# New Physics Results from DarkSide-50


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on behalf of the **DarkSide-50 Collaboration**


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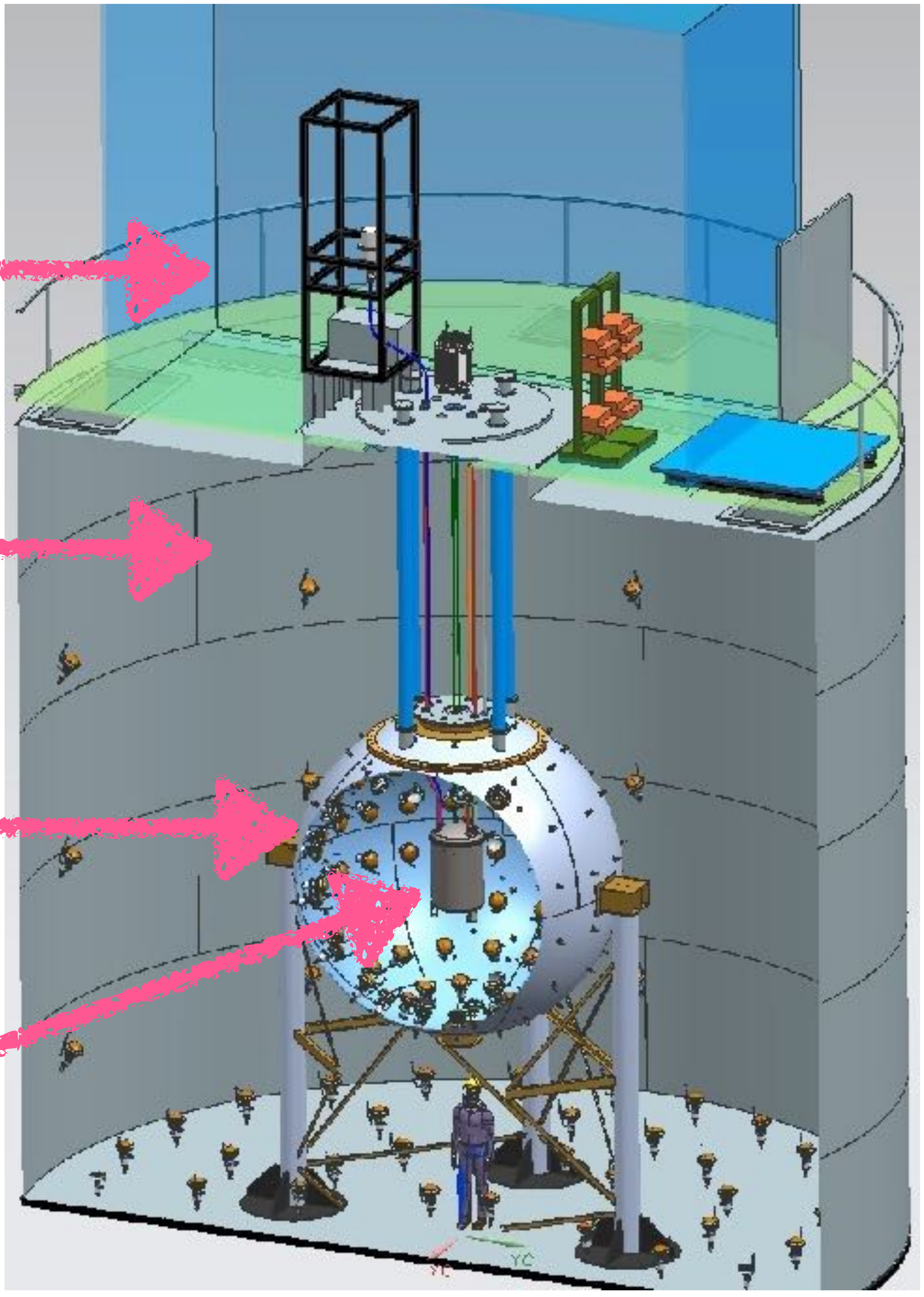
# DARKSIDE 50

Radon-free (Rn levels < 5 mBq/m$^3$)
**Assembly Clean Room**

1,000-tonne Water Cherenkov
**Cosmic Ray Veto**

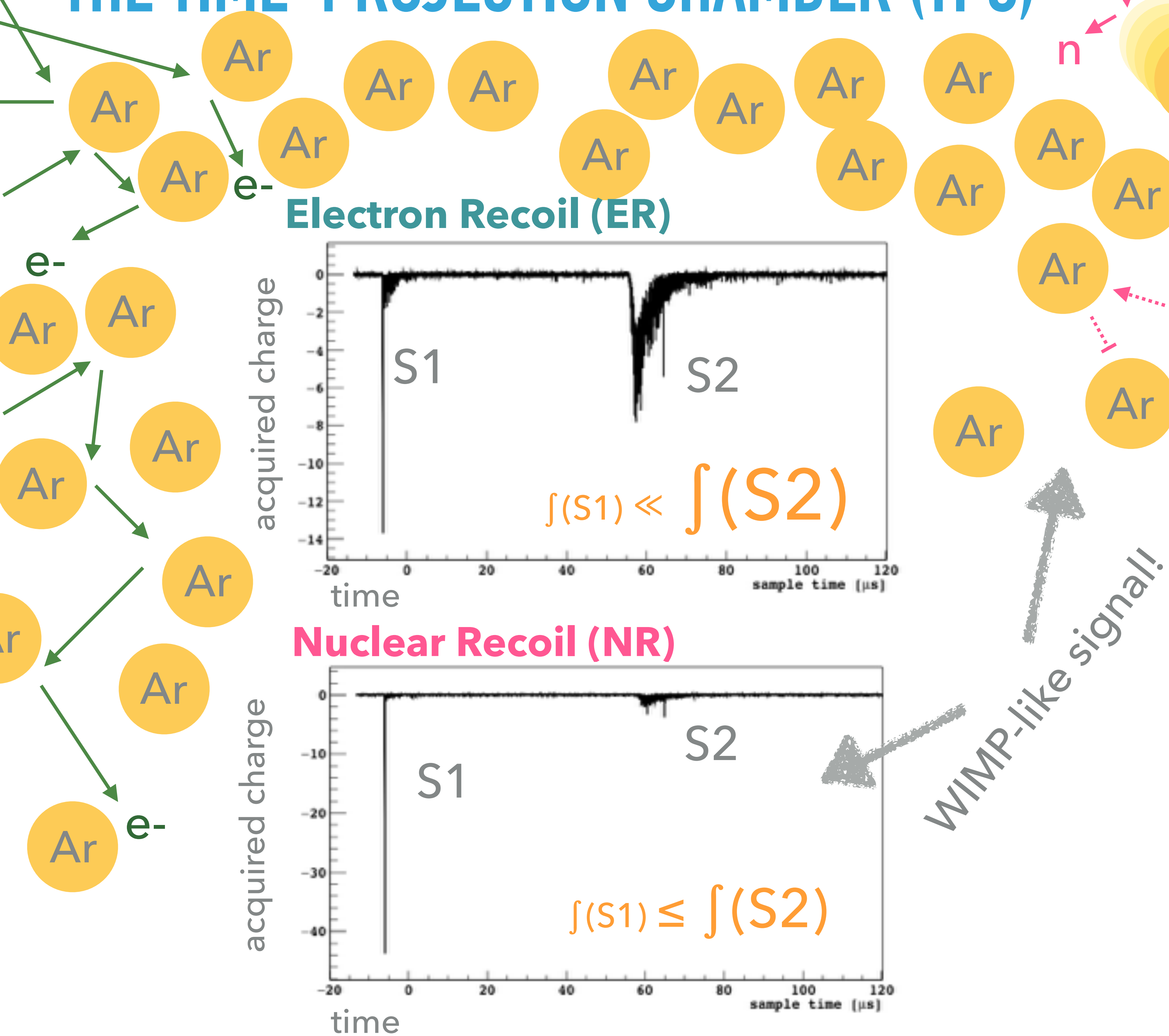
30-tonne Liquid Scintillator
**Neutron and γ's Veto**
Veto efficiency > 99.1%

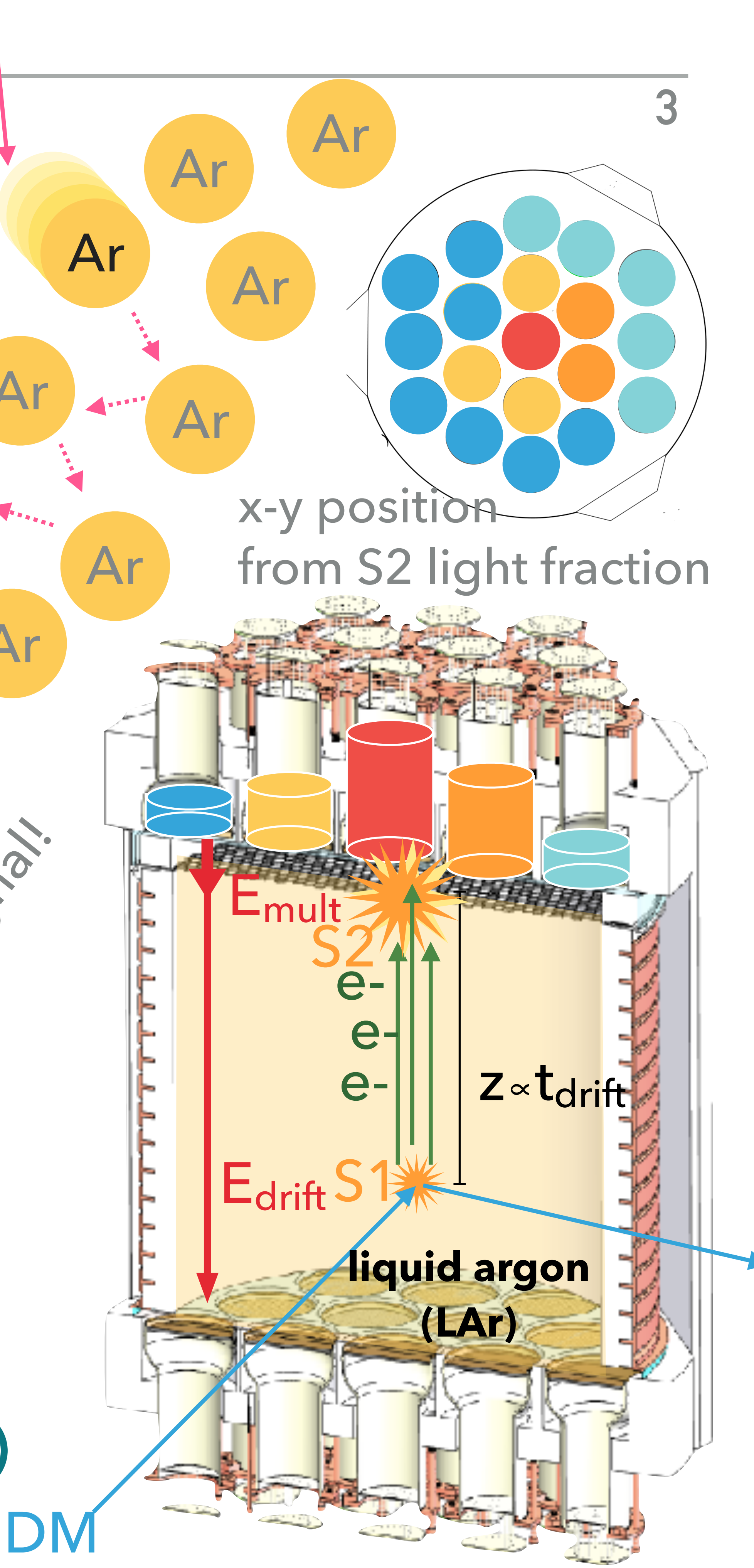
Inner detector **TPC**



# THE TIME-PROJECTION CHAMBER (TPC)






**S2/S1 ratio** and **Pulse Shape Discrimination (PSD)**

WIMPs will generate nuclear recoils (NRs)

# PULSE SHAPE DISCRIMINATION

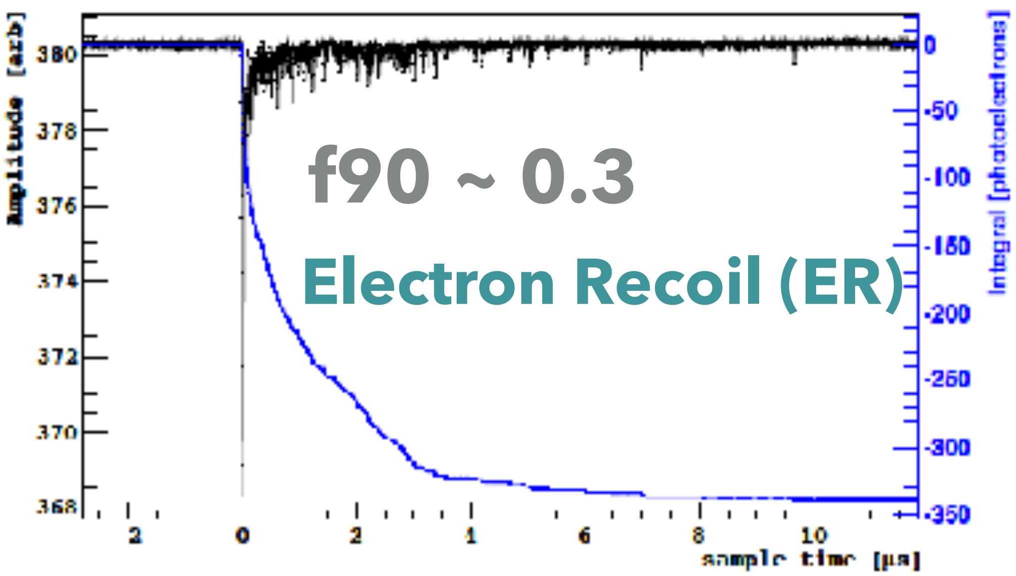
M. G. Boulay and A. Hime, Astropart. Phys. **25** (2006) 179

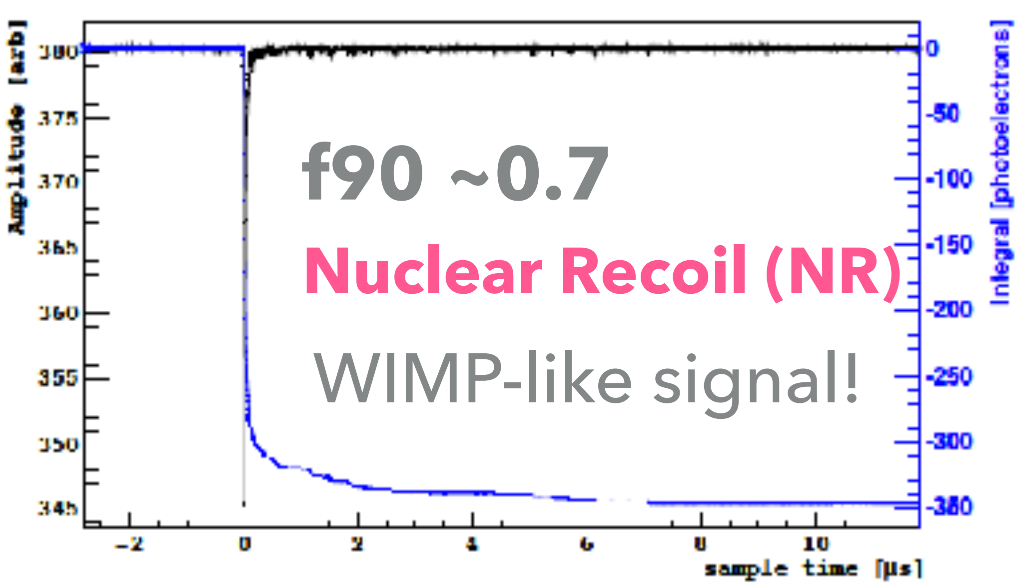


- Electron and nuclear recoils produce different excitation densities in the argon, leading to different **ratios of singlet and triplet excitation states**

