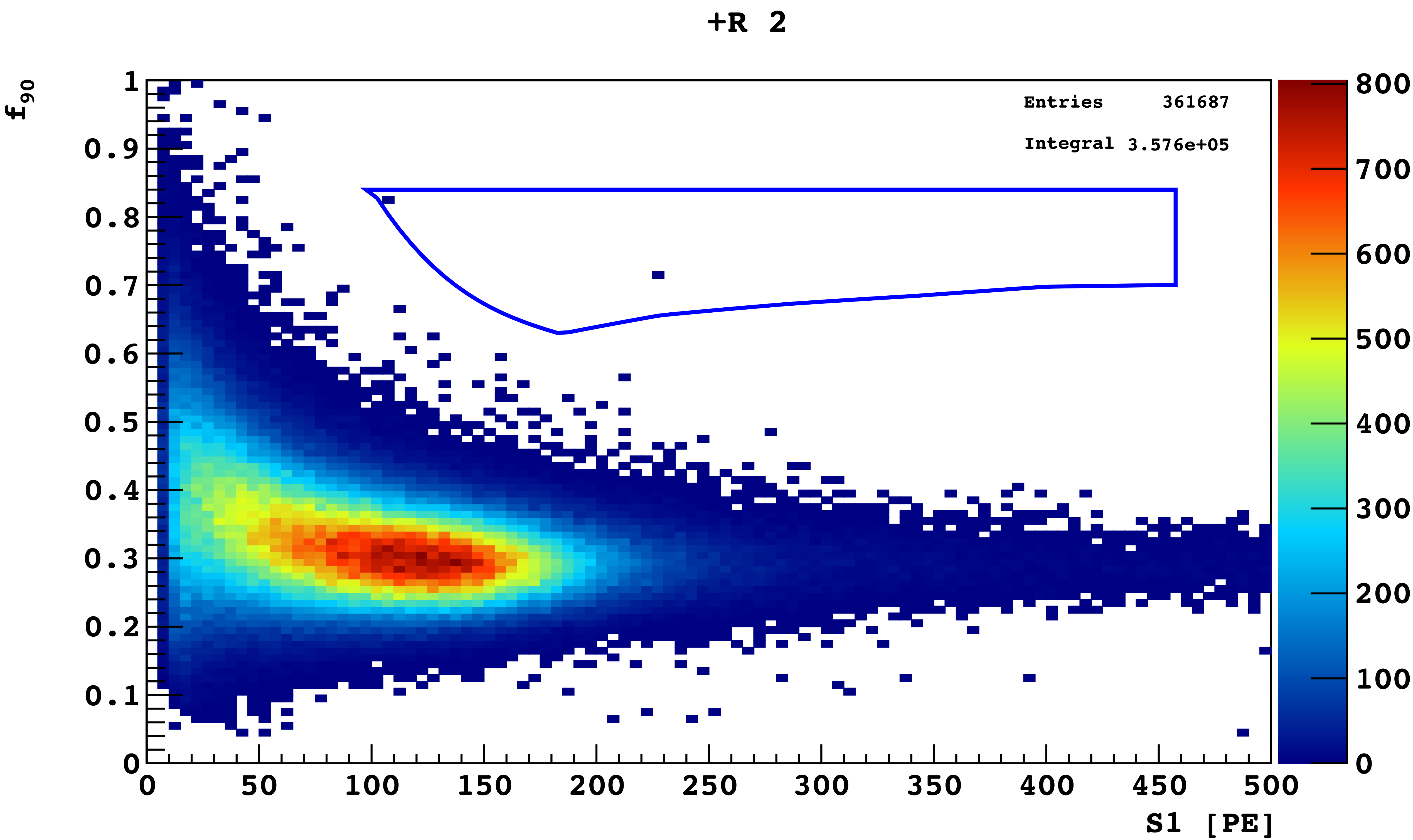
- S1 TBA: z-position from S1 Top-Bottom Asymmetry agrees with t_drift
- Remove random pileup S1 and S2



