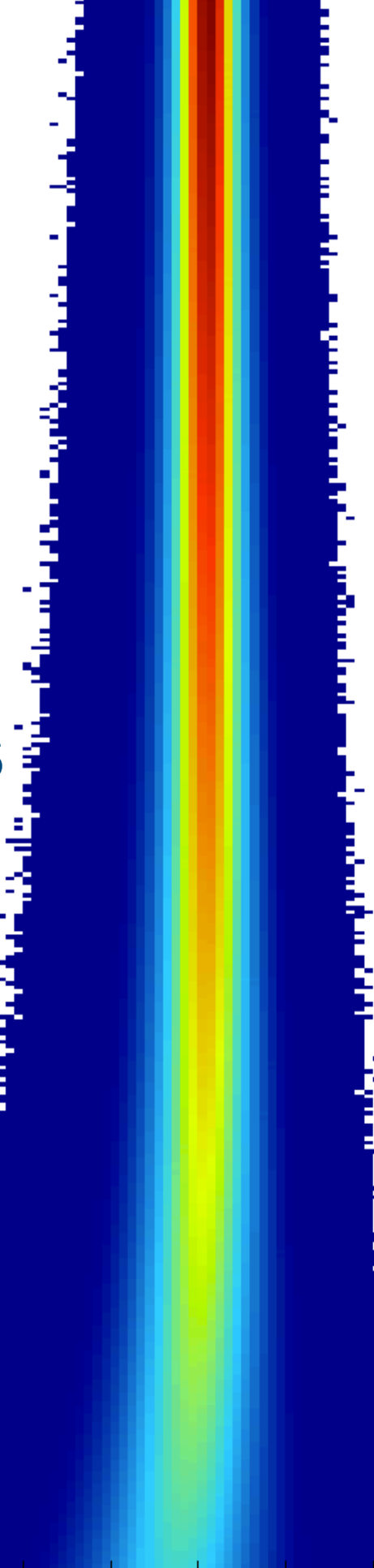
Constraining dark matter interactions using liquid argon detectors

Paolo Agnes
RHUL and University of Houston

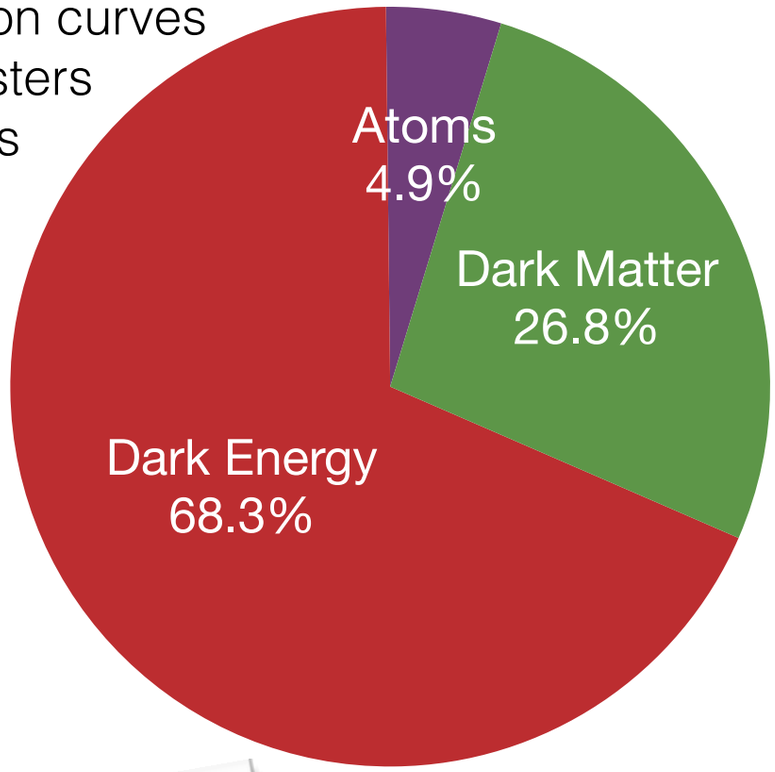
NExT workshop
Queen Mary University, 3rd April 2019

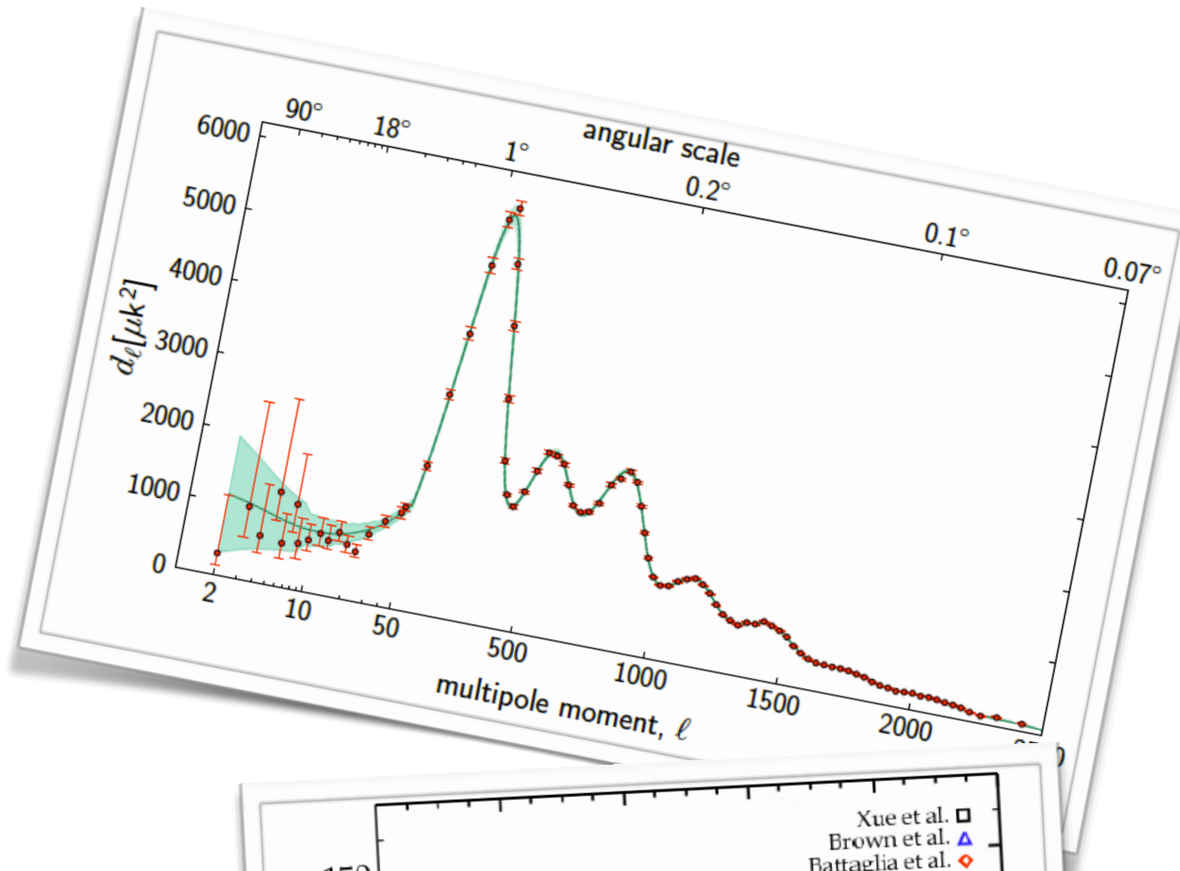


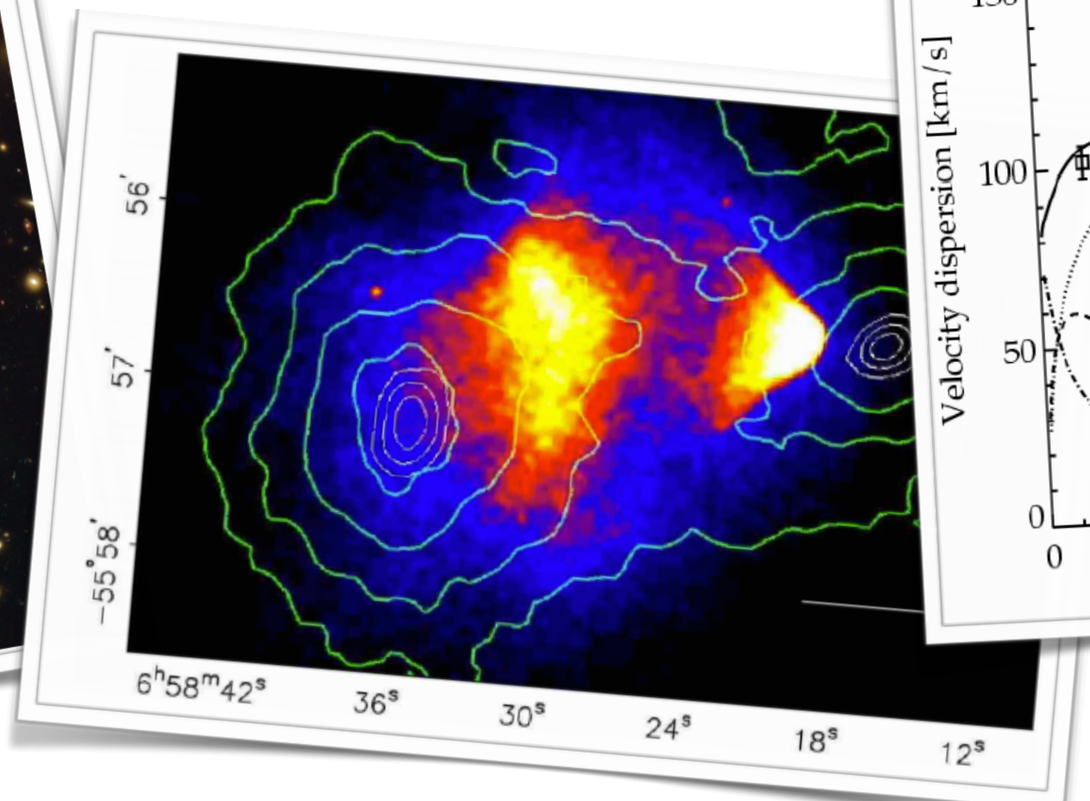
Evidence for dark matter

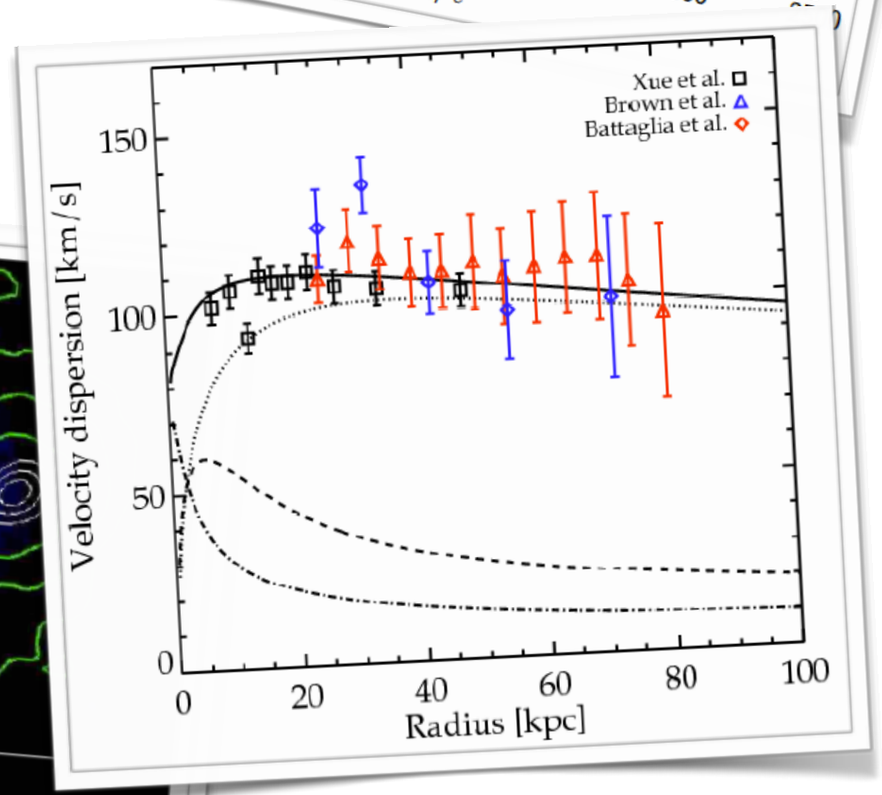
Several indirect observations:

- Galactic rotation curves
- Hot gas in clusters
- Galaxy clusters
- Strong lensing
- Weak lensing
- Bullet Cluster
- Supernovae
- CMB







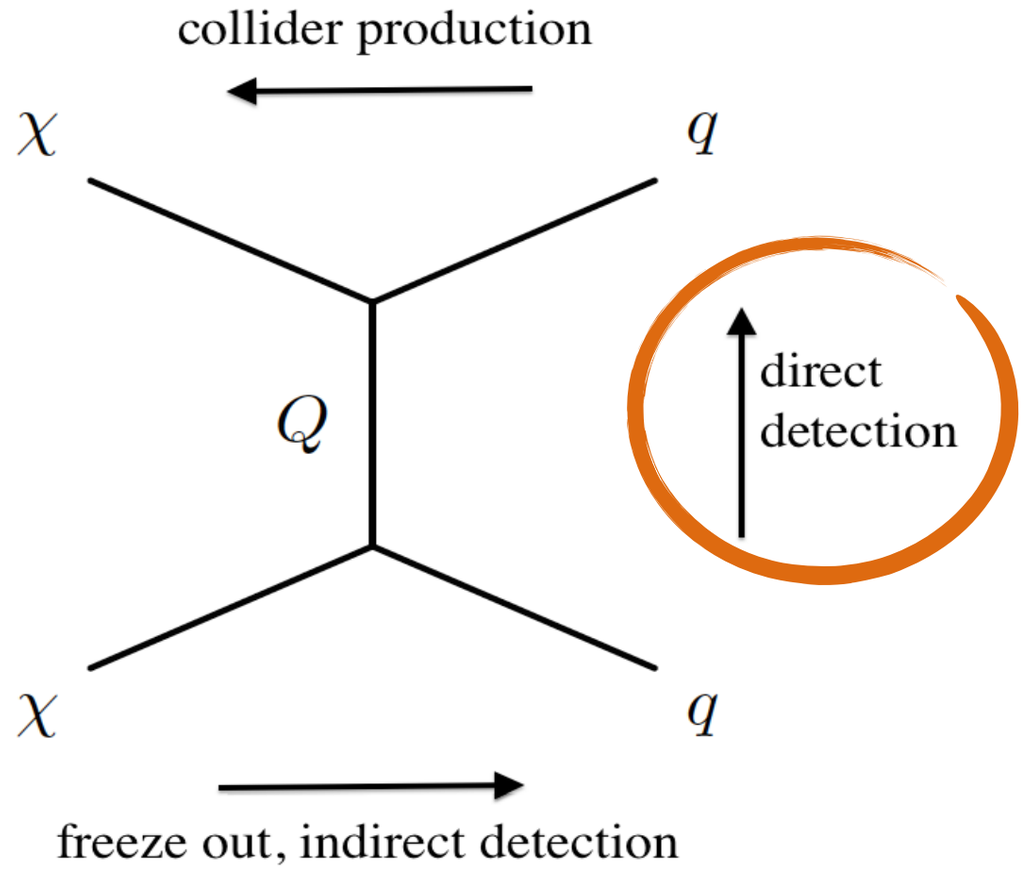


Direct detection

The Dark Matter particle properties:

- It is **stable**
- It is electrically **neutral**
- It does not interact strongly
- It interacts through gravitational force
- It may interact **weakly**
- It should show a direction signature

A favored candidate:
Weakly Interactive Massive Particles

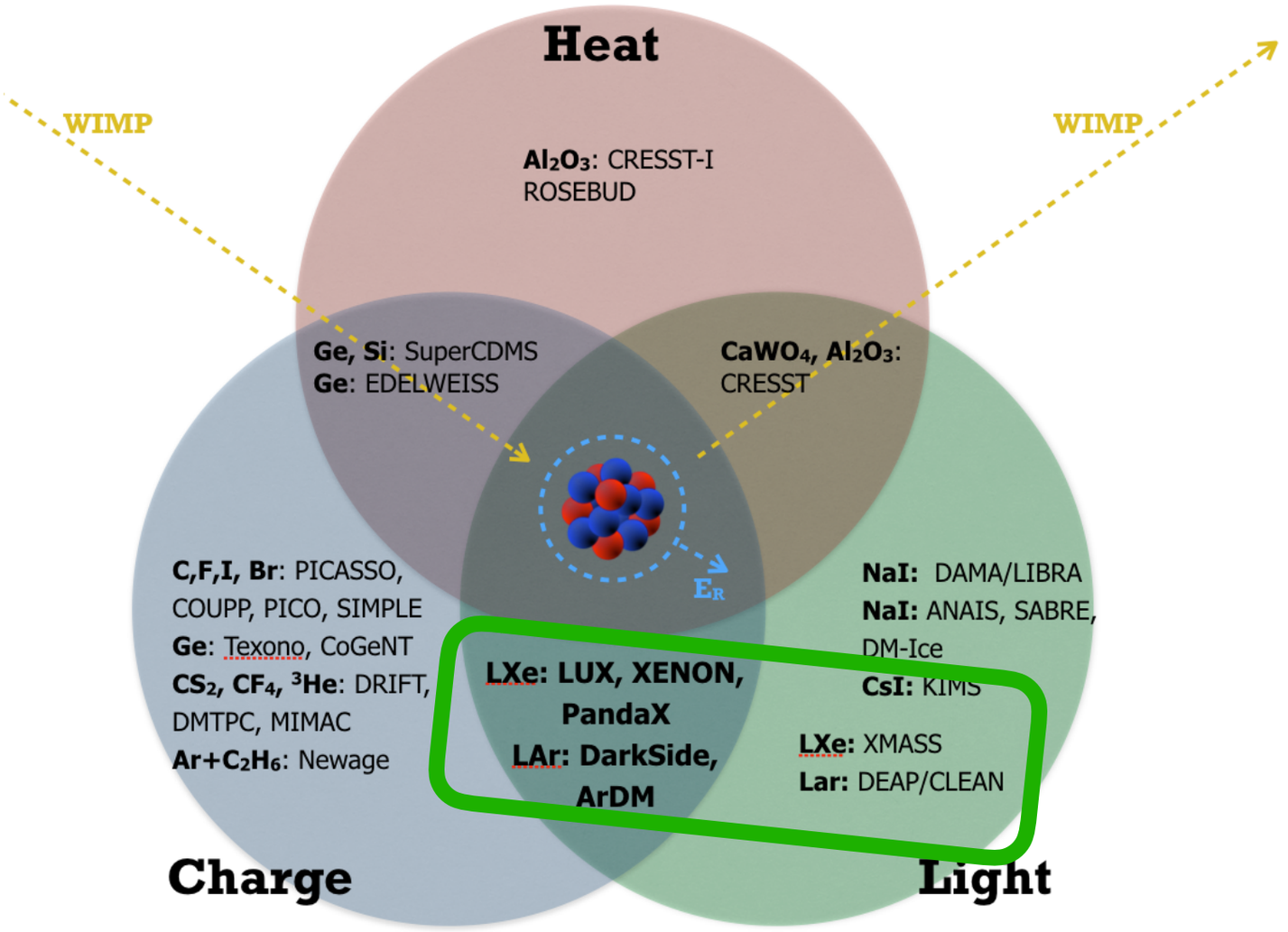


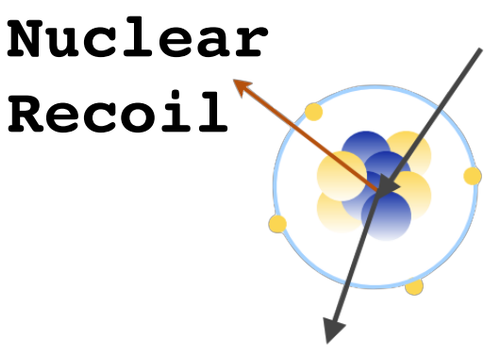
Detection requirements

Large masses
Low rate (~ 1 event/tonne/yr @ 10^{-47} cm^2 in noble liquids)

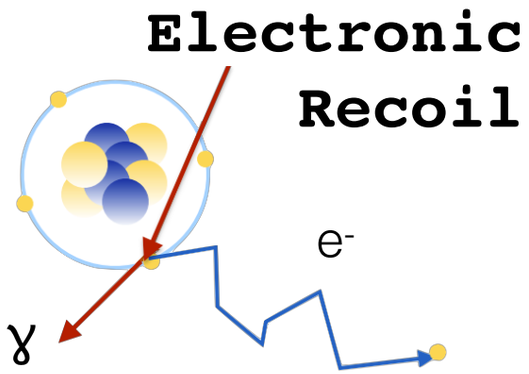
Low energy thresholds
Low energy nuclear recoils (< 100 keV)

Background suppression
Deep underground
Passive/active shielding
Low intrinsic radioactivity
Gamma background discrimination





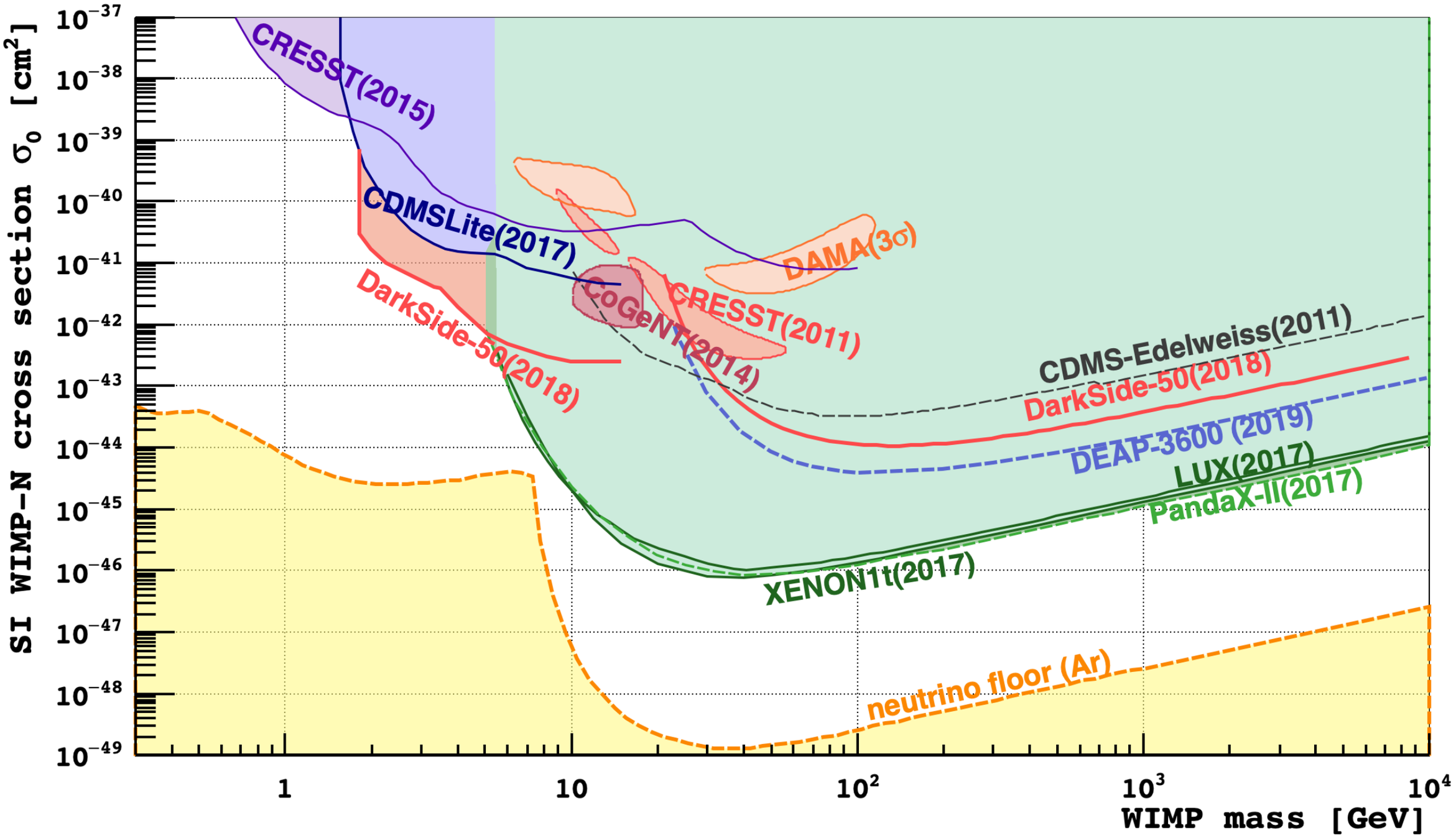
NR backgrounds	ER backgrounds
neutrons α's	internal and external β's, γ's



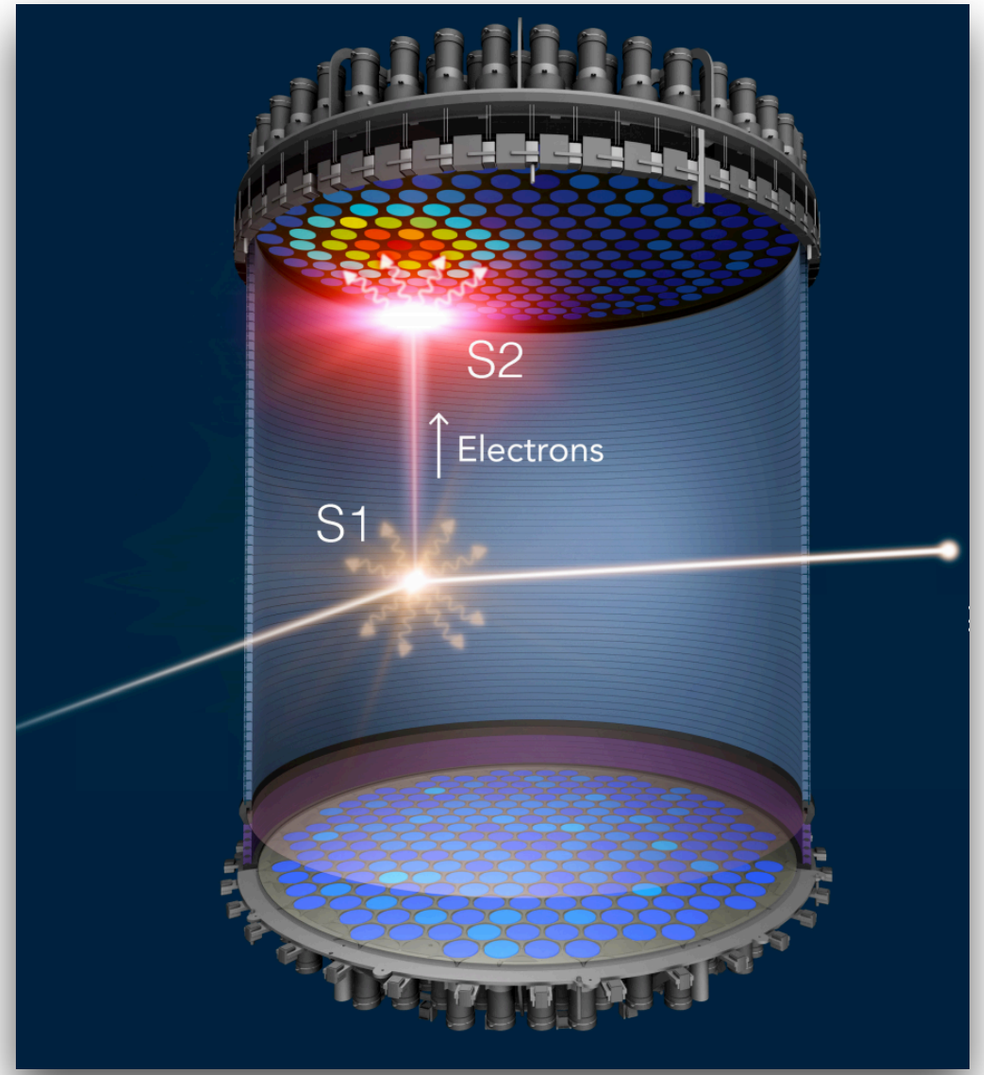
Spin-independent cross section

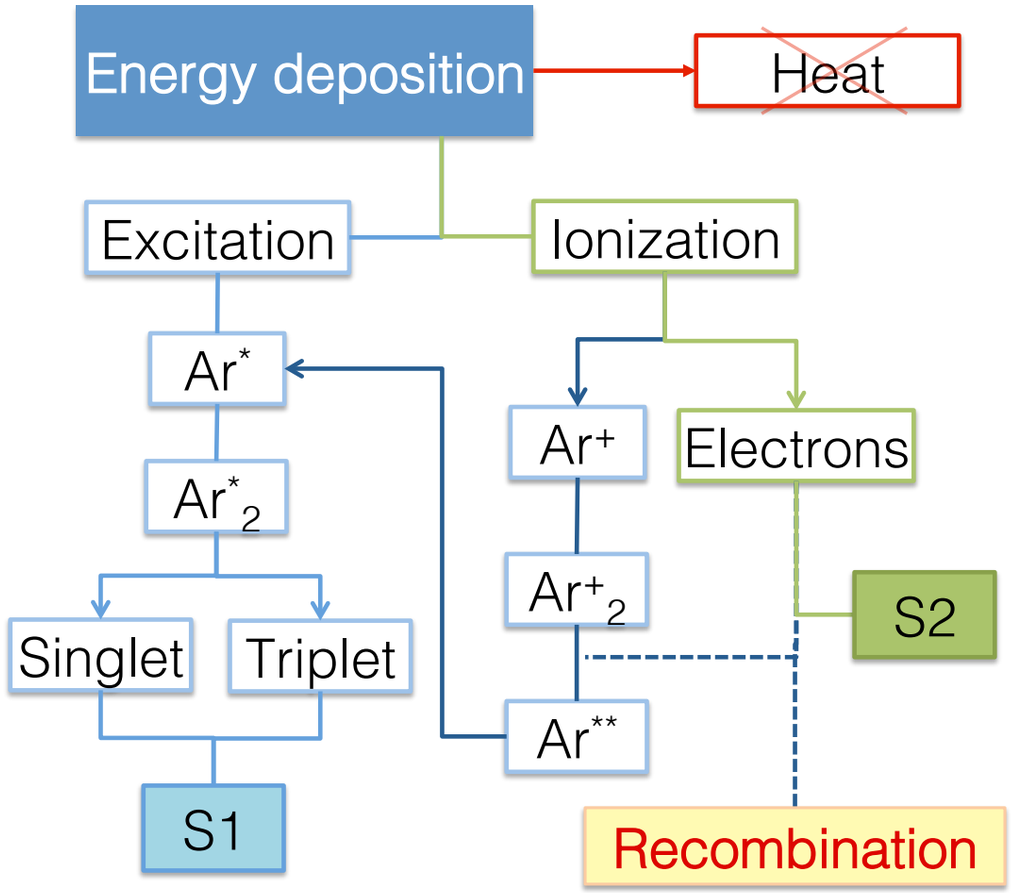
Noble liquids are suitable targets:

- ☑ dense, stable, easy to purify, inexpensive
- ☑ large ionization/scintillation yields (W~10 eV)
- ☑ transparent to own scintillation light