$\tau$ singlet ~ 7 ns

$\tau$ triplet ~ 1500 ns

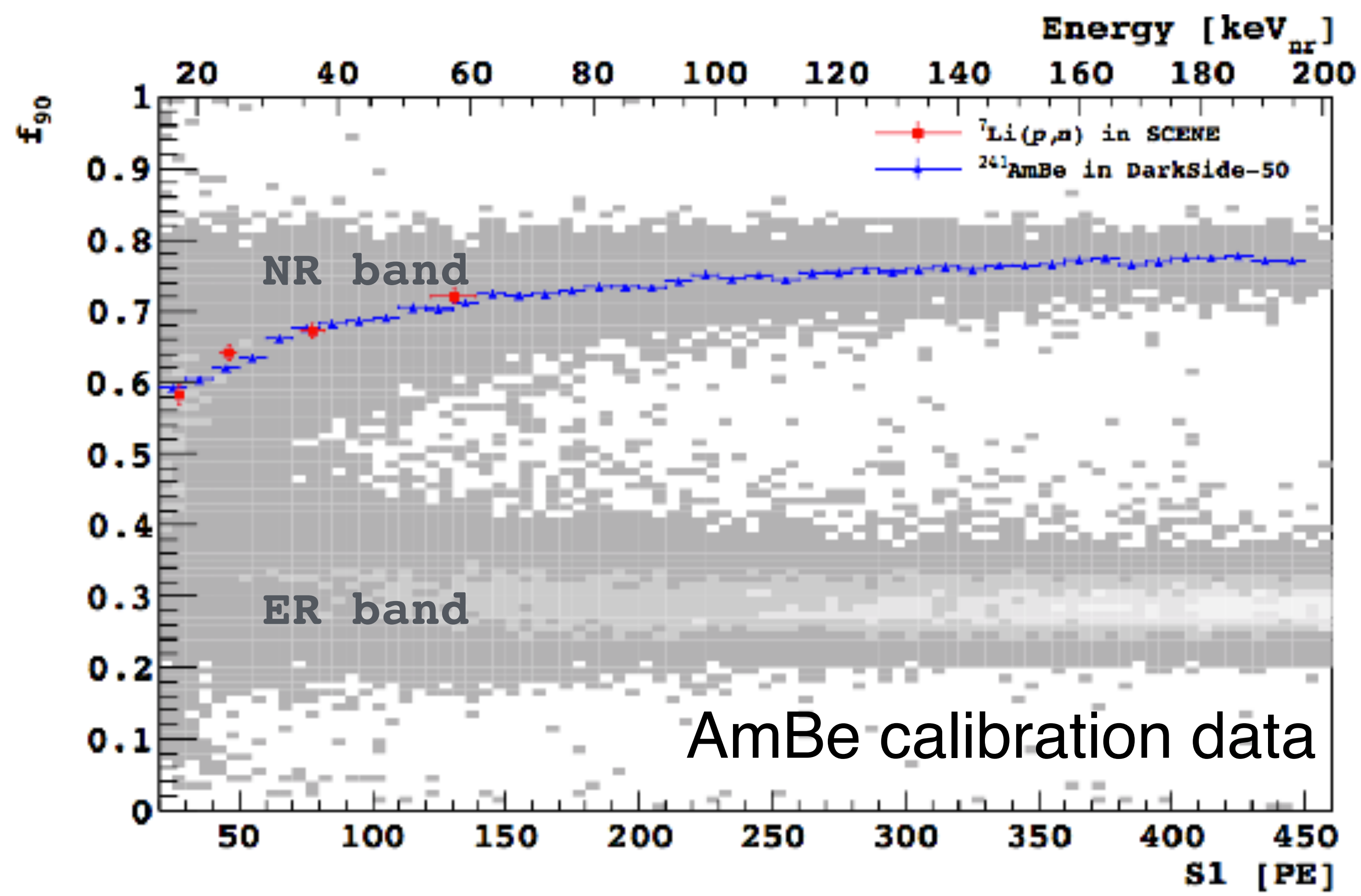


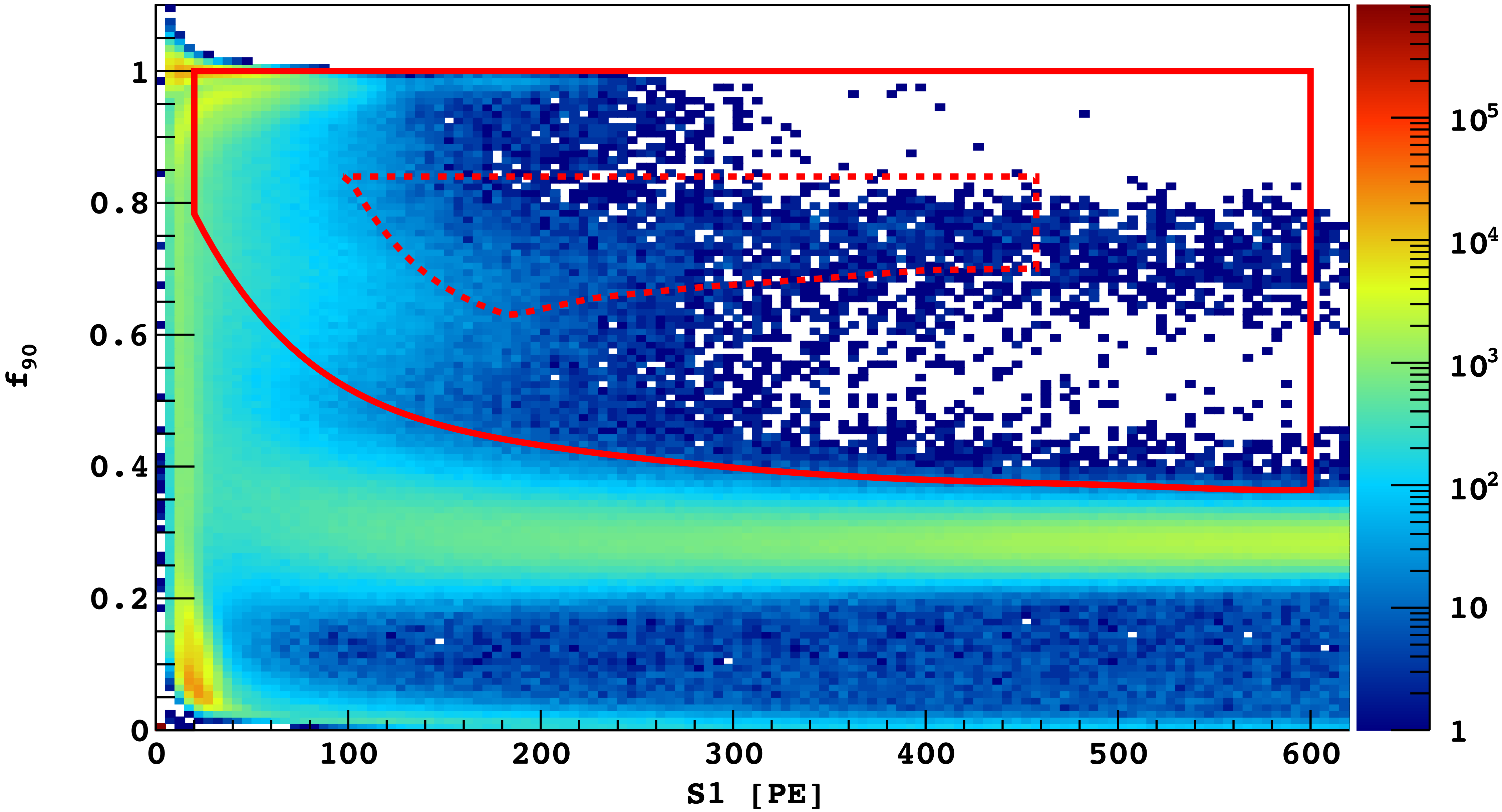

PSD parameter

**F90:** Ratio of detected light in the first 90 ns, compared to the total signal

~ Fraction of singlet states



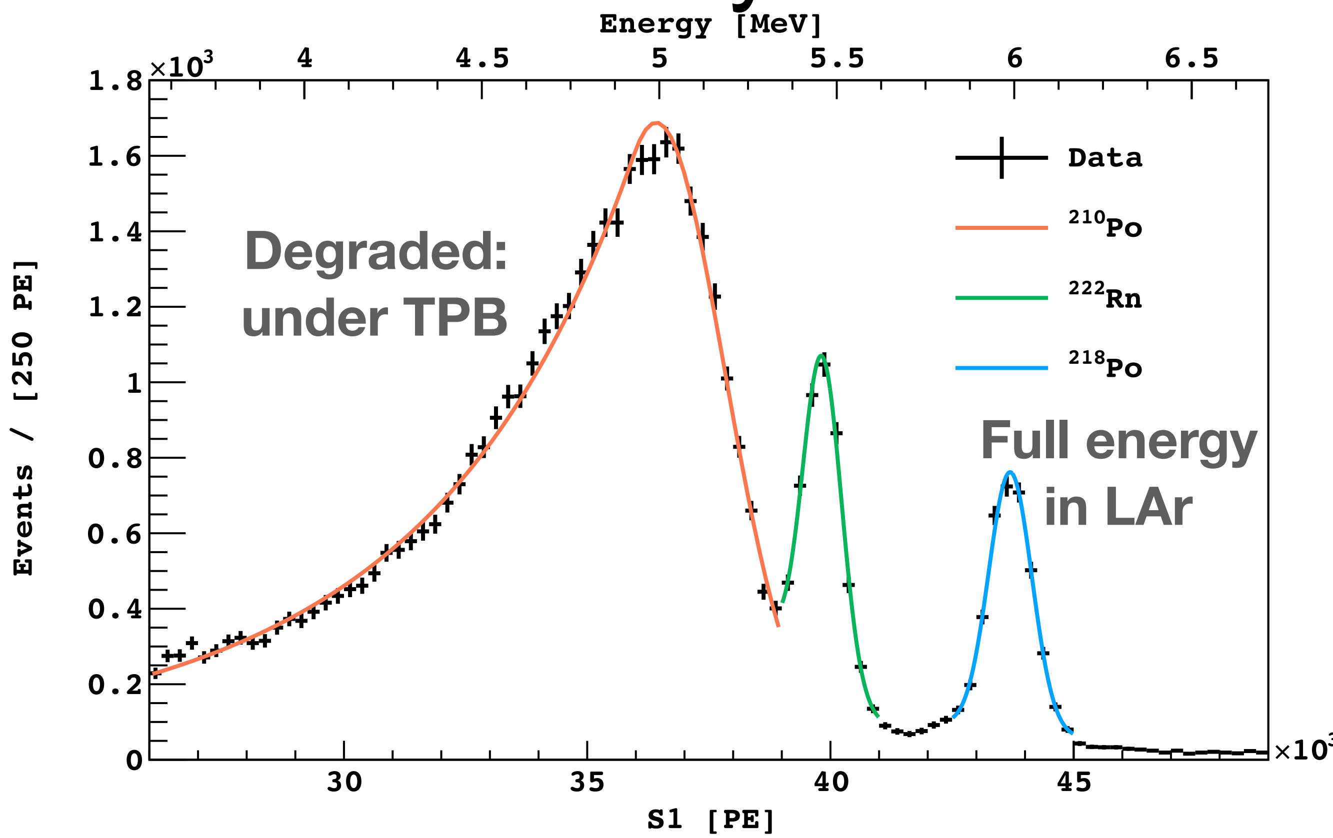
# A Blind Analysis of 534 live-days of data



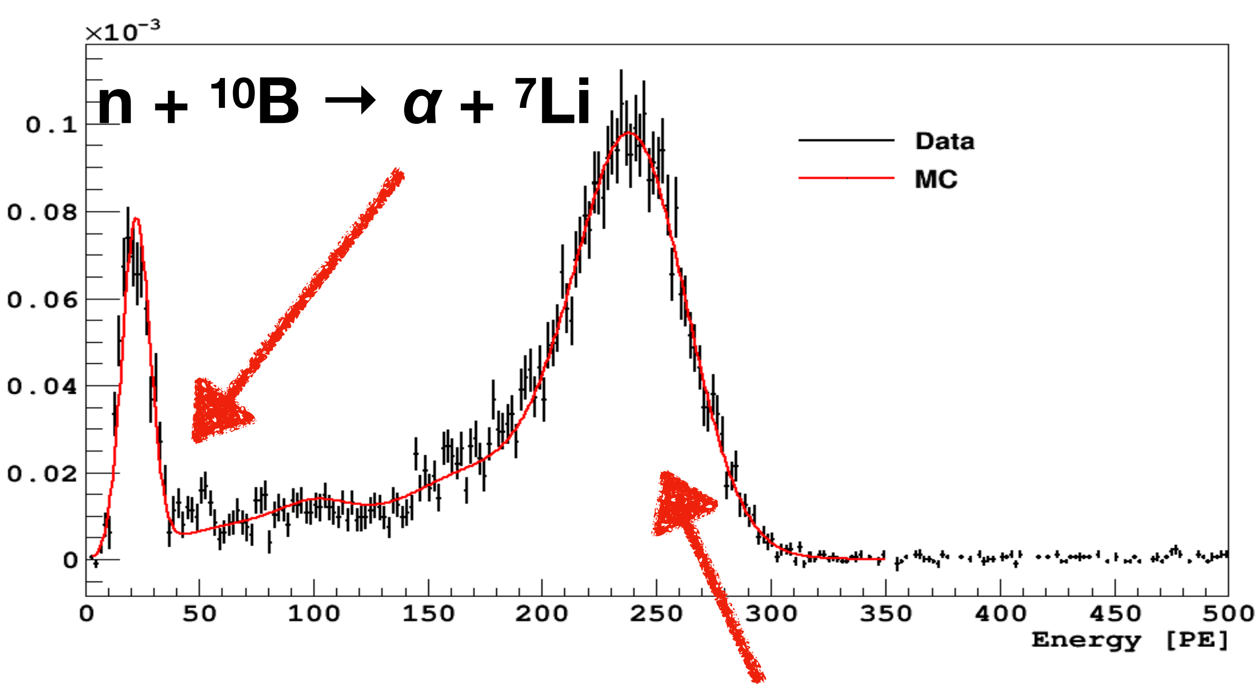

- Blinding box (red outline) shown with 71-day data: PR D 93, 081101 (2016)
- Goal: design an analysis that will have <0.1 event of background in the to-be-designed search box. (Final box chosen: dashed red)

# Nuclear Recoil BG

## Surface α decays




## Neutrons




n + $^{10}$B → α + $^{7}$Li + γ

**Background rejection:**

- S1 < 460
- Self-vetoing in DS-50!
- Small or no S2
- Long scintillation tail from TPB

**Background rejection:**

- TPC: multi-scatter
- LS Veto

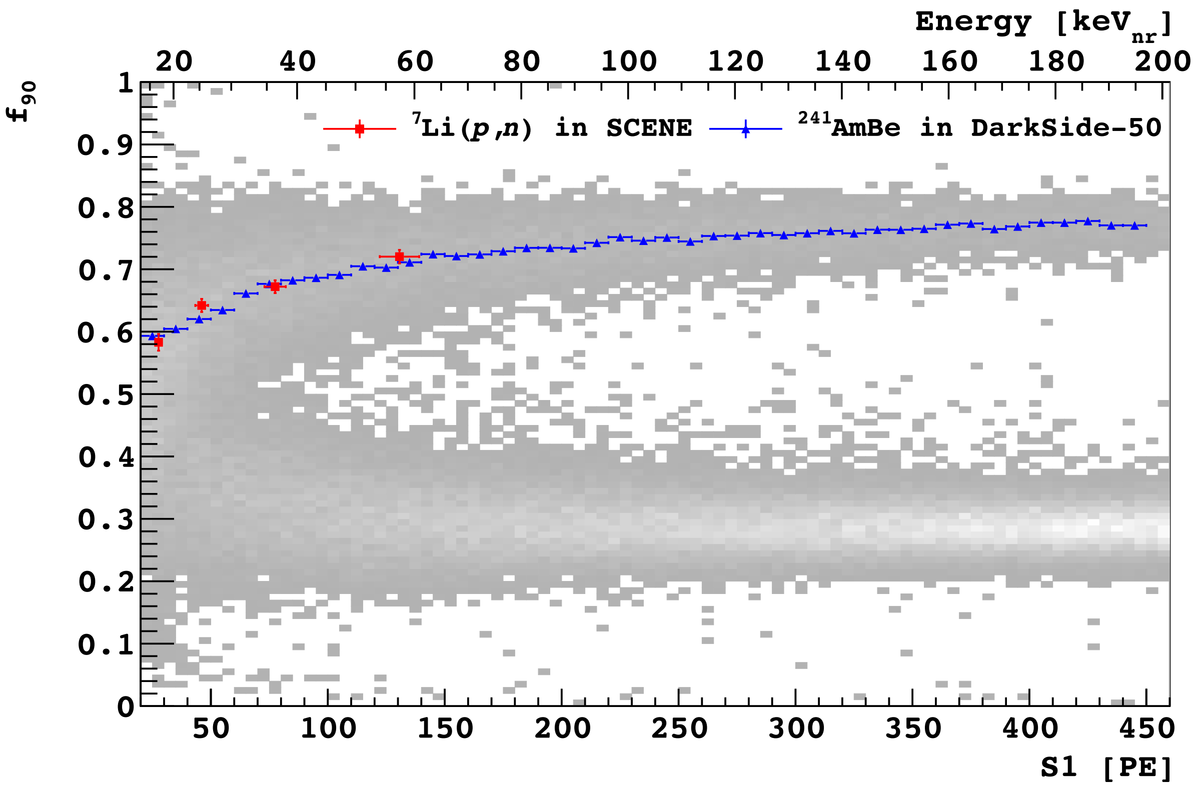
**Measured** n efficiency with Am-C for TPC single-NR: 0.9964±0.0004

Cosmogenics: Water Cherenkov Veto

Neutrons in data **counted**

# Electron Recoil BG

## S1+Cherenkov




**Background rejection:**

- Underground Ar
- S1 fraction in max PMT
- PSD: $f_{90}$ = S1 fraction in first 90 ns
  - Design cut to reduce ER to <0.08 event of background

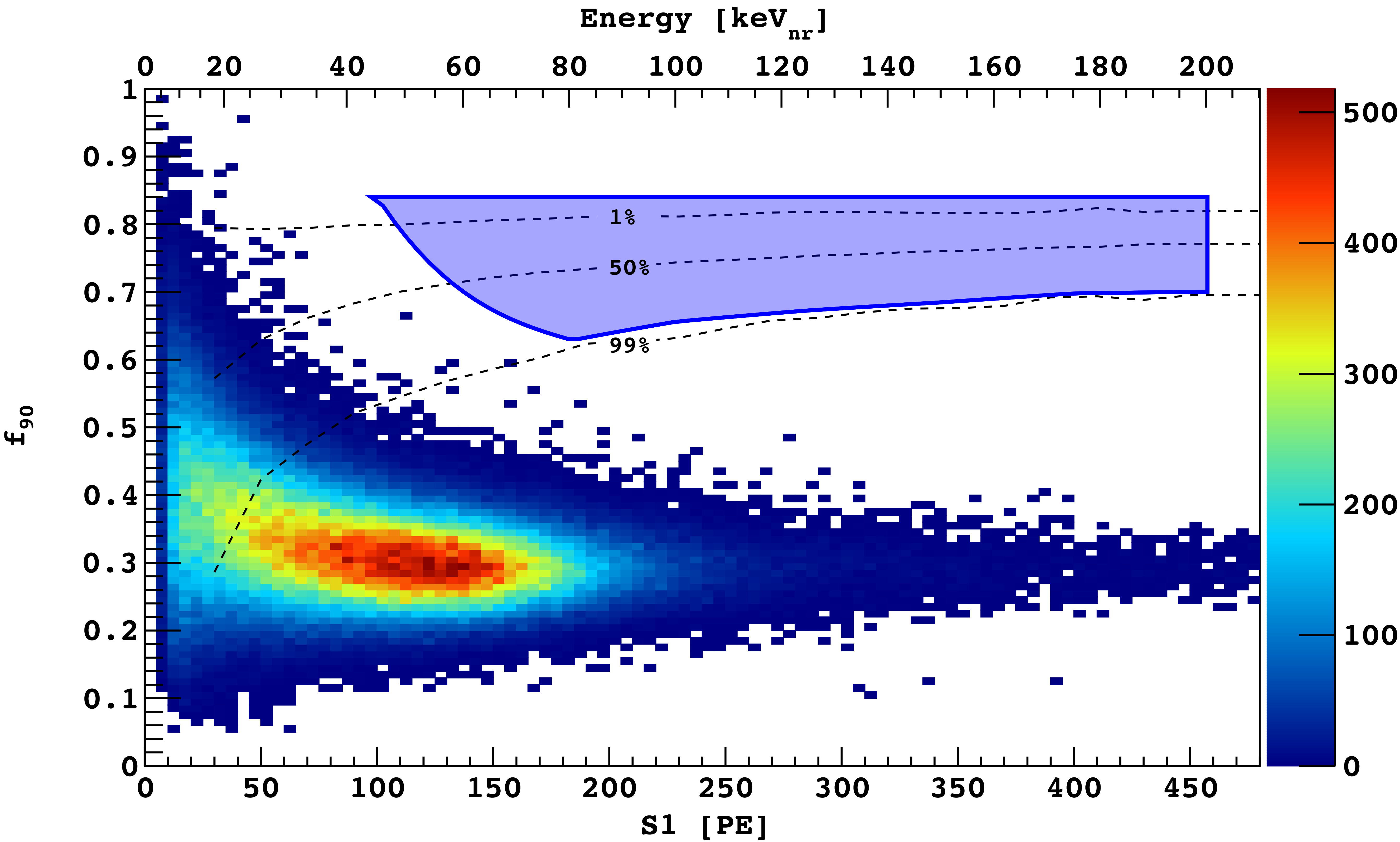
**S1 + Cherenkov events are Dangerous !!**

- Cherenkov light is all in prompt.
- Move regular scintillation events into NR band.

| Background | Est. Survive |
|---|---|
| Surface a decays | 0.001 |
| Cosmogenic n | <0.0003 |
| Radiogenic n | <0.005 |
| ER S1+Cherenkov | 0.08* |
| **Total** | **0.09±0.04** |