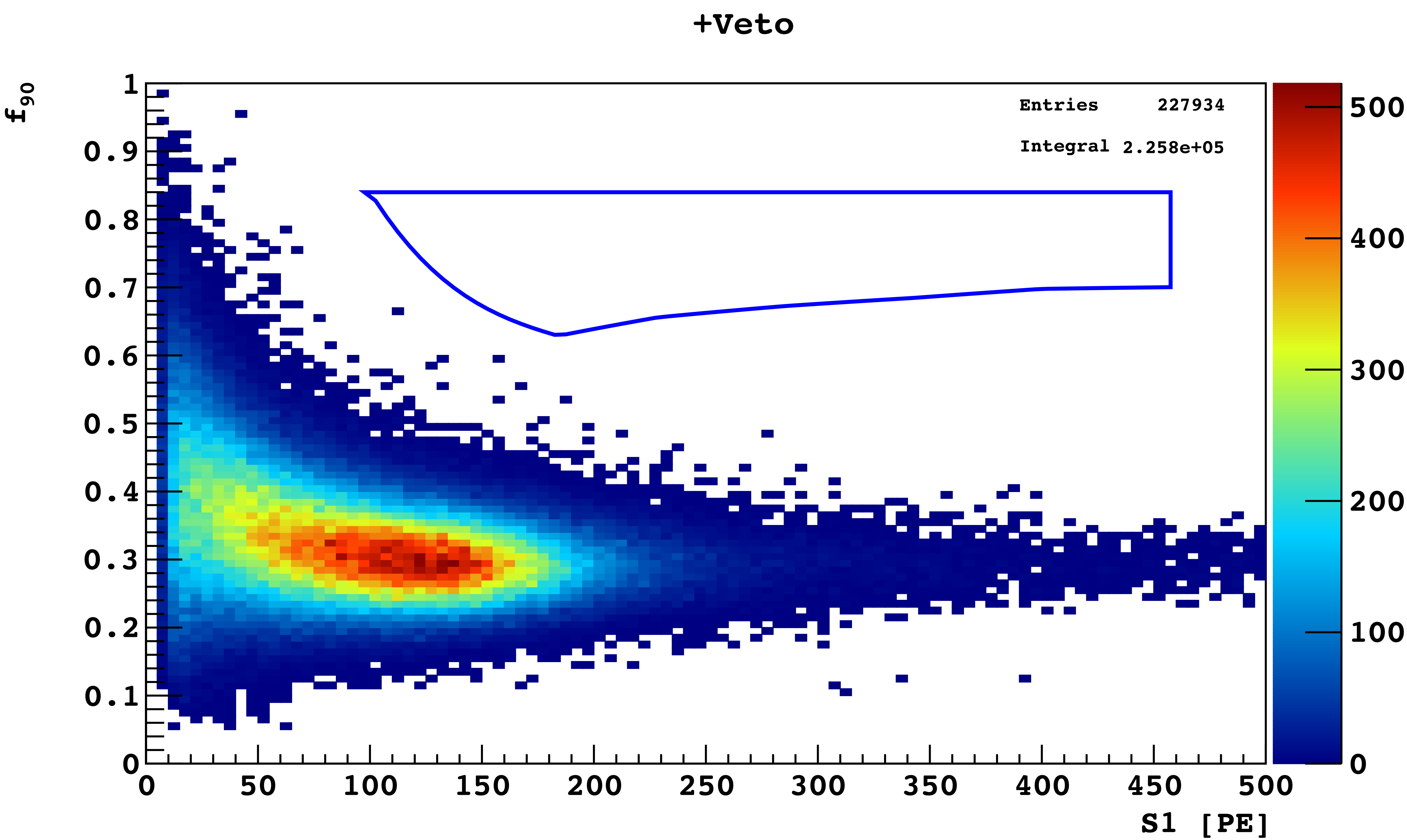
- TPB Tail: remove events, which have long tail of scintillation caused by TPB scintillation
- Remove surface events, in which α goes through TPB layer



- NLL: Negative Log Likelihood cut, which compare event position from S1 light distribution among PMTs and event position from t_drift and S2 x-y
- Remove S1 + Cherenkov events which deposit energy in separate locations