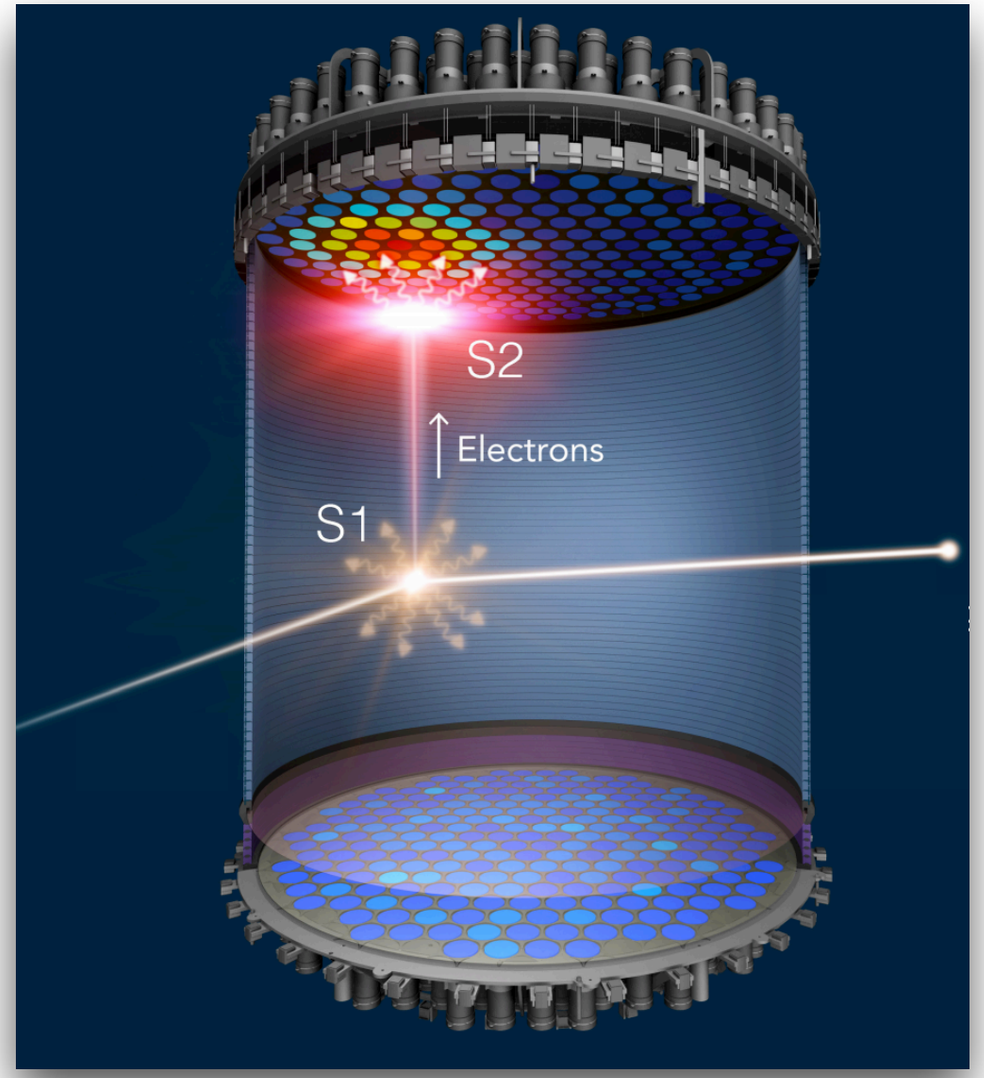


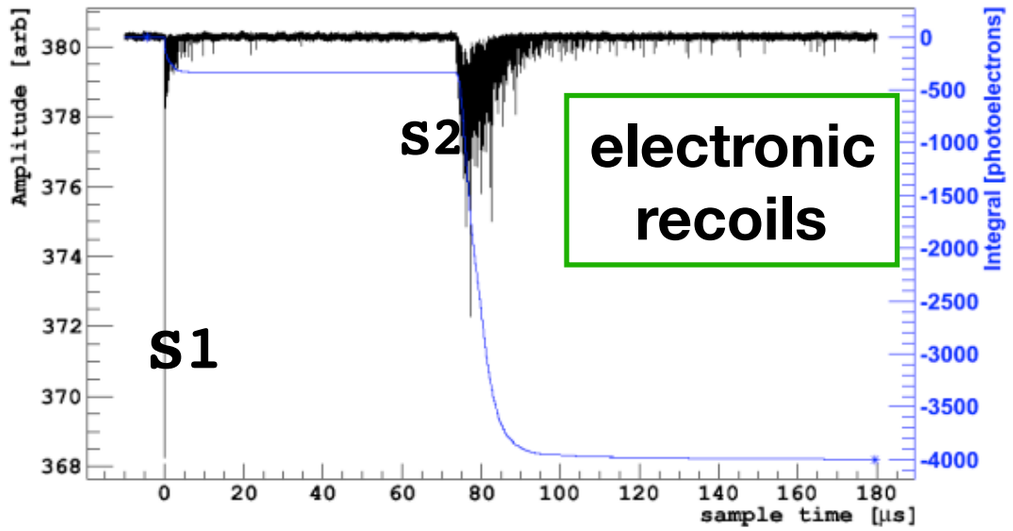
Detection in noble liquids

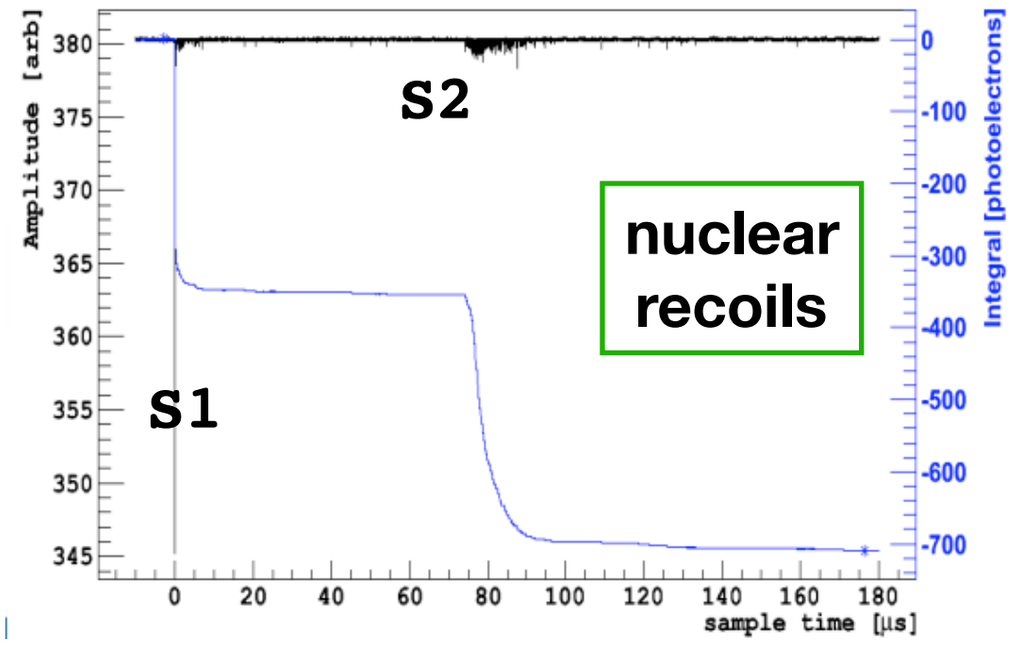




Dual-phase Time Projection Chamber







Dual-phase TPC

- ☑ 3D **vertex** reconstruction < 1 cm
- ☑ Rejection of **multi-sited** events (γ-rays and neutrons)
- ☑ **ER Rejection** based on **ionization/scintillation: 10^3**

The DarkSide-50 experiment

The DarkSide-50 detector

A **dual-phase LAr TPC**

- taking data since 2013 at Gran Sasso
- **50 kg** of **argon**
- in a 30 t liquid scintillator veto
- in a 1 kt water Cherenkov detector

S1 and S2 Yields:

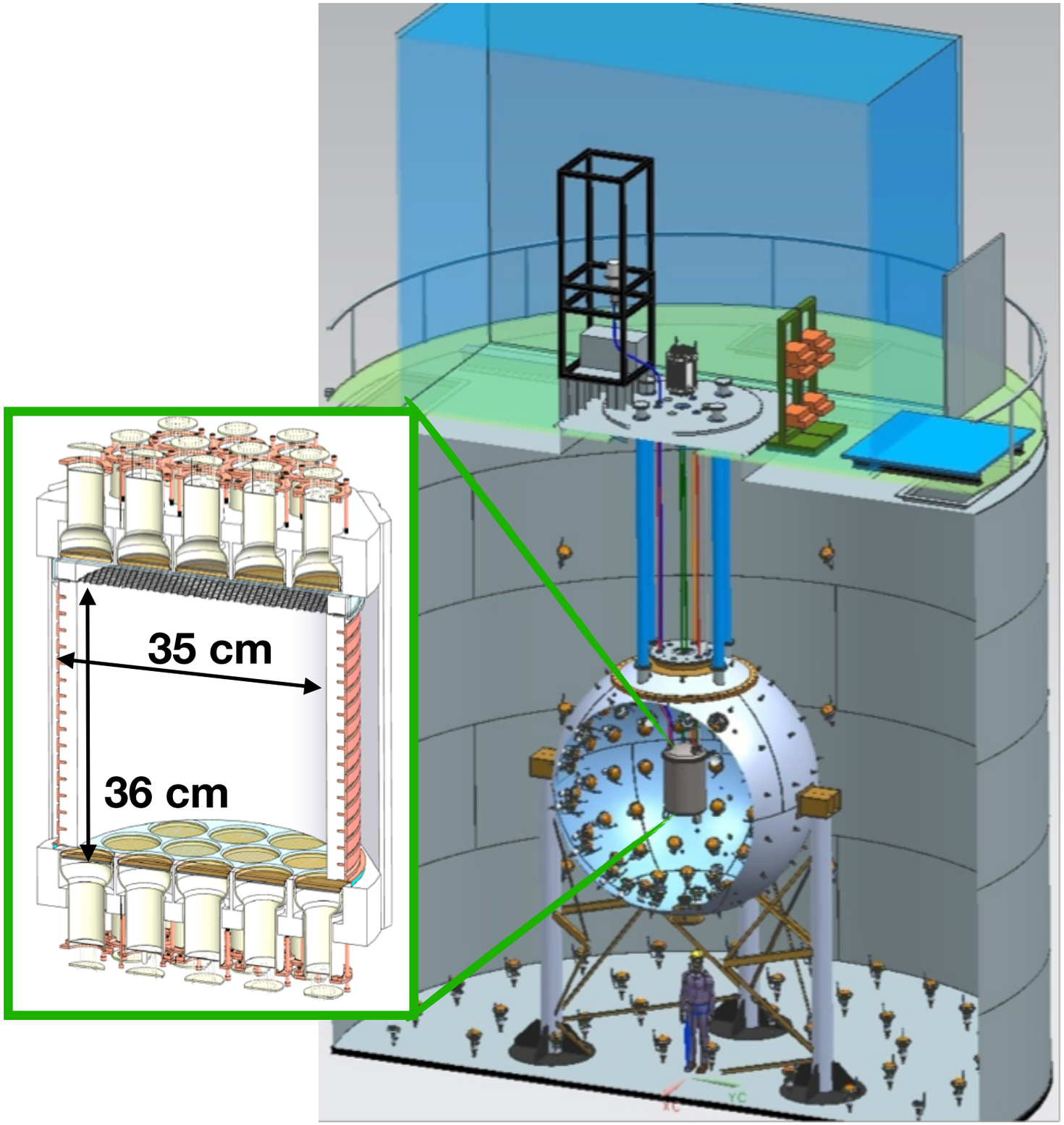
- S1 Yield ~7.9 pe/keV at null field
- S1 Yield **~7.0 pe/keV** at 200 V/cm
- S2 yield **~23 pe / e-**

Electron lifetime > 5 ms
Maximum drift time: 376 μs

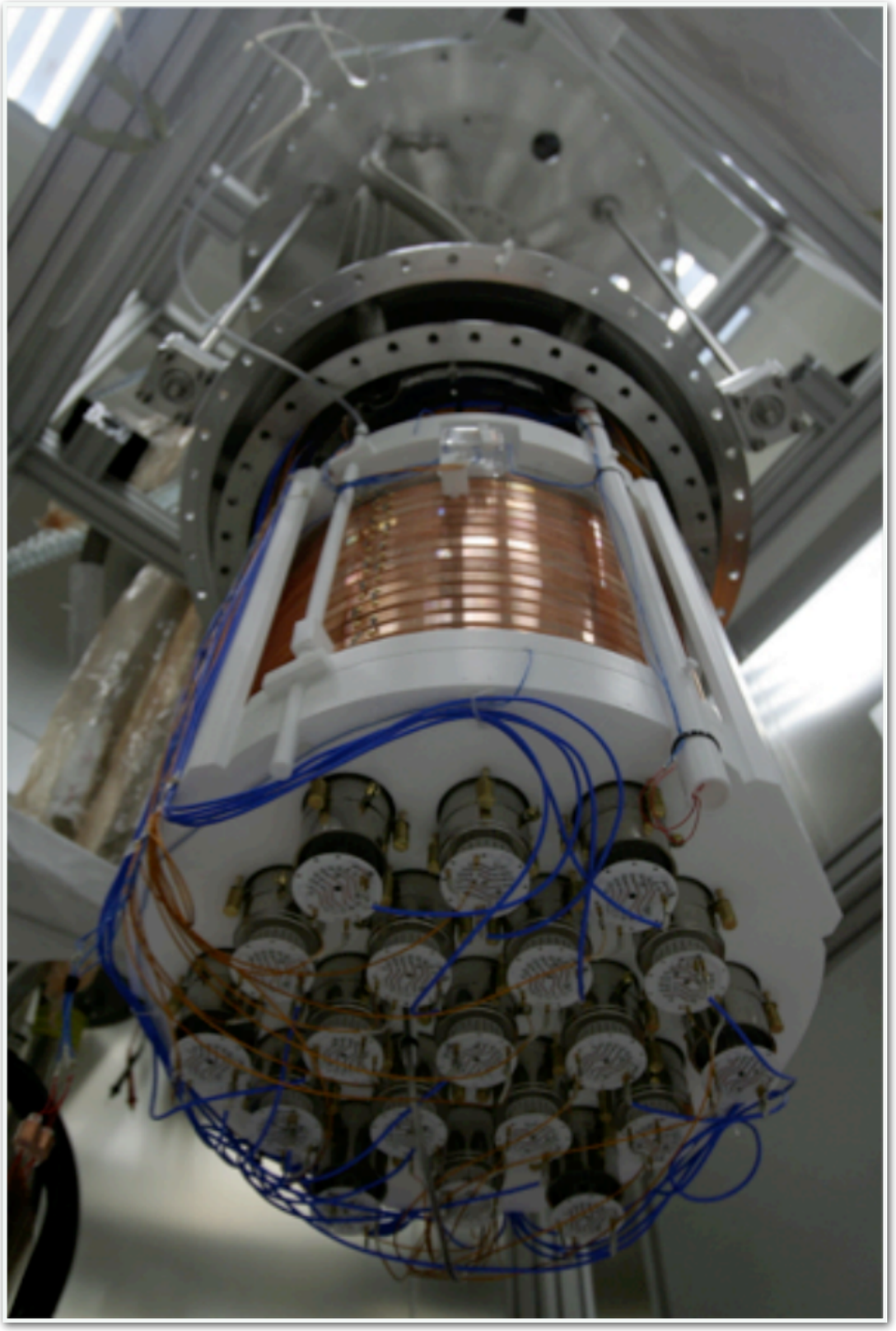
Position reconstruction:

- Resolution in Z **~1 mm**
- Resolution in XY **<1 cm**

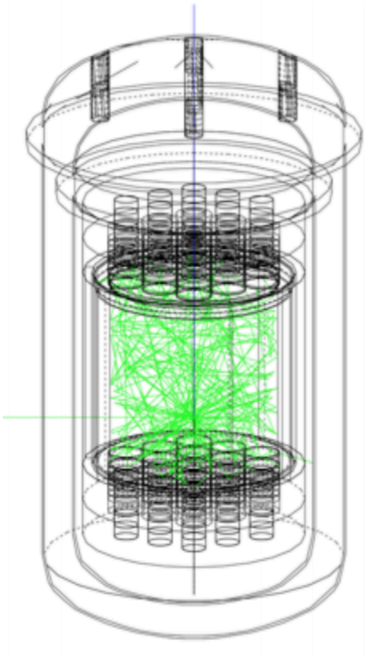
Neutron Veto Efficiency: 99.6%



DarkSide-50 installation



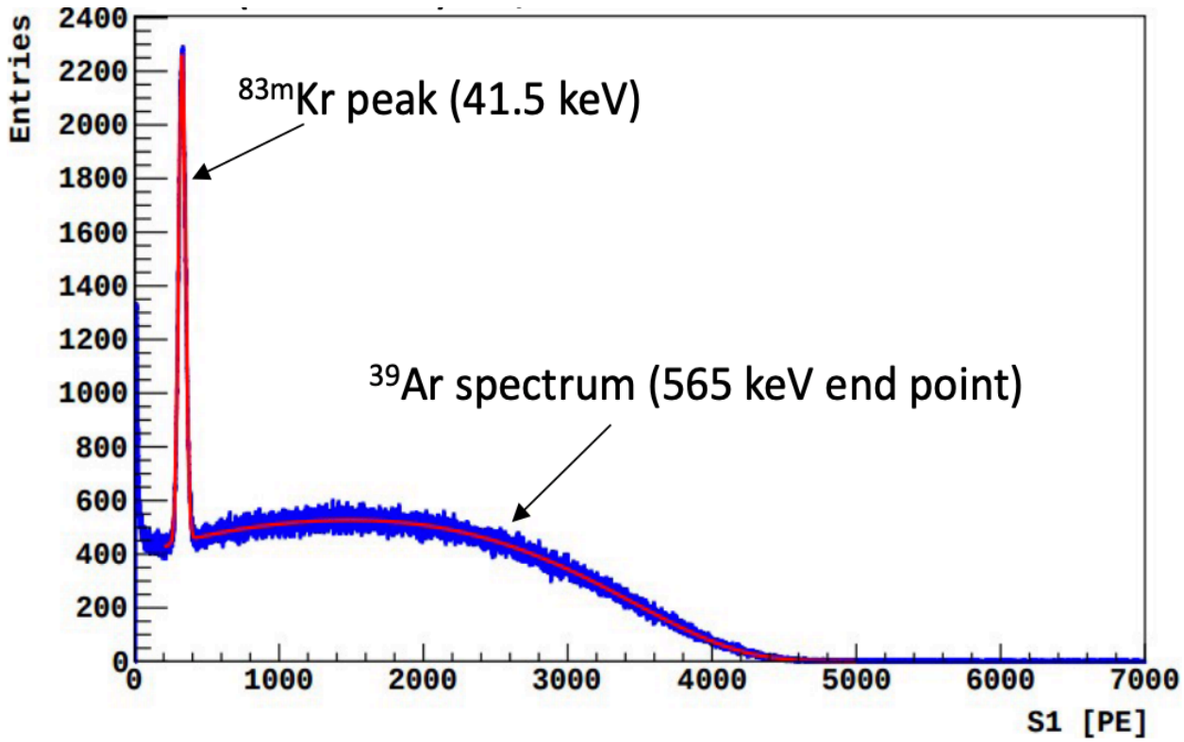
G4DS: optical tuning and energy scale



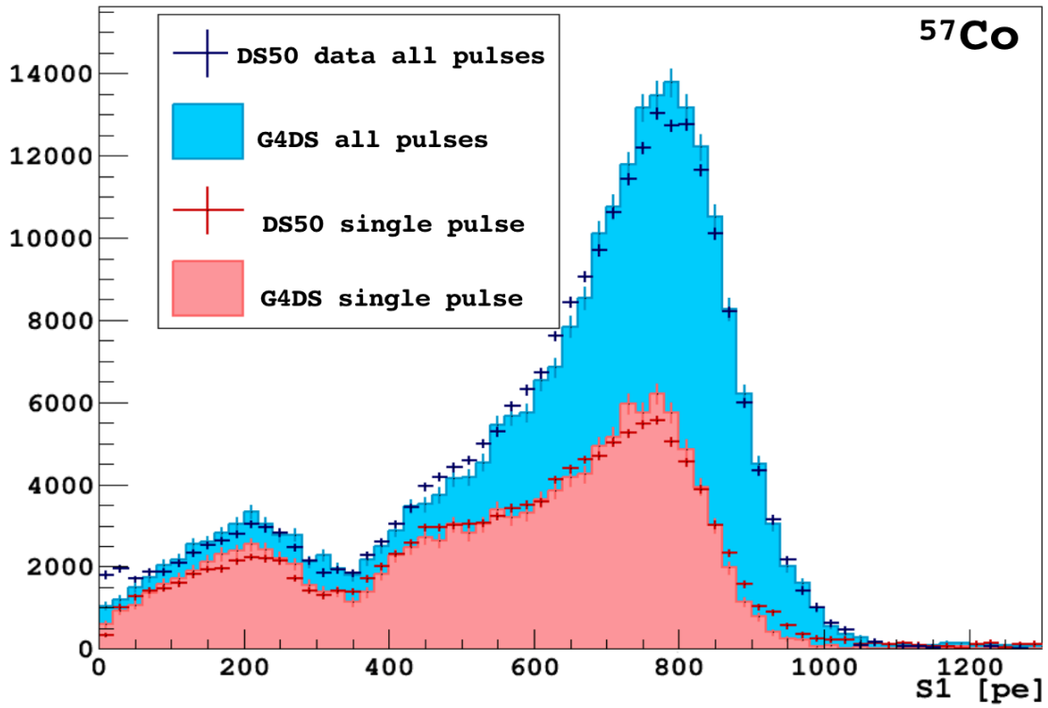
G4DS: the DarkSide simulation tool

- ☑ Geometry of detectors
- ☑ Several generators
- ☑ FLUKA interface
- ☑ Calibration of **TPC optical response**
- ☑ Reconstruction algorithms
- ☑ **Model for ionization and scintillation mechanisms in liquid argon**

Internal calibrations



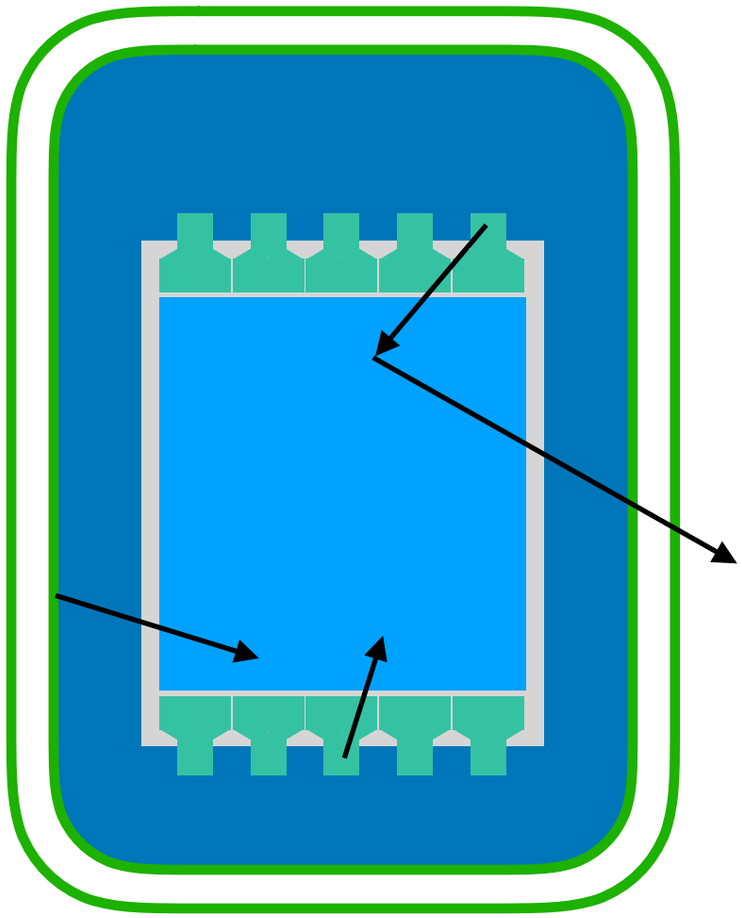
Data/MC: percent level agreement

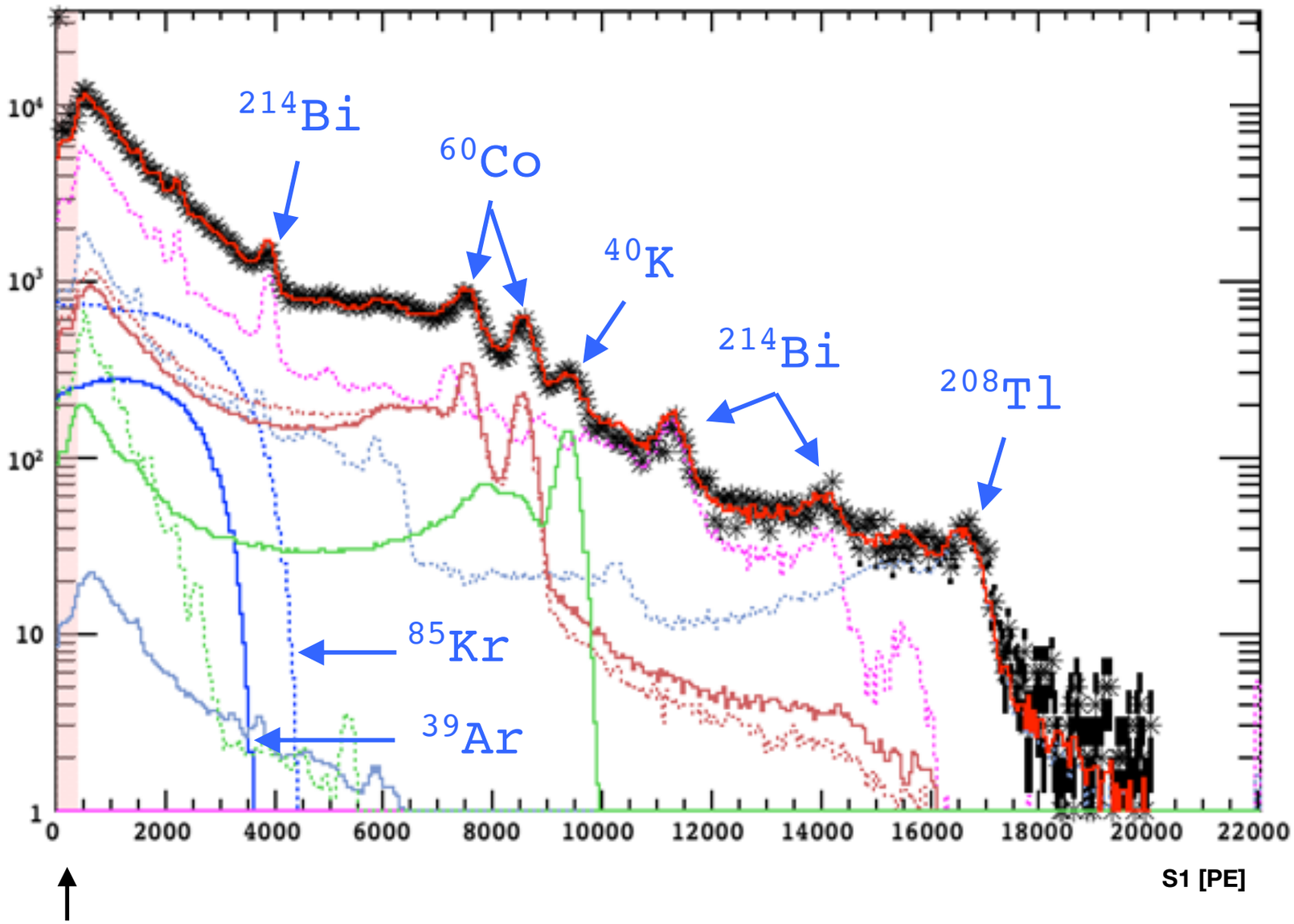


Background model

Background model for DarkSide-50

- Full simulation of **each background component** (^{238}U, ^{232}Th, ^{40}K, ^{60}Co) from detector materials and intrinsic to the target (^{39}Ar and ^{85}Kr).
- **Multivariate fit** based on S1 single scatter, S1 multiple scatter, and drift time
- **Excellent agreement** with measurements from material screening





dark matter search region

Low-energy searches

Ionization-only analysis

No S1:

- Loose fiducialization
- Loose discrimination

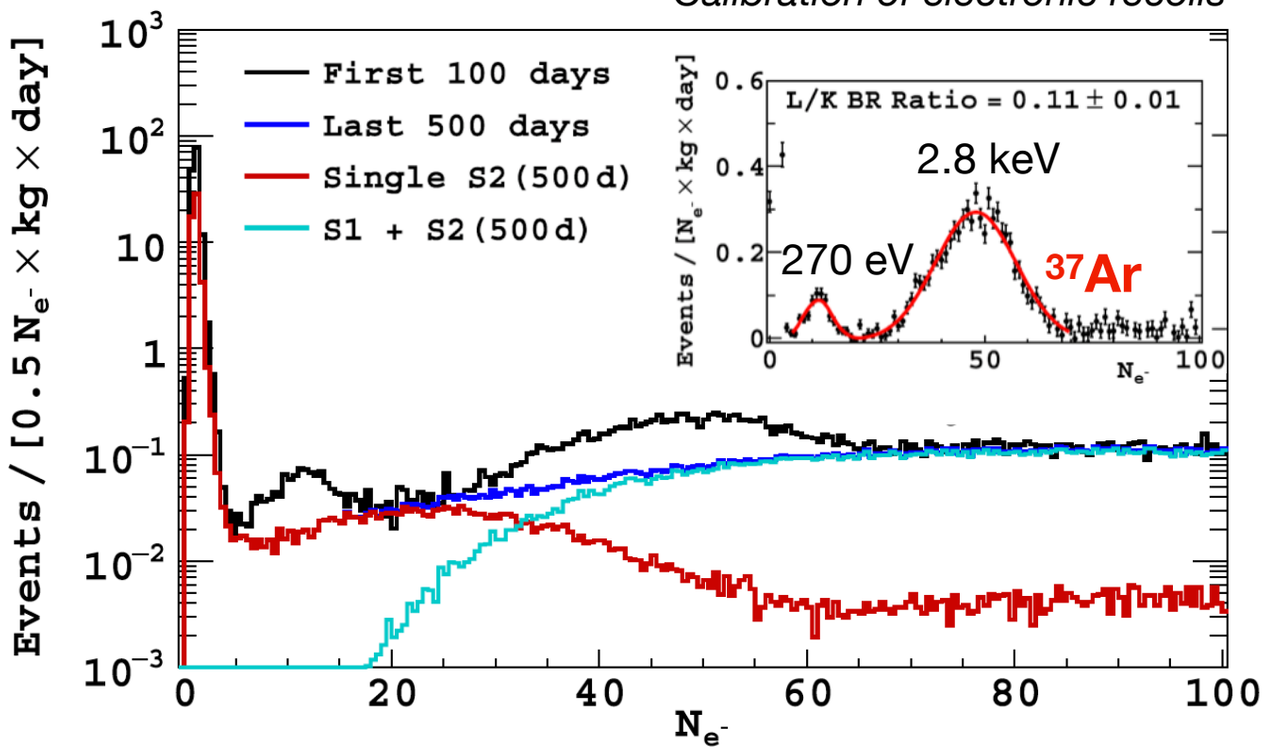
Multiplication in gas phase (**23 PE/e$^-$**)

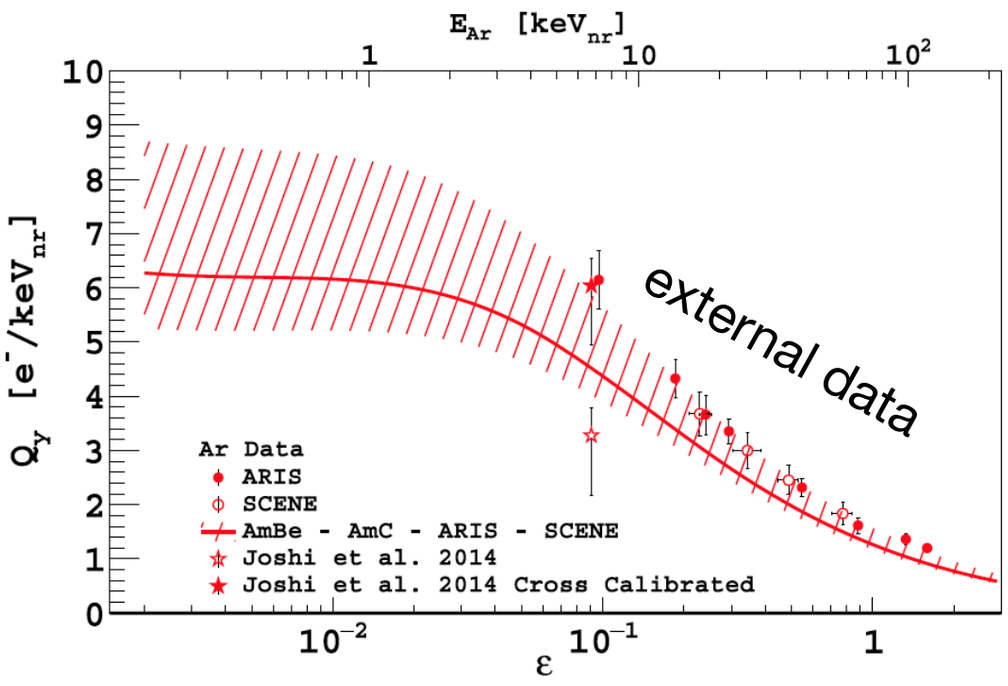
- **100% trigger** efficiency at 1.3 e$^-$ (**~30 eV**)