**Goal achieved: open the box!**

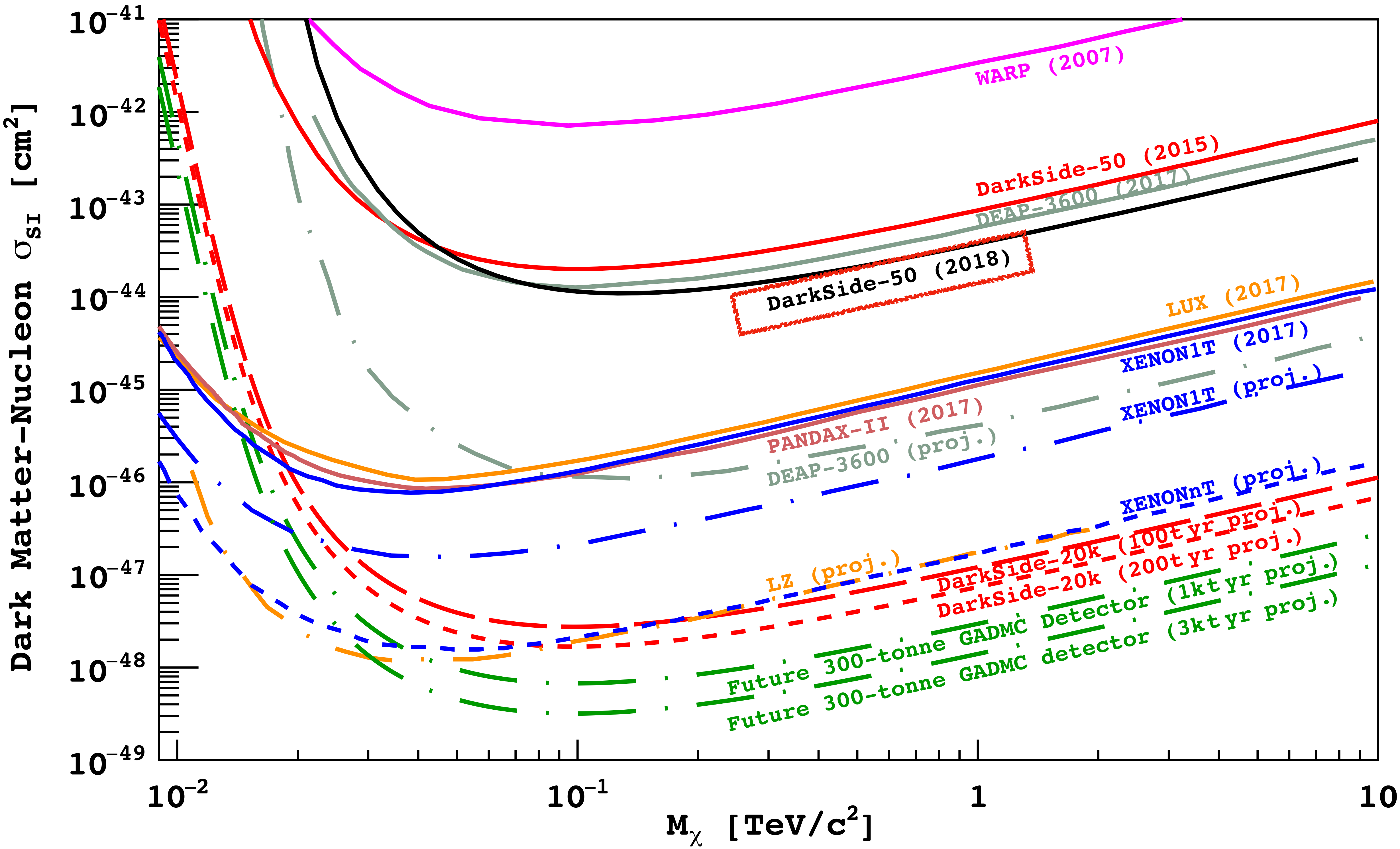
# Final Data Set






arXiv: 1802.07198

# 90% C.L. Exclusion Limits






arXiv: 1802.07198

# Low Mass Dark Matter Search Ionization Only Analyses

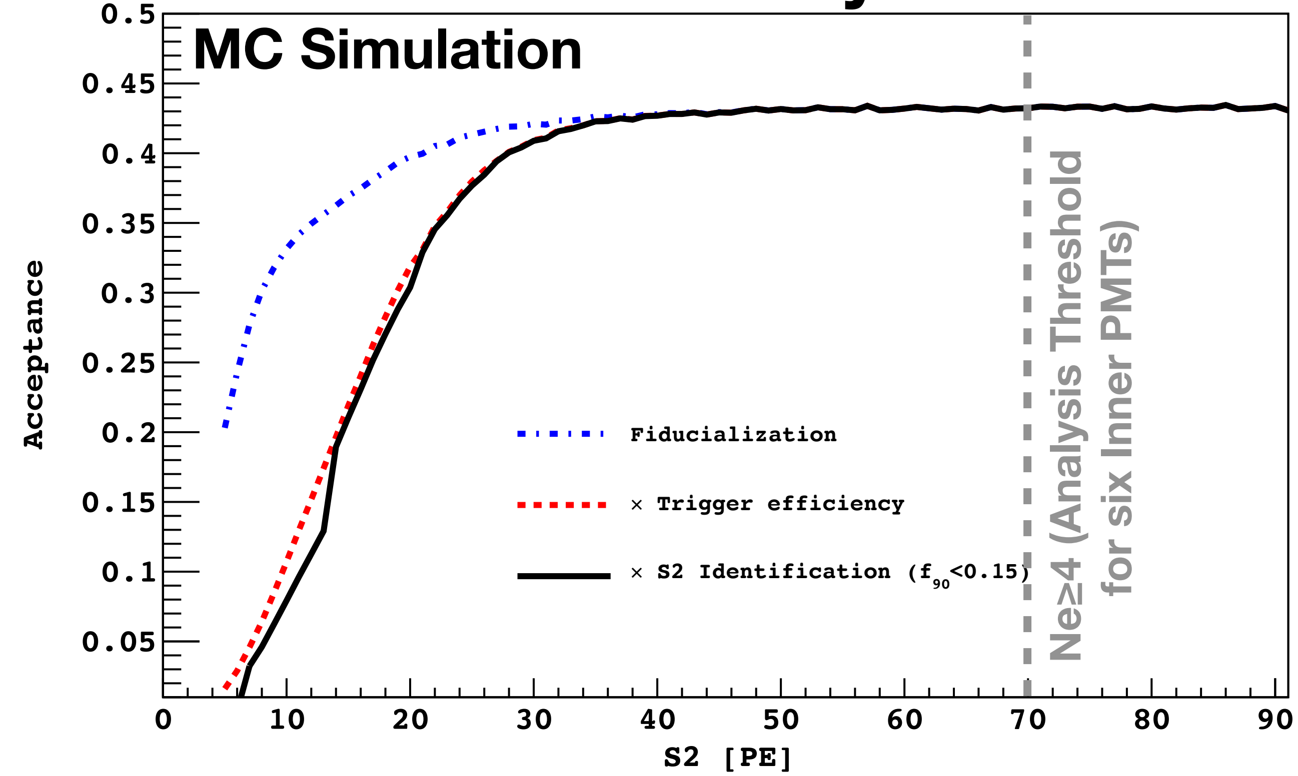
**arXiv: 1802.06994**
**arXiv: 1802.06998**

# Ionization Measurements

- **Scintillation signal** (S1): threshold at ~2 $keV_{ee}$ / 6 $keV_{nr}$ weak sensitivity to low mass WIMPs.
- **Ionization signal** (S2): threshold < 0.1 $keV_{ee}$ / 0.4 $keV_{nr}$ **Sensitive to low mass WIMPs!!**
- **Use Ionization (S2) Only.**
  - **PMTs have zero dark rate at 88K**
  - **Gain in the gas region (~70 e/e )**
  - **Sensitive to a single extracted electron**
  - **Radioactivity rate in the detector is remarkably low**
  - **No need of PSD**
  - **The electron yield for nuclear recoils increases at low energy**
- **Detection efficiency**: estimated from Data + MC
  - S2 light distribution pattern among PMTs
  - S2 waveform including longitudinal diffusion due to drifting
- **Fiducialization**: use volume under 7 central PMTs
- In DS-50, we can detect down to **single electron**.

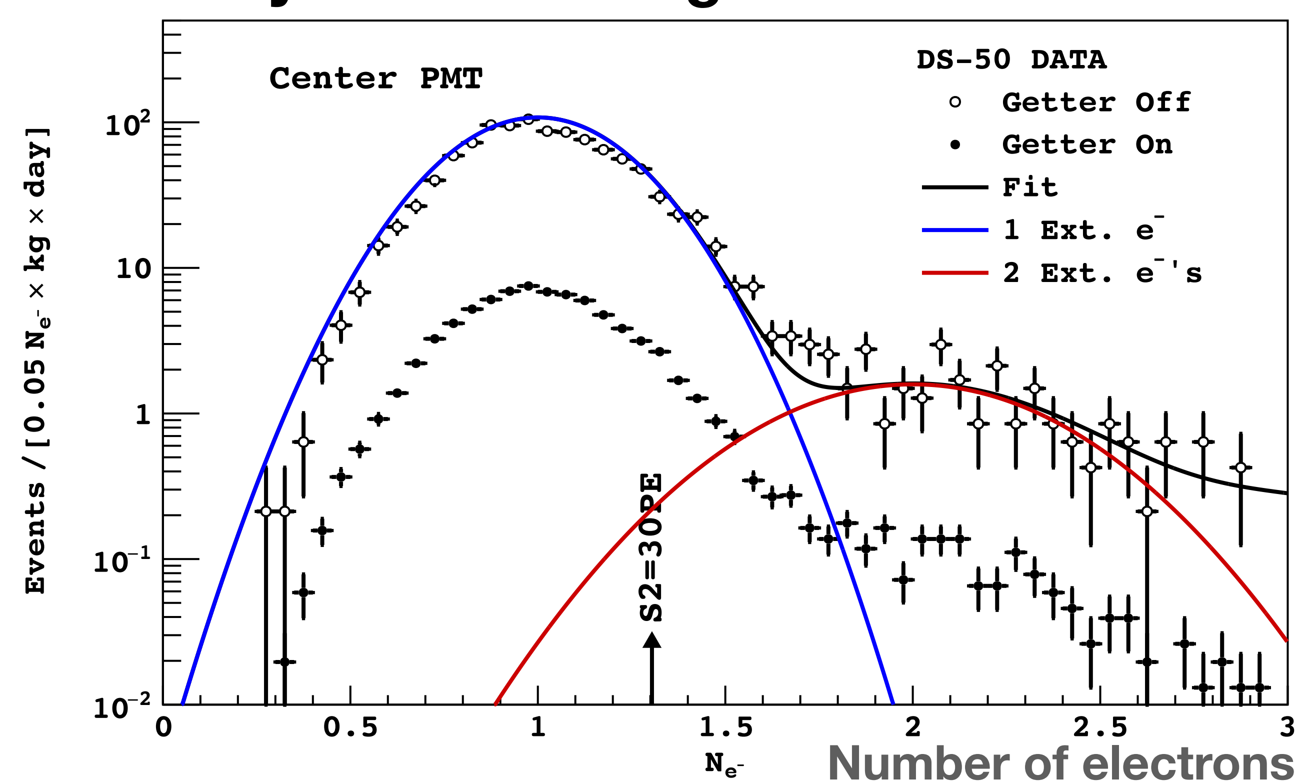
**arXiv: 1802.06994**

## Detection Efficiency




**The efficiency is flat above the analysis threshold of number of electrons >4.**

## S2 yield from Single-electrons




$$Ne \stackrel{\text{def}}{=} S2/\eta, \quad \eta_c = 23\ PE/e^-$$

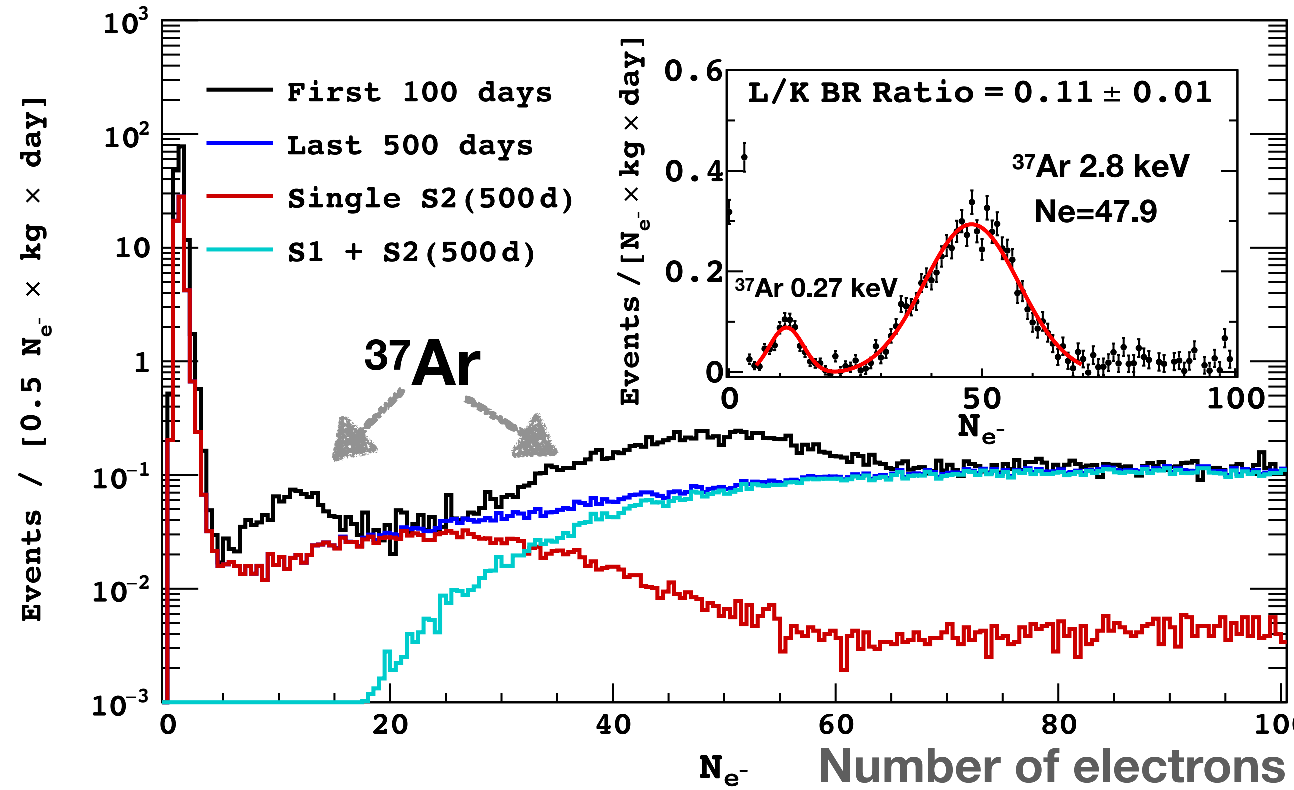
**One electron creates 23 ±1 PE at the center PMT**

# Energy scale for ER and NR

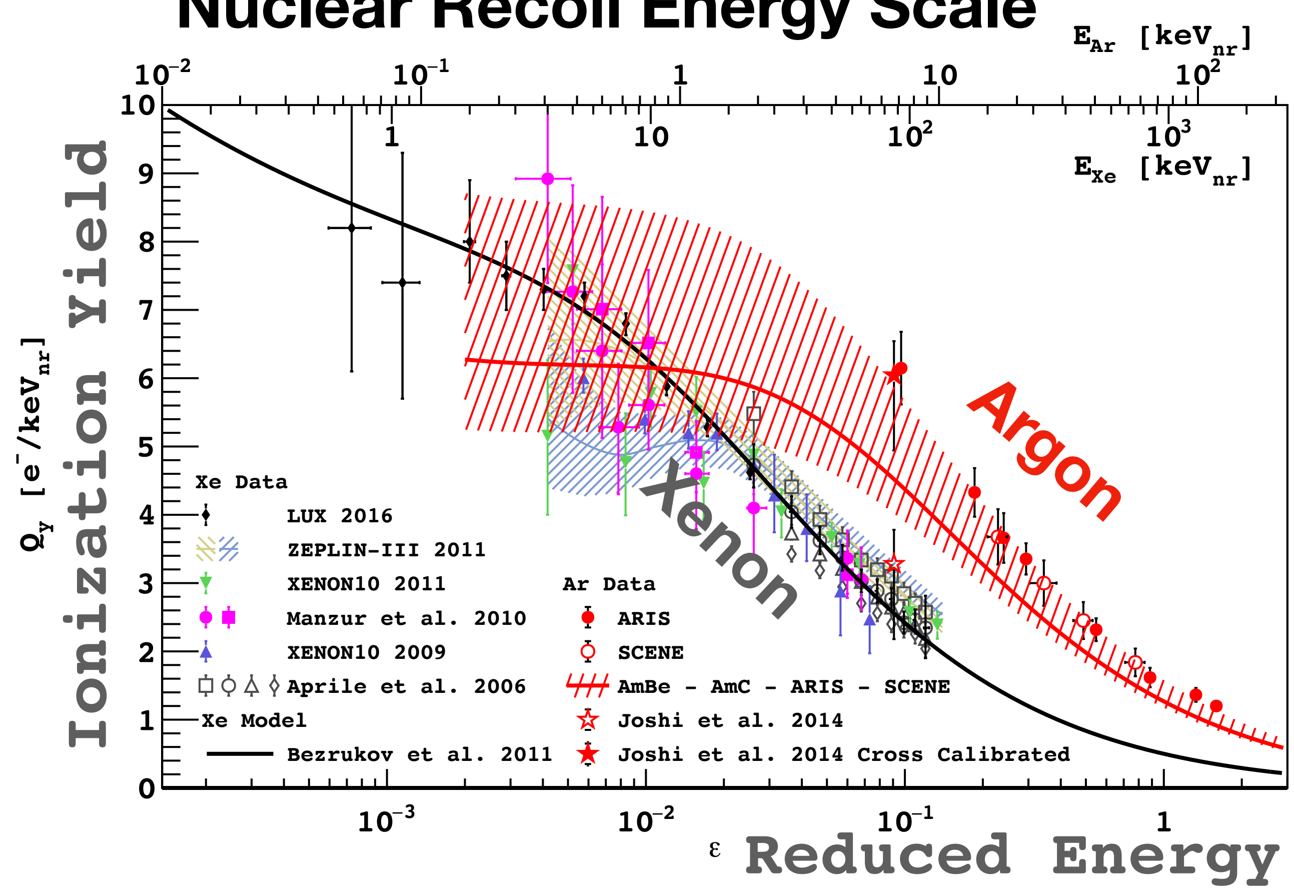
- $^{37}$Ar provides two x-rays, 2.82 keV and 0.27 keV.
- Decayed out with 35 day half-life and not remain in the last 500-days data set.
- Good agreement of BR with expected value.
- Confirmation of the trigger efficiency and acceptance
- AmBe and AmC neutron sources are used to extract ionization yield at ROI.
- The difference between other measured points is take as systematics