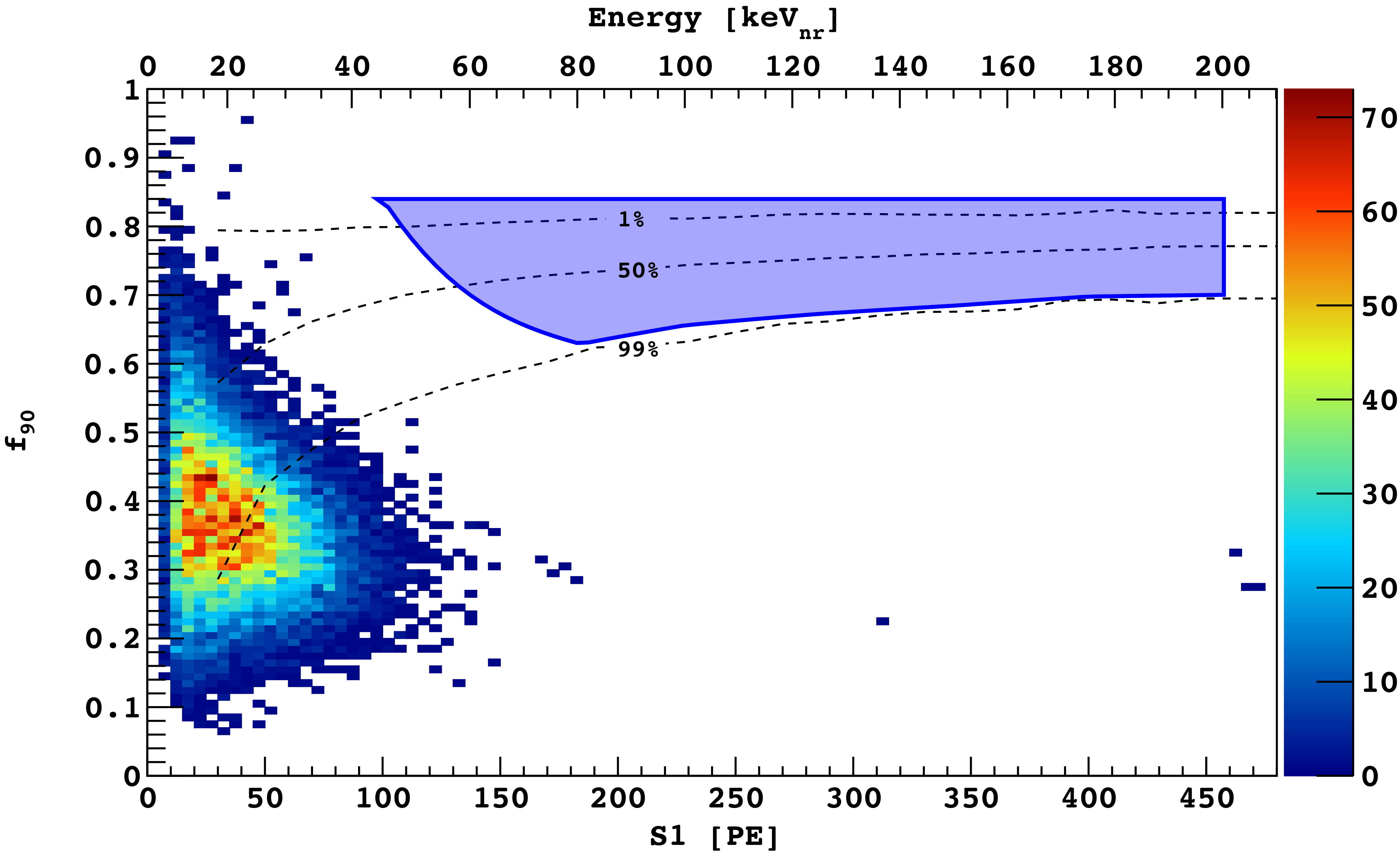


- R 2: Radial cut as a function of t_drift

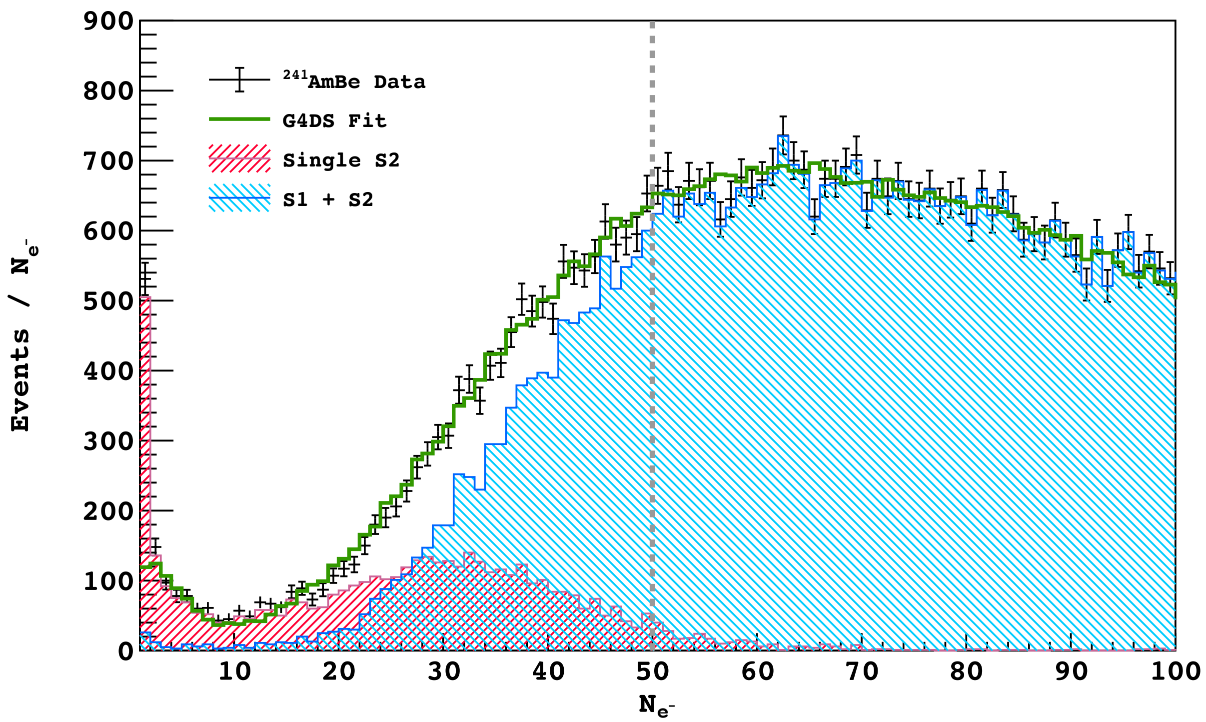


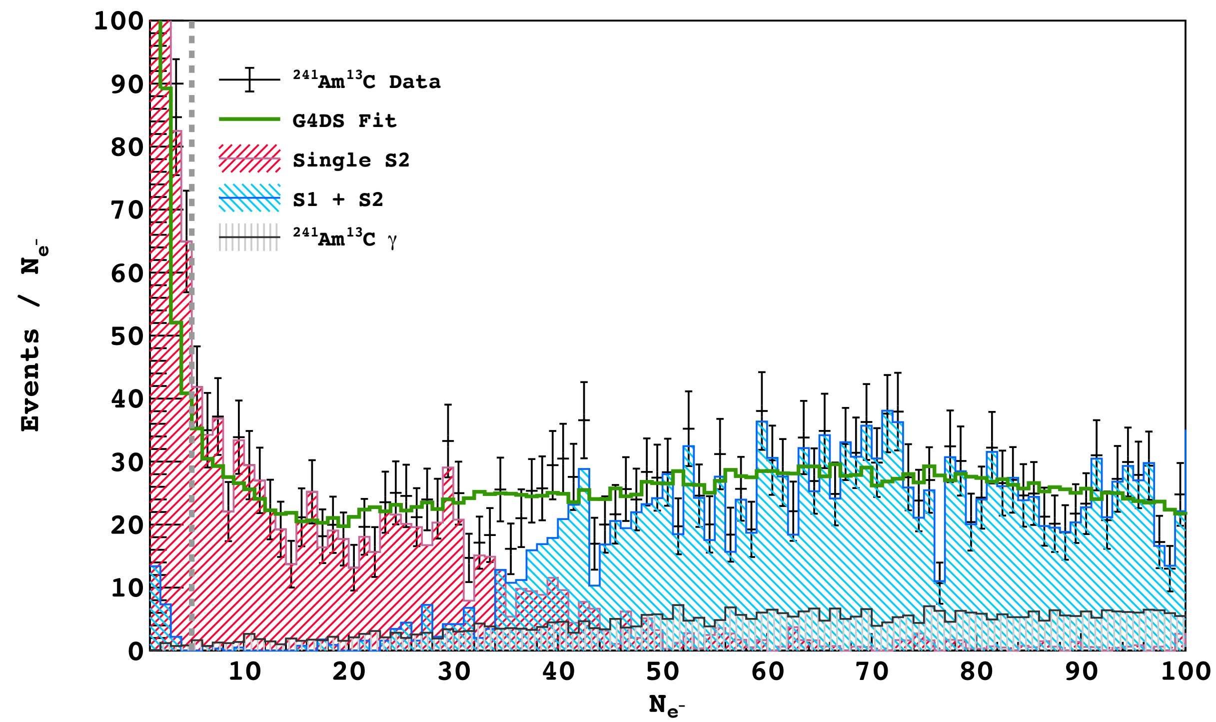
- Veto: all veto cuts
- Remove neutrons

Additional rejection S2/S1



Energy scale for NR





- NR energy scale obtained with AmBe and AmC fitted with Bezrukov model