Calibrations:

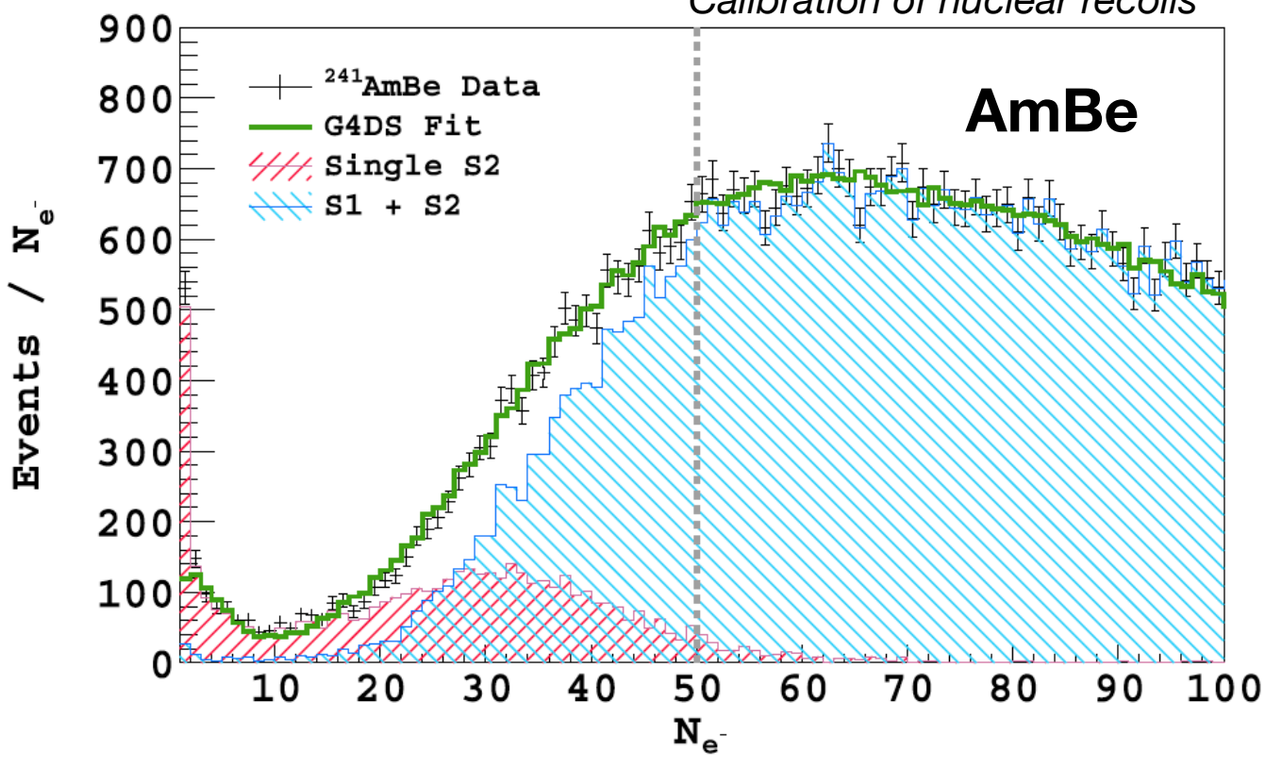
- ER Internal with ^{37}**Ar** with **270 eV** and **2.8 keV** lines
- external with **neutrons** sources

Calibration of electronic recoils



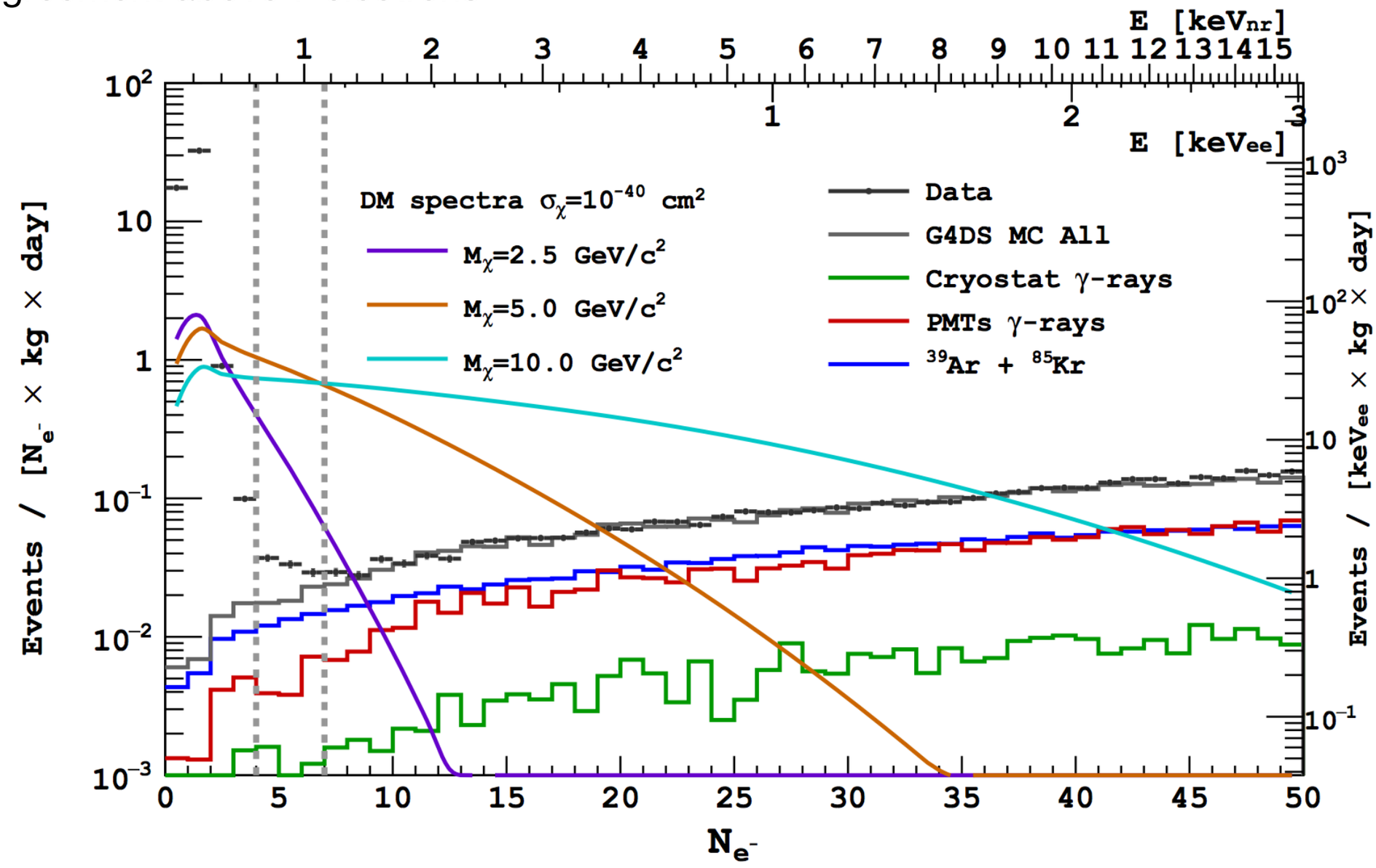


Calibration of nuclear recoils



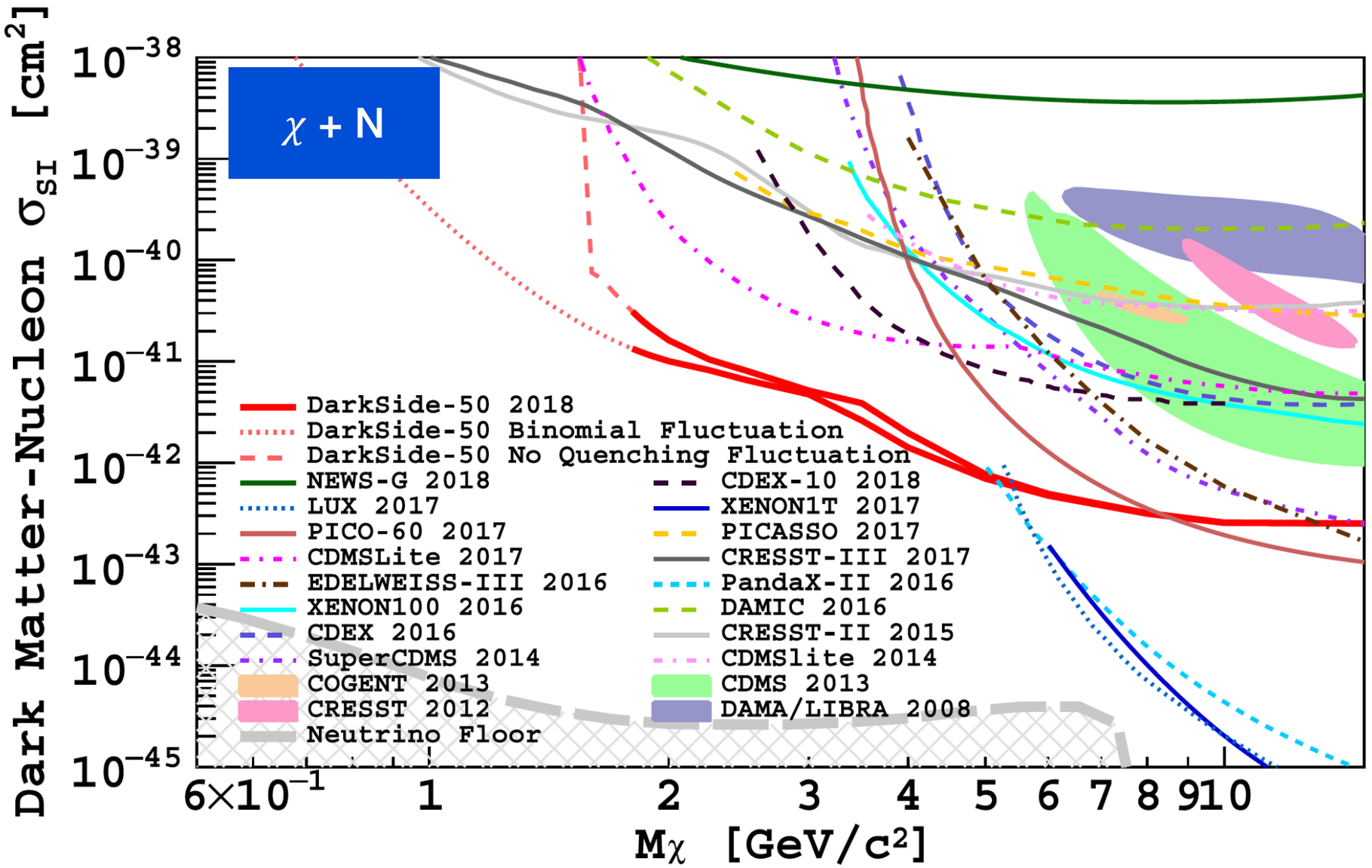
Low-mass WIMPs

- Profile Likelihood analysis; analysis threshold set at 4 electrons
- **Background model from high energy** (internal and external β and γ). Un-modeled but understood peak at very low N_e
- Good agreement above 7 electrons



Low-mass WIMPs

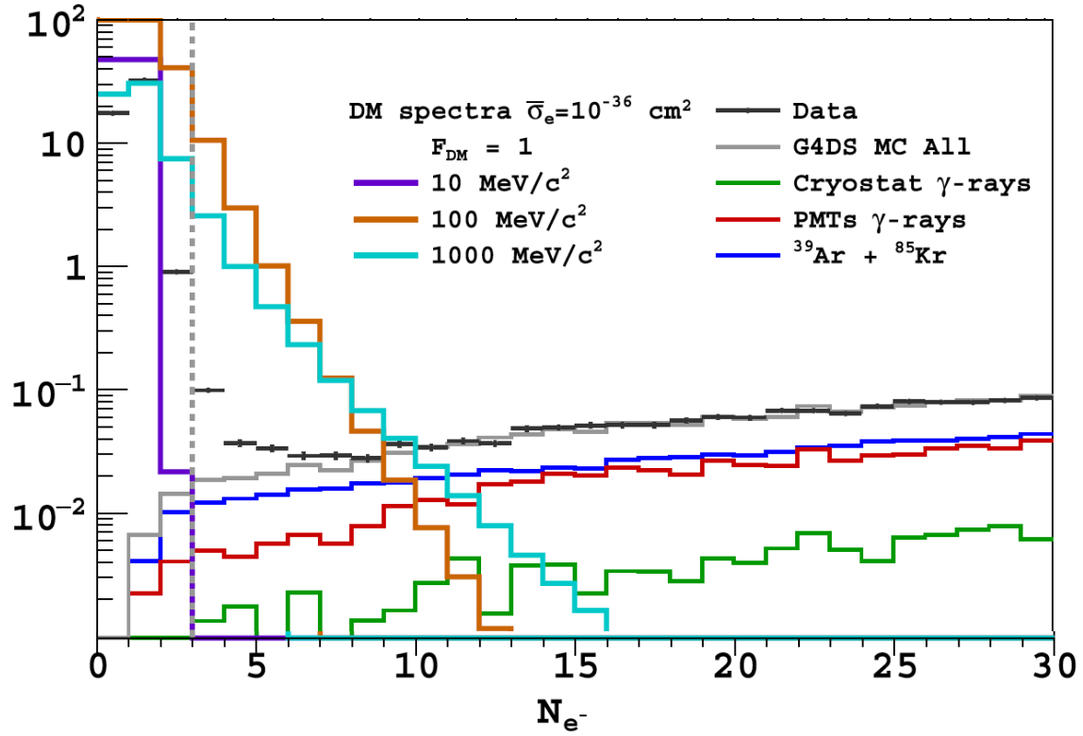
- **World leading exclusion** on WIMP-N cross section **between 2 and 6 GeV/c²**



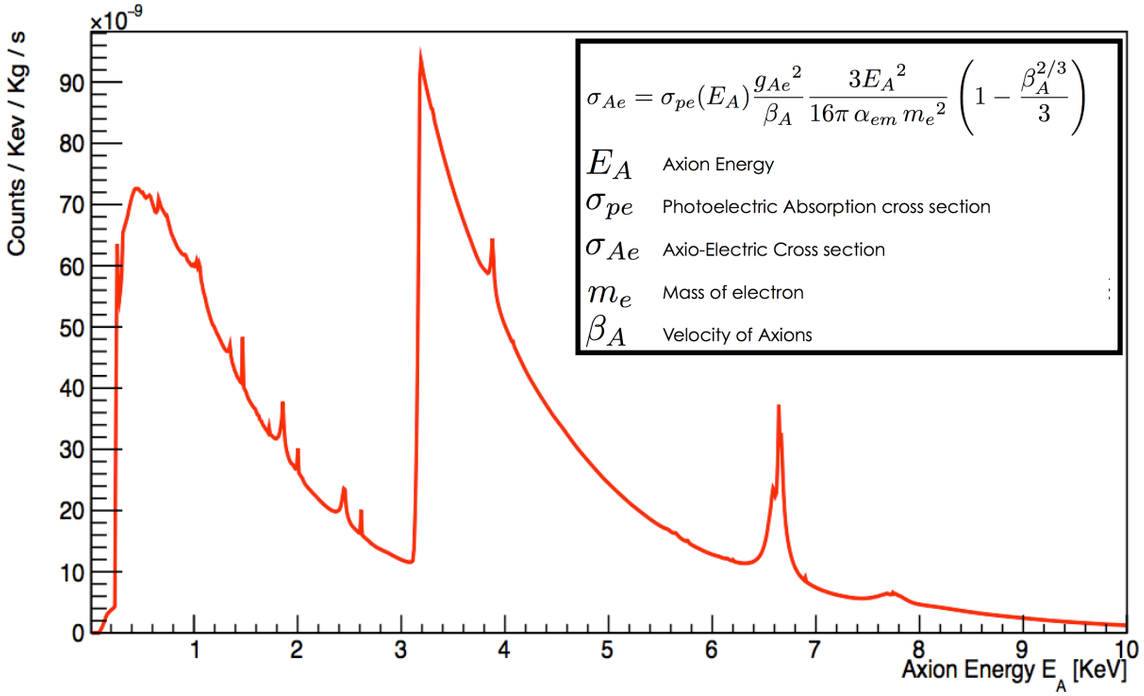
Low energy analysis

Same data to constraint other interactions

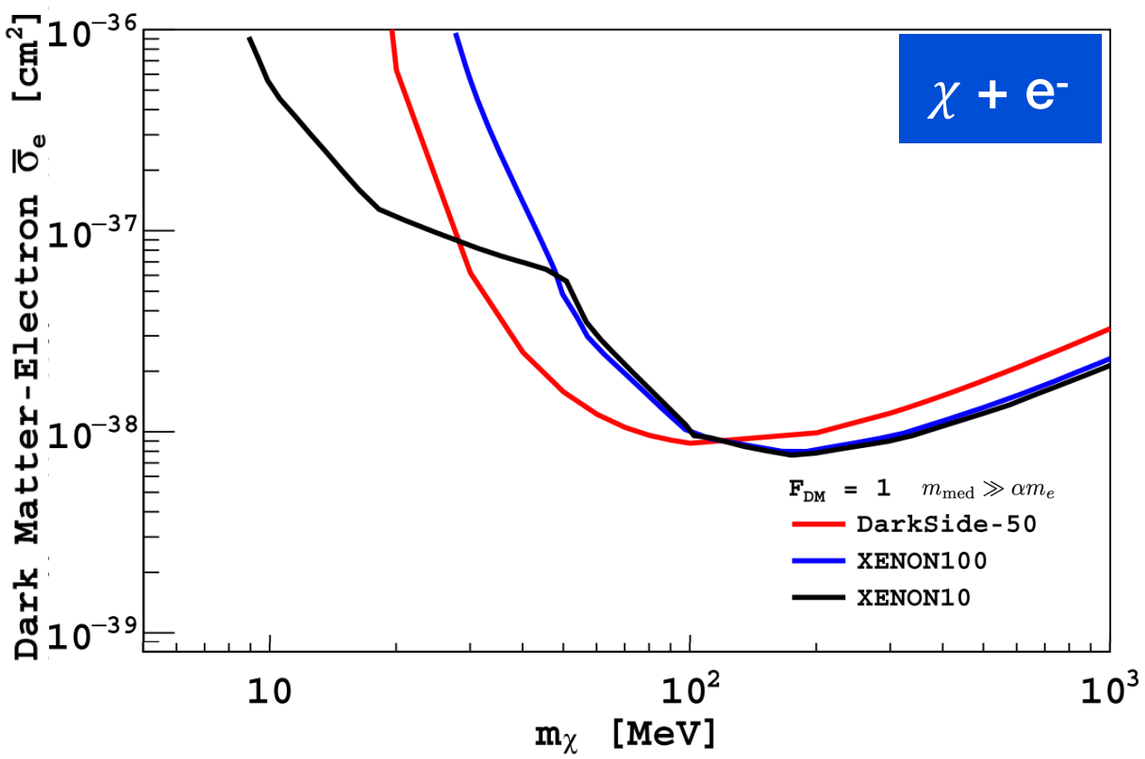
- WIMP-electron coupling ==>



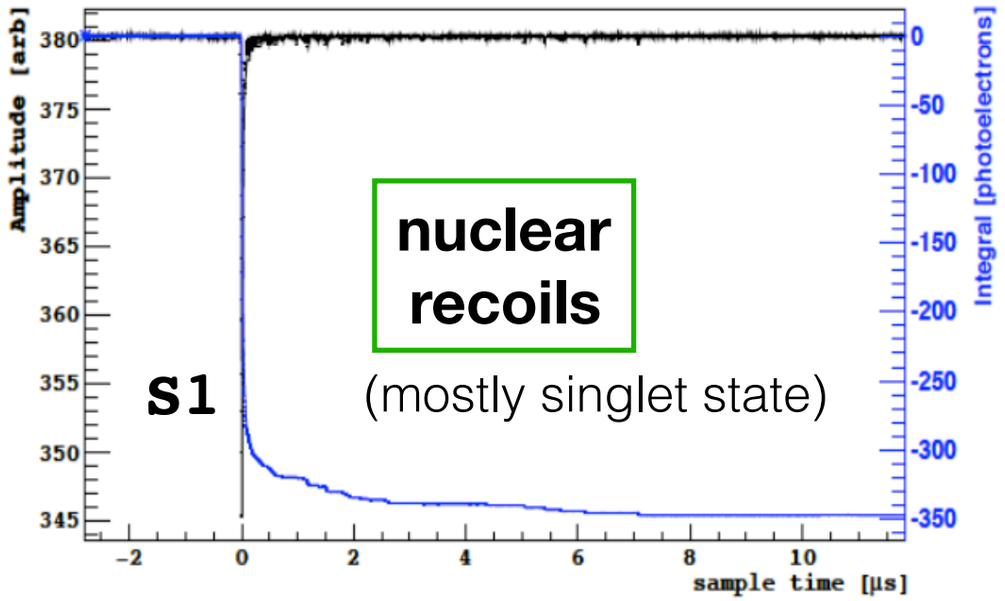
- Axions (work in progress)

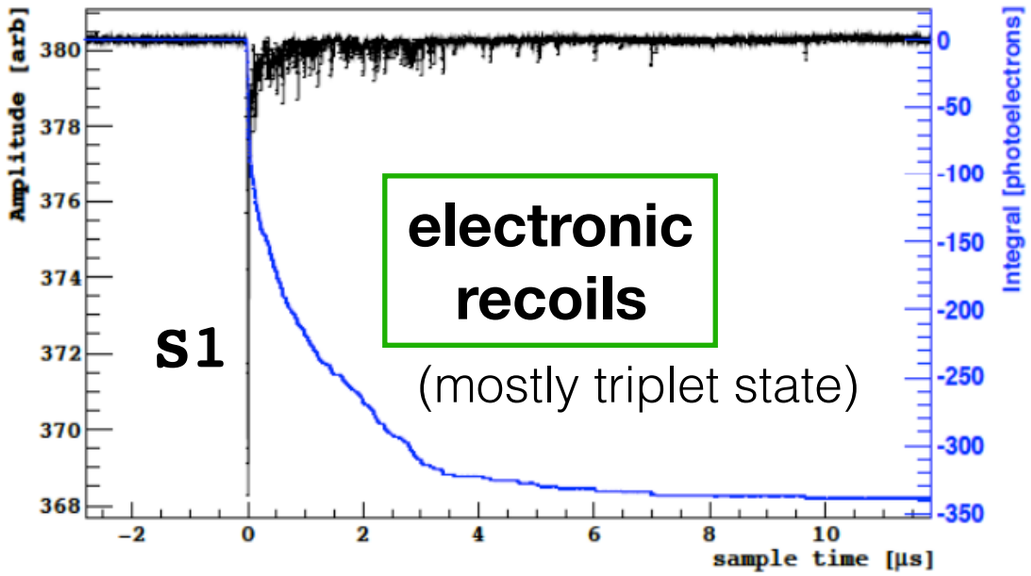


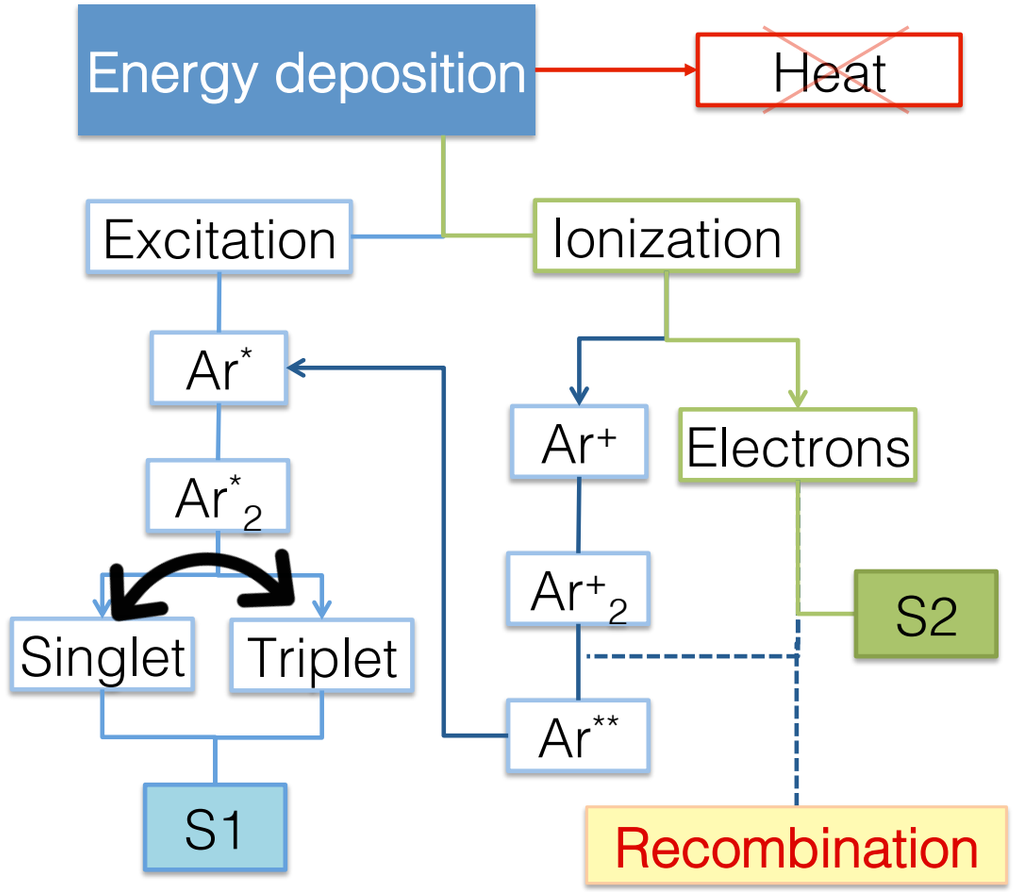
- ...



Pulse Shape Discrimination in LAr





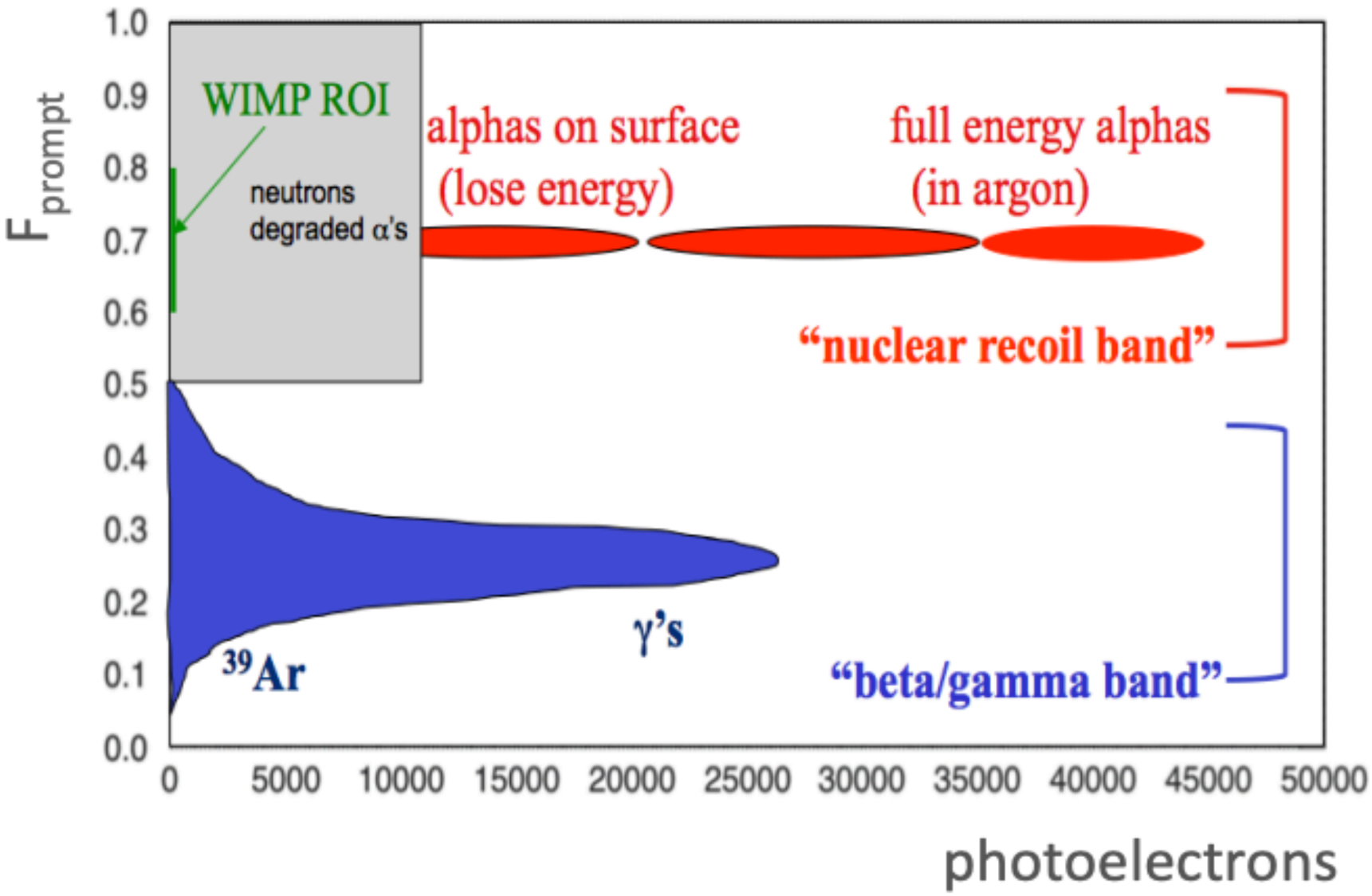


$$\text{LAr } \tau_{\text{singlet}} = 7 \text{ ns}$$
$$\text{LAr } \tau_{\text{triplet}} = 1600 \text{ ns}$$

PSD: fraction of S1 in the first tens of ns

Experimental signatures

prompt/fast component fraction



Define **ROI** with a (blind) **analysis**:

- **maximize** acceptance to **nuclear recoils**
- **minimize** leakage of **backgrounds** in ROI

DarkSide-50 successfully performed 500 days search, similar to the result of DEAP (stronger exclusion)

The DEAP experiment

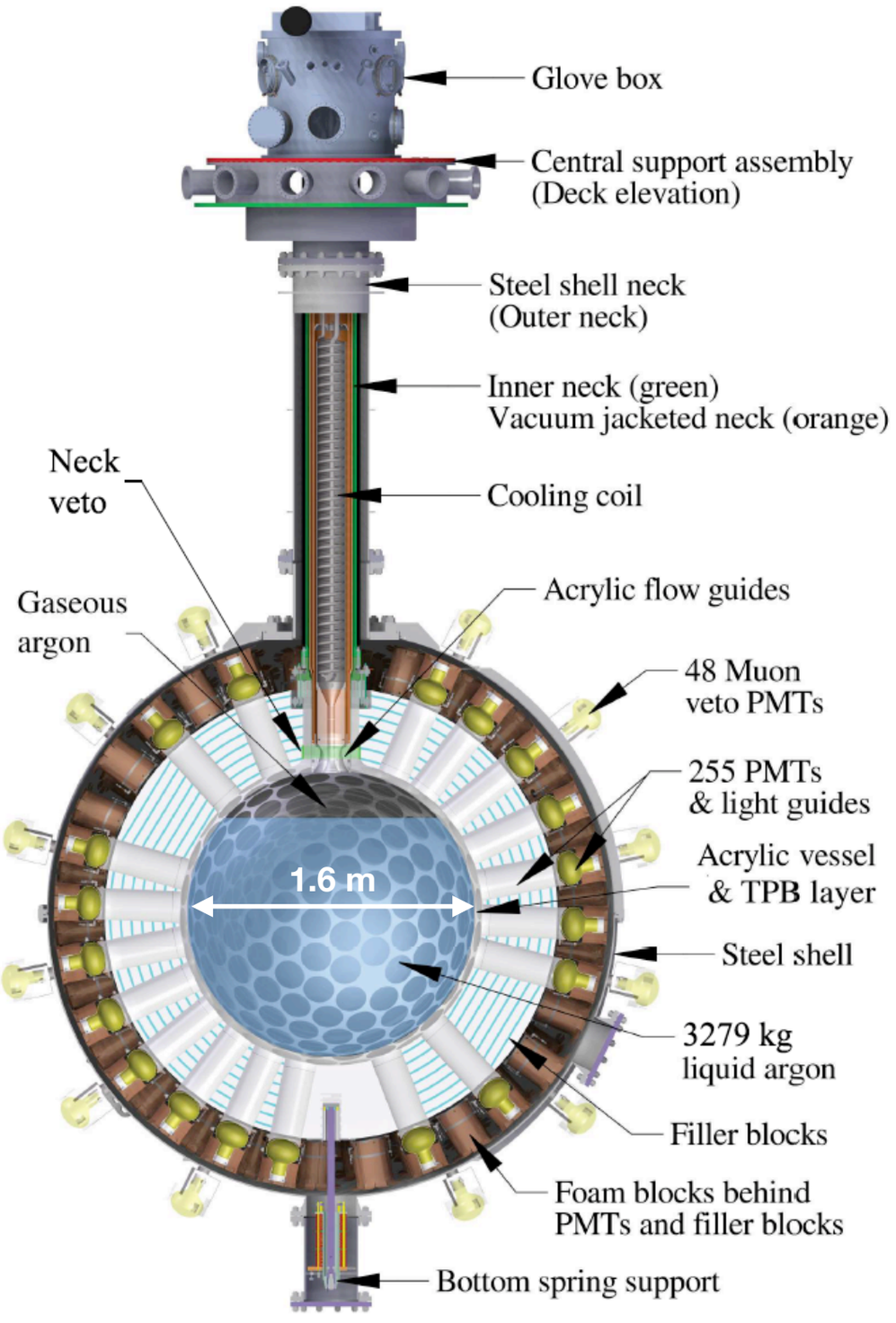
Dark matter **E**xperiment using **A**rgon **P**ulse shape discrimination