**arXiv: 1802.06994**

## Electron Recoil Energy Scale




## Nuclear Recoil Energy Scale

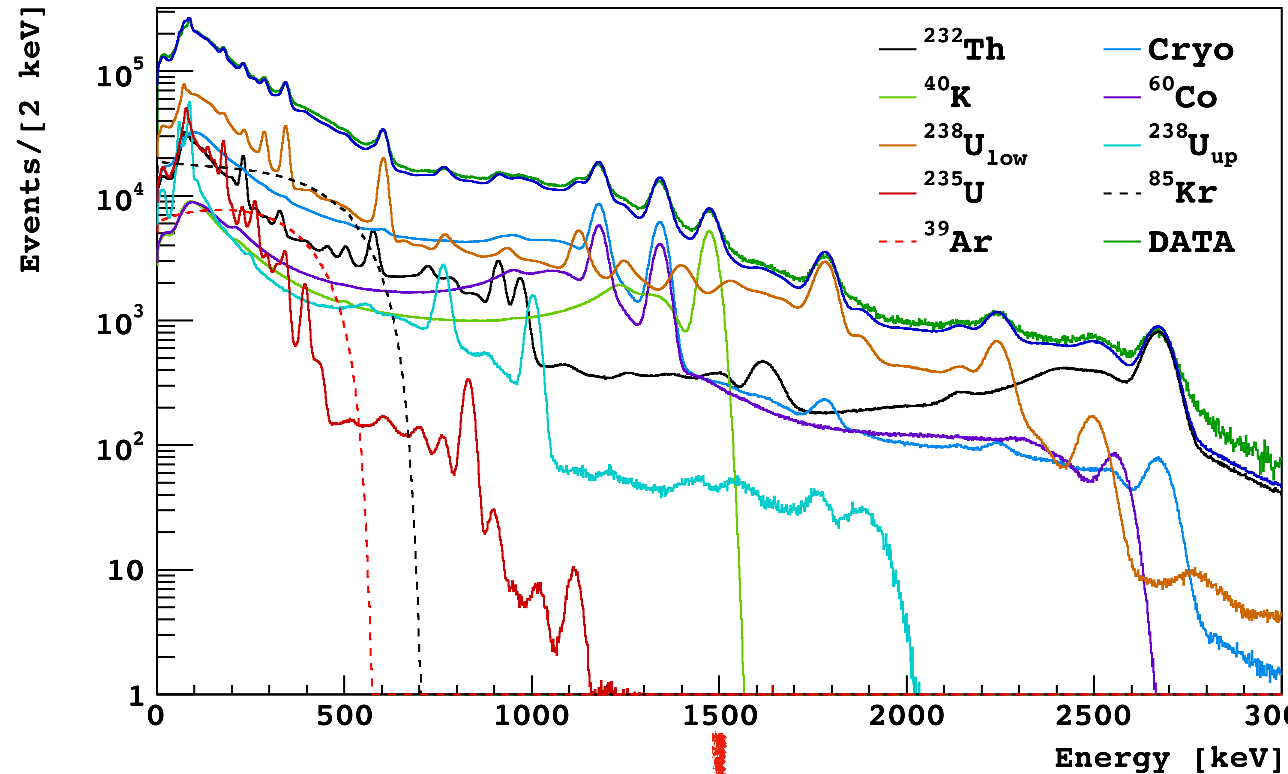



**NR ionization yield is obtained by fitting AmBe and AmC neutron calibration data**

# Background and WIMP Signals

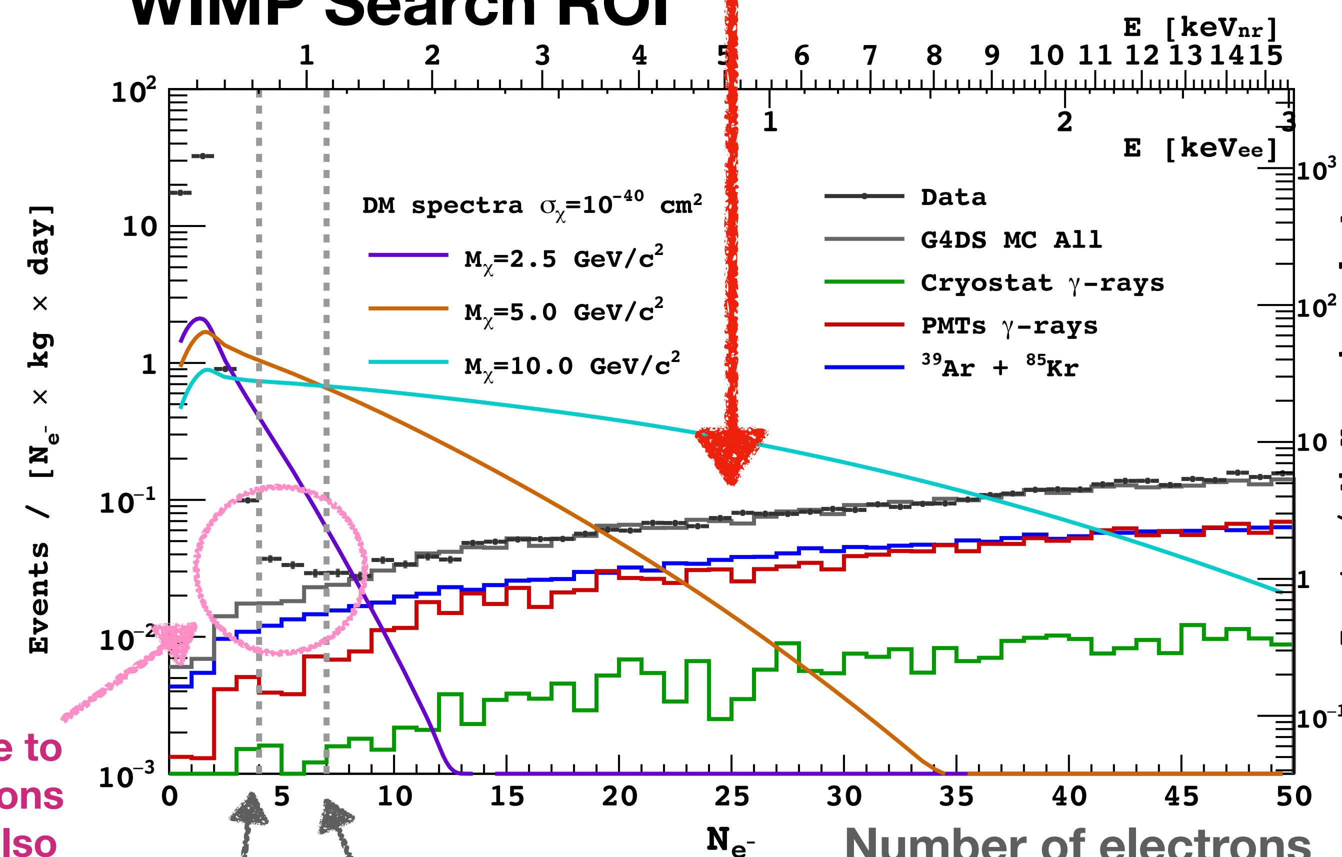
- Fit the BG components at high energy in the same dataset (field on @ 200 V/cm)
- Put constraints on the rate of BG at ROI
- BG events in ROI are modeled with ER Ionization yield and detector response.
- The excess of events due to tail of the delayed electrons are not modeled as BG.
- WIMP recoil spectra are modeled with
  - NR Energy Quenching
  - Ionization
  - Detector Response

## High Energy Spectra




Extrapolation at low energy, ok within few %

## WIMP Search ROI




Number of electrons

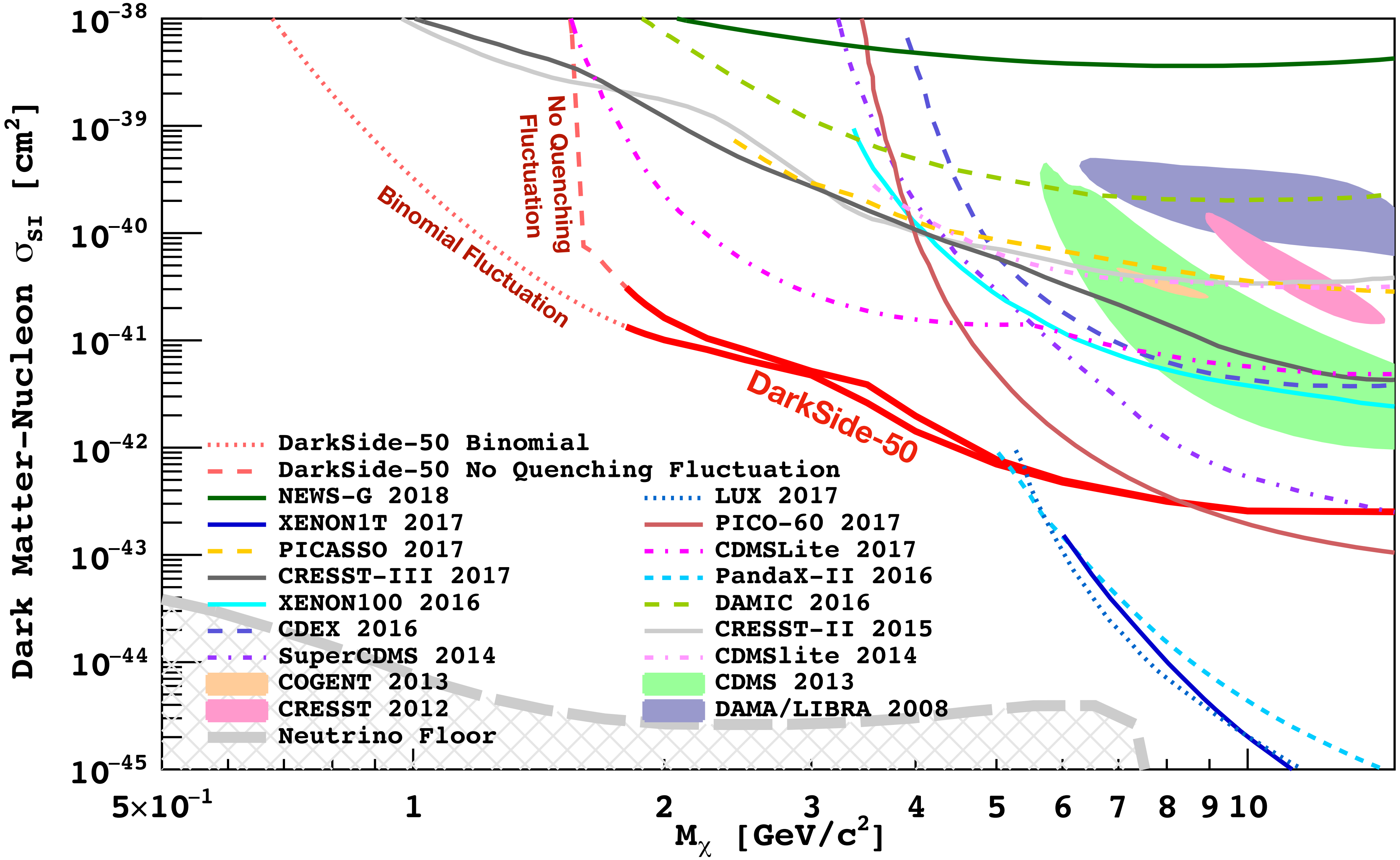
- Excess of events due to tail of delayed electrons
- Those events were also observed in XENON100.

Ana. Thres. $M\chi \gtrsim 4$ GeV

Ana. Thres. $M\chi \lesssim 4$ GeV

arXiv: 1802.06994

# 90% C.L. Exclusion Limits




- **Profile Likelihood Method** is used
  - Uncertainties from both WIMP signals (NR ionization yield, single electron yields) and BG spectrum (rates, ER ionization yield)
- Due to lack of knowledge about fluctuation at low recoil energy, two cases are considered.
  - **Binomial fluctuation** for NR energy quenching, ionization, and recombination processes.
  - **No Fluctuation** for NR energy quenching process. Corresponding to apply hard cut off in quenched energy ~0.6 keVnr.

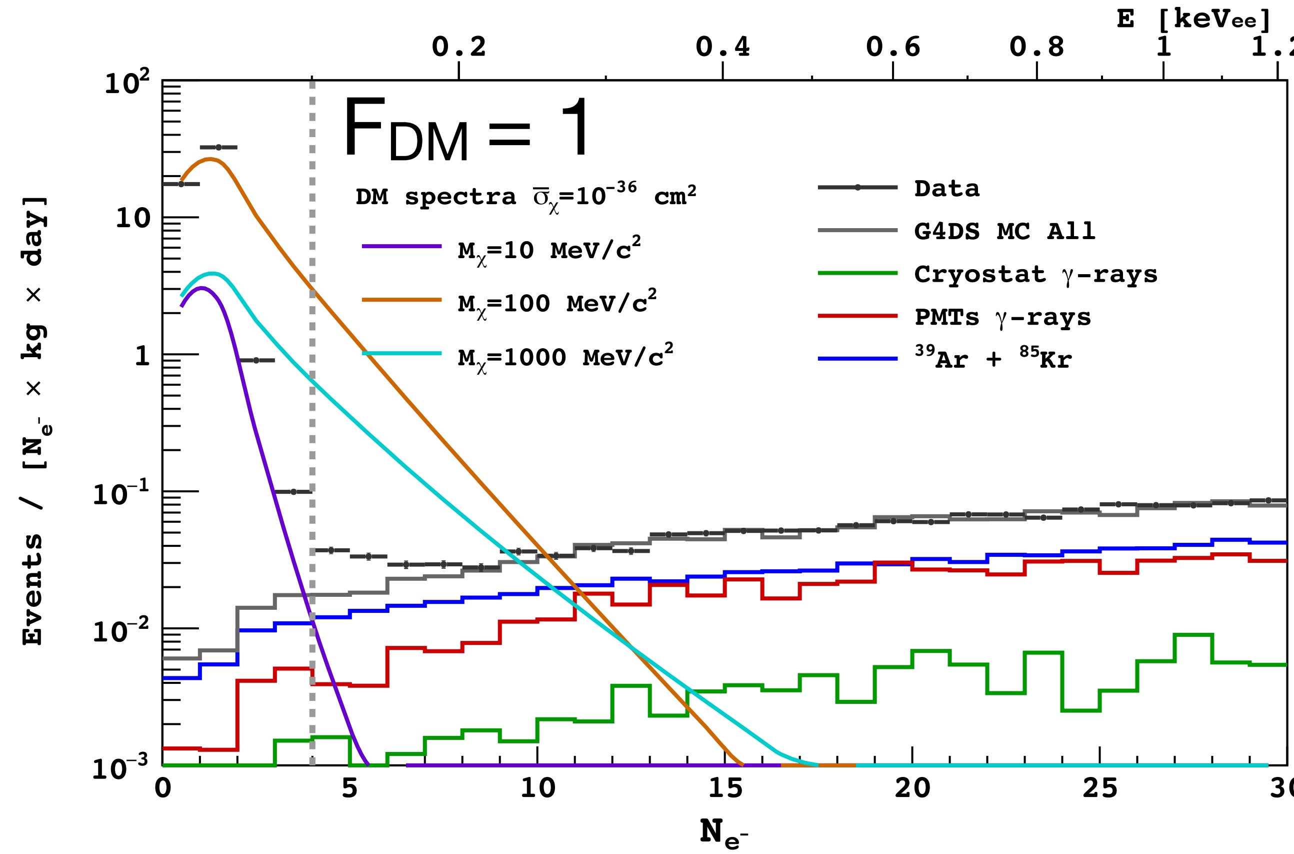


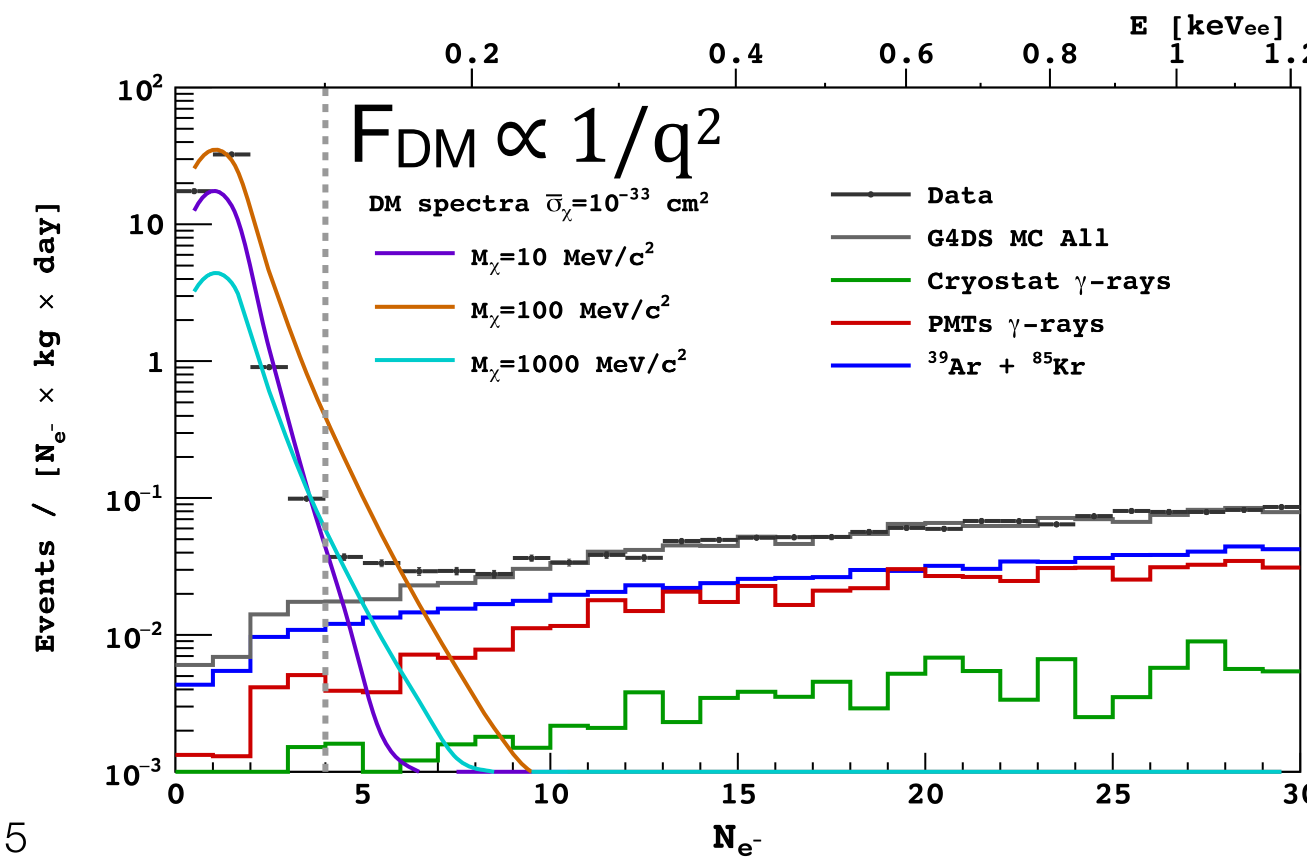
arXiv: 1802.06994

# Sub-GeV Dark Matter Search

arXiv: 1802.06998

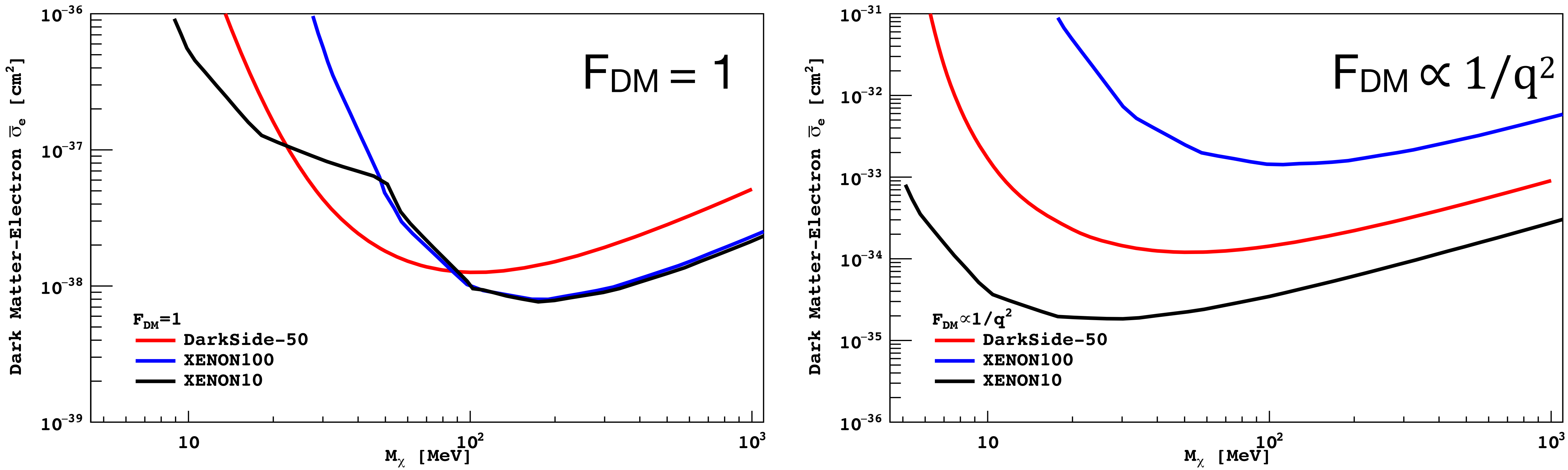
- Light DM scatter off electrons
- DM signals are also ER.
- The same measured spectrum as the WIMP search is used.
- Two extreme cases of Dark Matter form-factor are considered
  - $F_{DM}=1$ heavy mediator
  - $F_{DM} \propto 1/q^2$ light mediator



arXiv: 1802.06998

# Sub-GeV Dark Matter Exclusion Limits




- Profile Likelihood Method is used
  - Uncertainties from ER ionization yield and single electron yields are included both DM spectra and BG spectra. Rates uncertainties are included in BG spectra.
- In the case of a heavy mediator, $F_{DM} = 1$, we improve the exclusion limit in the range from 30 MeV/c$^2$ to 70 MeV/c$^2$.

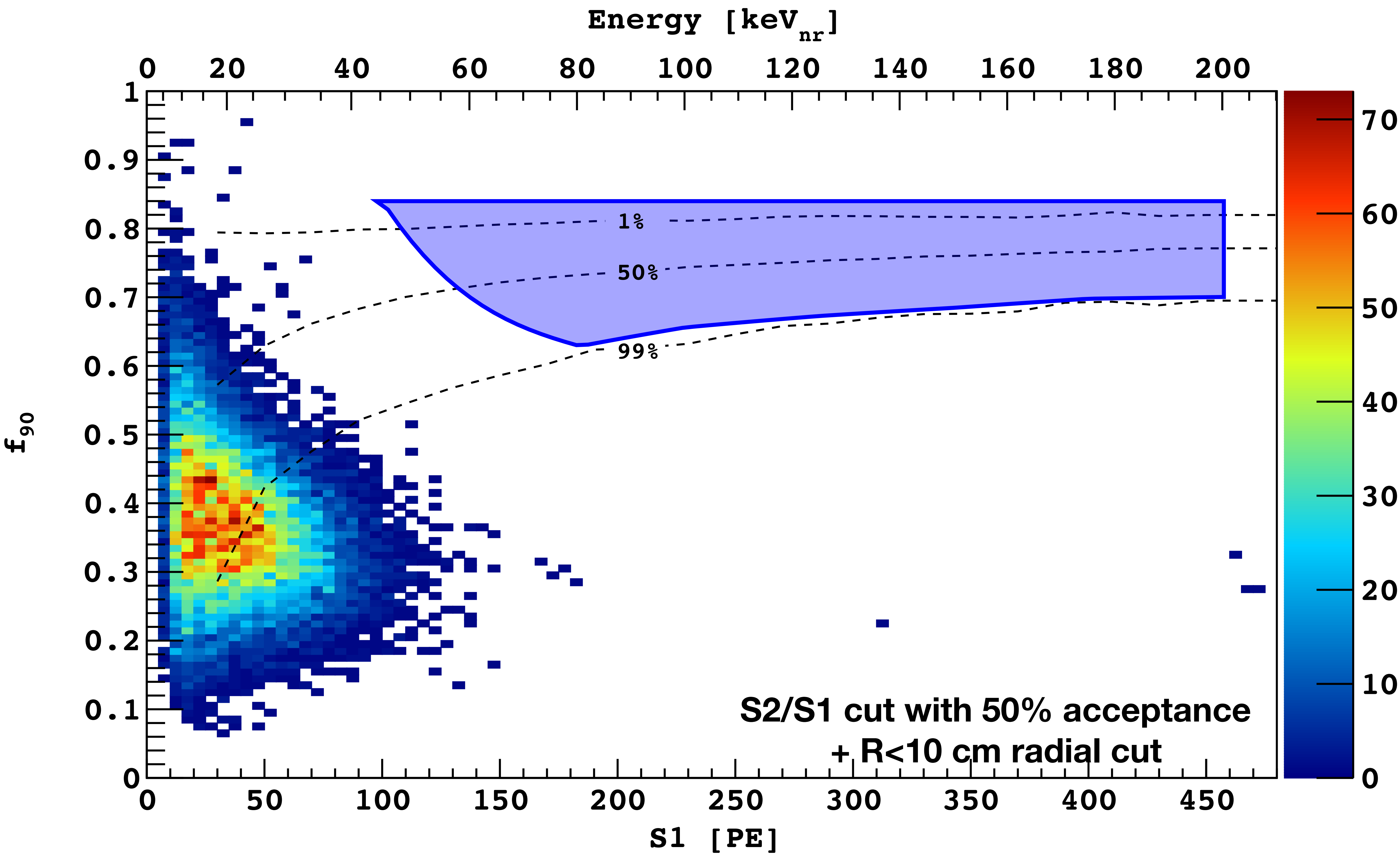
# Summary

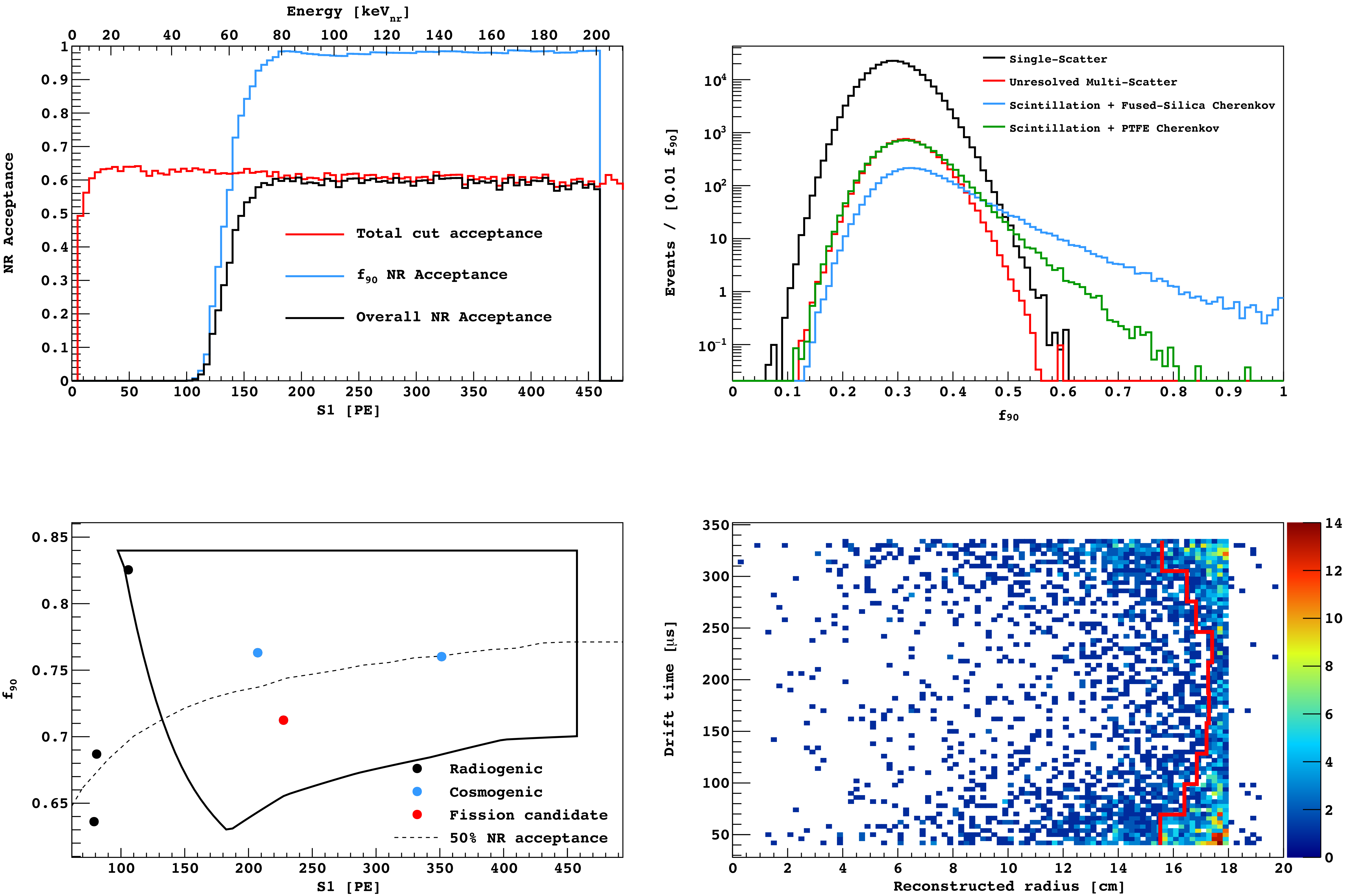
- Blind Analysis is successfully done with 534 live-days of data.
- Pulse Shape Discrimination ($f_{90}$) is strong discriminator and necessary for BG free WIMP search at high mass.
- Liquid Argon is also sensitive to low mass WIMPs and sub-GeV DM.
- Next generation DarkSide-20k is coming!

**arXiv: 1802.07198** **arXiv: 1802.06994** **arXiv: 1802.06998**

# Thank You!

# Additional Rejection S2/S1

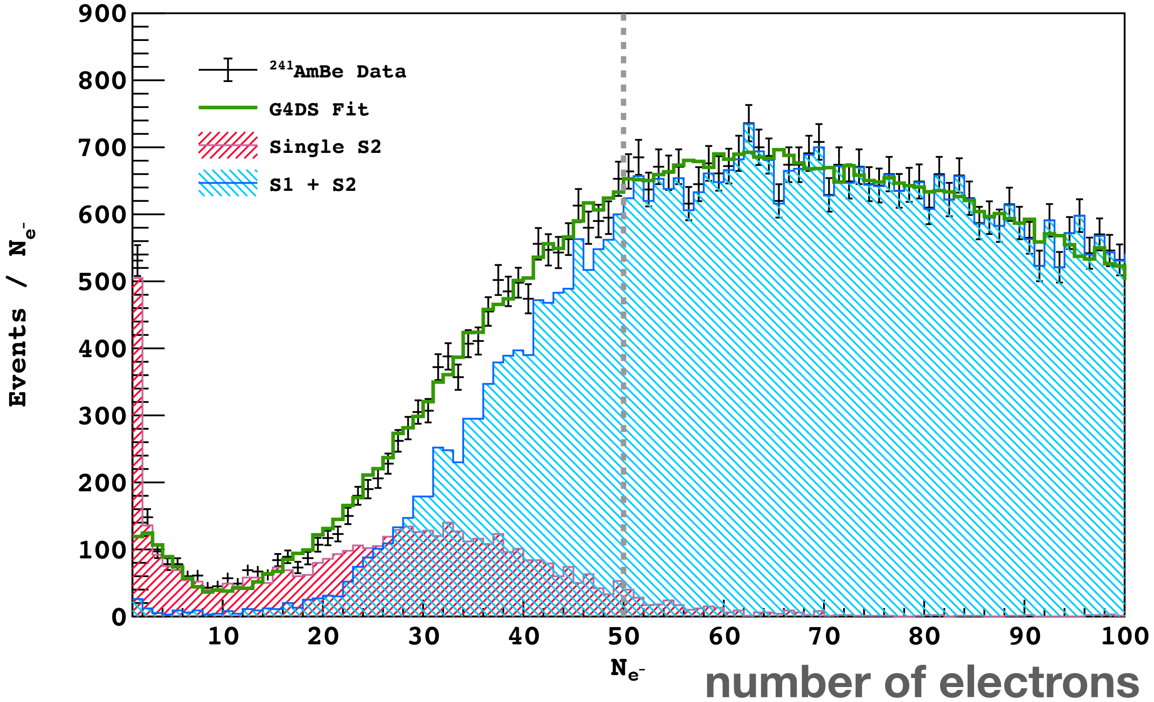




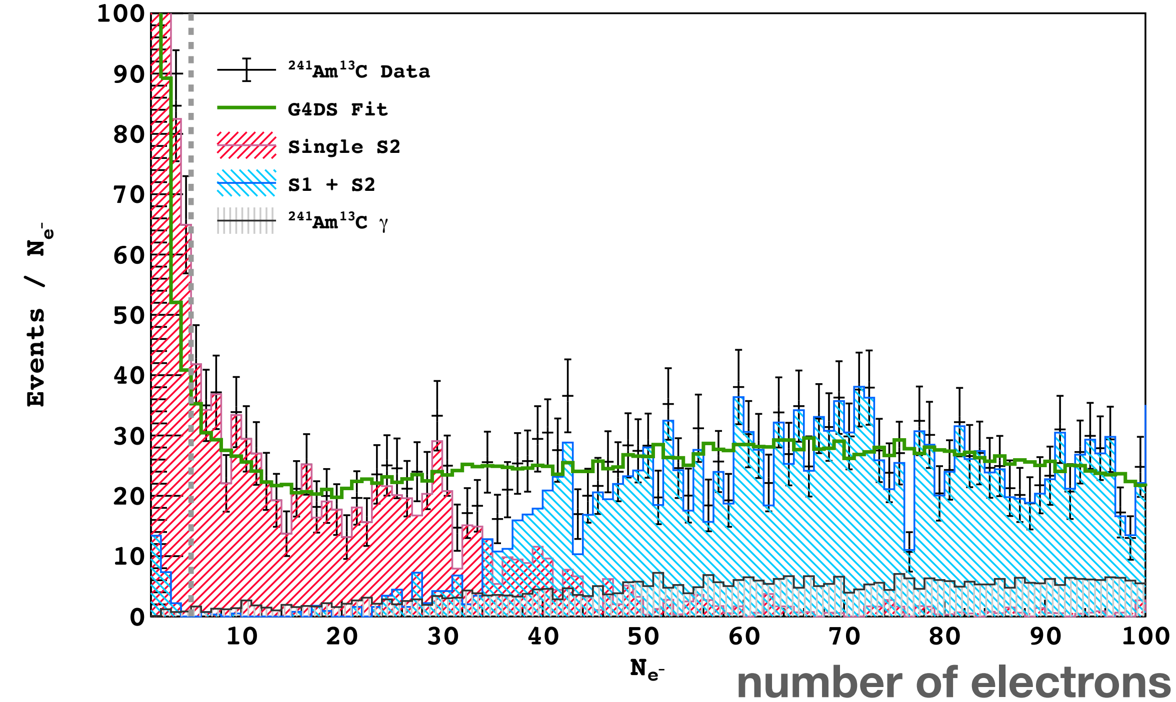
Energy [keV$_{nr}$]
NR Acceptance
S1 [PE]
Total cut acceptance
$f_{90}$ NR Acceptance
Overall NR Acceptance
Events / [0.01 $f_{90}$]
$f_{90}$
Single-Scatter
Unresolved Multi-Scatter
Scintillation + Fused-Silica Cherenkov
Scintillation + PTFE Cherenkov
$f_{90}$
S1 [PE]
Radiogenic
Cosmogenic
Fission candidate
50% NR acceptance
Drift time [μs]
Reconstructed radius [cm]