A **single-phase detector**

- taking data since 2016 at SNOLAB
- **3300 kg** of **argon**
- in a 8 m water shield

- Acrylic vessel, **resurfaced** *in-situ*
- 255 PMTs at room temperature
- 50 cm acrylic light guides

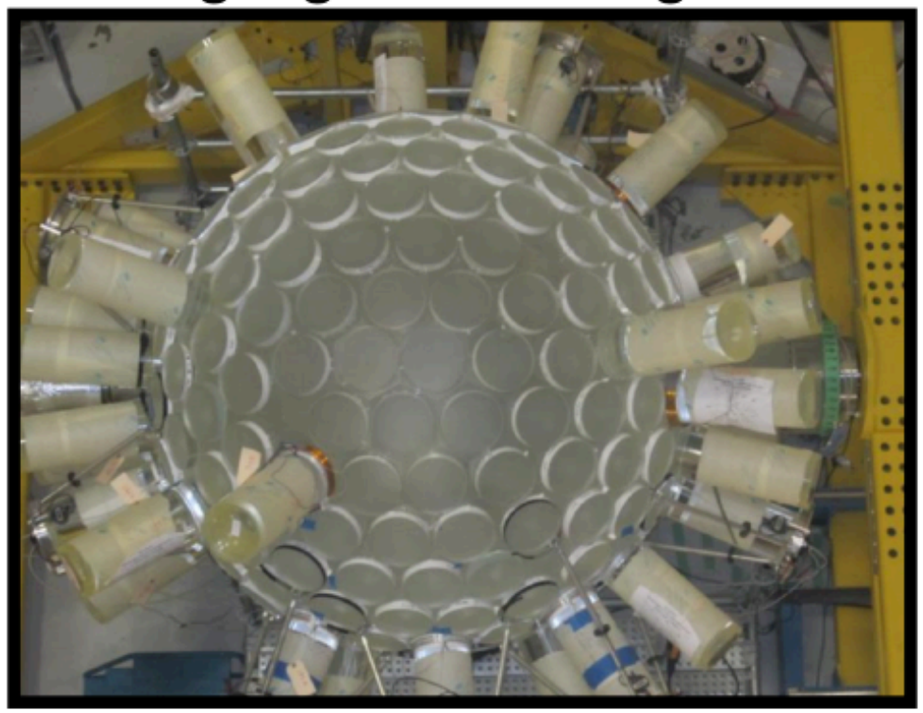
- Spatial resolution better **than 3 cm**
- **LY of > 6 PE/keV**



DEAP installation

acrylic vessel

light guide bonding

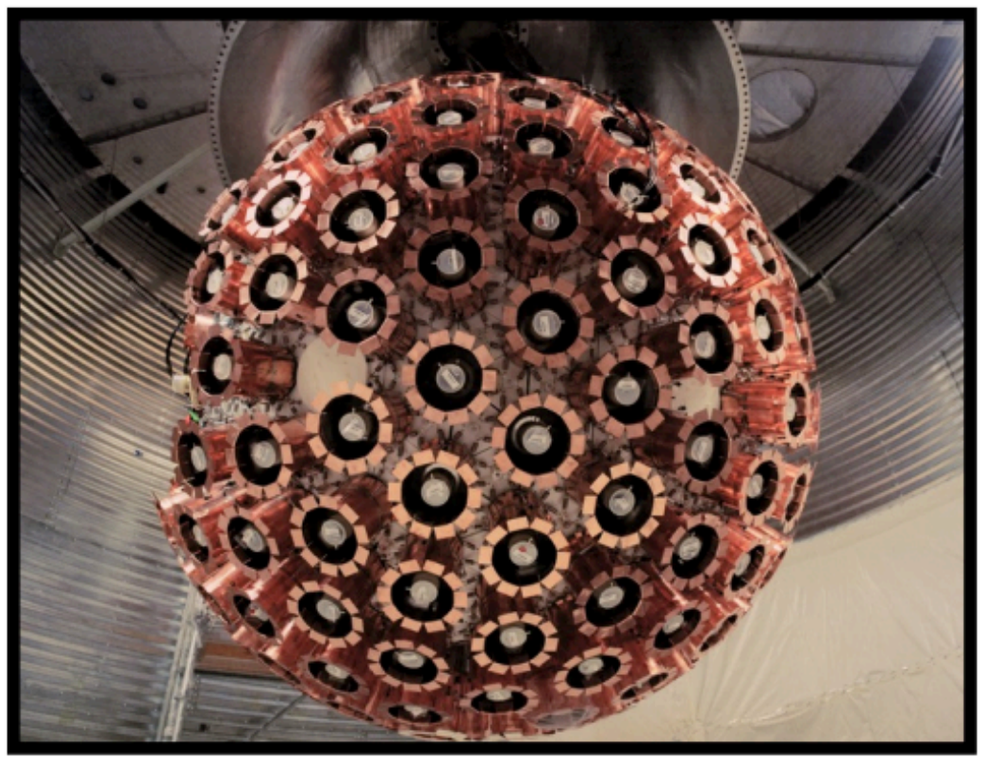


AV + LGs

light guide reflectors

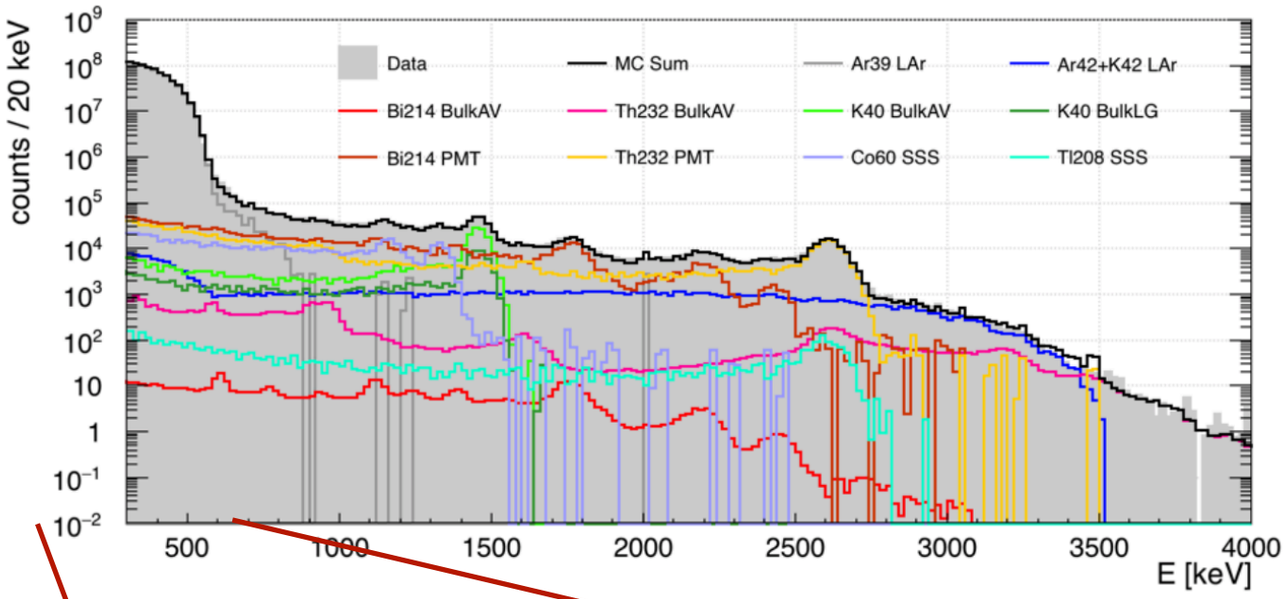
filler block and PMTs

assembled inner detector

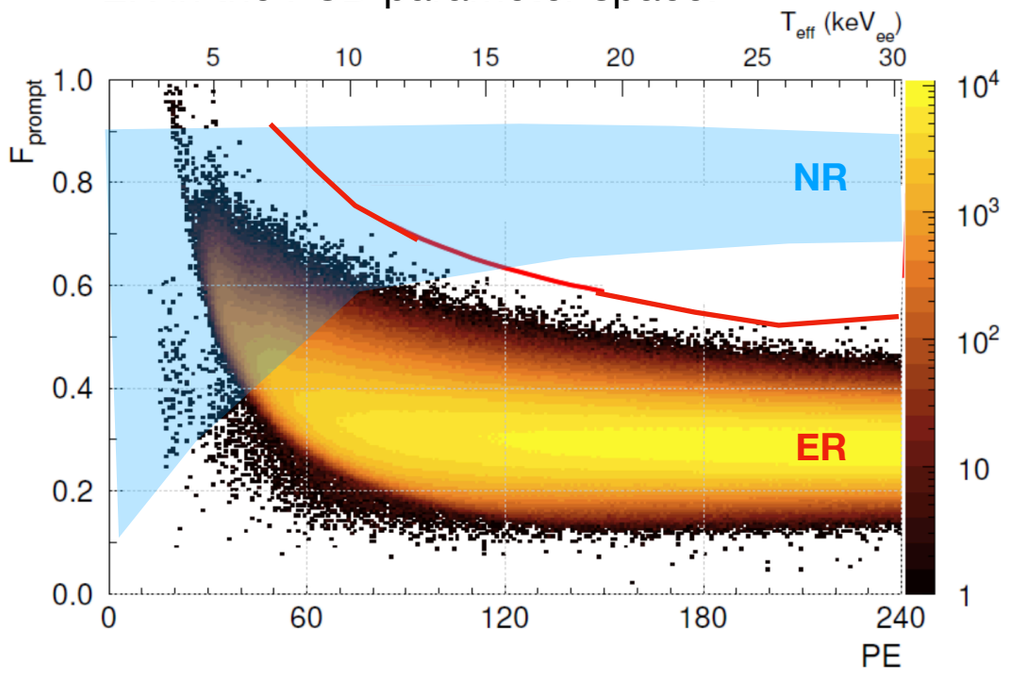


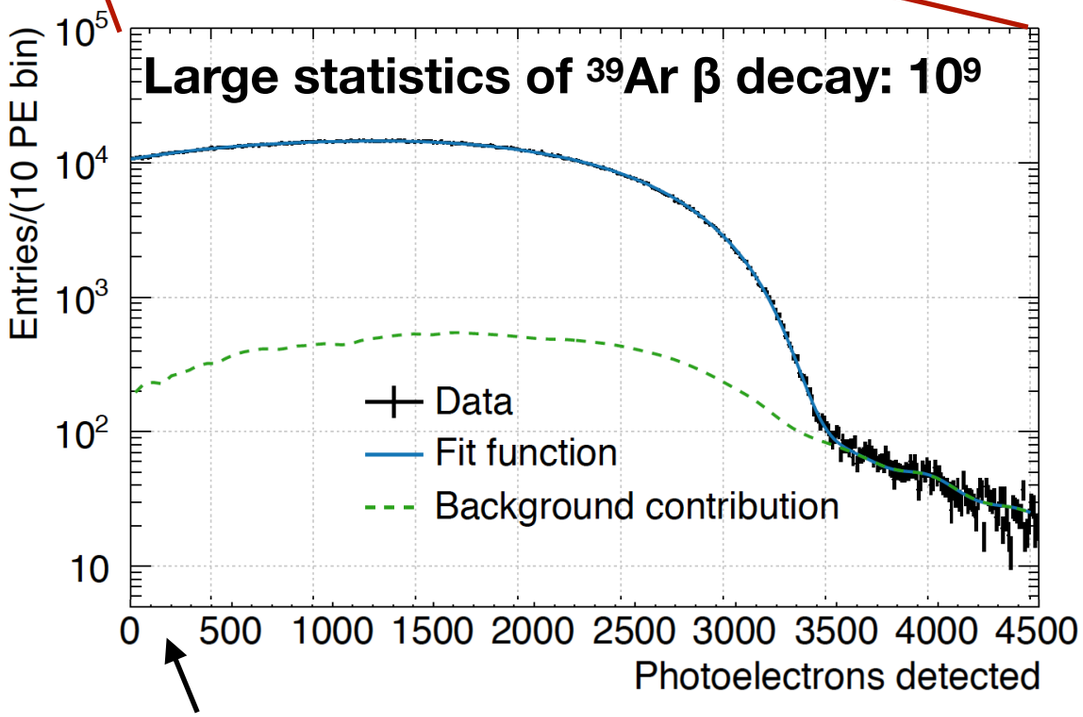
Backgrounds - ER

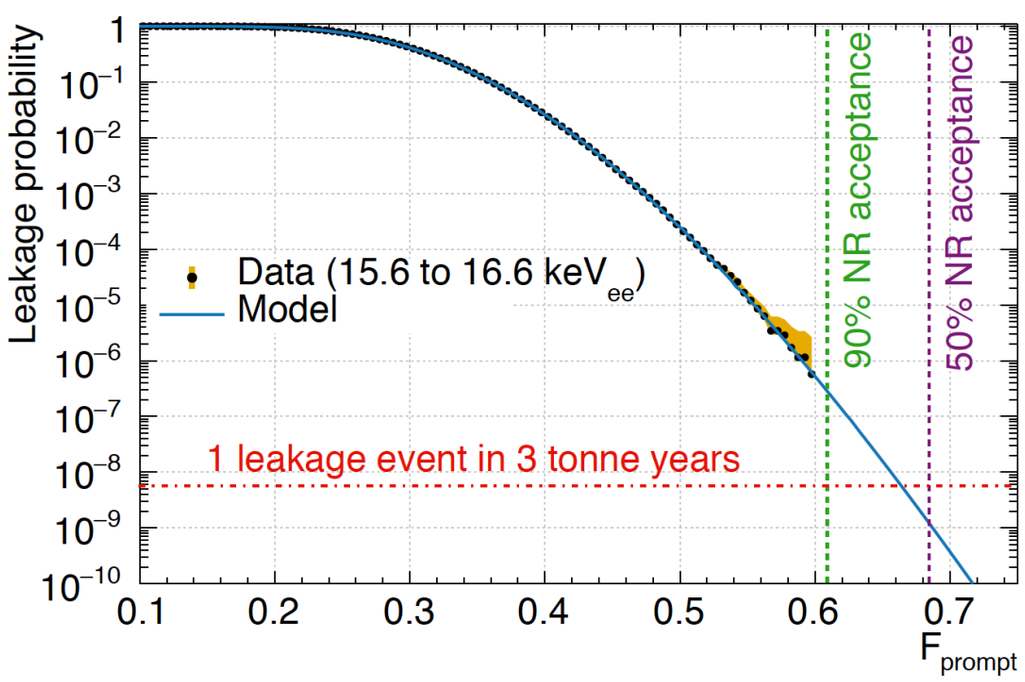
Monte Carlo scaled to activities from material screening:



ER in the PSD parameter space:





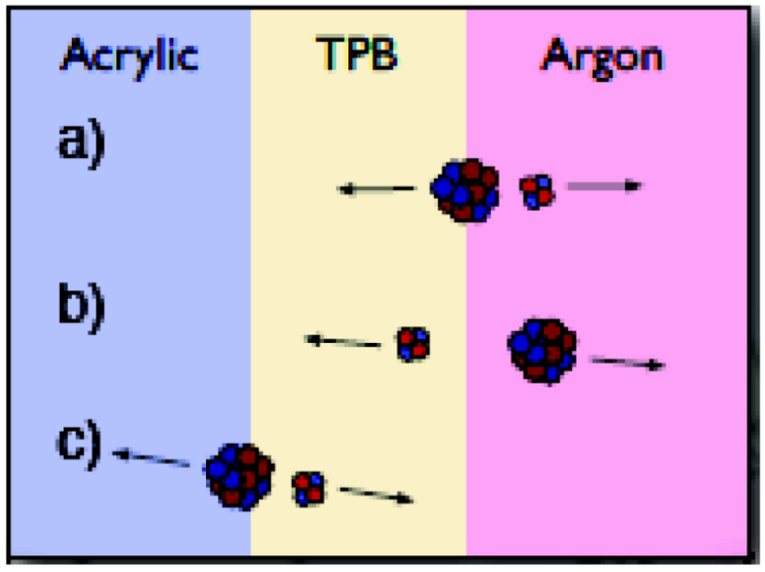


N_{ROI} = 0.03 ± 0.01

Rejection: **4 x 10^{-9}** in [16, 33] keV_{ee}

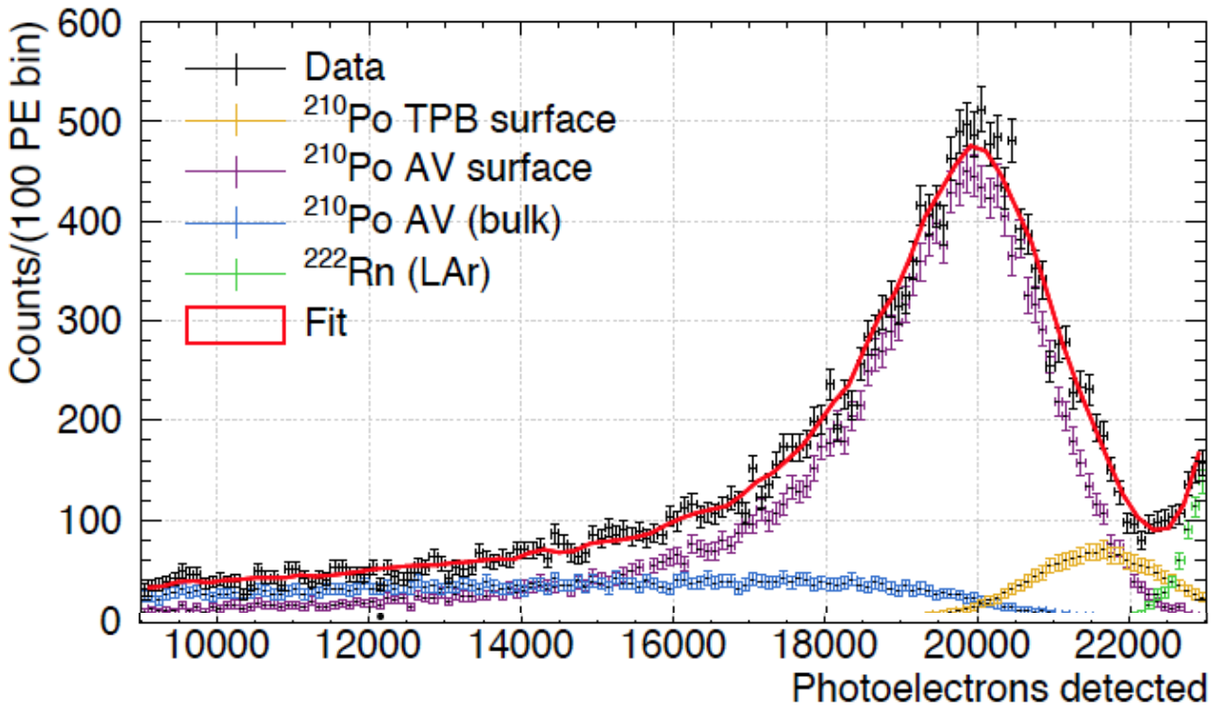
Backgrounds - alphas

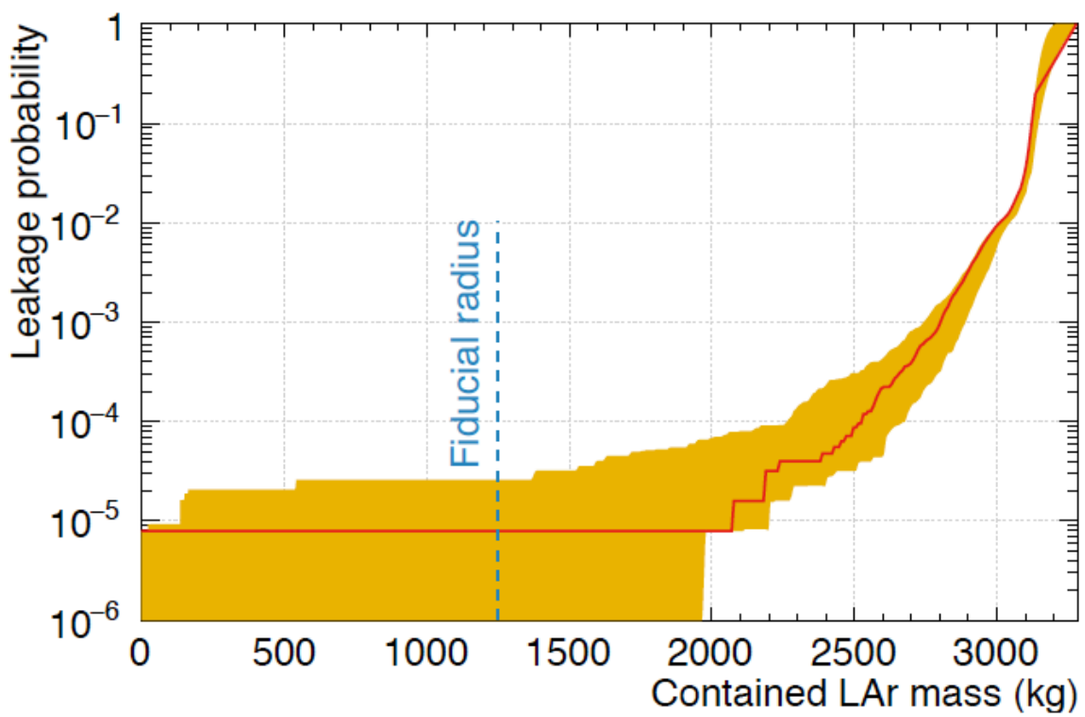
- **Bulk alphas** are not a concern: high energy in LAr
- **Degraded alphas** are fiducialized out



Lowest ^{222}Rn activity in Xe/Ar experiment

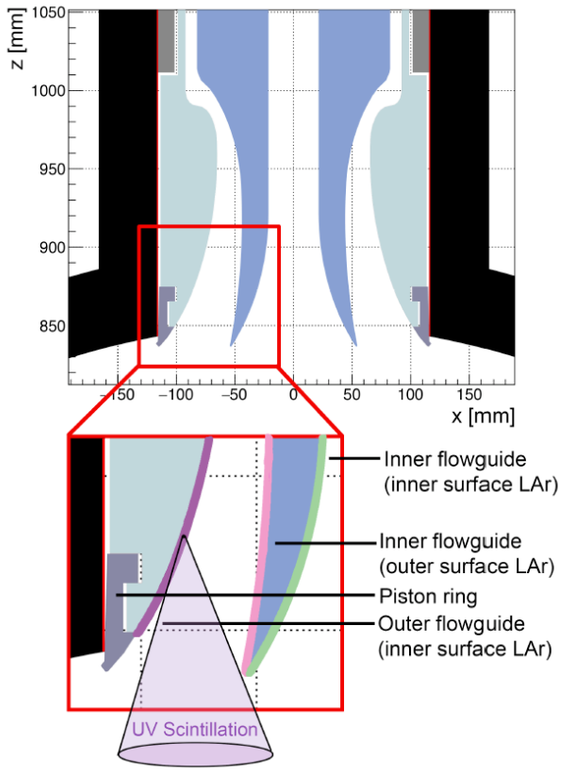
Component	Activity	
^{222}Rn LAr	$(1.8\pm0.2)\times10^{-1}$	μBq/kg
^{214}Po LAr	$(2.0\pm0.2)\times10^{-1}$	μBq/kg
^{220}Rn LAr	$(2.6\pm1.5)\times10^{-3}$	μBq/kg
^{210}Po AV surface	0.22 ± 0.04	mBq/m^2
^{210}Po AV bulk	<3.3	mBq

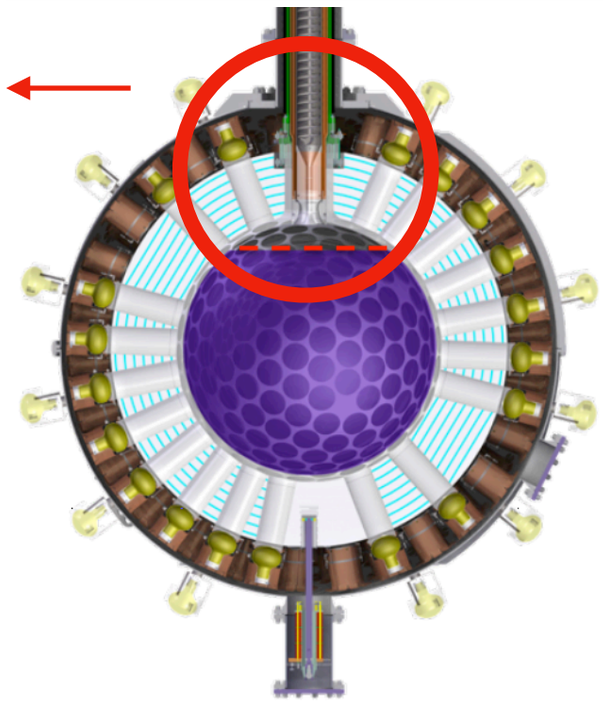




N_{ROI} < 0.08

Backgrounds - Neck alphas





Refill of the detector in 2017 after argon leak

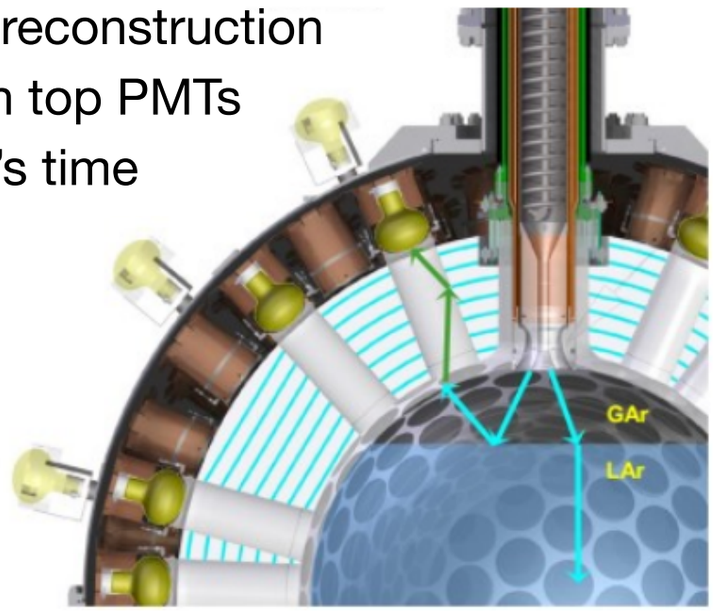
Lower the Ar level to avoid new leaks brings in a new class of background

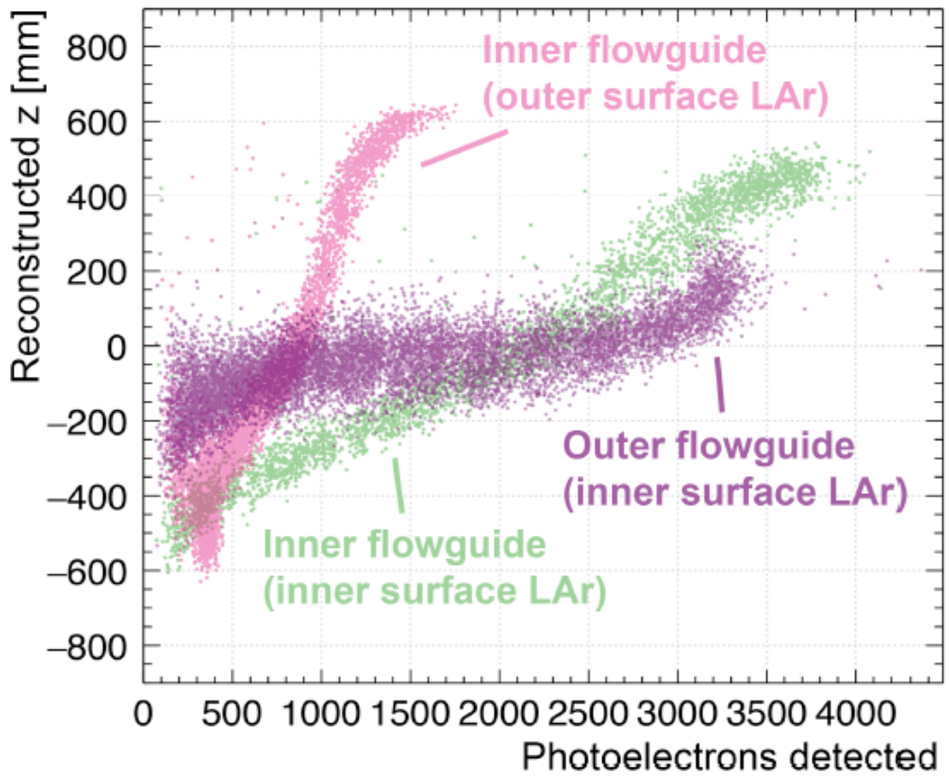
Alphas from the **neck** may be reconstructed:

- **in the FV** and
- **at low energy**

Need to develop **specific cuts** to reject this background:

- position reconstruction
- charge in top PMTs
- early PE's time





$N_{ROI} = 0.5 \pm 0.27$

Box opening

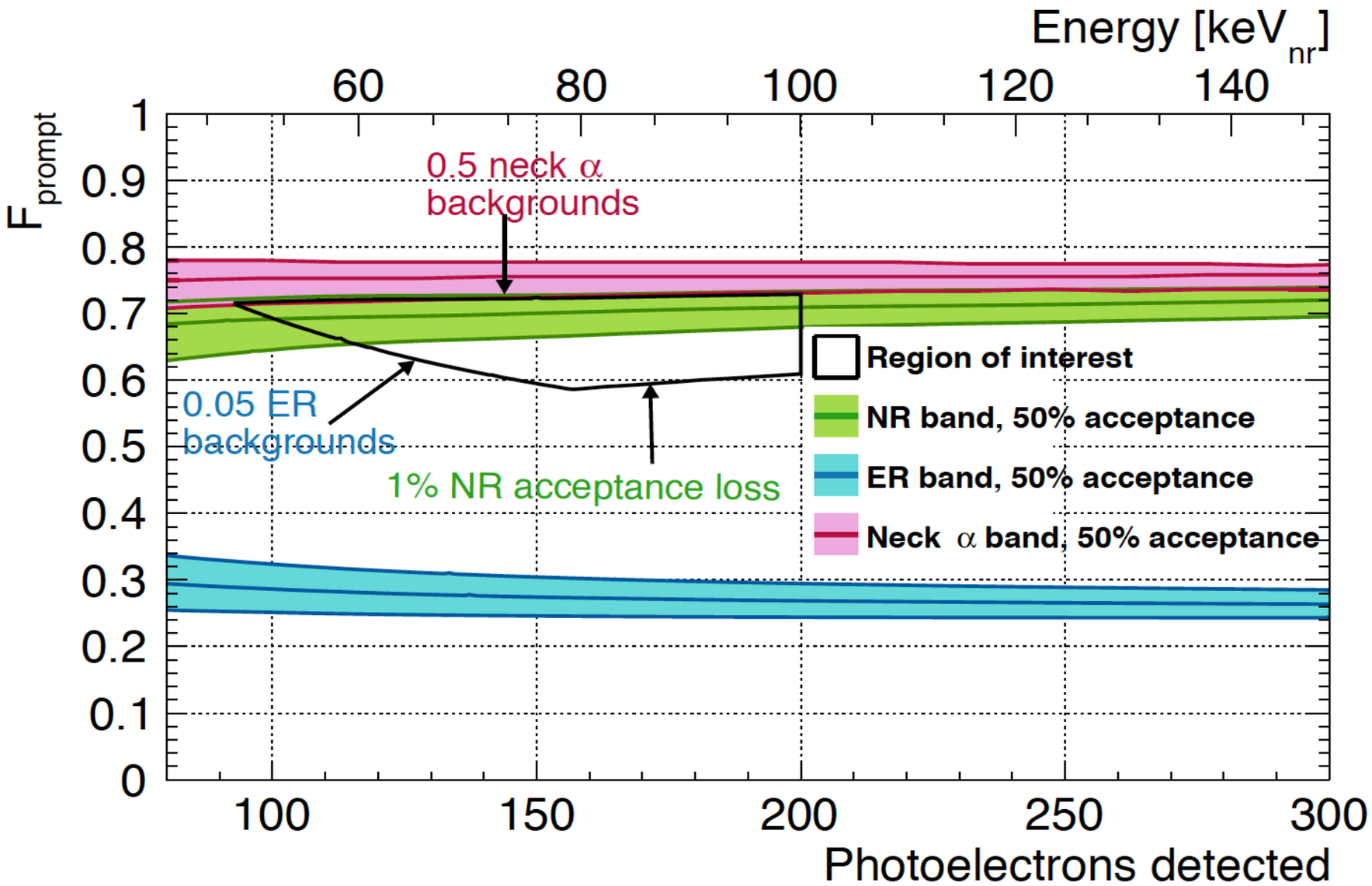
Mentioned background sources:

- **Leakage of ER**: $N^{ER}_{ROI} = 0.03 \pm 0.01$
- **Bulk alphas** : $N^{\alpha}_{ROI} < 0.08$
- **Neck alphas**: $N^{N\alpha}_{ROI} = 0.49 \pm 0.27$

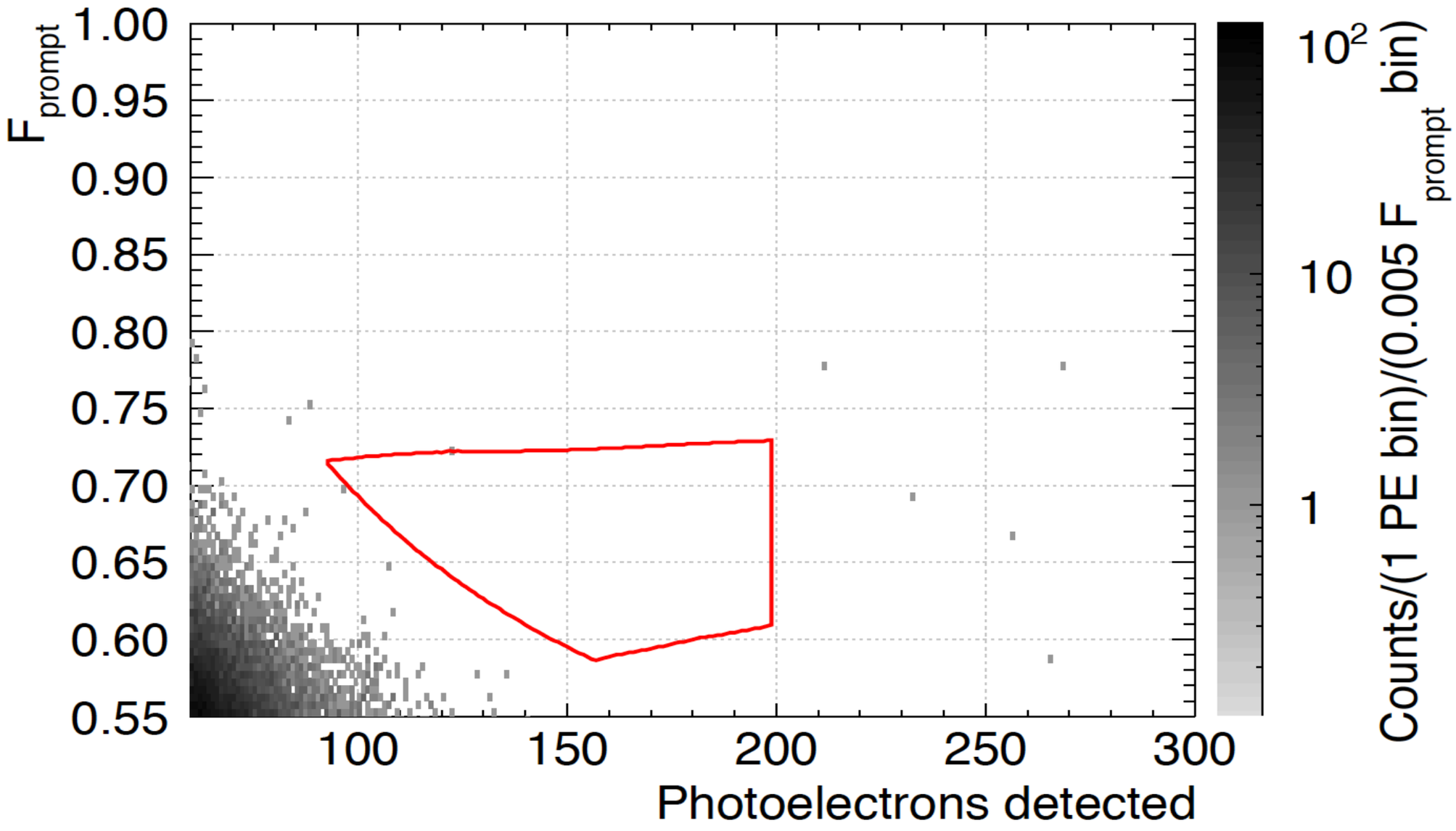
Other background sources:

- **Radiogenic neutrons**: $N^{rn}_{ROI} = 0.10 \pm 0.10$
- **Cosmogenic neutrons**: $N^{cn}_{ROI} < 0.11$
- **Cherenkov** in the acrylic: $N^{Ch}_{ROI} < 0.14$

TOTAL: $N_{ROI} = 0.62 \pm 0.3$

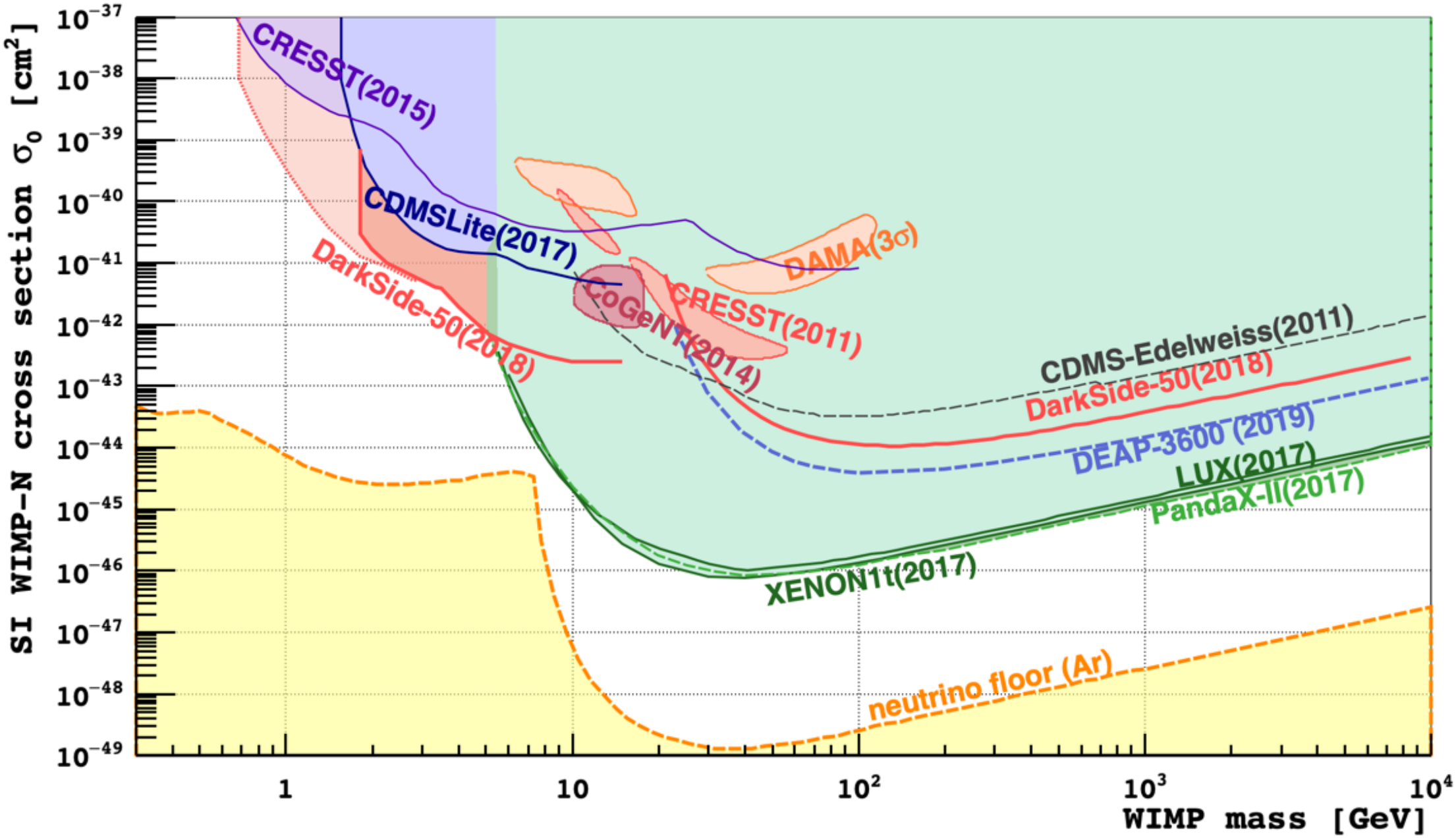


Box opening



No event in the WIMP search region
Background-free exposure of 3 tonne x year
Pulse Shape Discrimination proven at the **level of 4 x 10^{-9}** in [16, 33] keV_{ee}

Exclusion from noble liquids



DarkSide-20k

DarkSide-50, **DEAP**, **ArDM, MiniCLEAN** formed the **Global Argon Dark Matter Collaboration** (GADMC) to reach the neutrino floor.

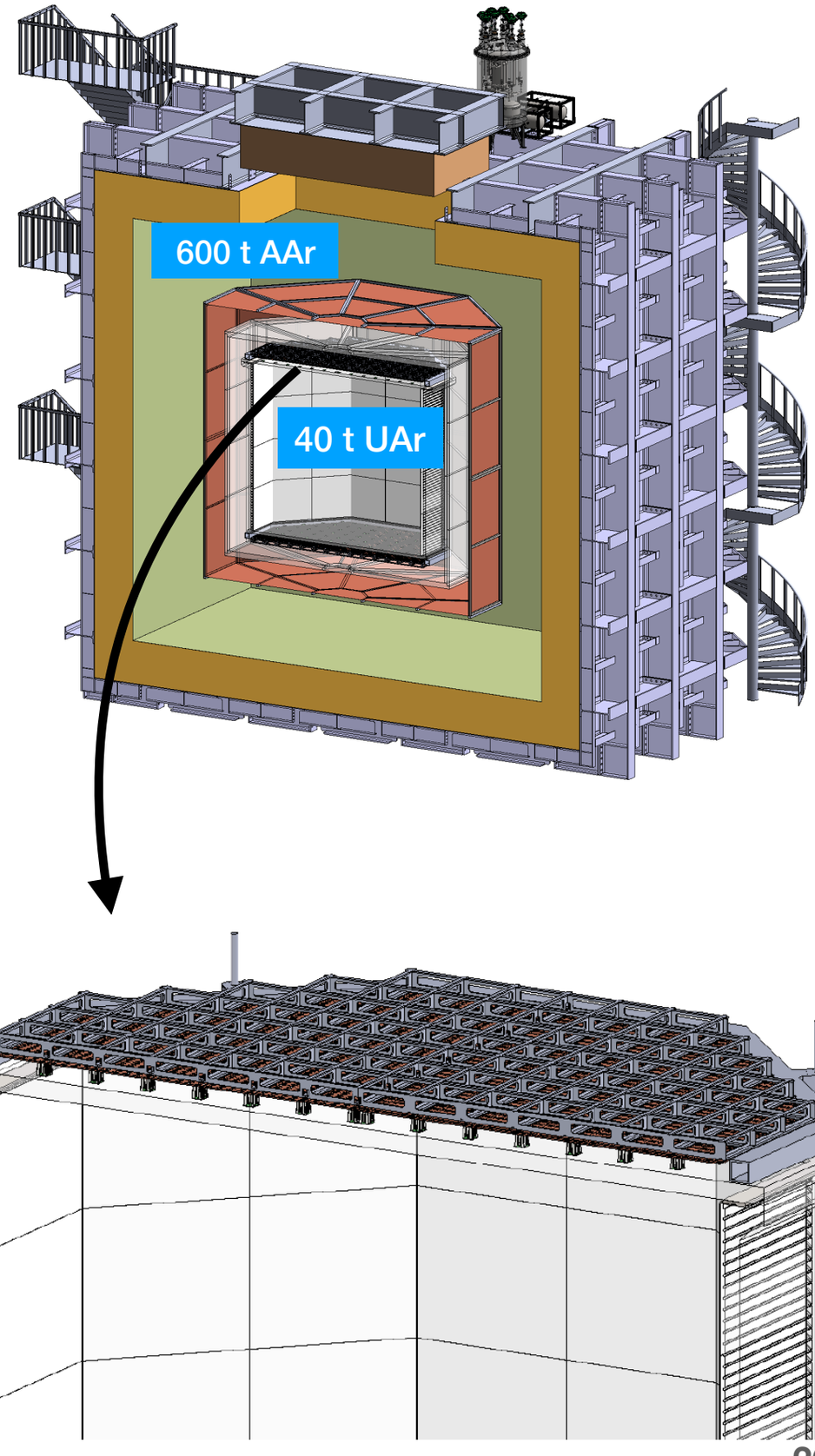
>100 t yr (instrumental) bg free UAr exposure

DarkSide-20k will use:

- 40 t (20 t) active (fiducial) UAr **dual-phase TPC**

It requires:

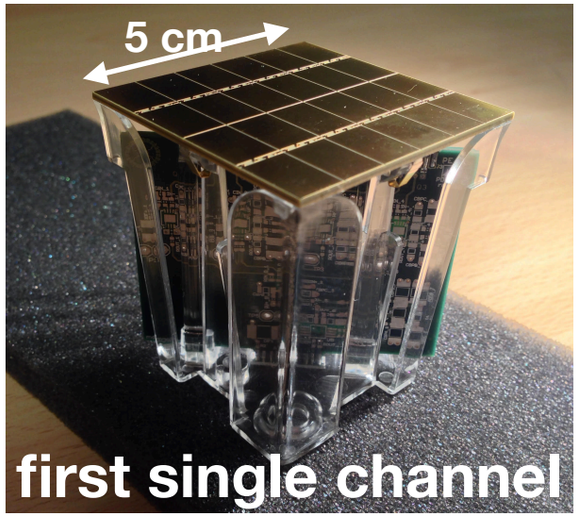
- Extraction of **50 t of UAr**
  (UAr is **^{39}Ar depleted x1400**: no pile-up)
- 600 t LAr **ProtoDUNE cryostat**
  (move material away from the active volume)
- Instead of PMTs: grouped **SiPM arrays**

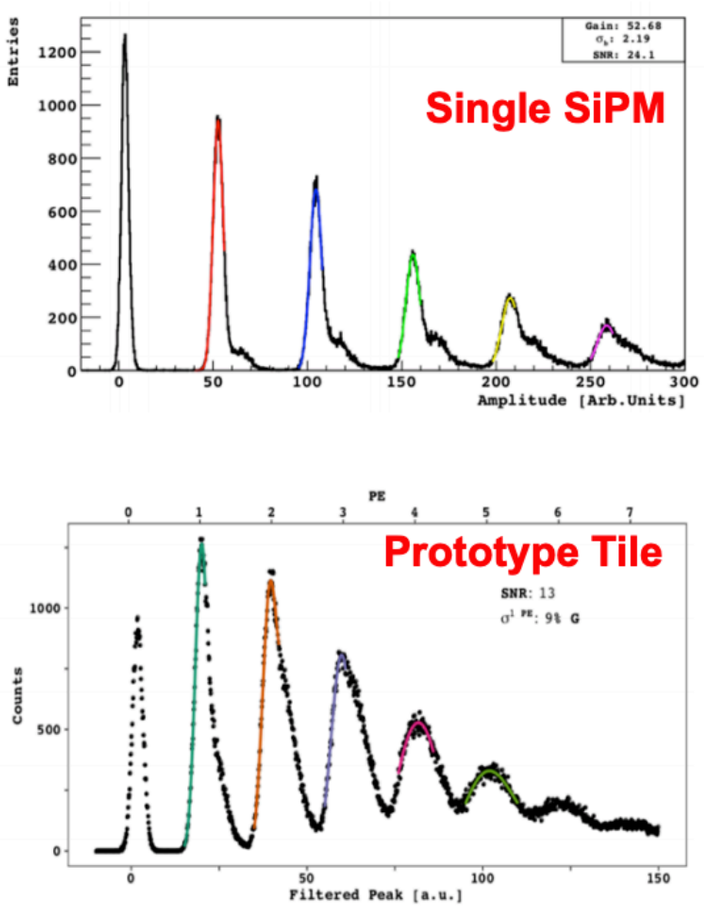


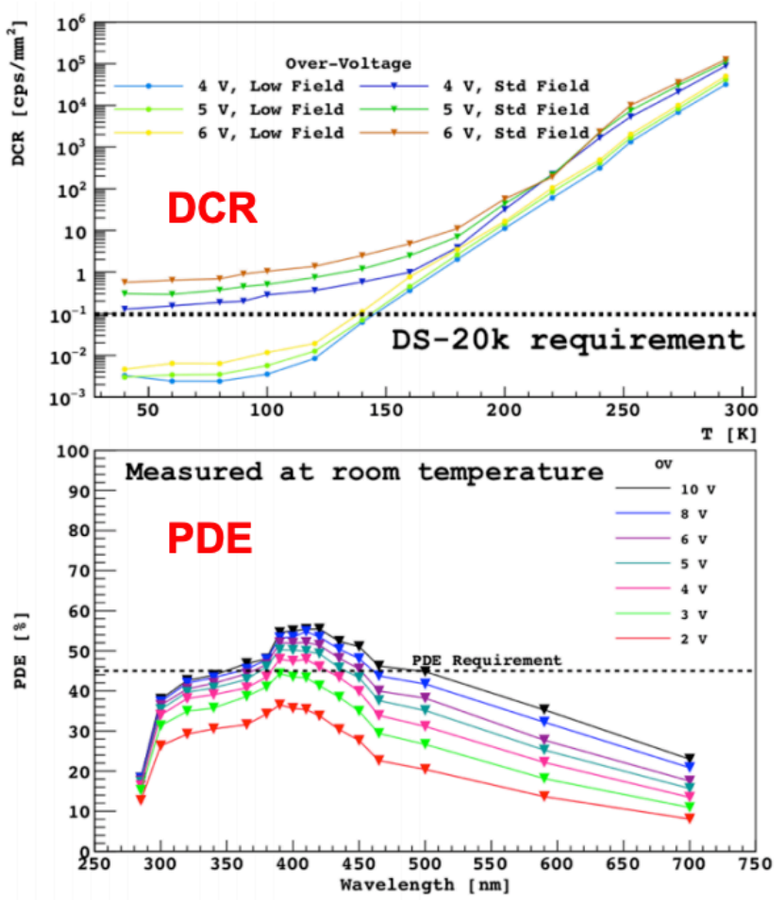
DarkSide-20k SiPMs

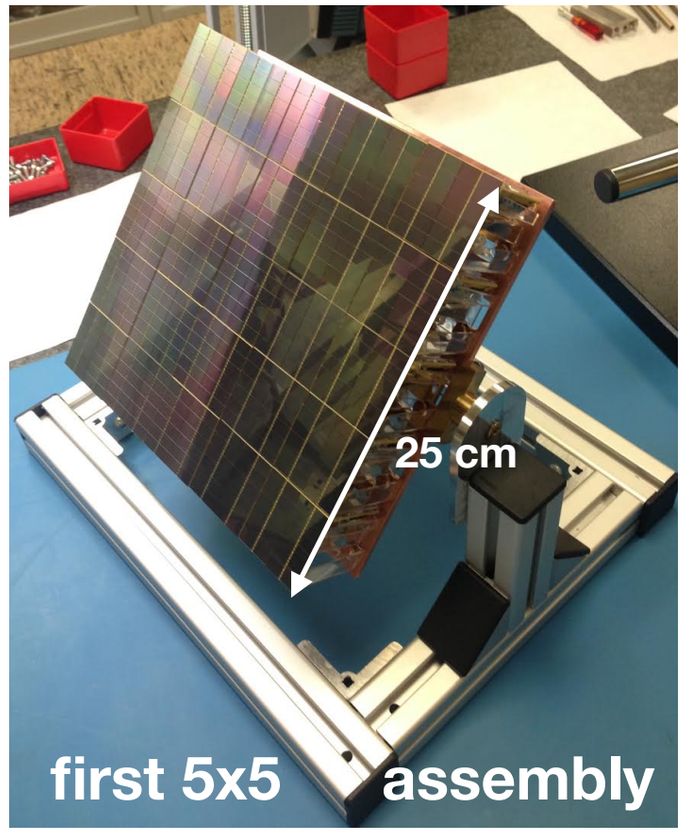
SiPM based light readout system **(FBK):** intrinsically radio-pure

	DS-20k requirement	SiPM tile (PDM)	
Surface	5x5cm^2	24cm^2 prototype 25cm^2 final PDM	✓
Power dissipation	<250mW	~170mW	✓
PDE	>40%	50% · ε_{geom} = 45%	✓
Noise Rate	<0.1cps/mm^2	0.004cps/mm^2	✓
Time Resolution	O(10ns)	16ns	✓
Dynamic Range	>50	~100	✓



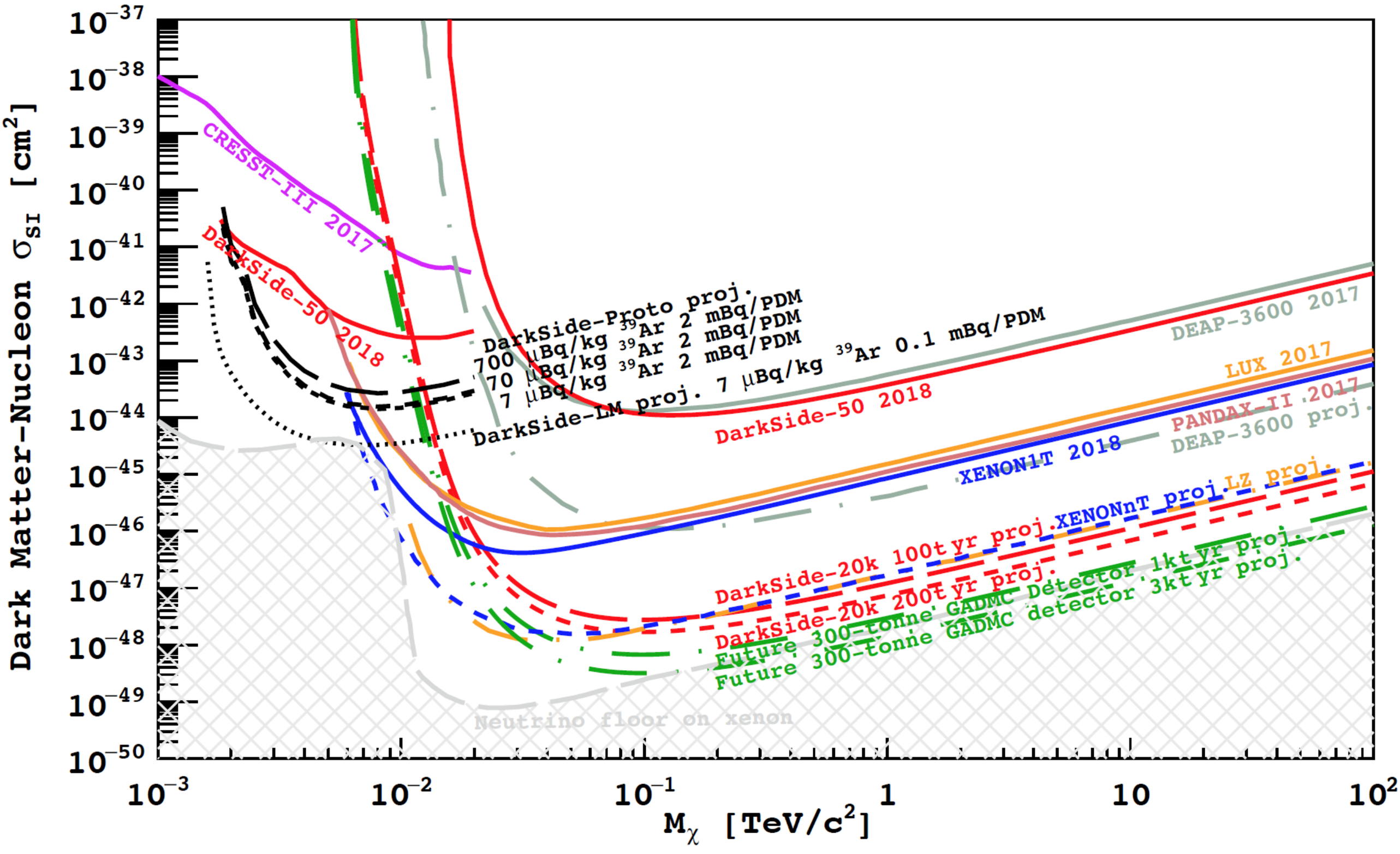






Mass production is about to start

Expected sensitivity



Extra Slides

Predicted signal

$$\frac{dR}{dE_R} = \frac{N_A}{A}\rho_0\sigma(q)\frac{m_N}{2\mu^2 m_\chi} \times \frac{1}{k}\int_{v_{min}}^{v_{max}} \frac{f(\boldsymbol{v}, \boldsymbol{v_E})}{v} d^3v$$

Astrophysics

velocity distribution in halo

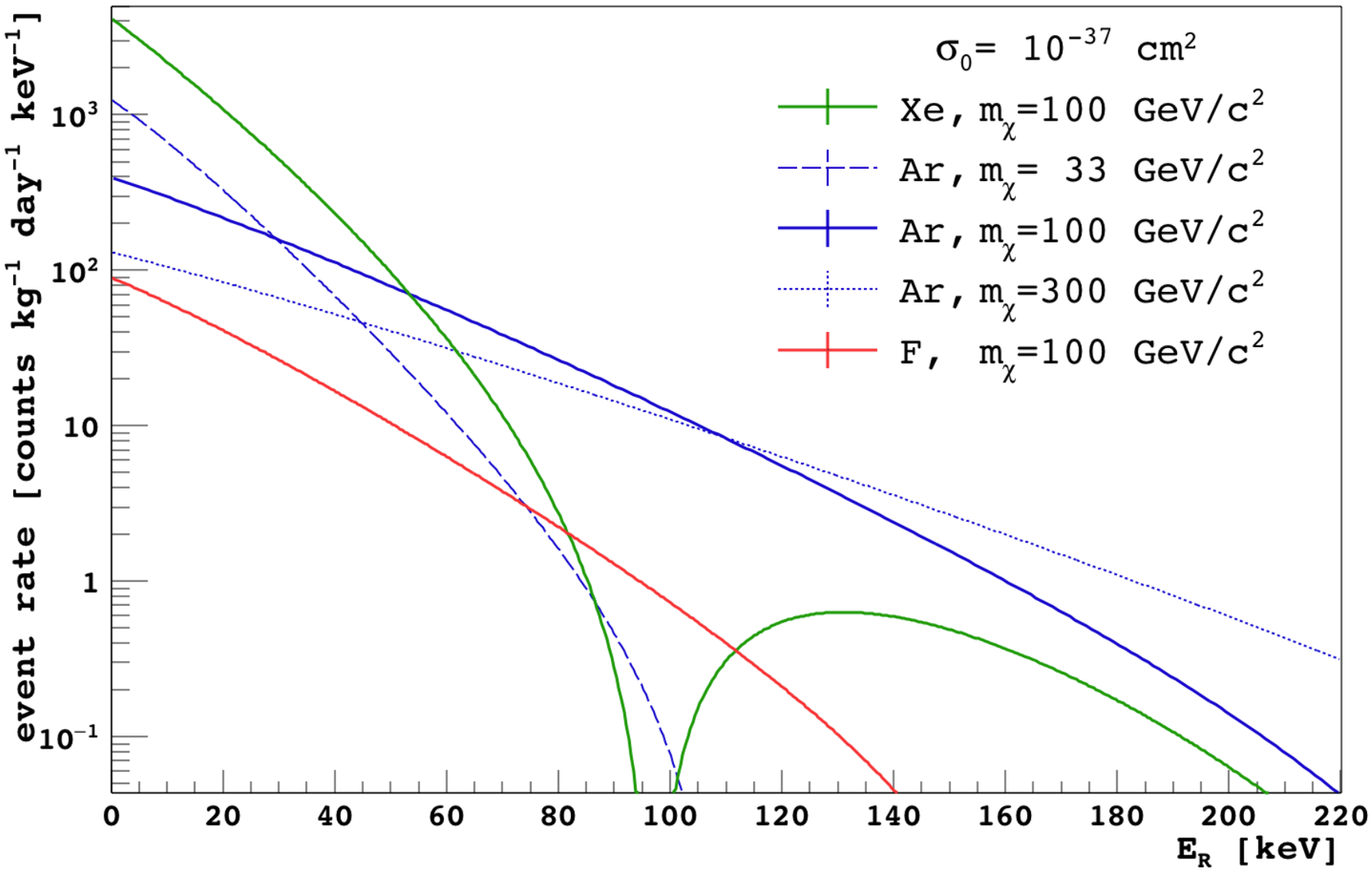
Particle and nuclear physics

$$\sigma(q) = \sigma_0 F^2(q)$$

with σ_0:

$$\sigma_0^{SI} = \sigma_p \left(\frac{\mu}{\mu_p}\right)^2 A^2$$

$$\sigma_0^{SD} = \frac{32}{\pi} G_F^2 \mu_N^2 \frac{J+1}{J} [a_p\langle S_p\rangle + a_n\langle S_n\rangle]^2$$