# NR Ionization Yields

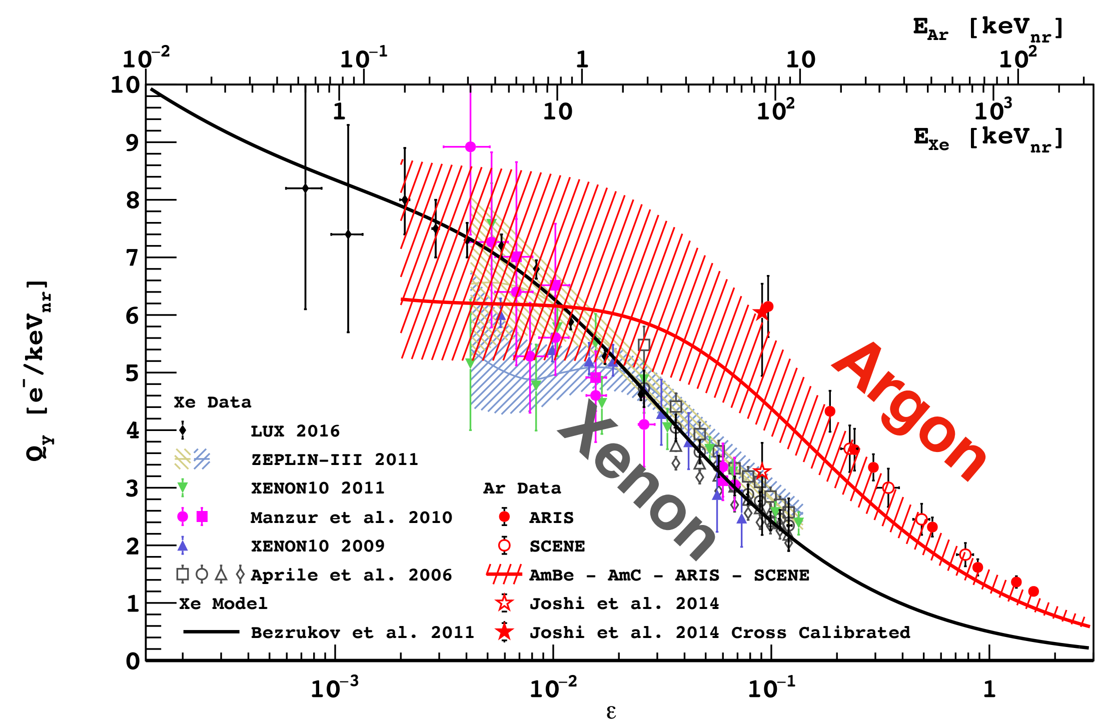
**AmBe neutron source**



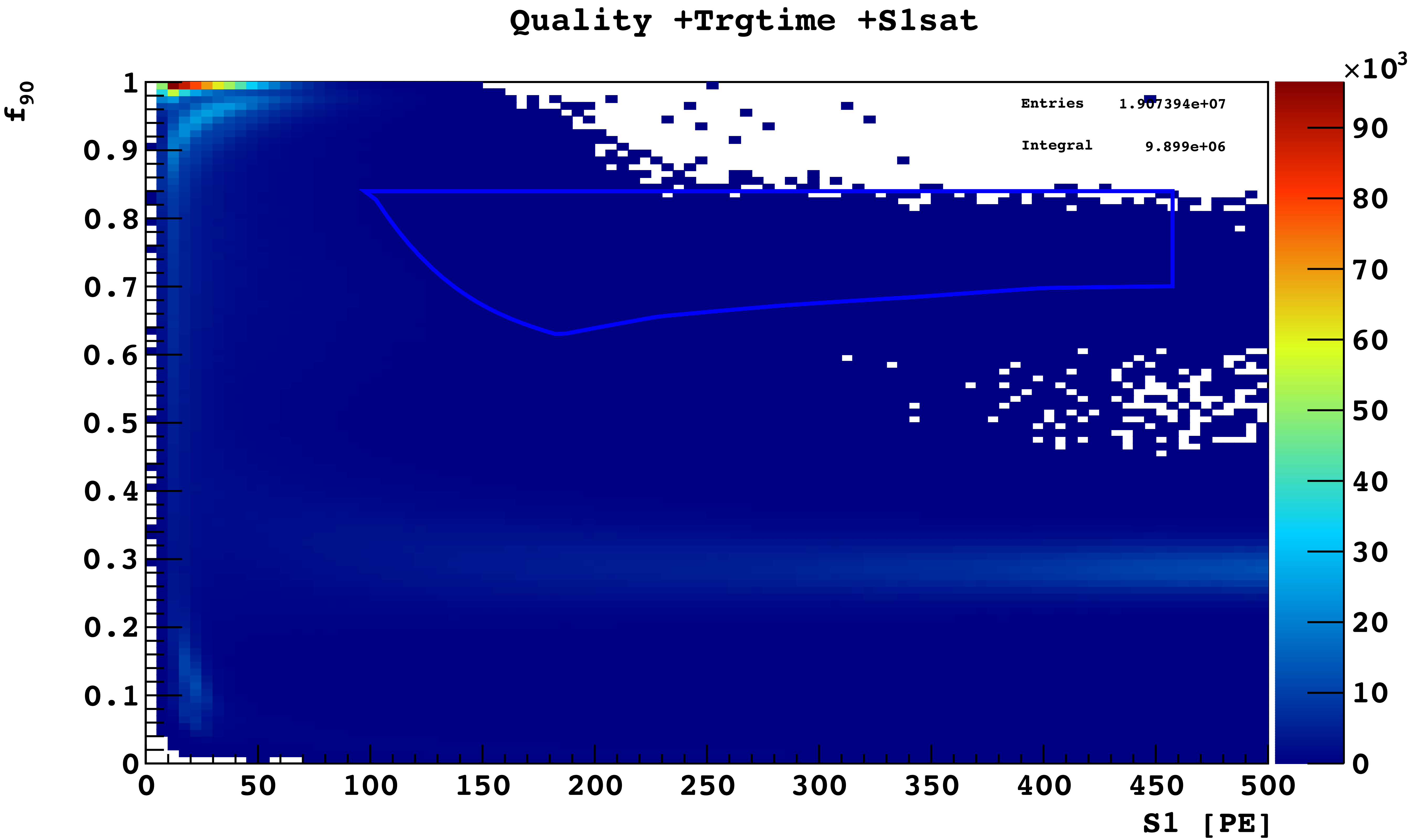

**AmC neutron source**



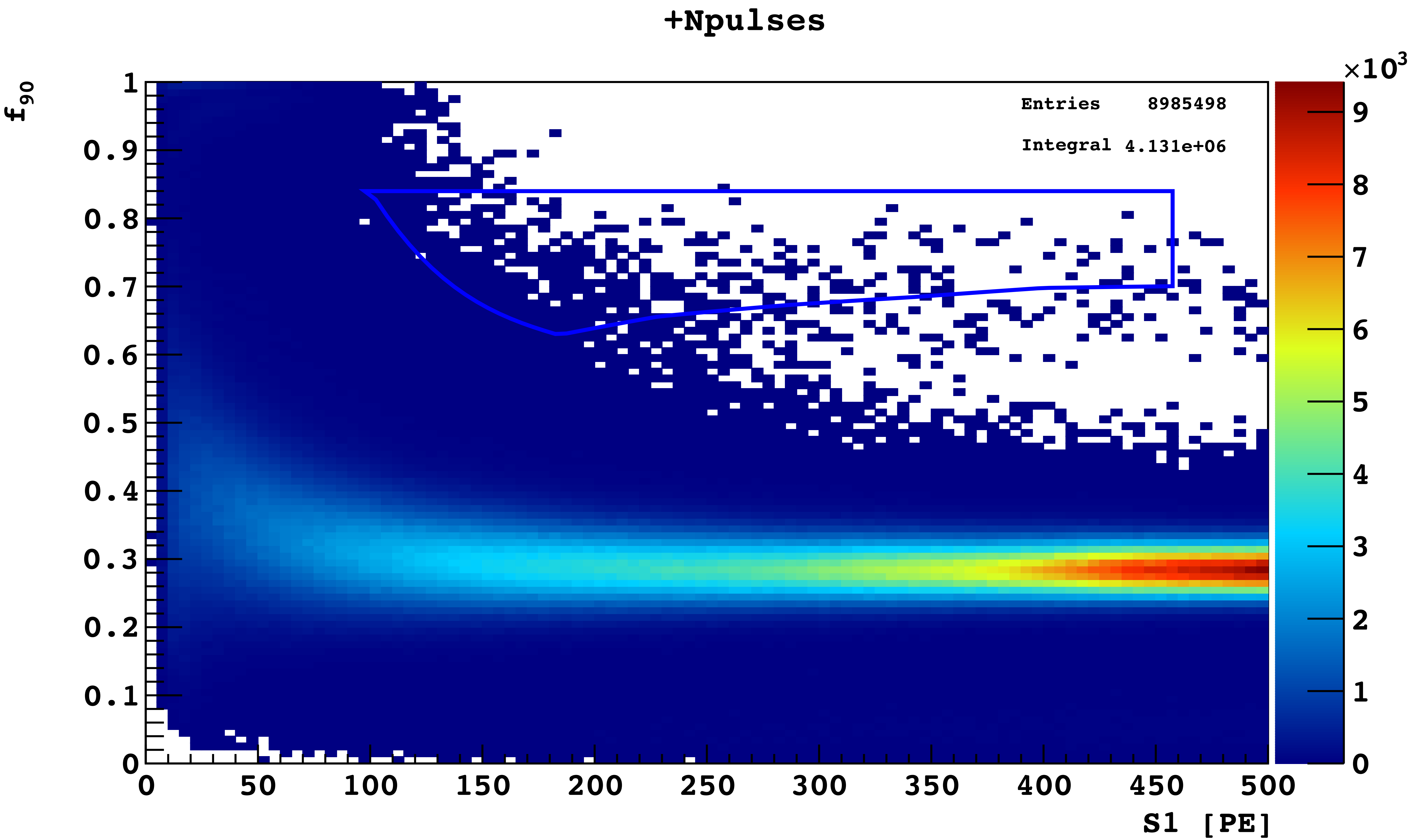

- MC + Ionization model [1] fit to NR data from AmBe and AmC.
- The systematic discrepancy between the extracted and measured ionization yield is taken as systematic uncertainty.



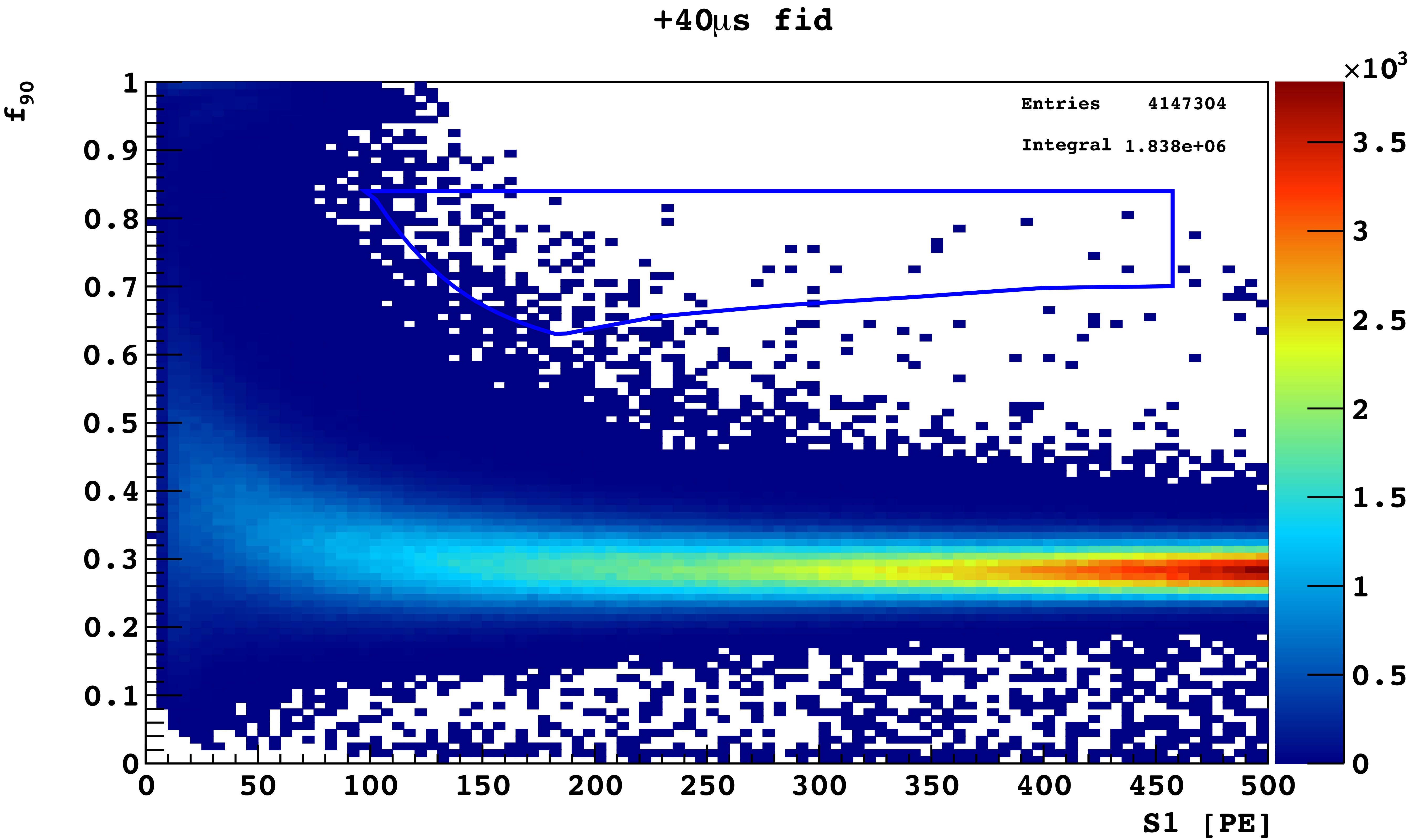

[1] F. Bezrukov, F. Kahlhoefer, and M. Lindner, Astropart. Phys. 35, 119 (2011).



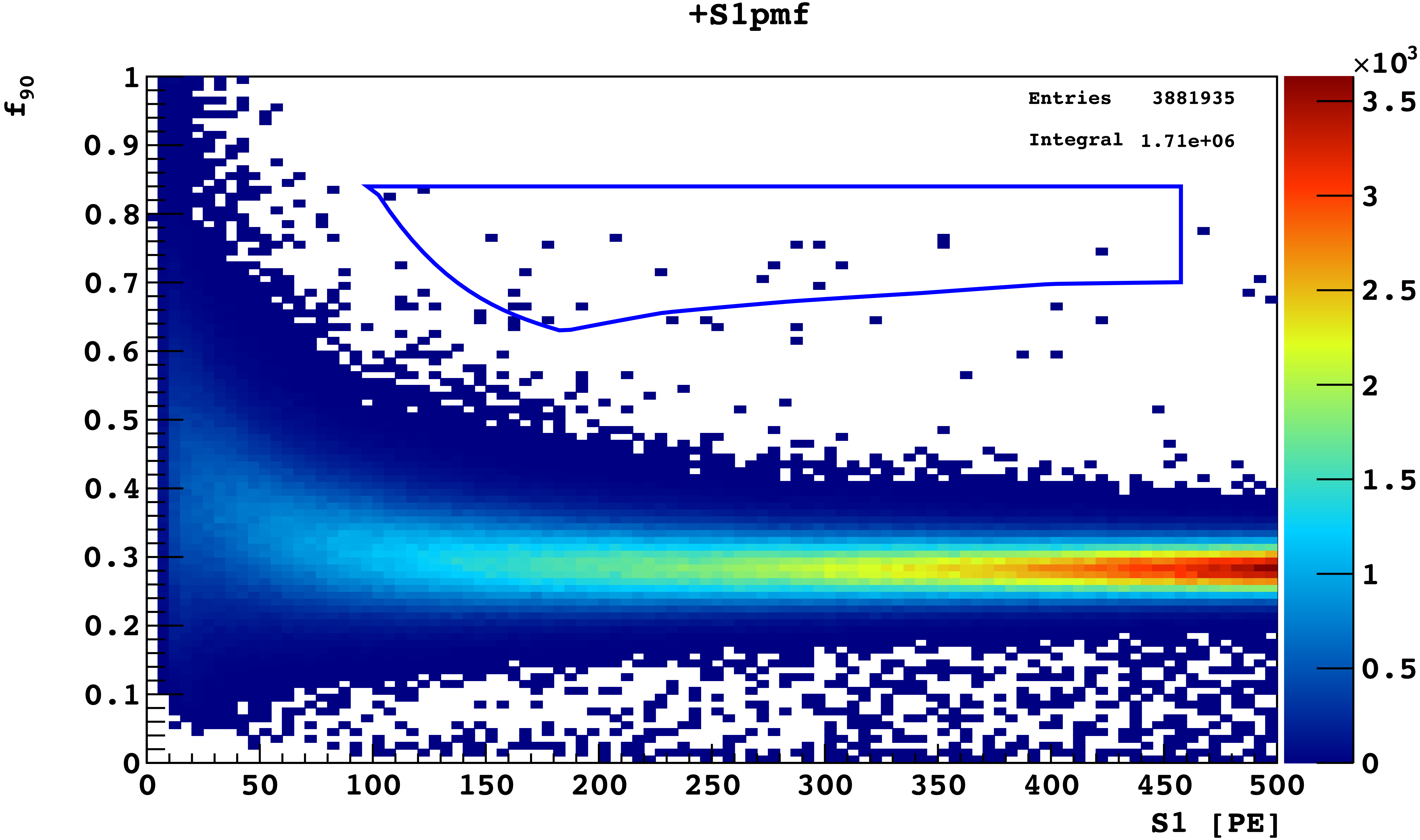

- Trigtime: the first pulse is within expected trigger time window
- S1sat: S1 pulse is not saturated



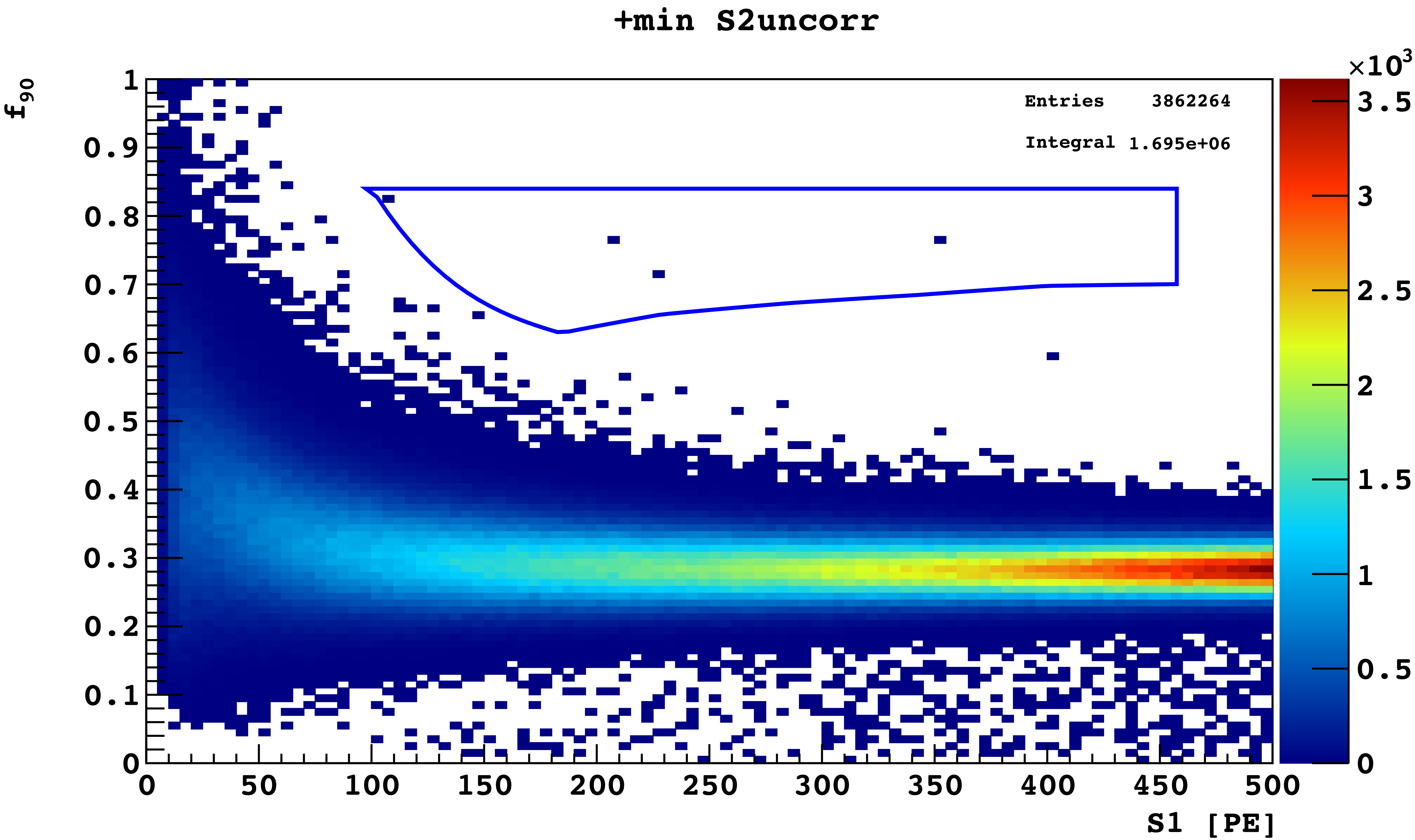

- Npulses: number of pulse is 2 or 3 if there is S3 (echo of S2).
- Most of surface events are gone.



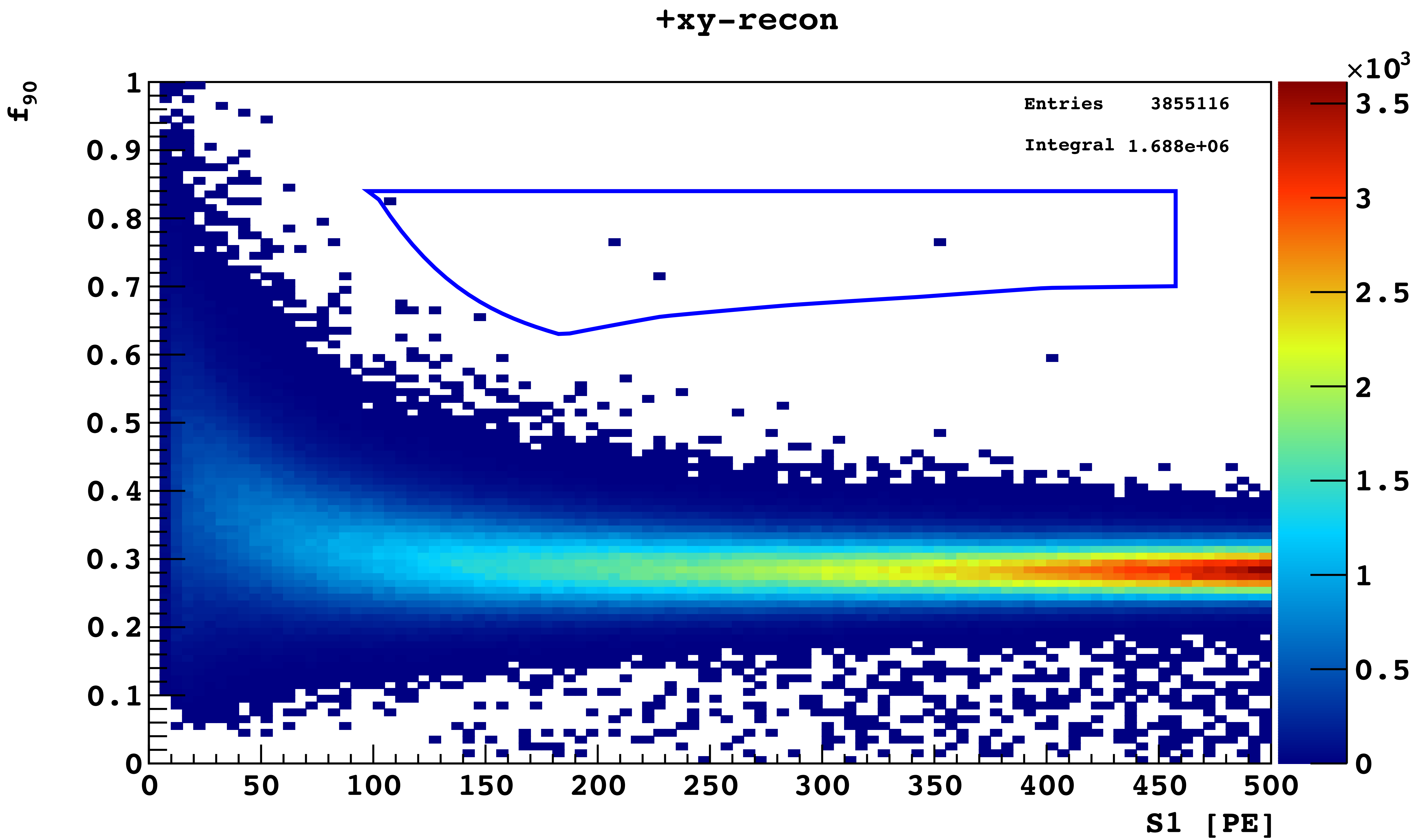

- 40us fid: remove 40 us from top and bottom in t_drift.
- Lots of γs from PMTs, unresolved S1+S2 events, and surface close to top are removed.



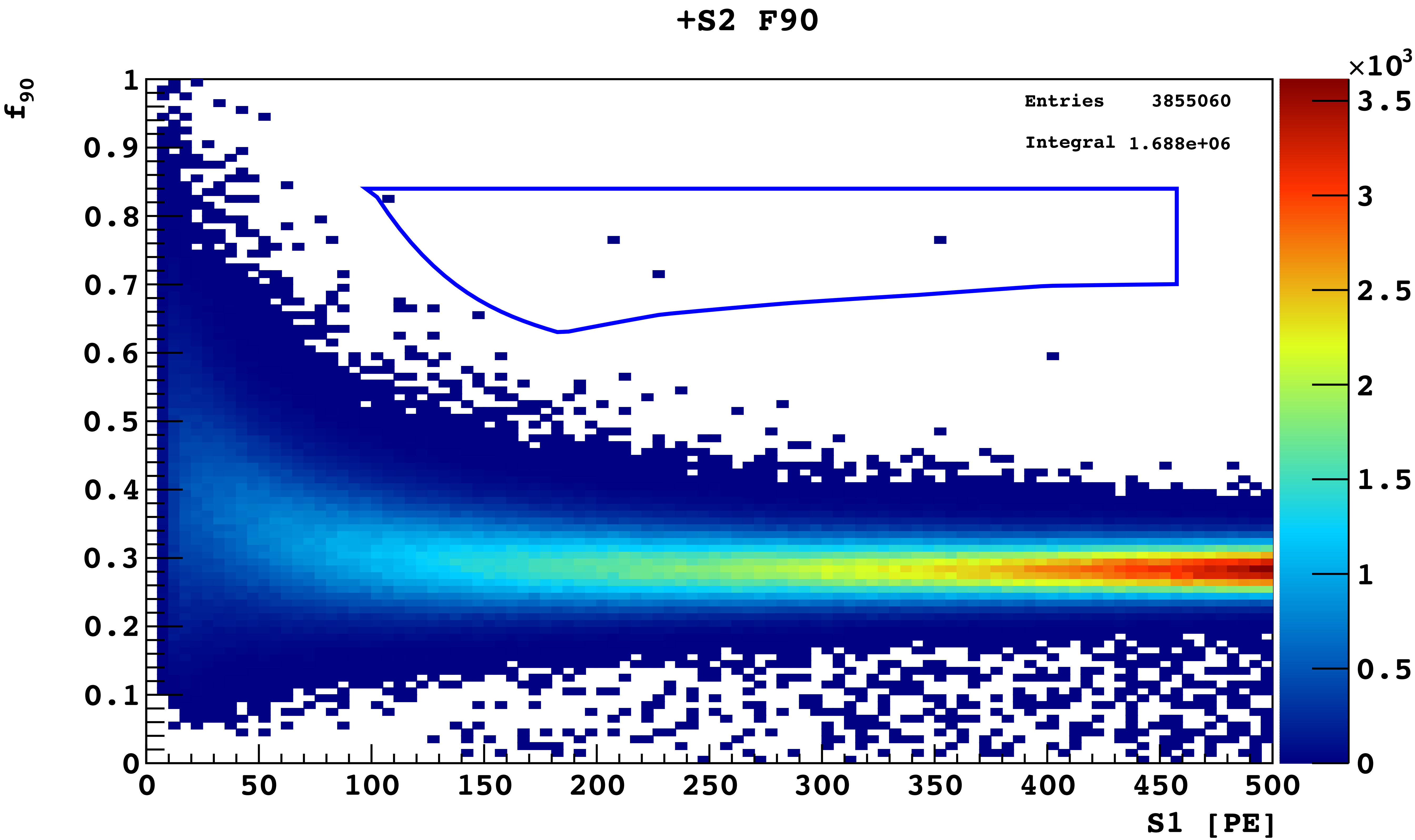

- S1pmf: fraction of prompt light in the maximum PMT is less than a threshold, which is a function of t_drift and S1
- Remove scintillation + Cherenkov events from Fused Silica



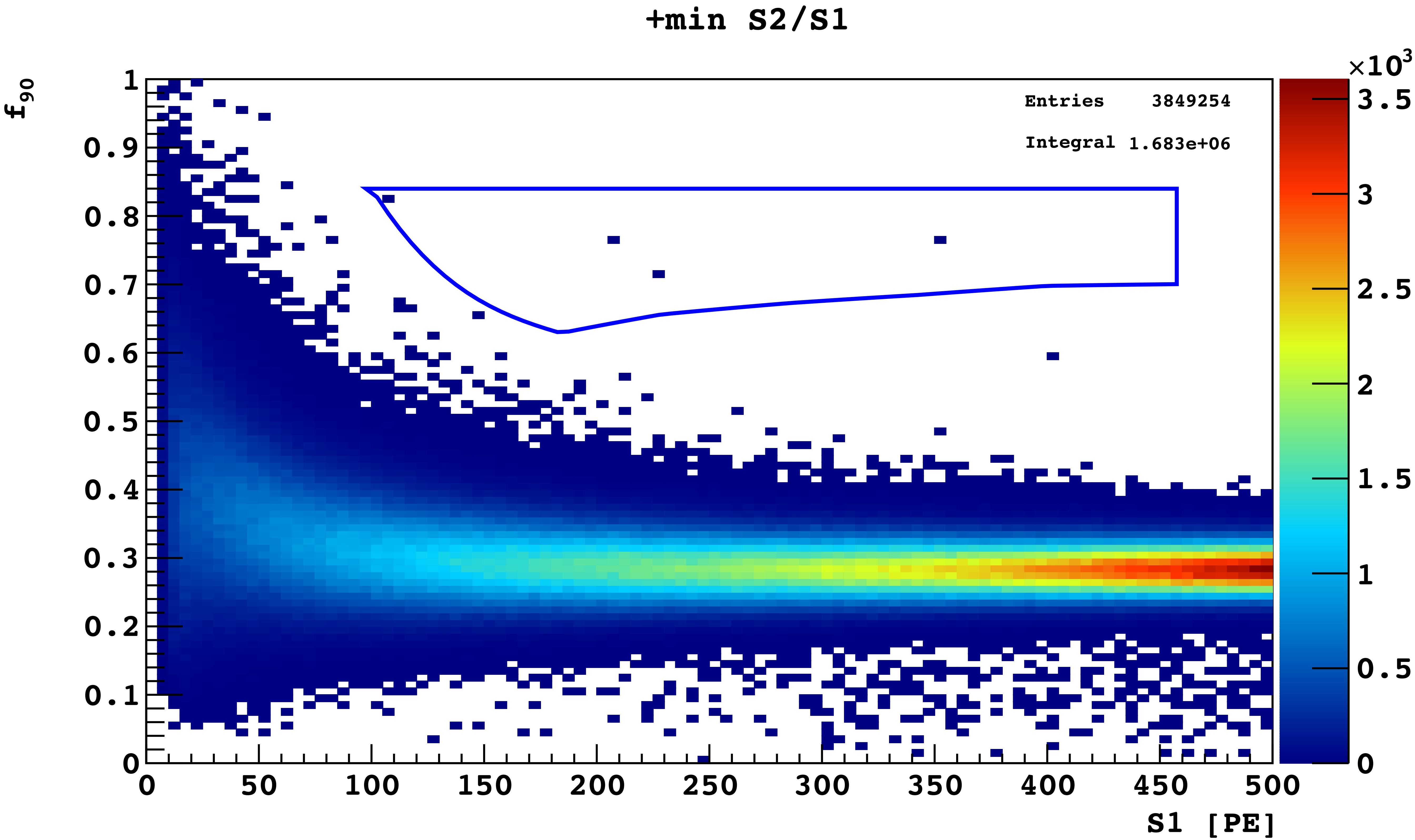

- min S2uncorr: S2 have ≥ 200 PE
- This is more like quality cut, but remove surface events, which number of electrons are reduced by the surface effect.



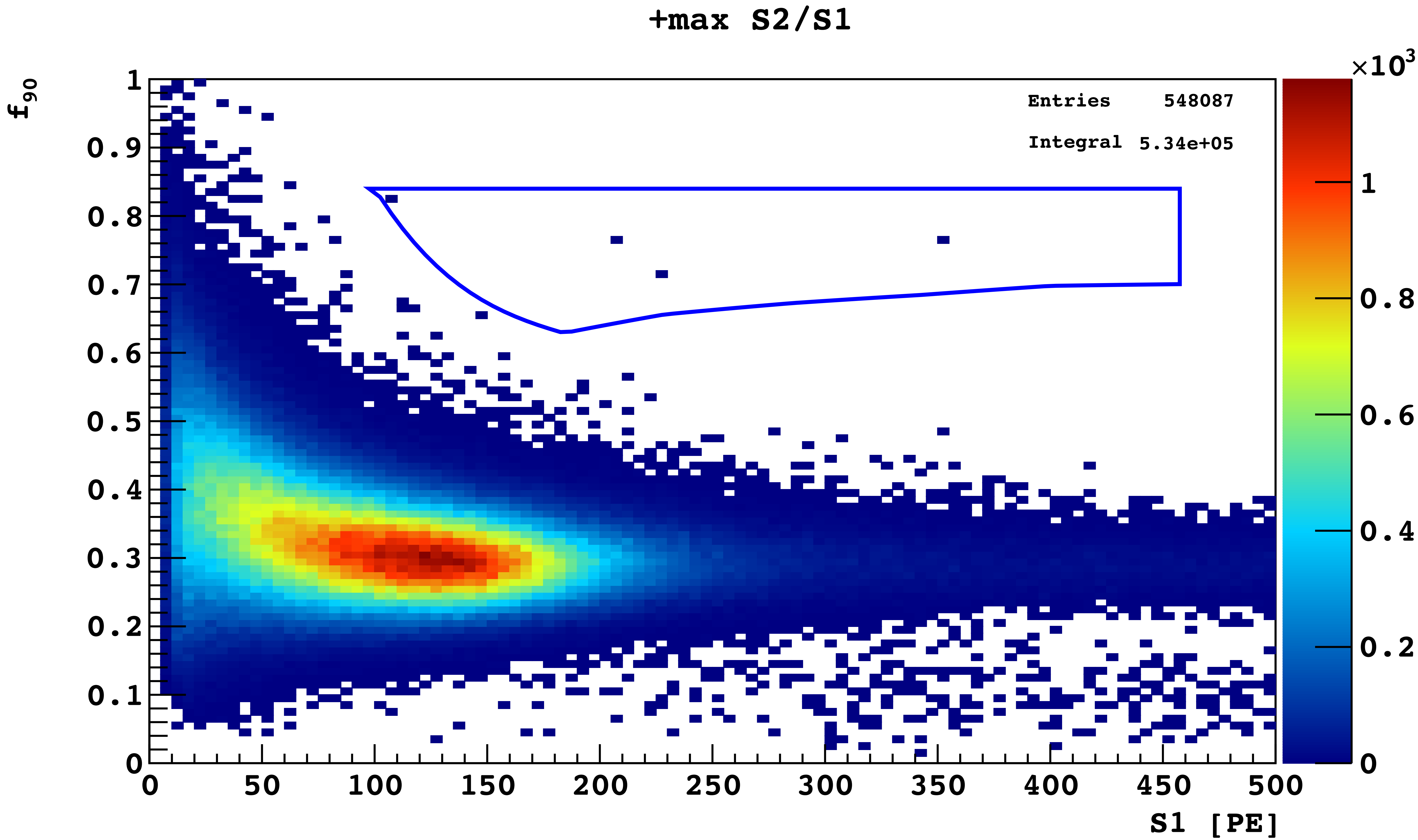

- xy-recon: reasonable x-y reconstructed values (reconstruction does not failed)