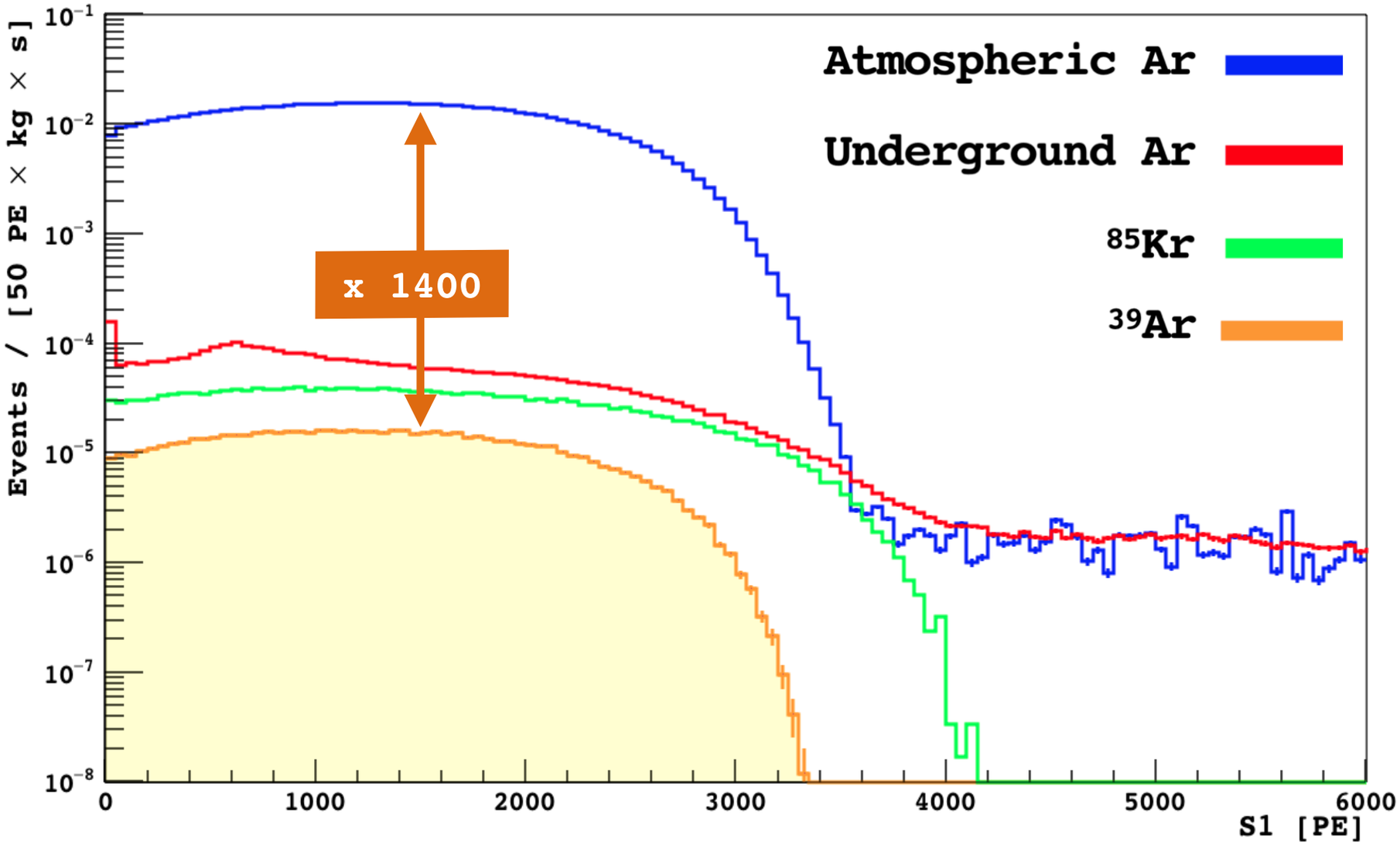


…To be folded with target intrinsic behavior and with the detector response function

Underground Argon

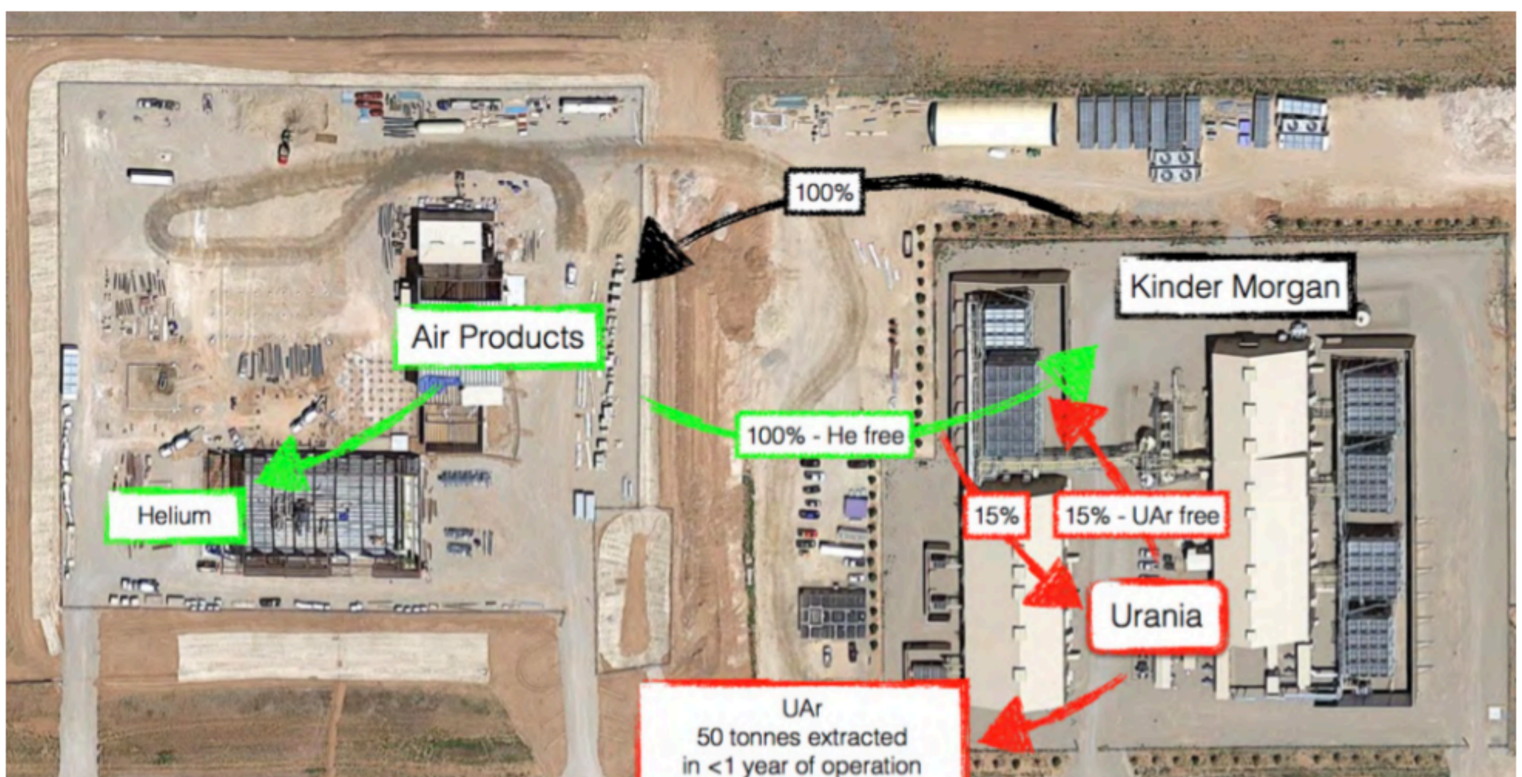
Main results

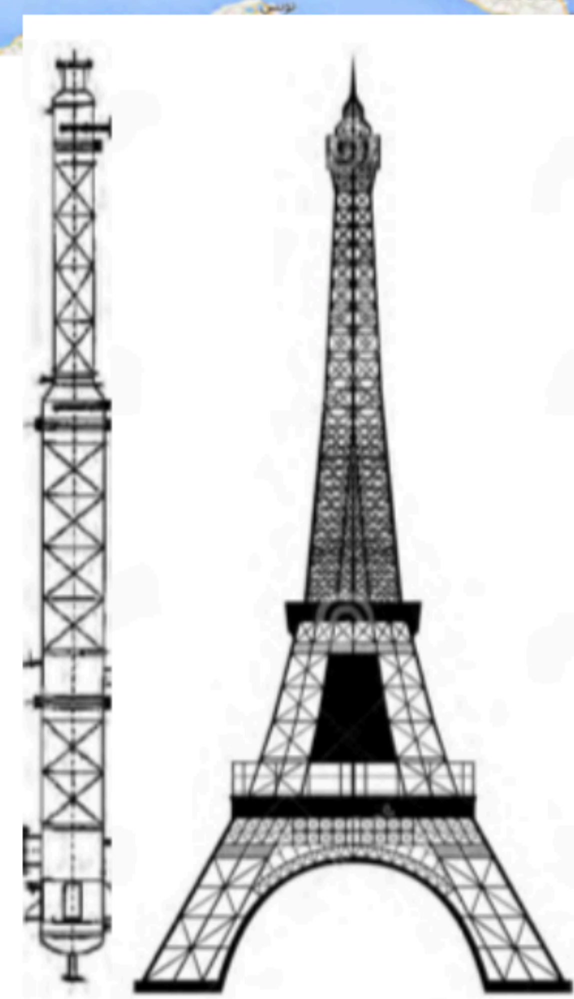
- **First measurement of ^{39}Ar activity in underground argon** (0.73 ± 0.10 mBq/kg)
- Identification of a **^{85}Kr contamination**
- Background model for low-mass WIMP search




URANIA


ARIA
Italia
Italy


100%
Kinder Morgan
Air Products
100% - He free
Helium
15%
15% - UAr free
Urania
UAr
50 tonnes extracted
in <1 year of operation



^{85}Kr

Unexpected contamination (no specific purification procedure put in place).

Two independent measurements: MC spectra fit and beta+gamma coincidence (0.04% BR)

-Decay: $^{85}Kr \rightarrow {}^{85m}Rb$

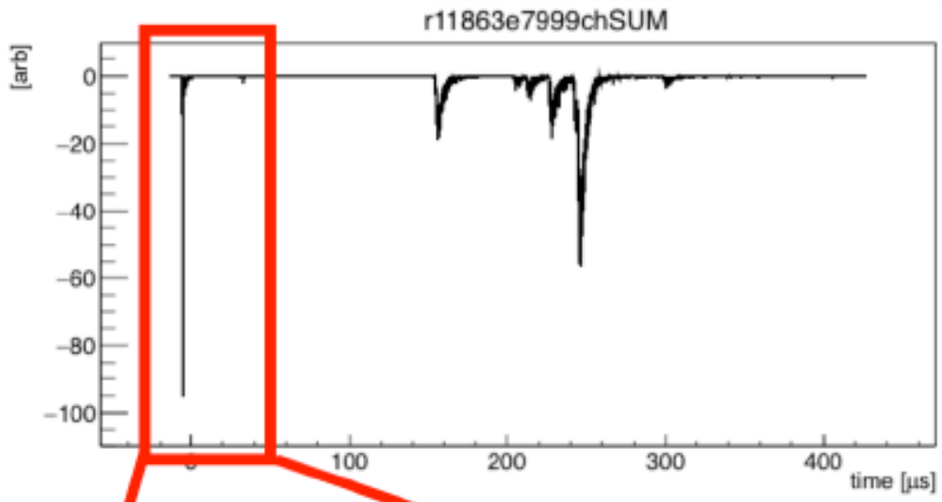
BR=0.4% ($\tau_{1/2}$~1 μs, E_γ~514 keV)

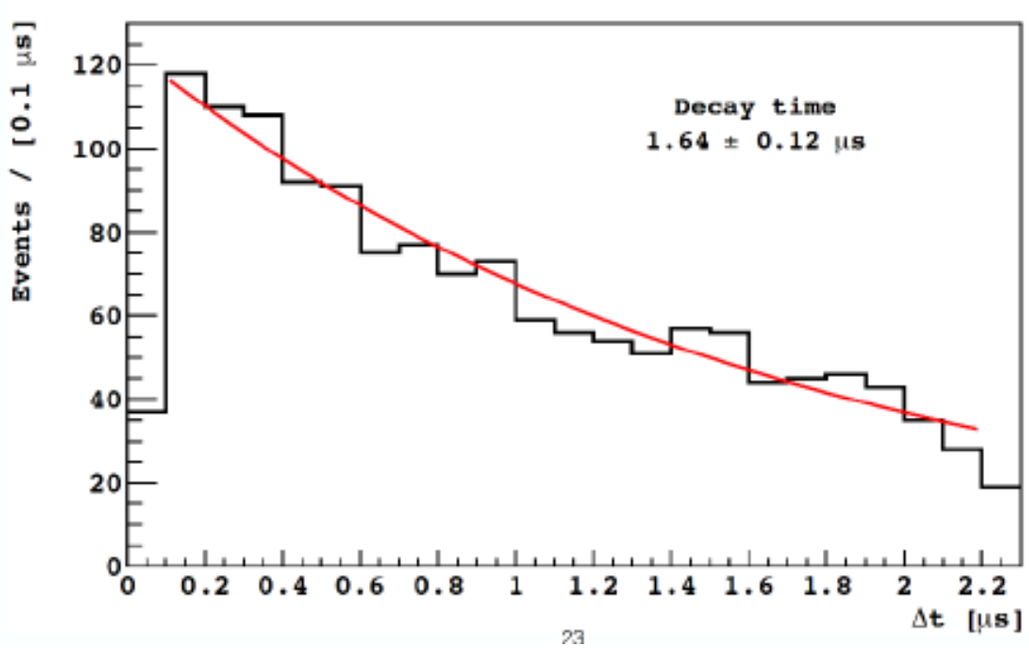
- Signature: 2 S1s (β+γ) in delayed

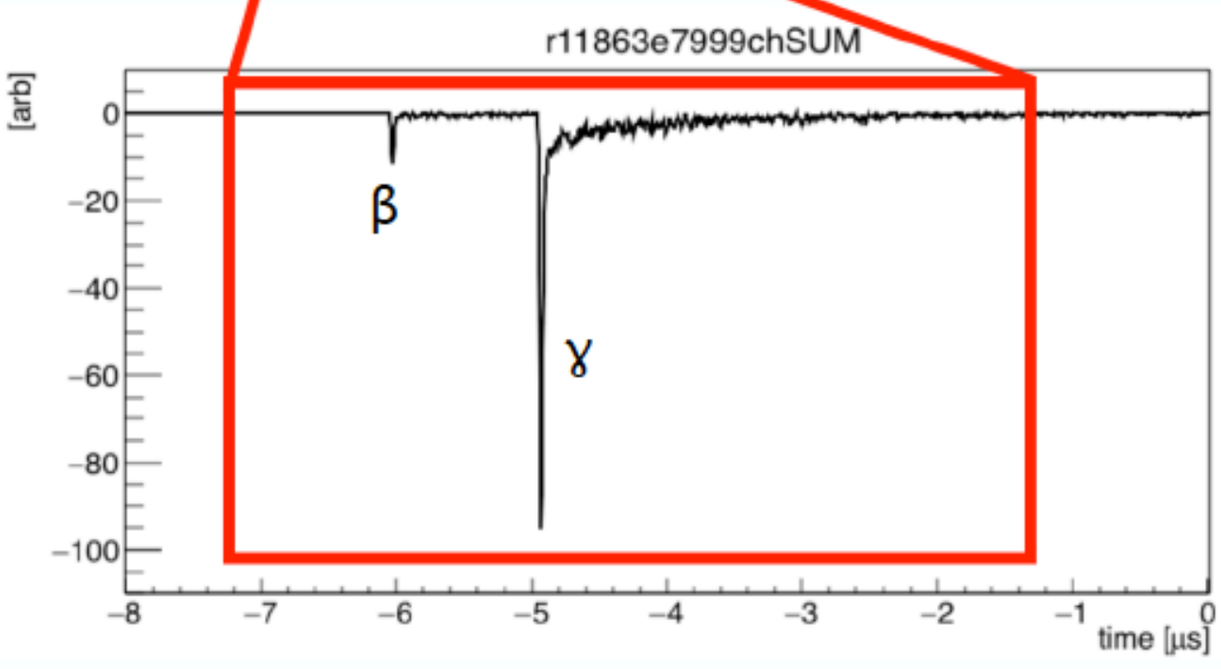
-Rate:

observed: 33.1 ± 0.9 events/d

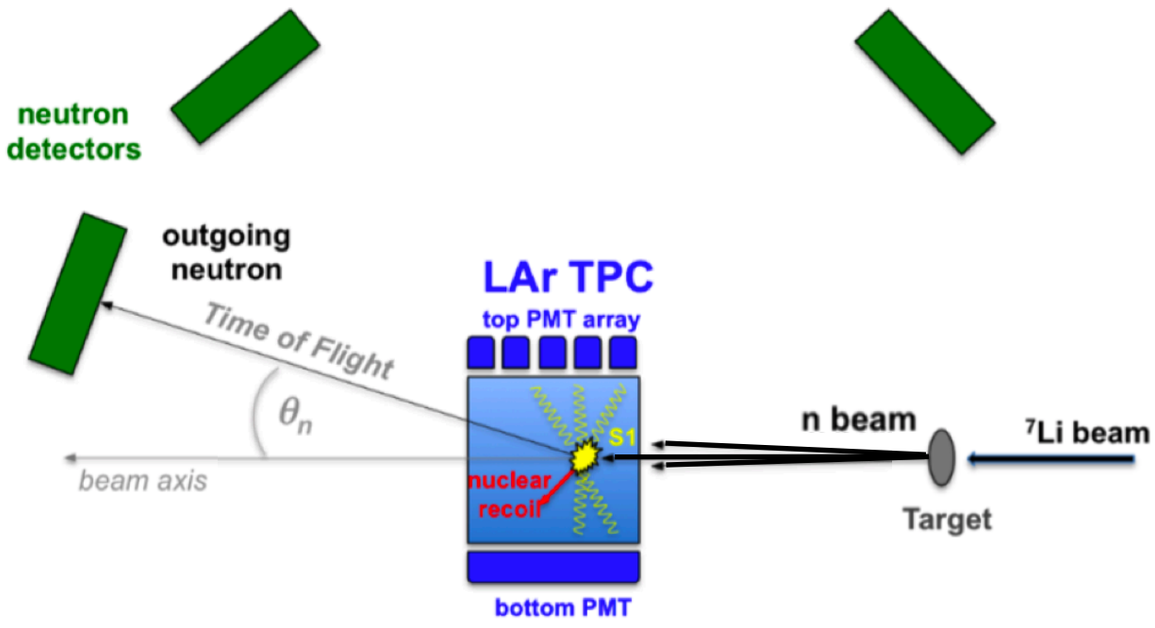
spectral fit: 35.3 ± 2.2 events/d





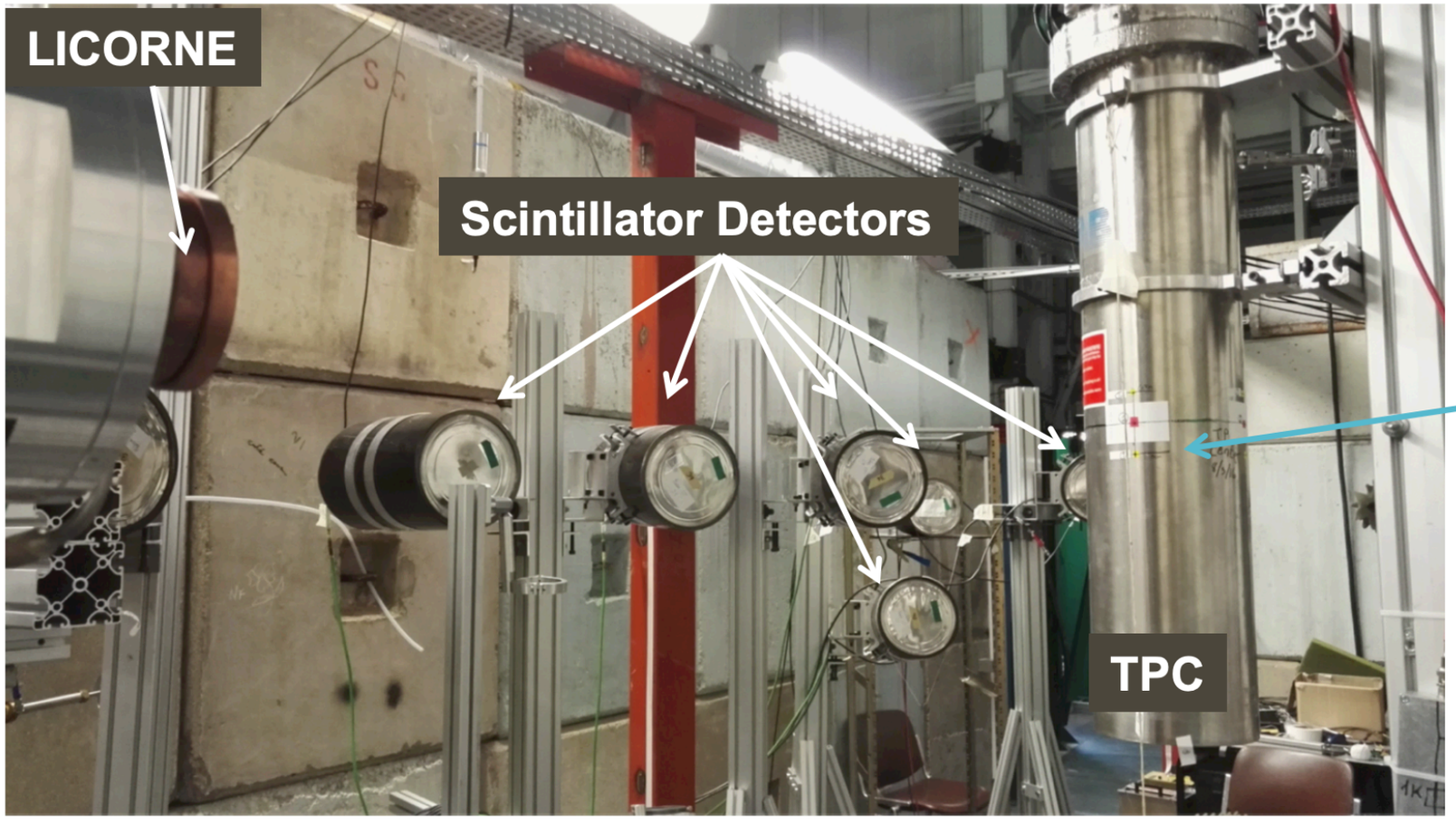


ARIS: calibration of nuclear recoils

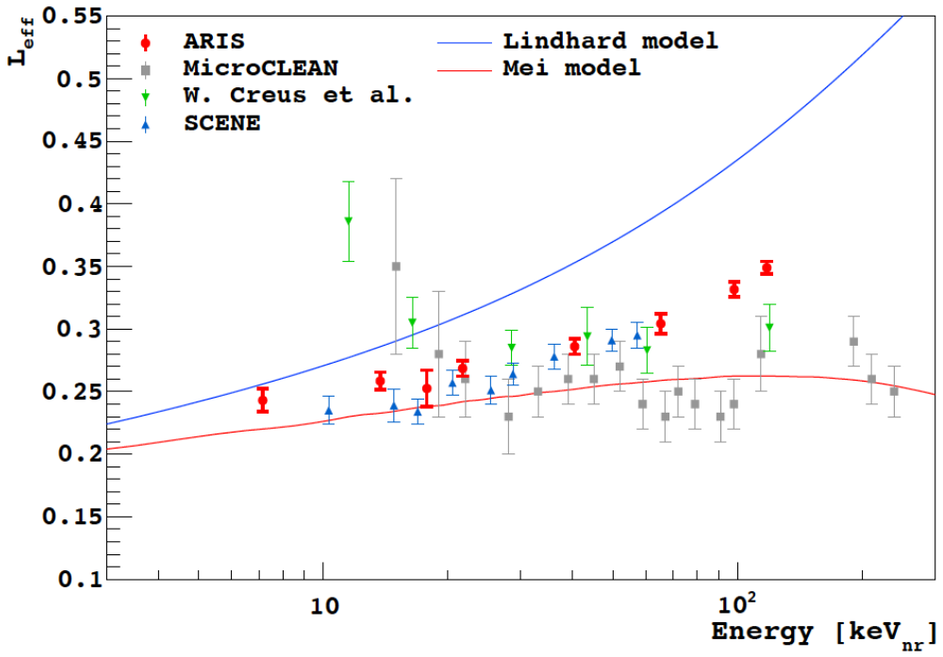


LICORNE source**: inverted ^{7}Li(p,n)^{7}Be reaction**

- Pulsed: 1.5 ns width
- Collimated**:** <2 degrees
- Monochromatic**:** <6% (μ~1450 keV, σ~85 keV)

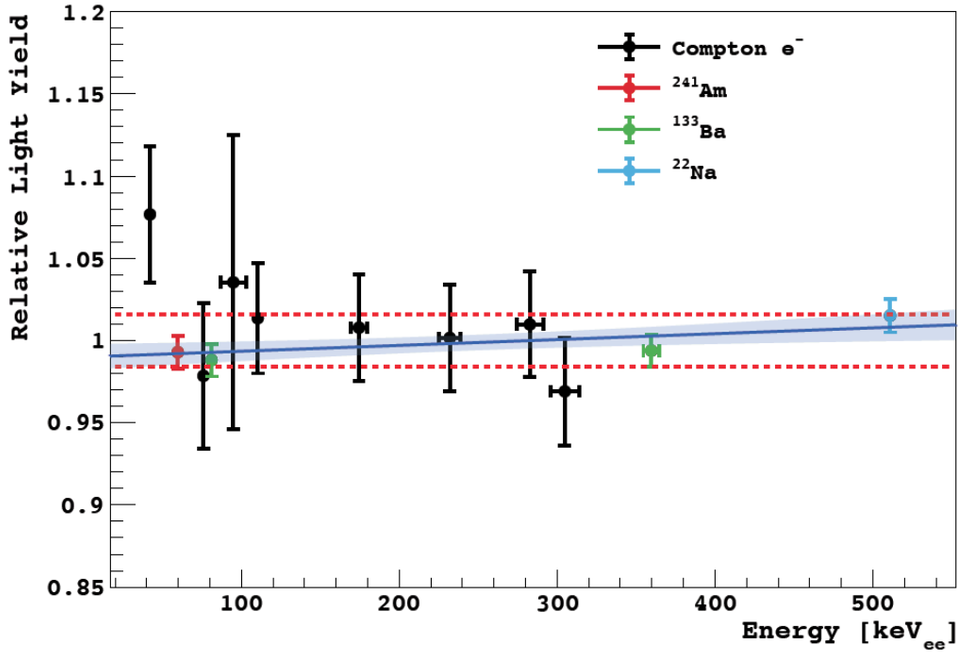


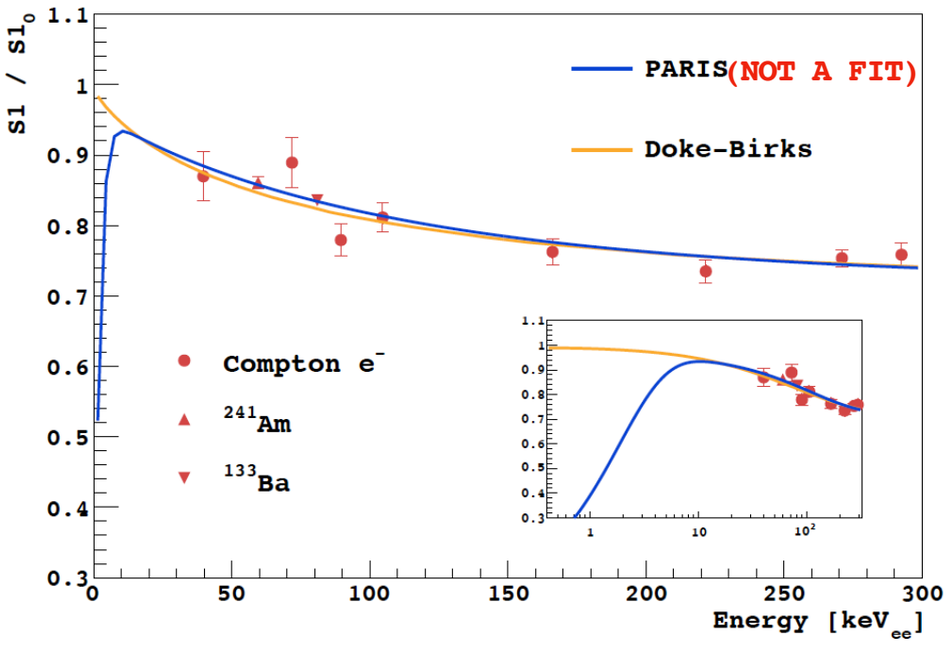
The ARIS results



Most precise measurement of **nuclear recoil quenching** and with the **lowest energy** (7 keV$_{NR}$)

Best constraint of the **linearity of LAr response** to electronic recoils at field-off at 1.6% level





Excellent agreement with PARIS model at 200 V/cm

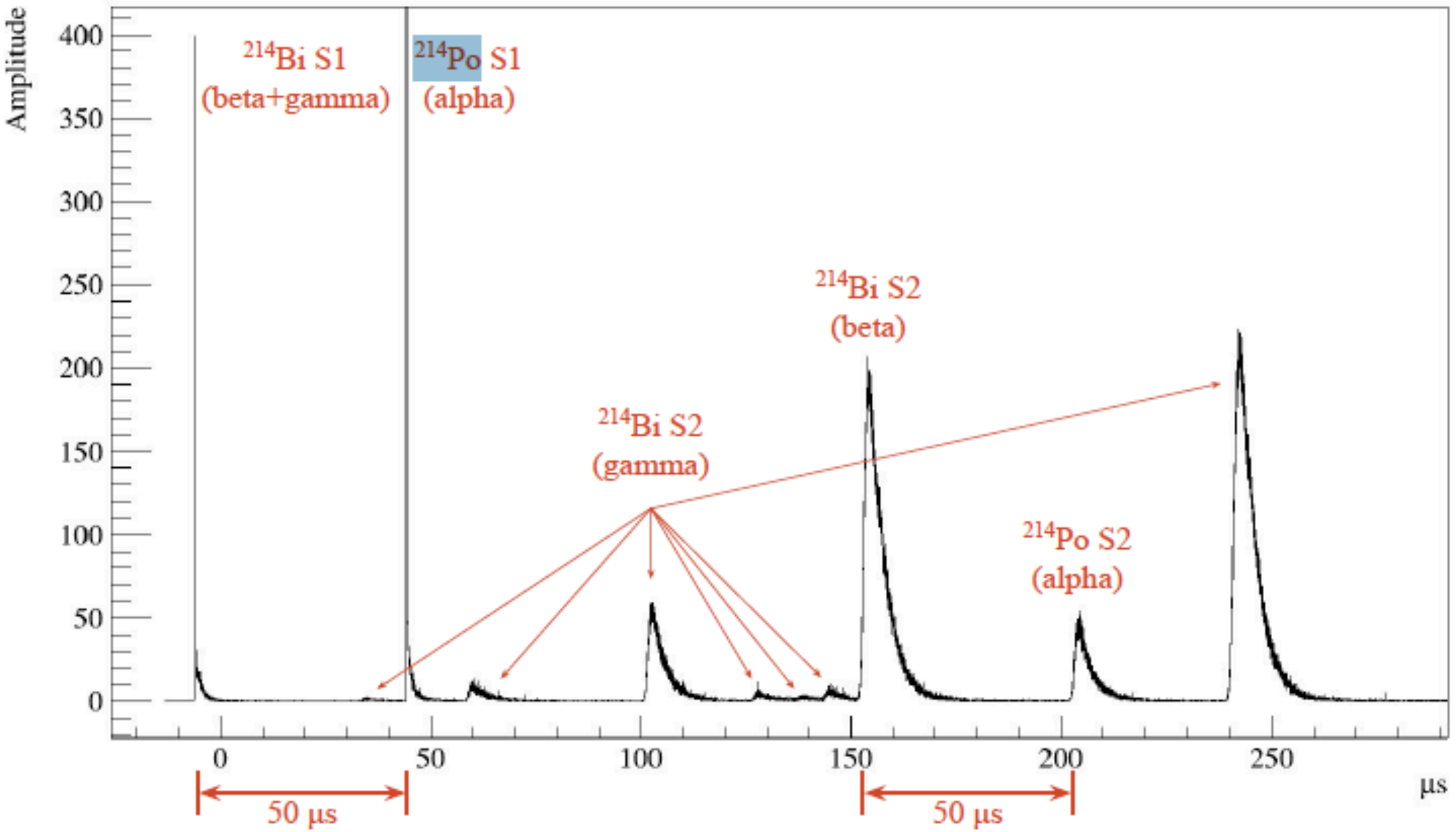
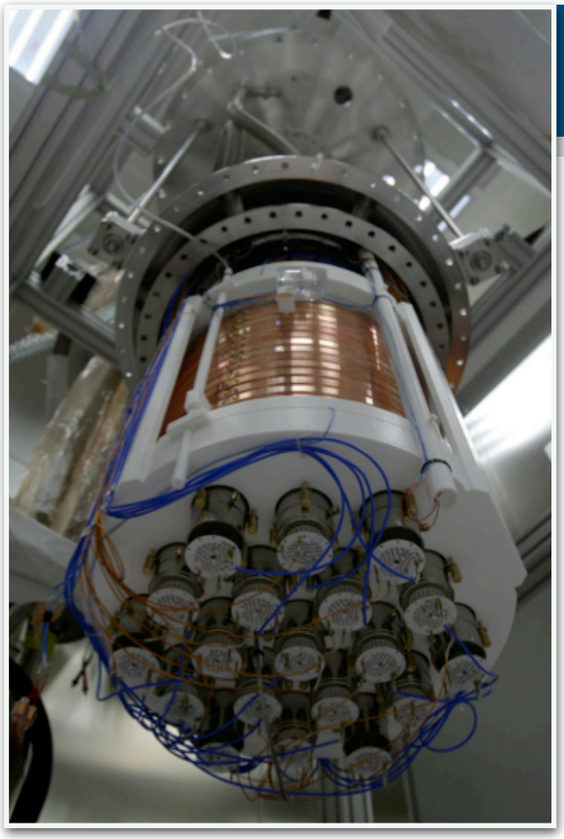
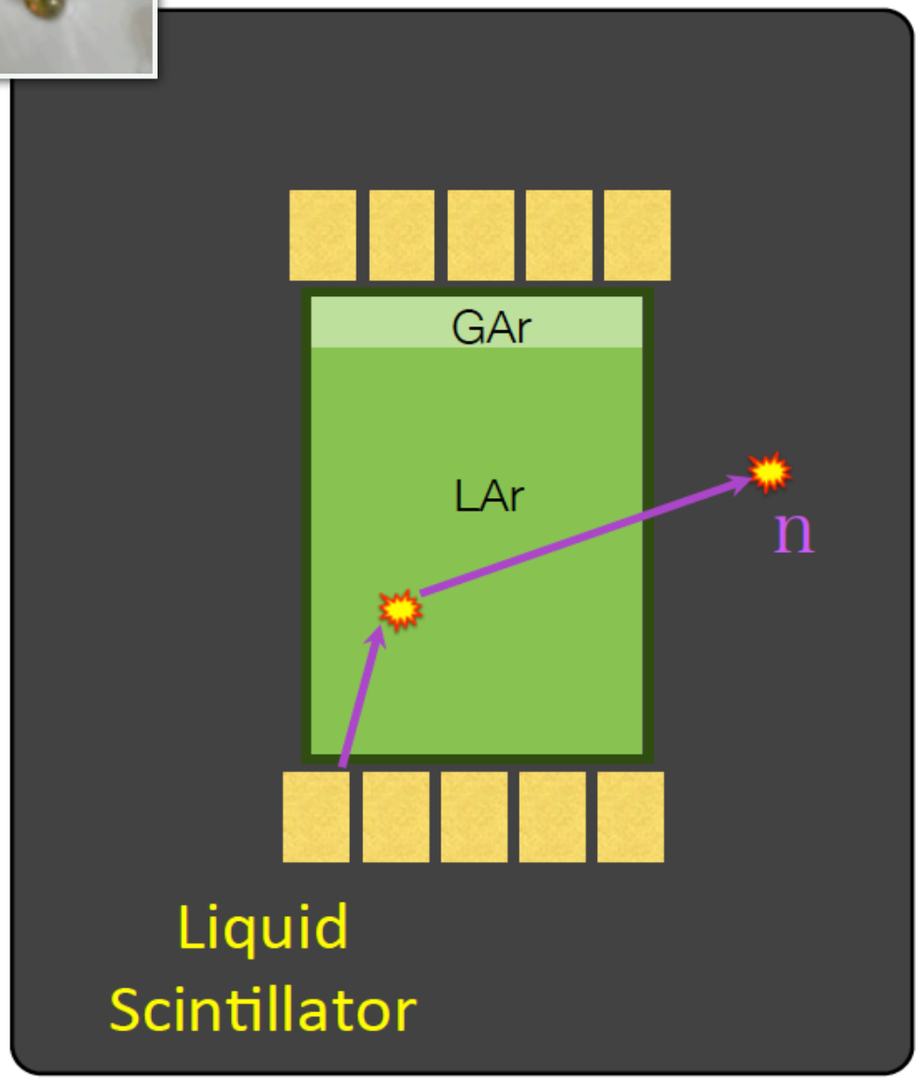


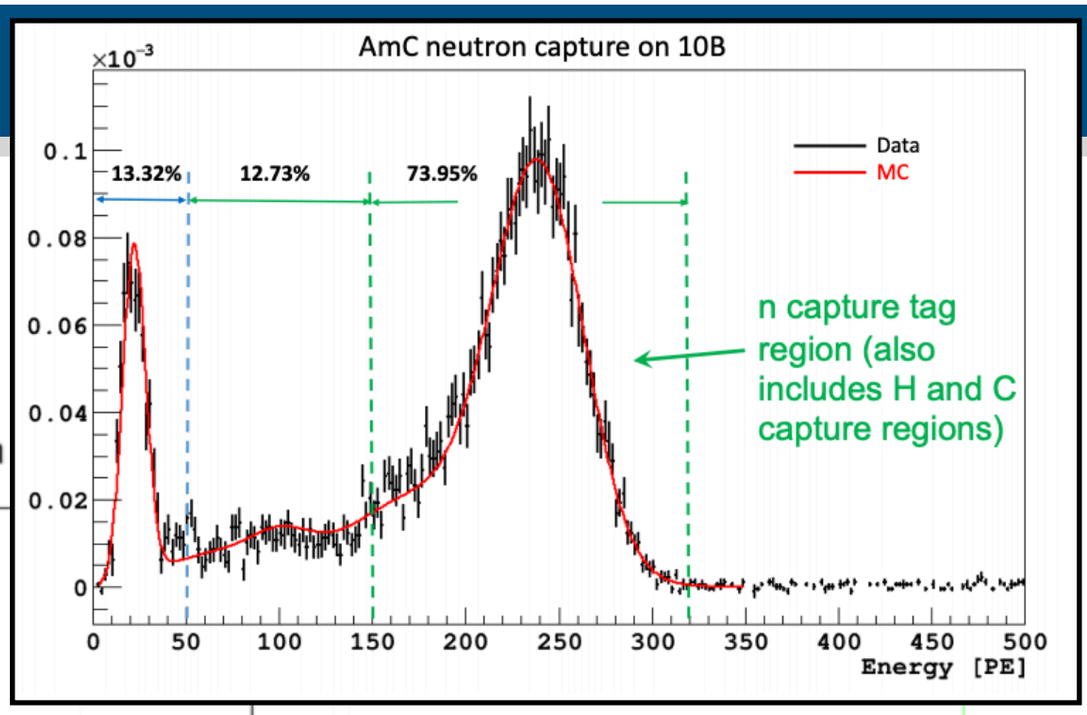
Figure 8.9: A BiPo event with many S2s coming from coincident ^{214}Bi gammas.

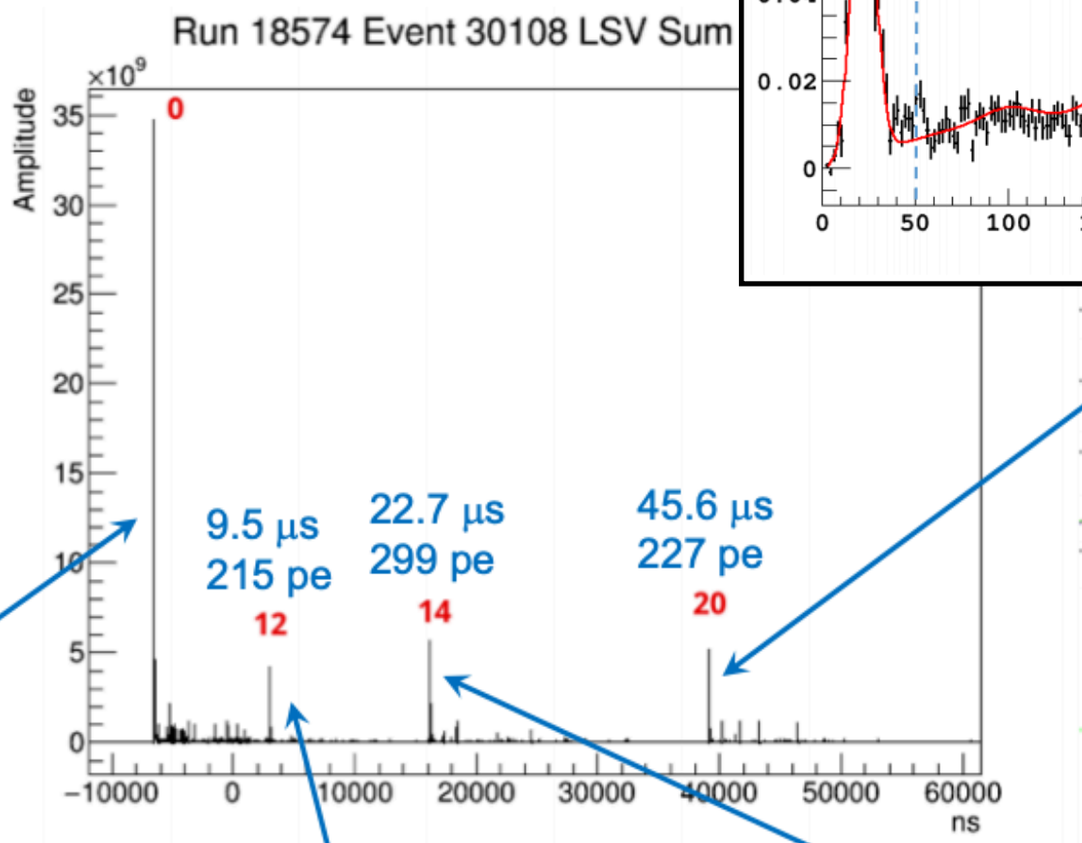
DarkSide-50 neutron veto

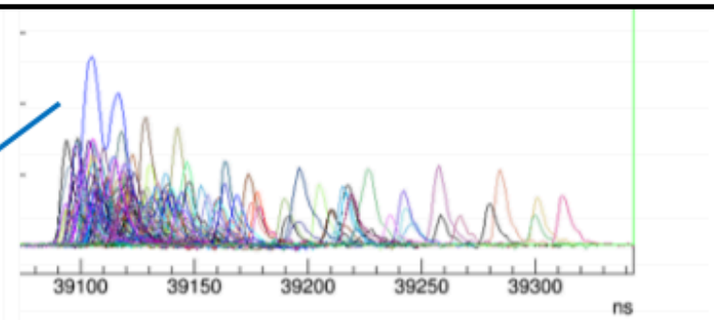


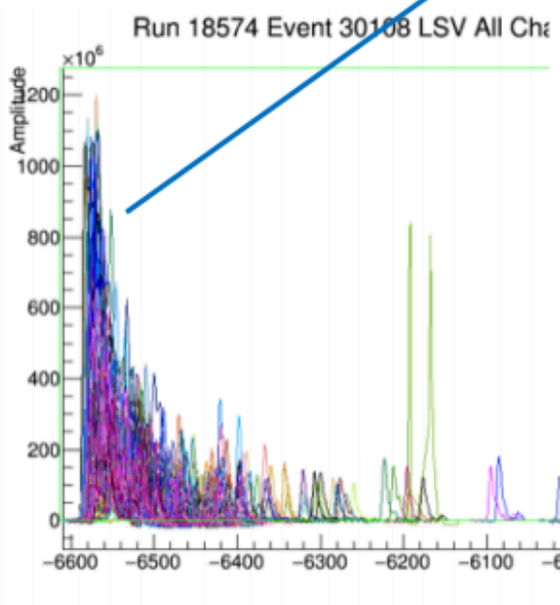


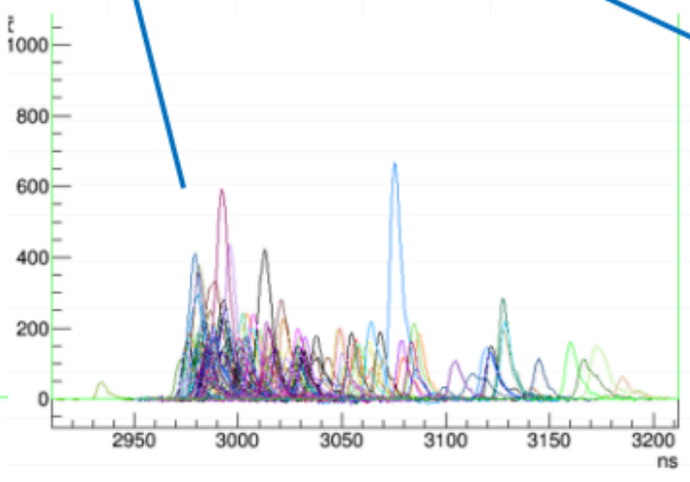
THREE perfect neutrons in LSV!

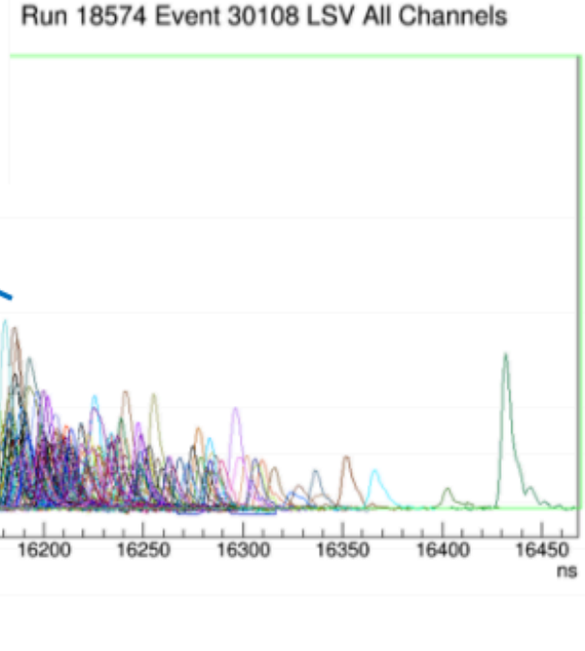




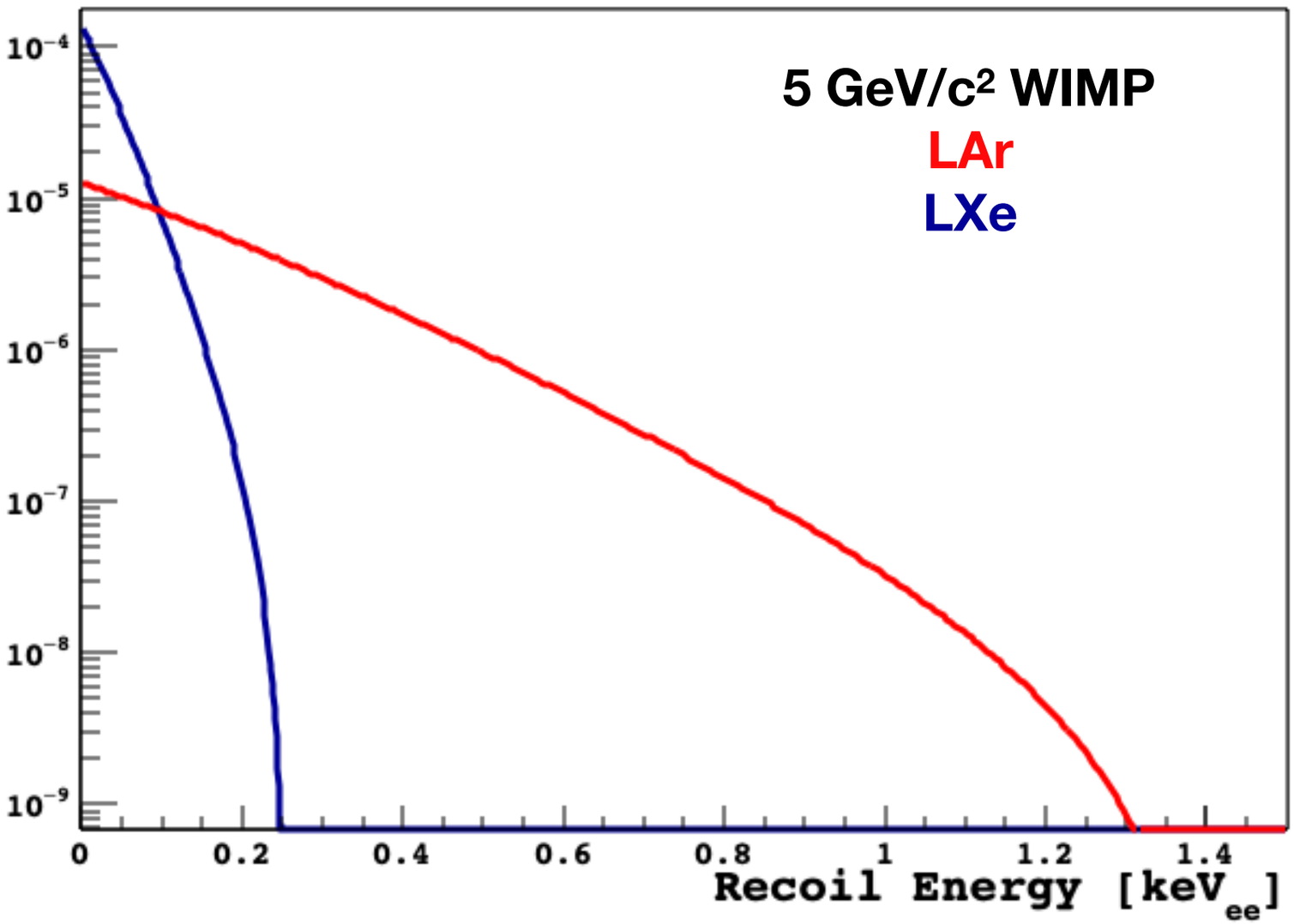






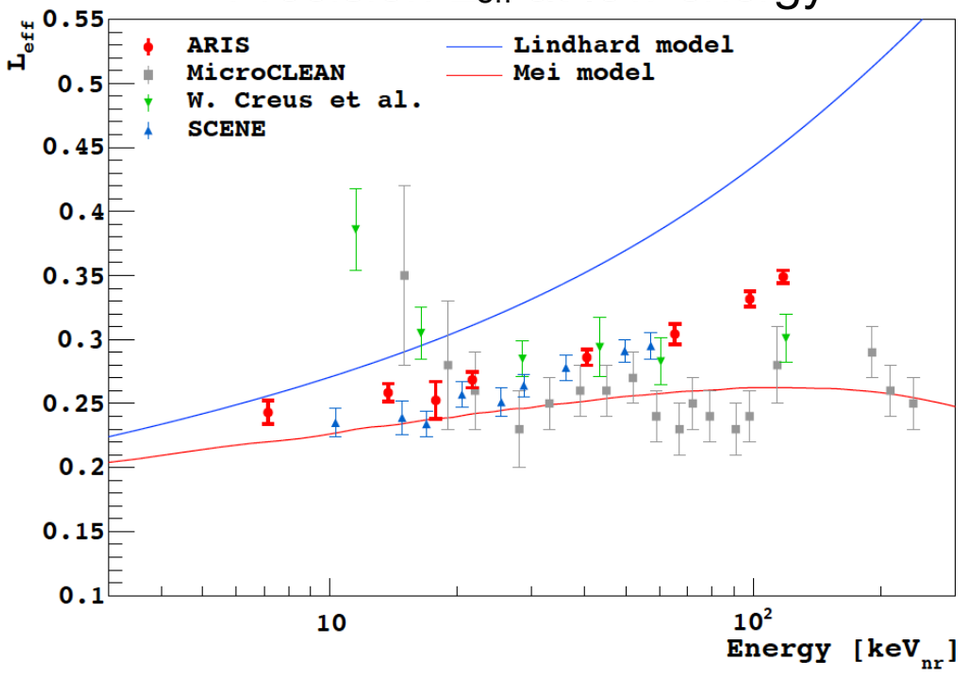


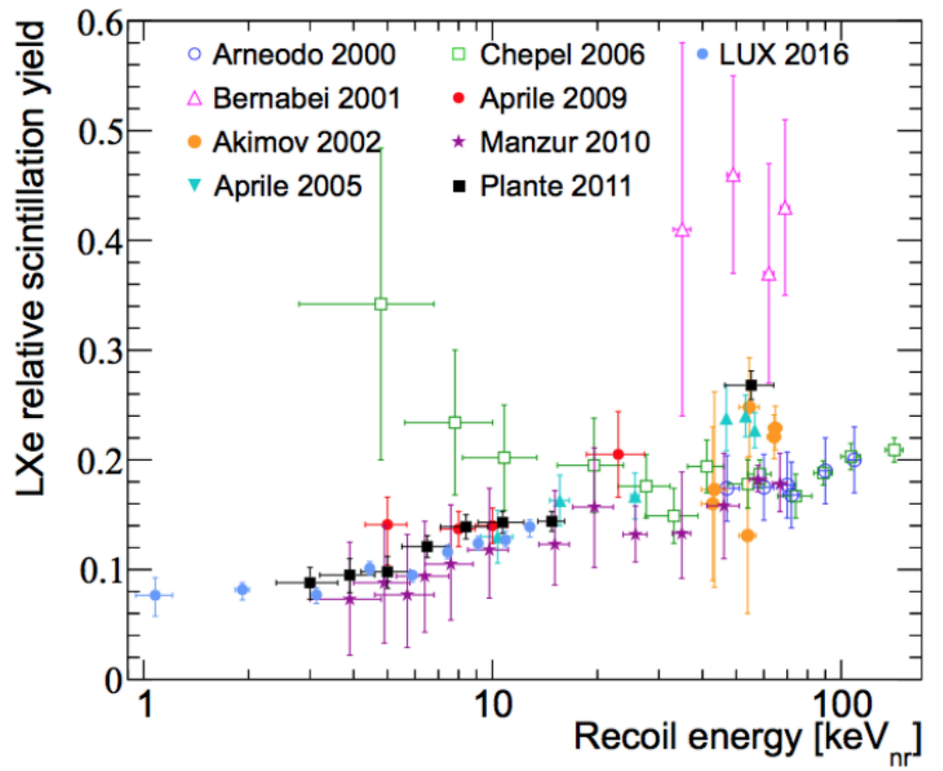
6



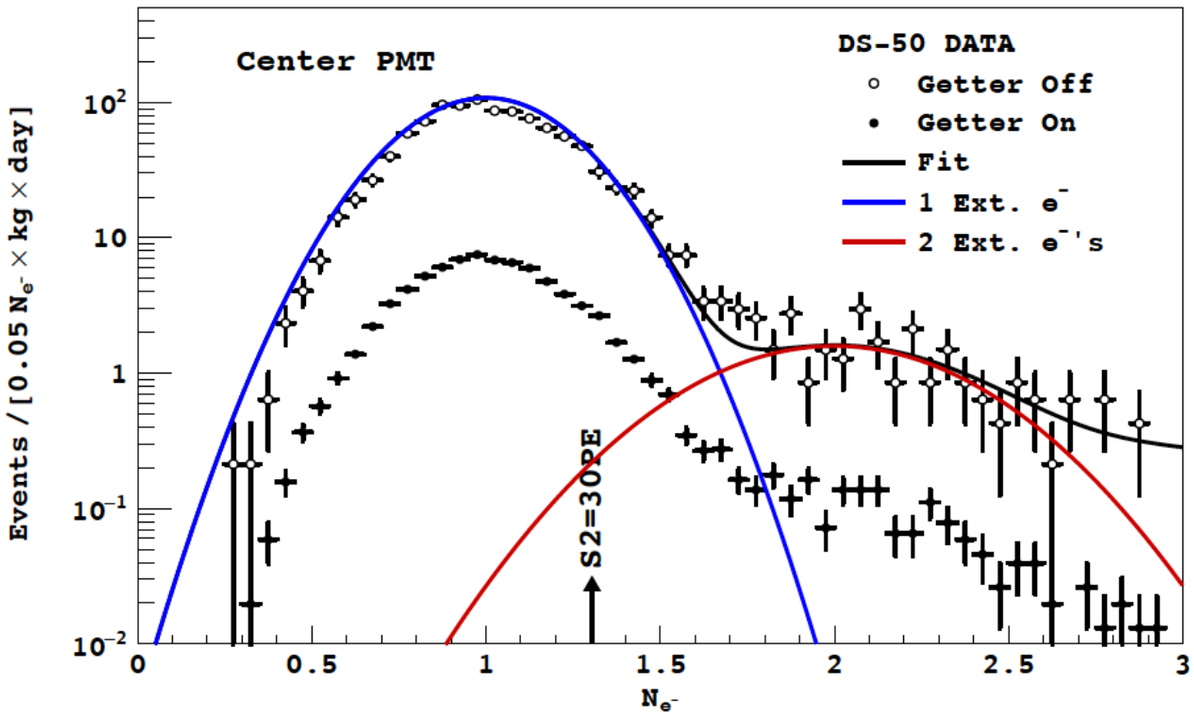
Missing: Eq -> electrons
WAr ~ 20 eV, WXe ~ 10 eV

Precision L_{eff} at low energy

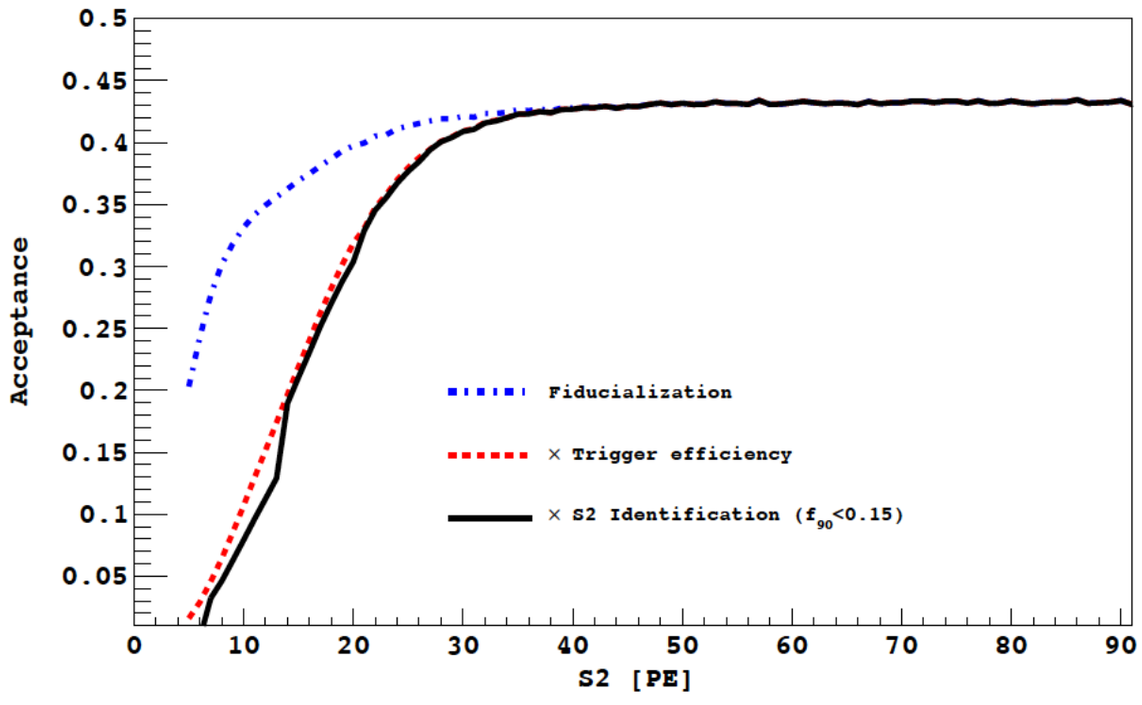




low-mass WIMPs



Trigger efficiency is 100% at 4 N_{e^-}

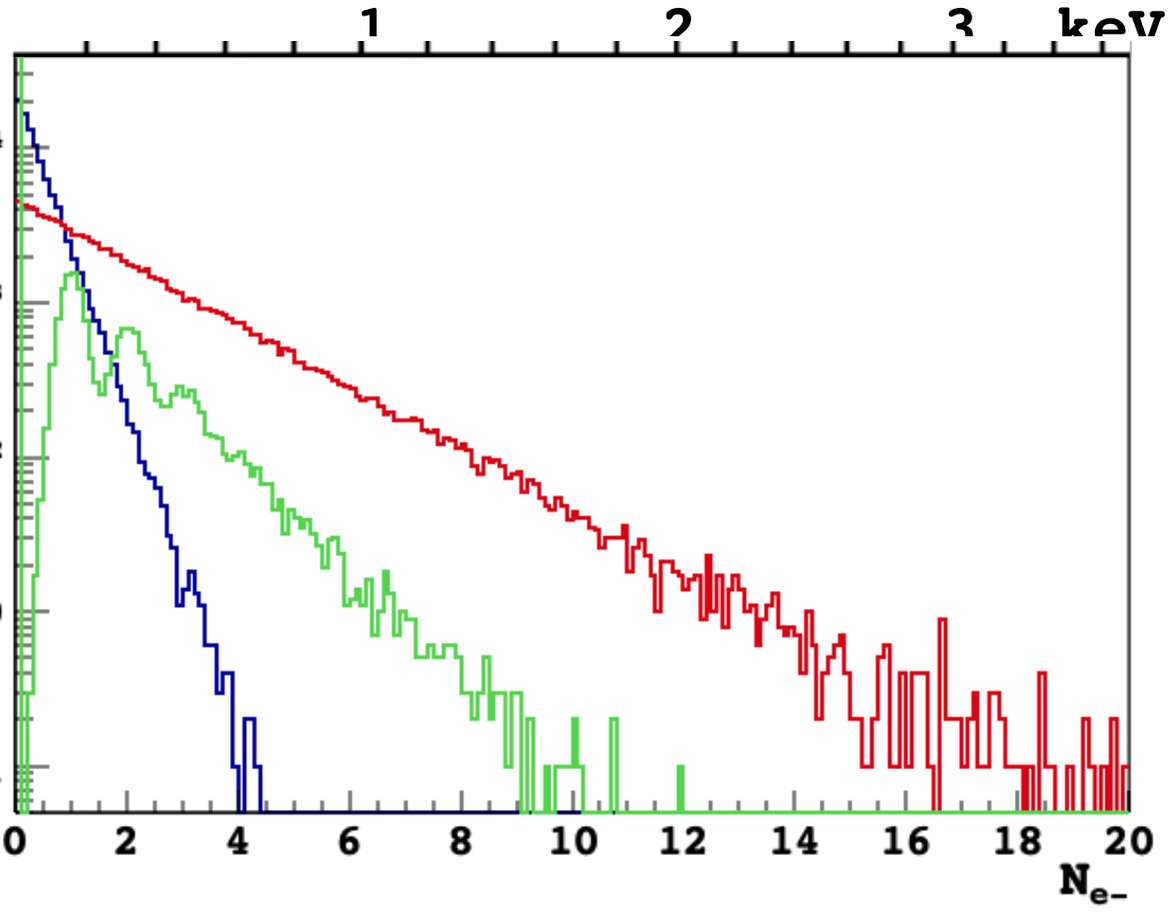


signal produced by a 1 GeV/c^2 WIMP

no quenching ($Ne = E/W_i$)

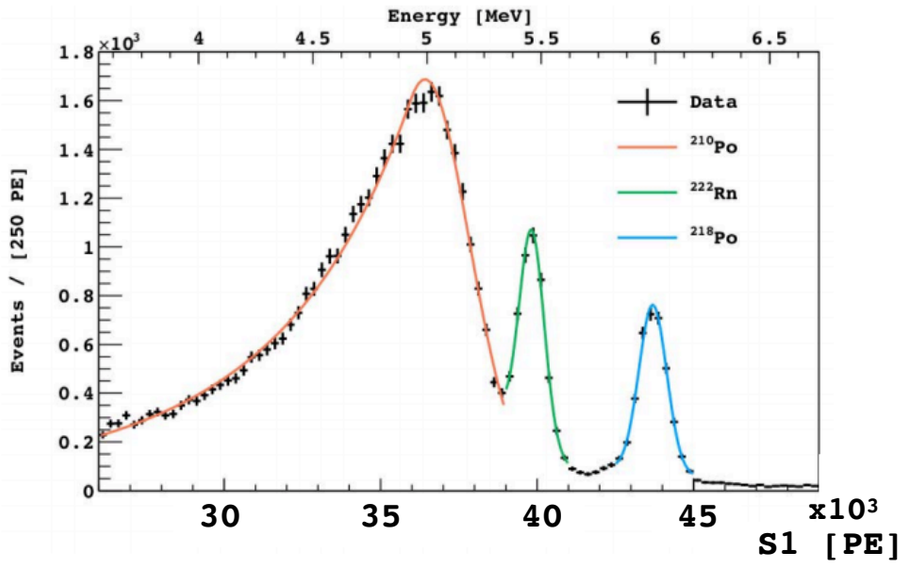
Add quenching w\out fluctuations ($Ne = q \times E/W = Q_y \times E$)