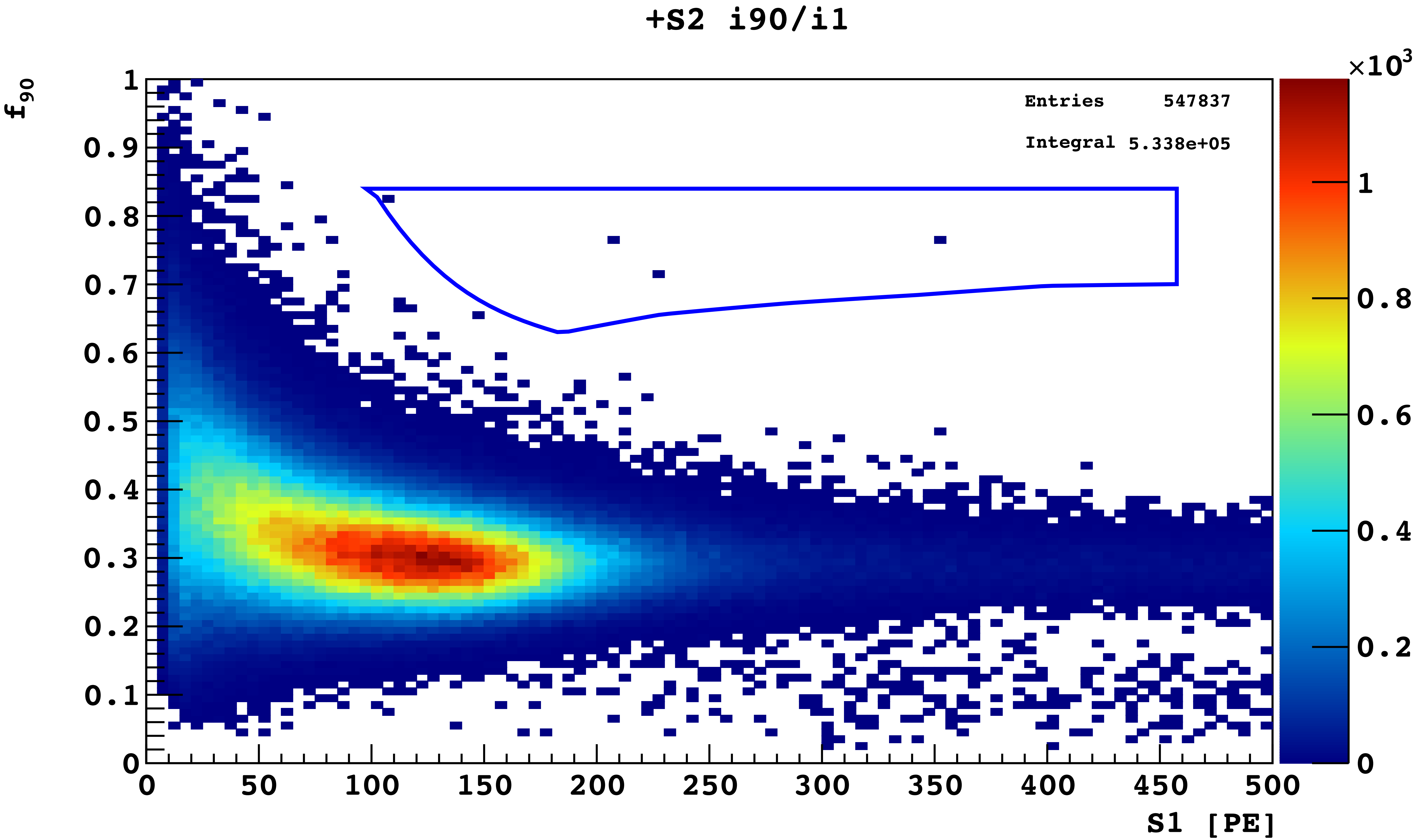

- s2 F90: F90 of S2 pulse < 0.20
- Remove S1 + S1 pileup events



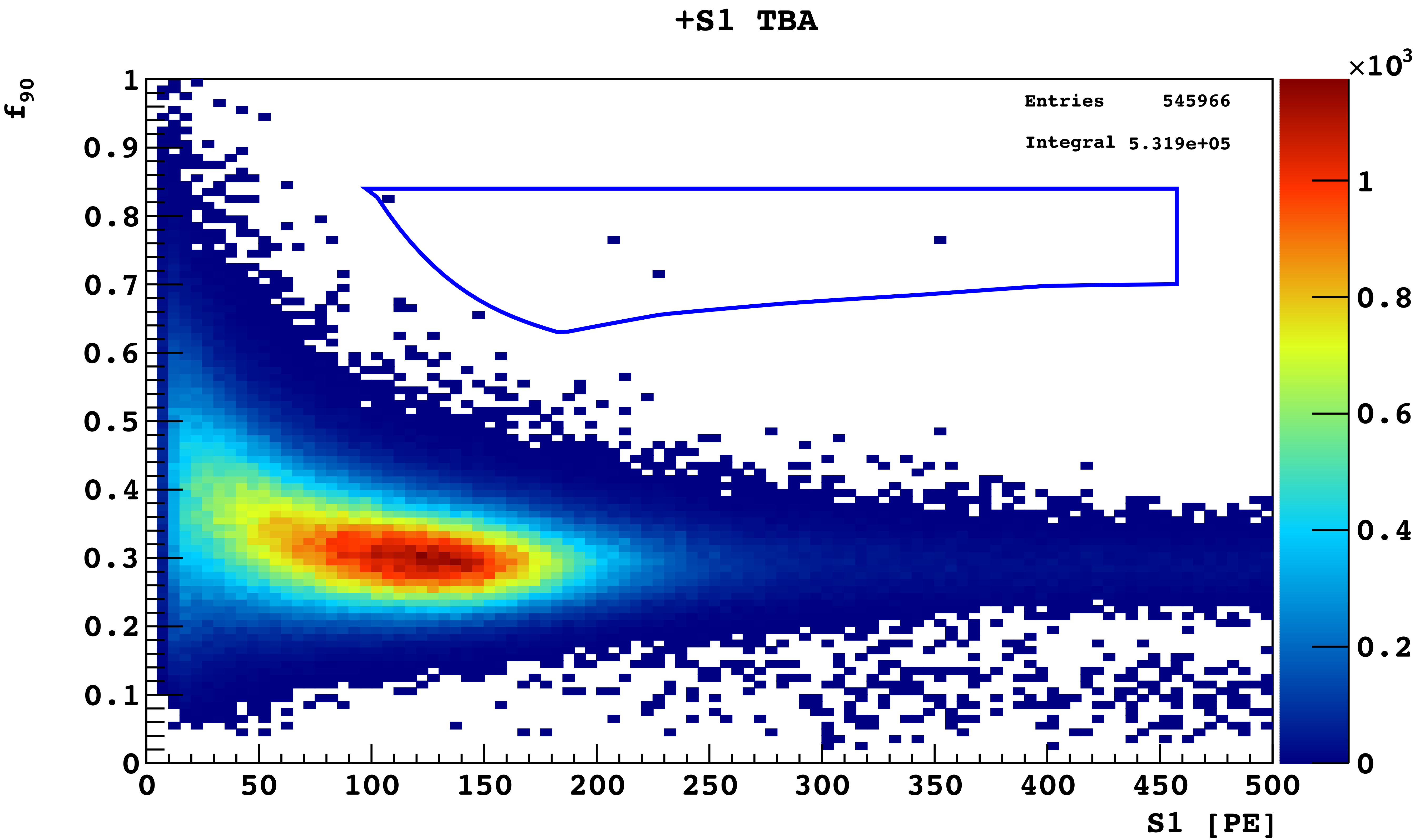

- min S2/S1: S2/S1 need to be above threshold, which is a function of S1.
- Remove strangely small S2 events, like surface events.




- 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.

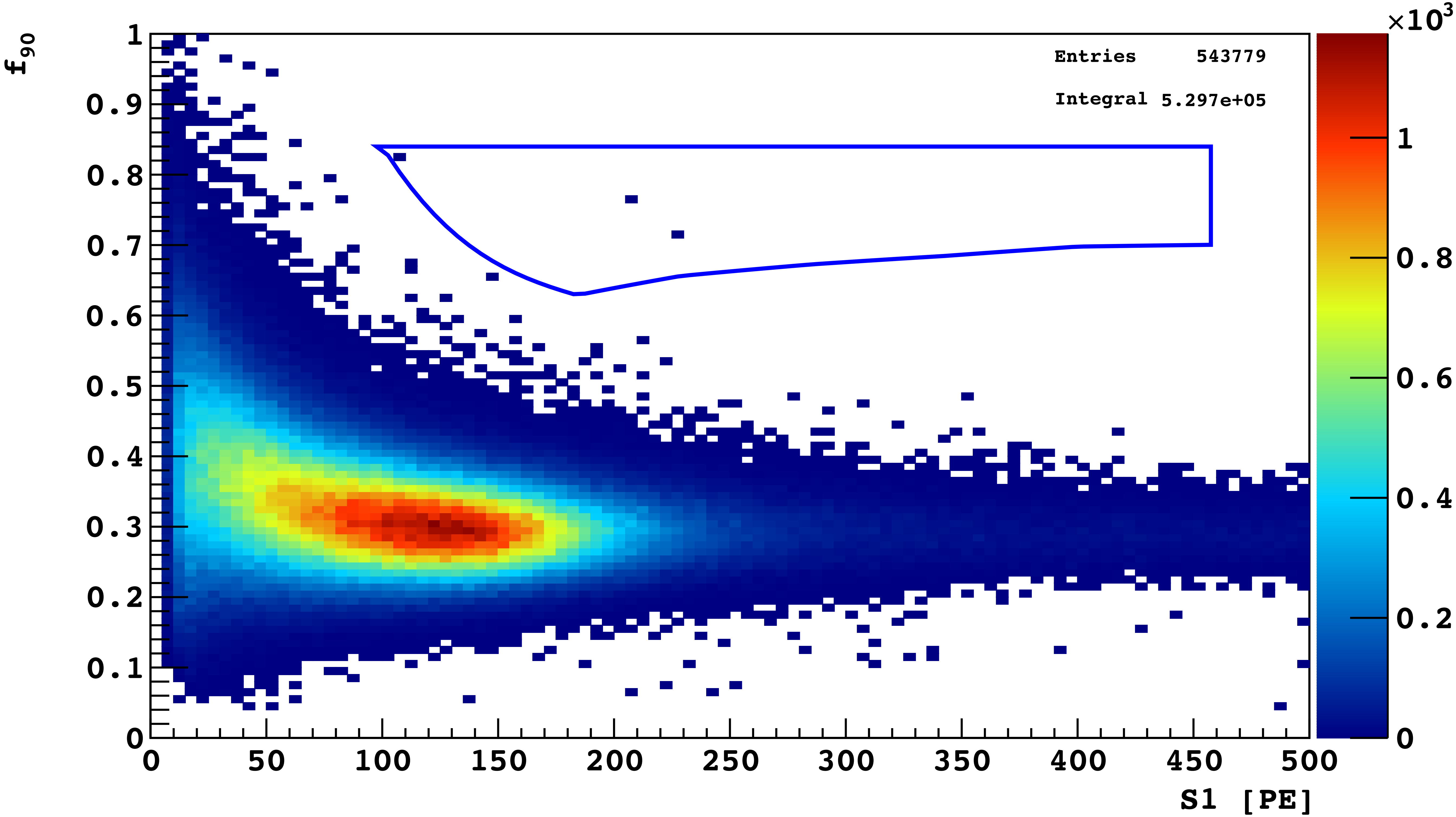



- S2 i90/i1: S2 have reasonable rise time.
- Remove events in which S2 is actually S1+S2 pulses.



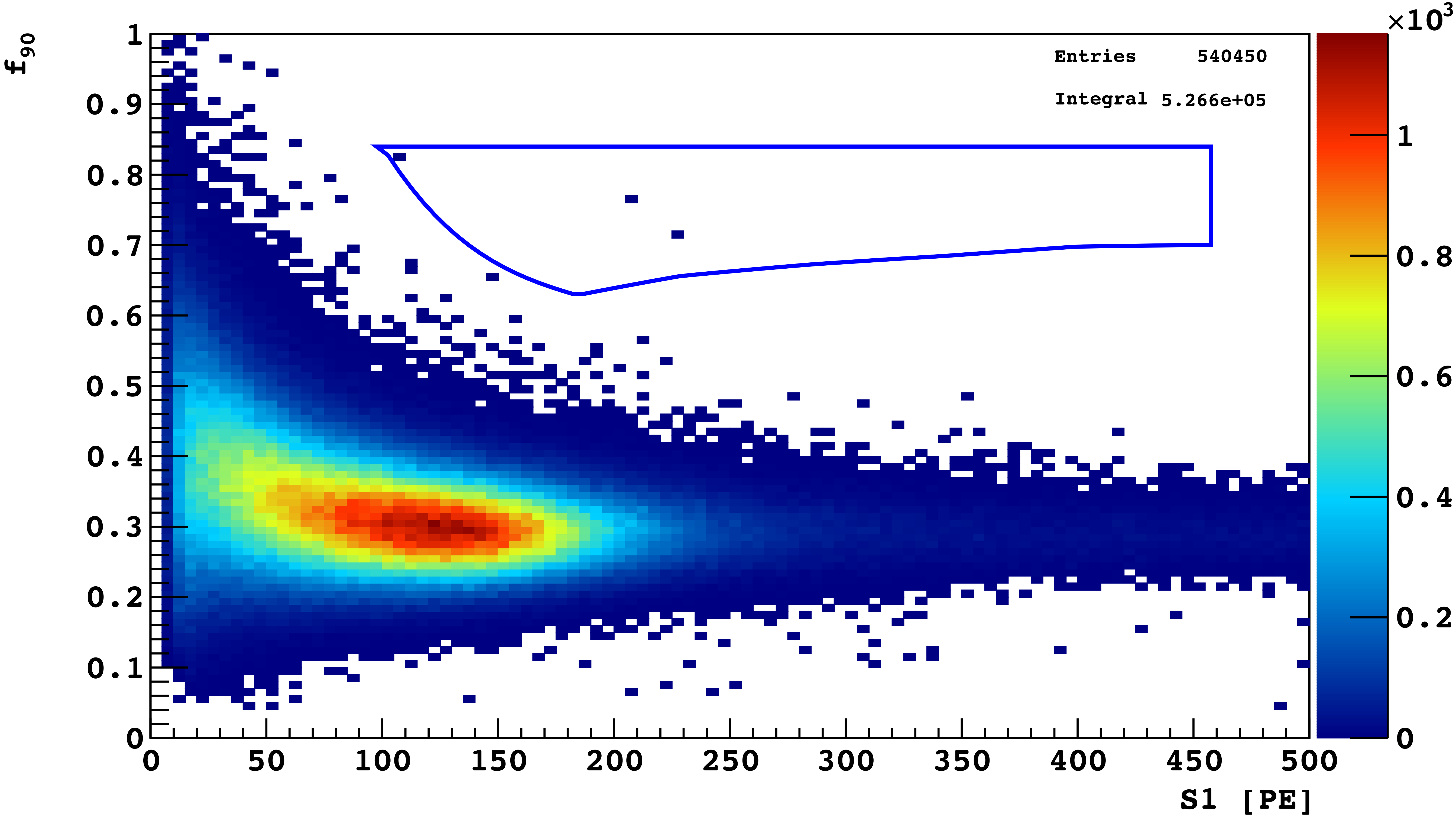

- S1 TBA: z-position from S1 Top-Bottom asymmetry agrees with t_drift.
- Remove random pileup S1 and S2.

## +TPB Tail

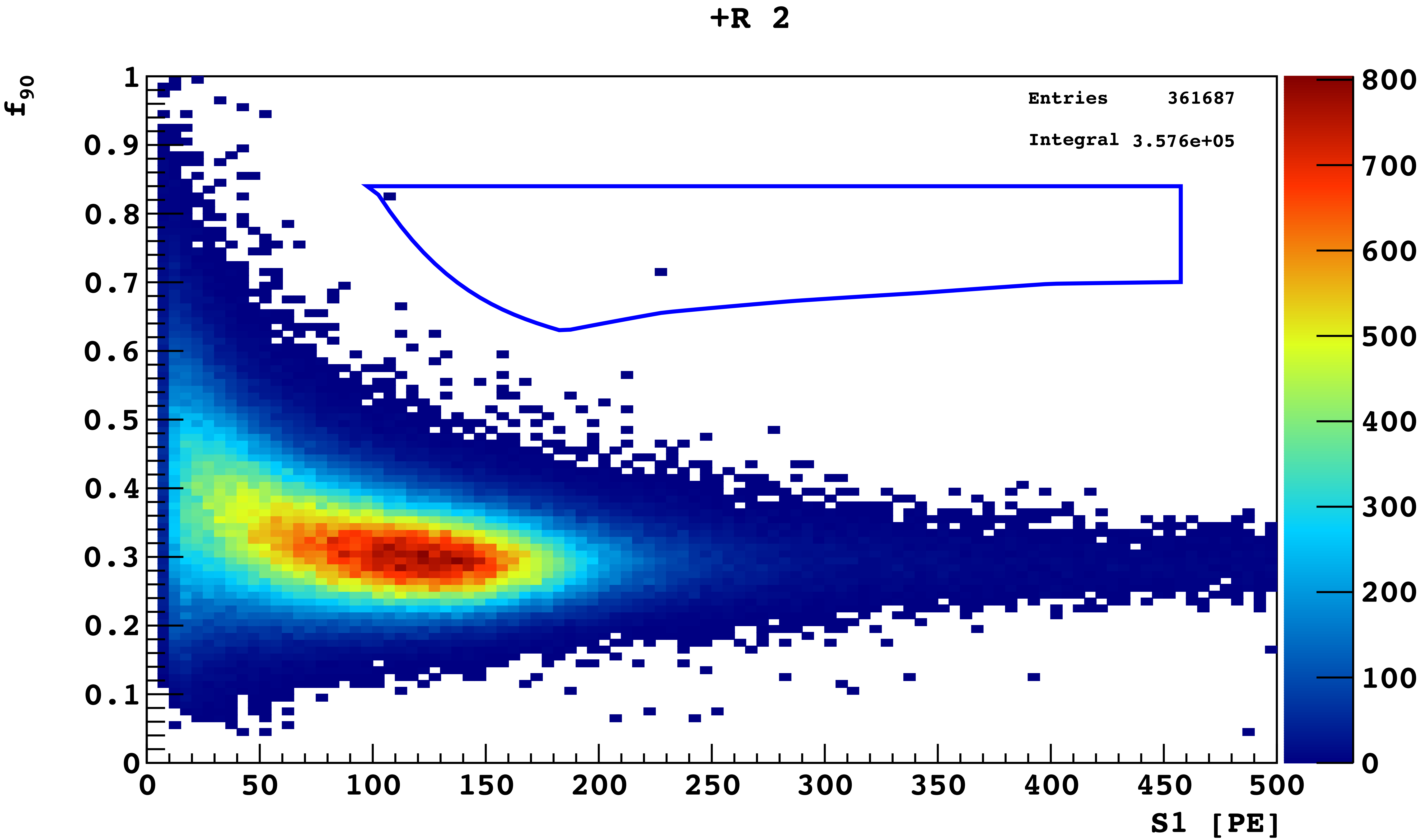



- TPB Tail: remove events, which have long tail of scintillation caused by TPB scintillation.
- Remove surface events, in which alpha goes through TPB layer.

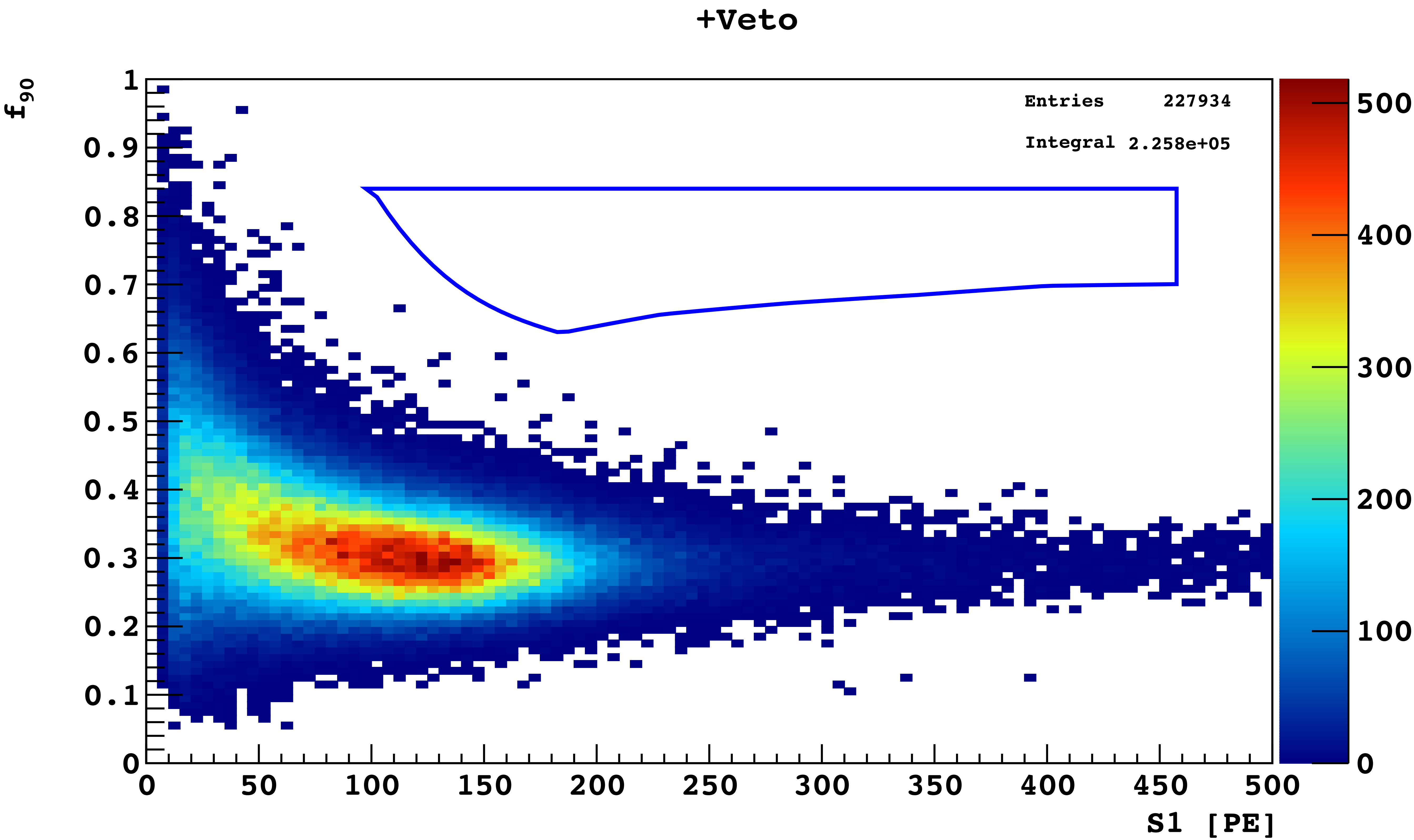
# +NLL




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




- R 2: Radial cut as a function of t_drift




- Veto: all veto cuts
- Remove neutrons