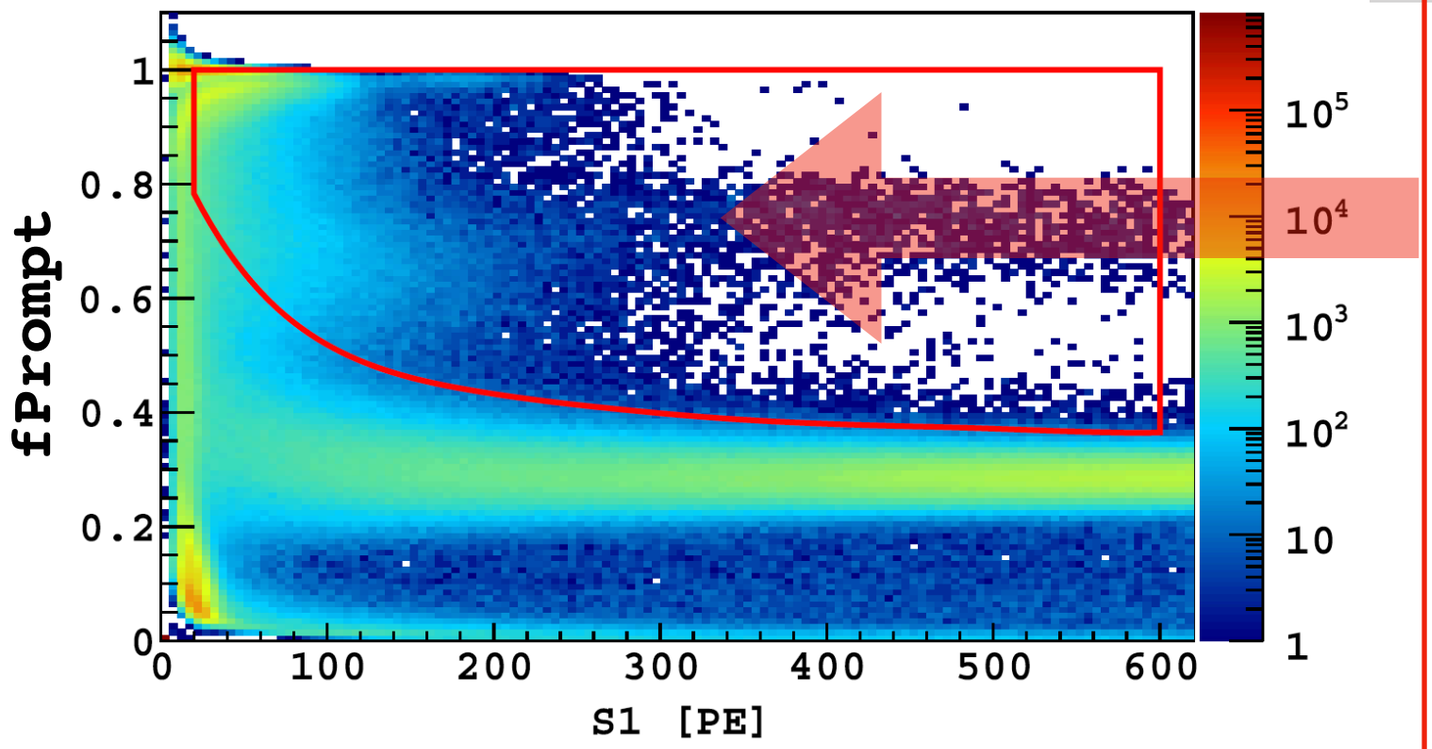
Add quenching w\ fluctuations (Ne = Poisson (Binomial (E/W, q)))



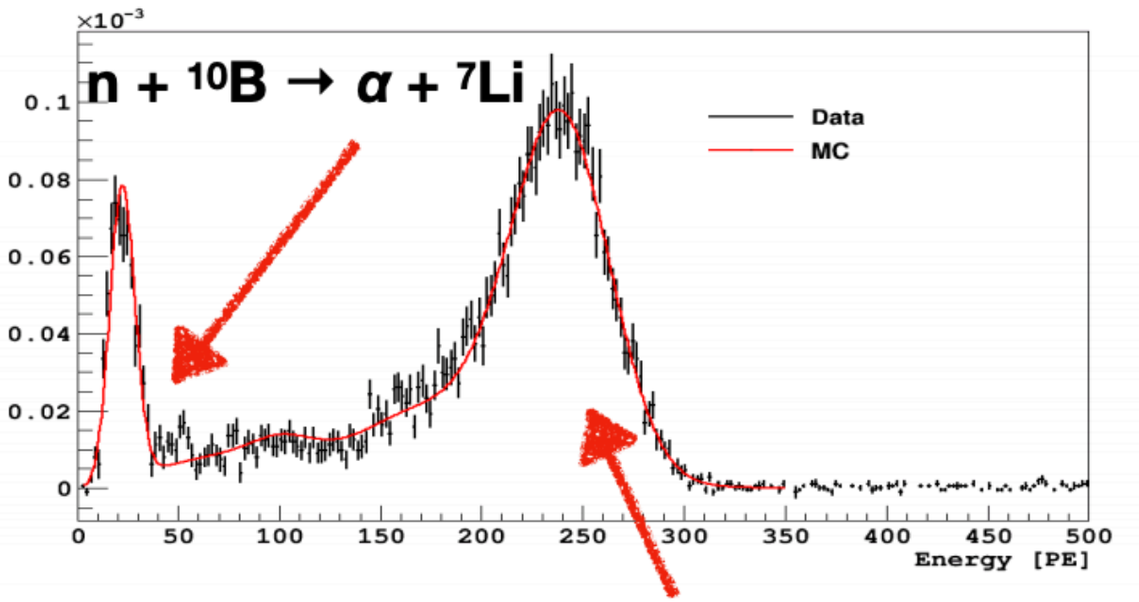
Backgrounds in DS50

surface α's can leak from high energy.
Self vetoed (no S2 + TPB long tail)

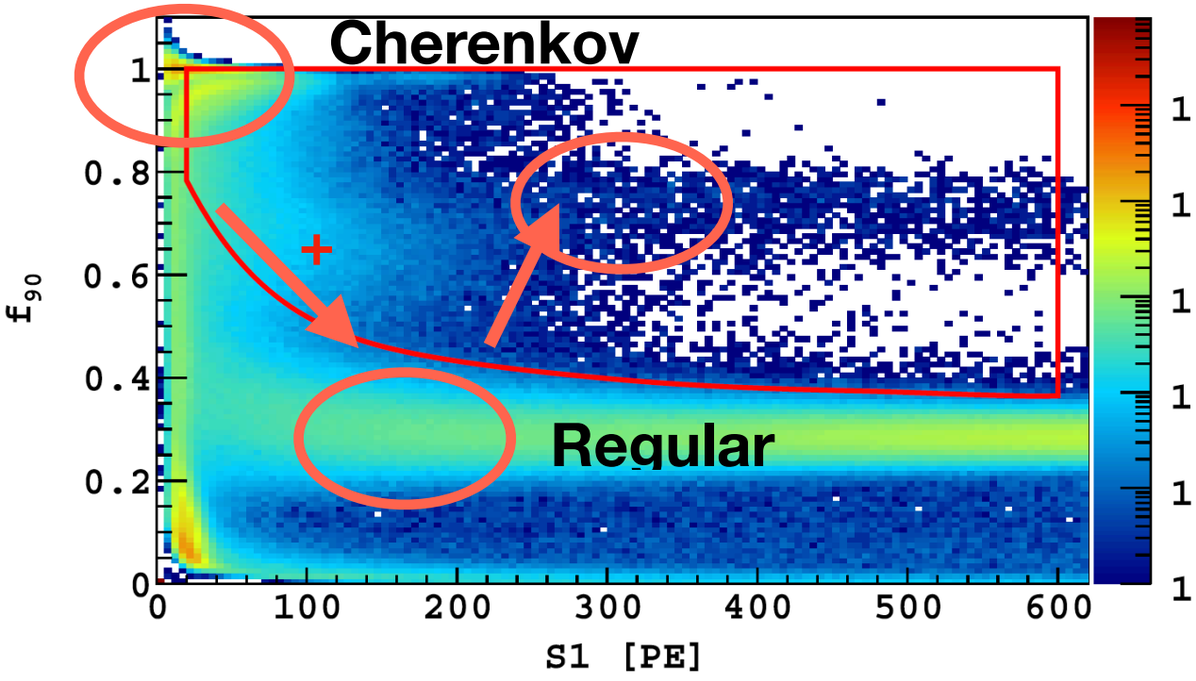




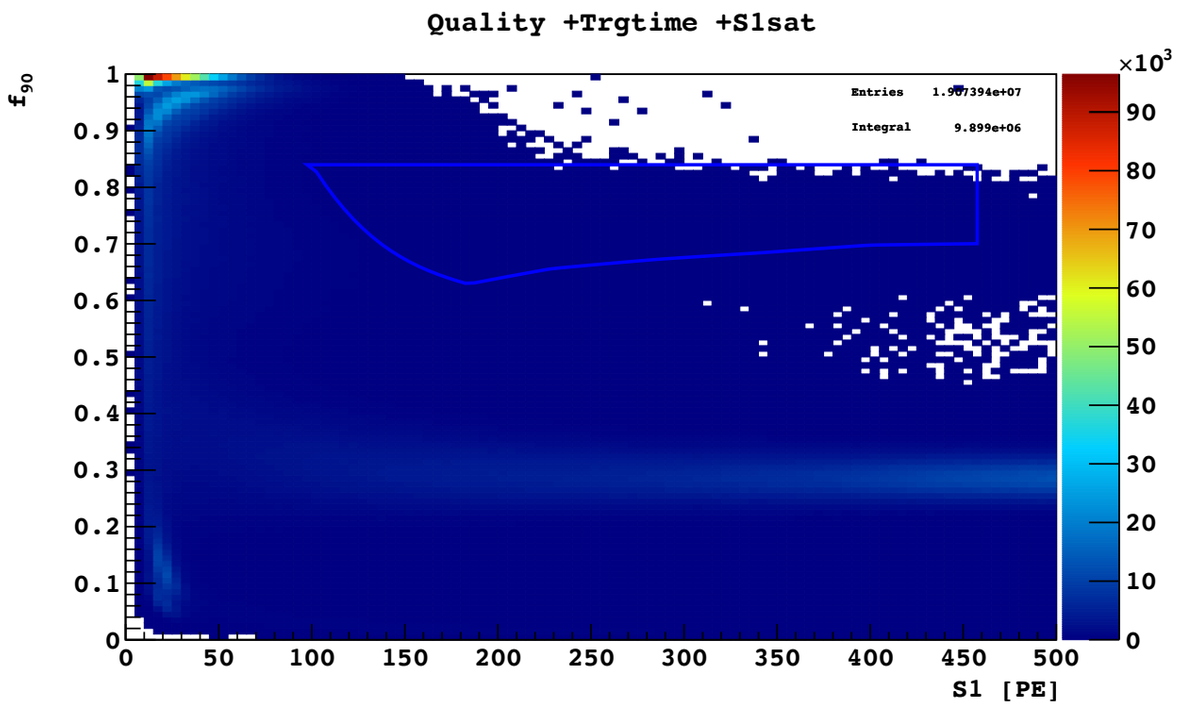
Radiogenic neutrons tagged by the veto.
Efficiency: estimated with G4DS and measured with external n sources

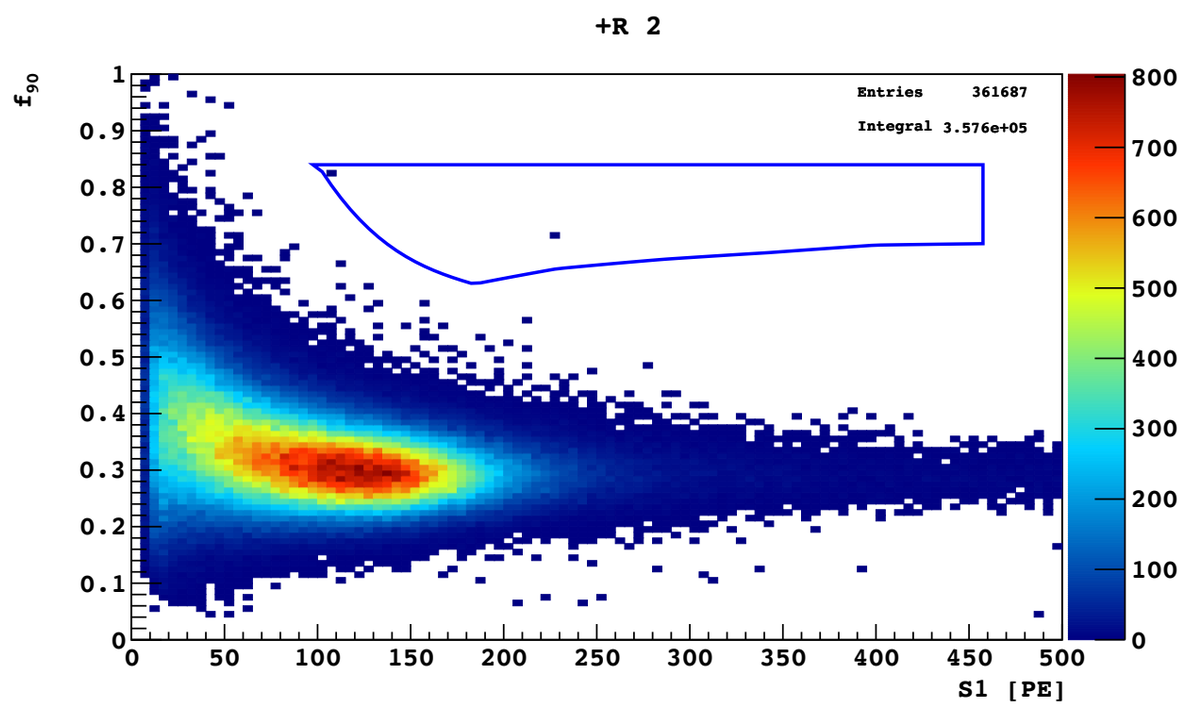


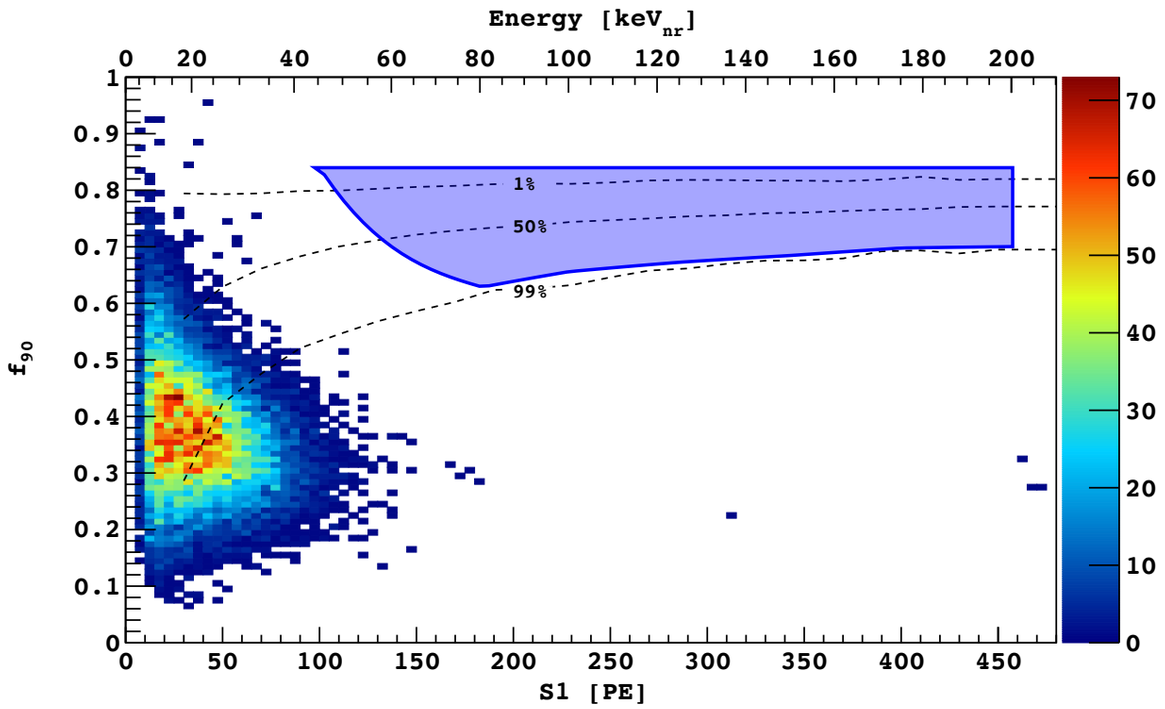
n + ^{10}B → α + ^{7}Li + γ

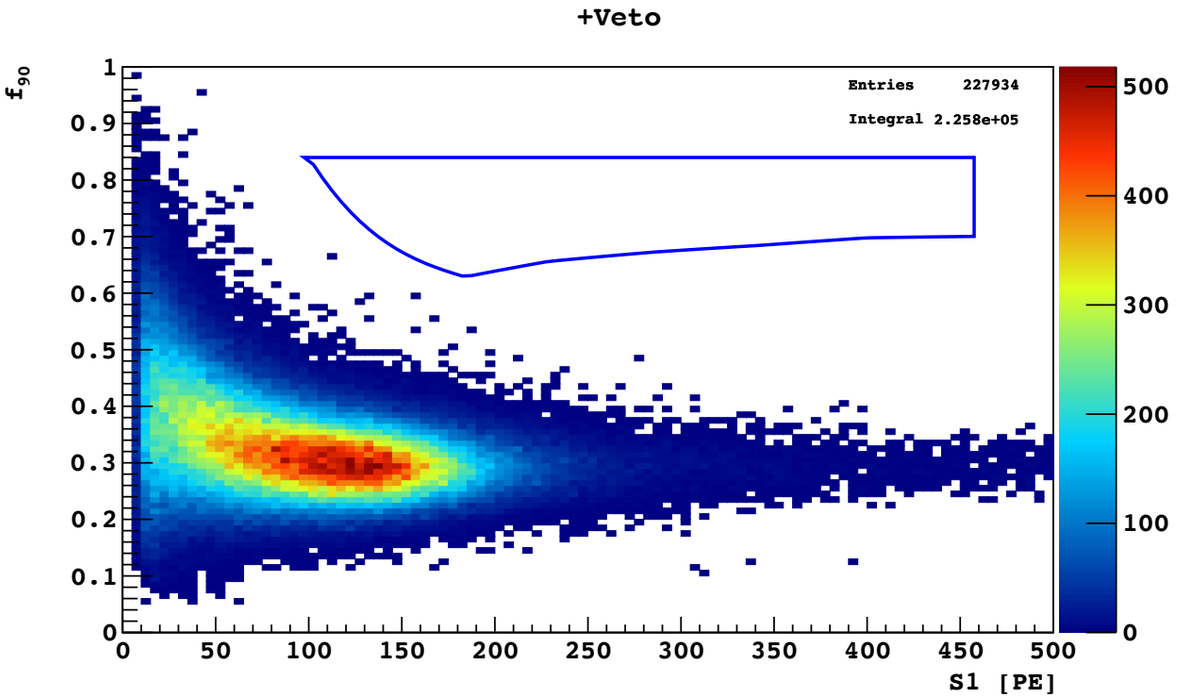


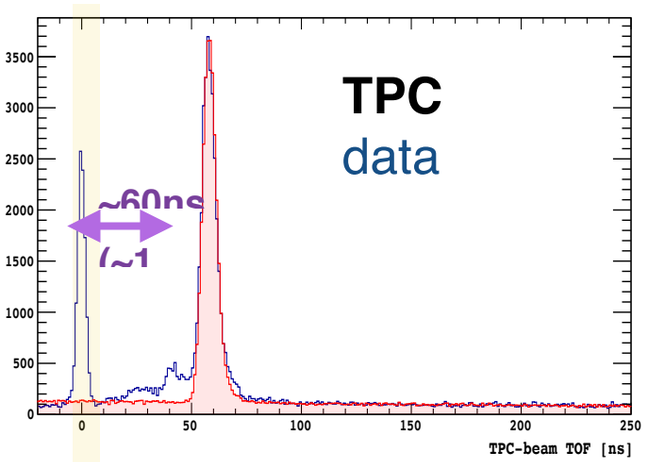
high-mass WIMP result

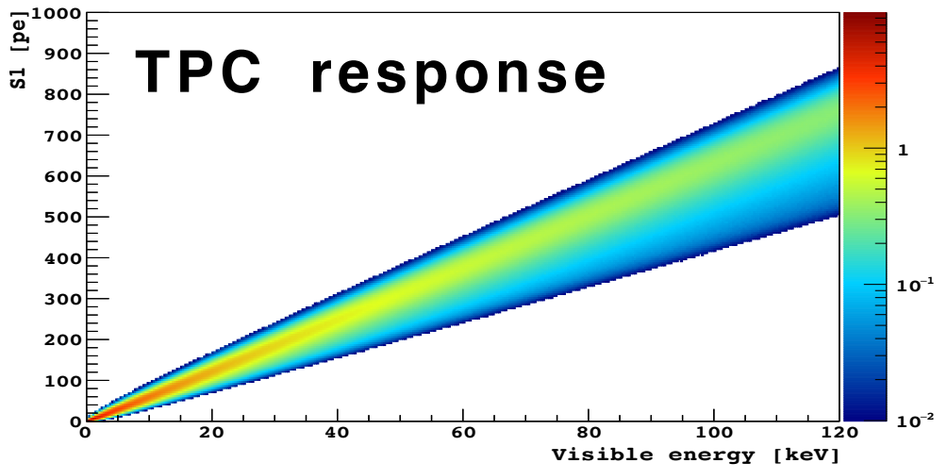


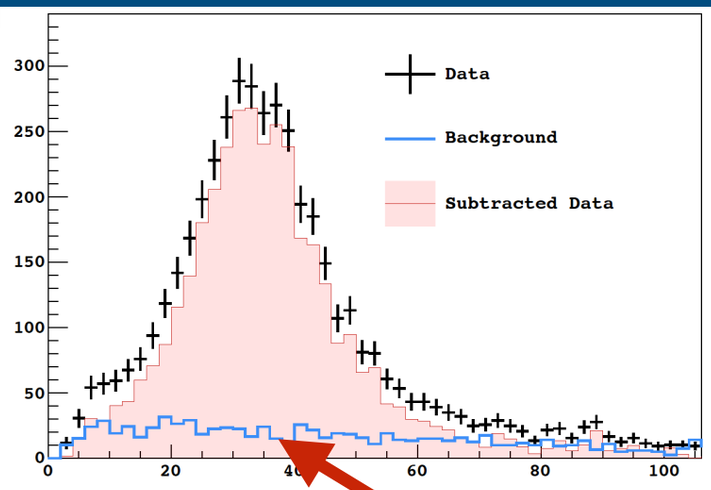


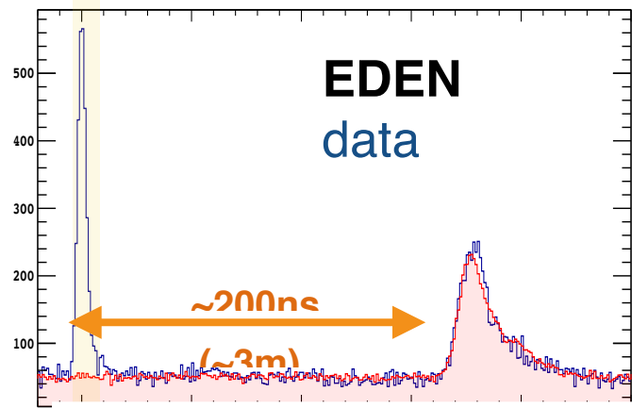


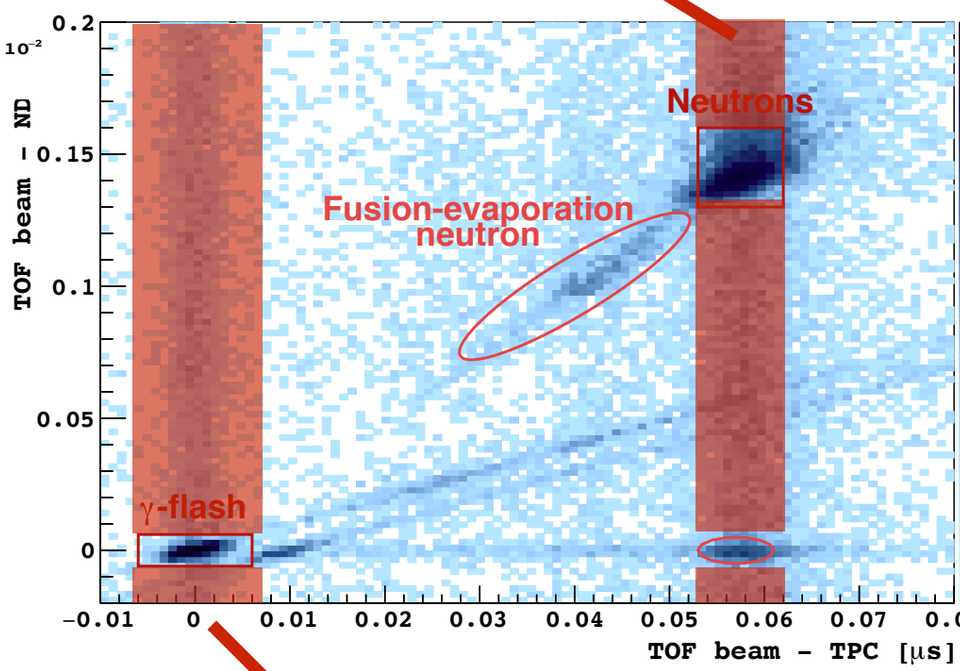


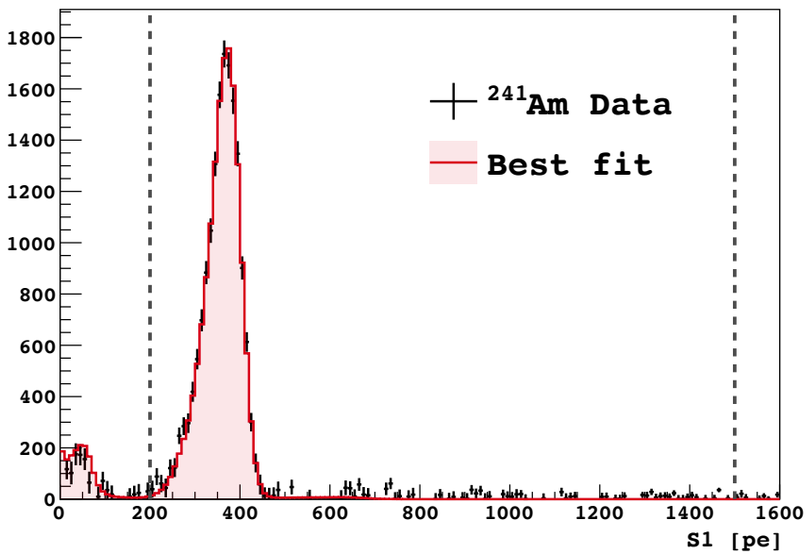

TPC
data
~60ns
(~1
TPC-beam TOF [ns]

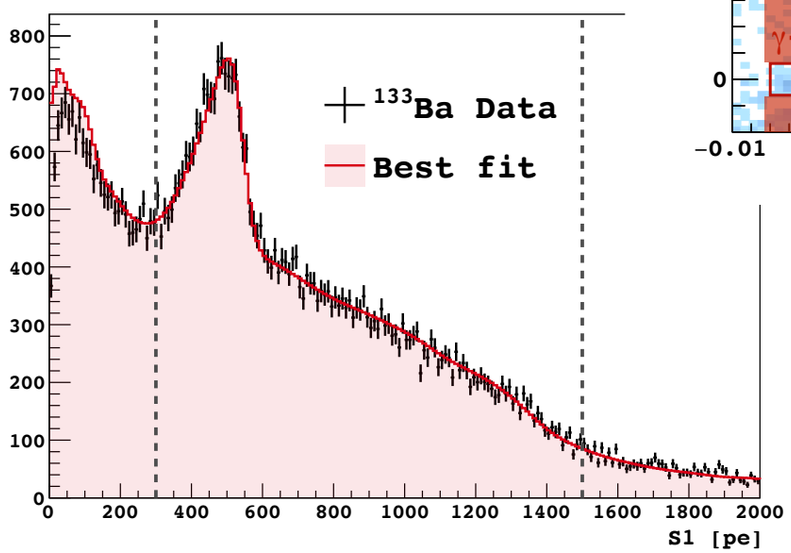

TPC response
S1 [pe]
Visible energy [keV]

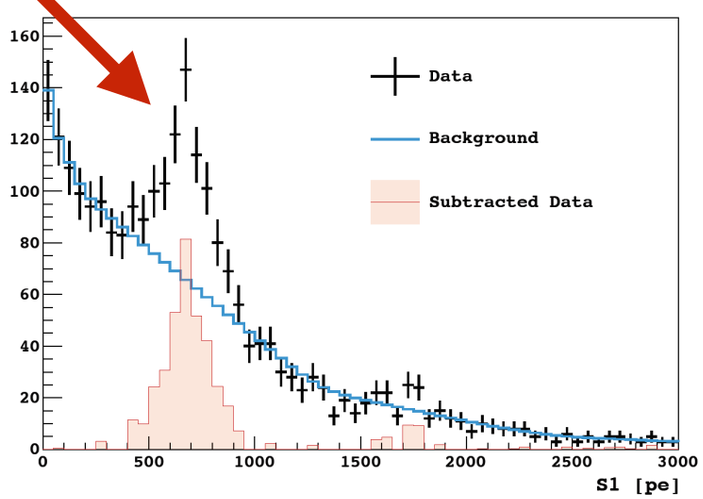

Data
Background
Subtracted Data


EDEN
data
~200ns
(~3m)

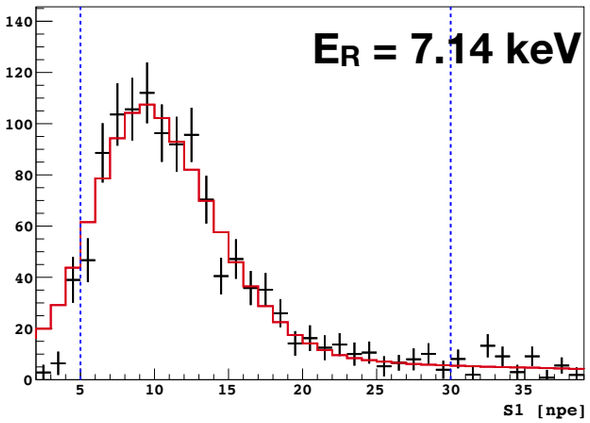

Neutrons
Fusion-evaporation neutron
γ-flash
TOF beam - TPC [μs]
TOF beam ND

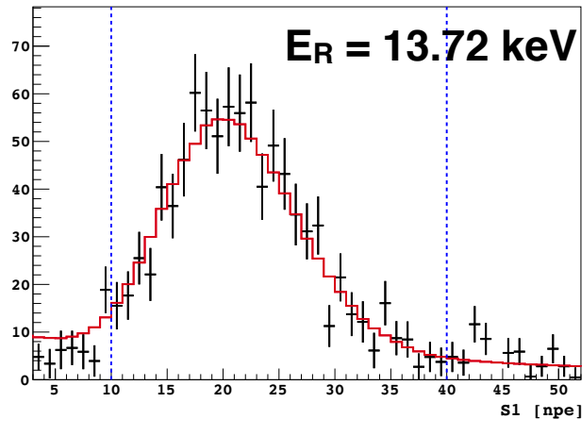

241Am Data
Best fit
S1 [pe]

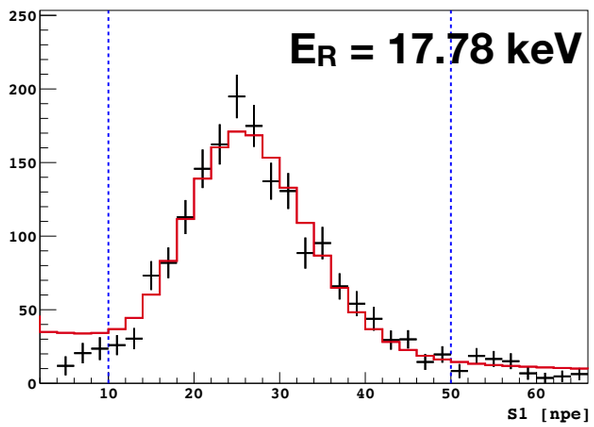

133Ba Data
Best fit
S1 [pe]

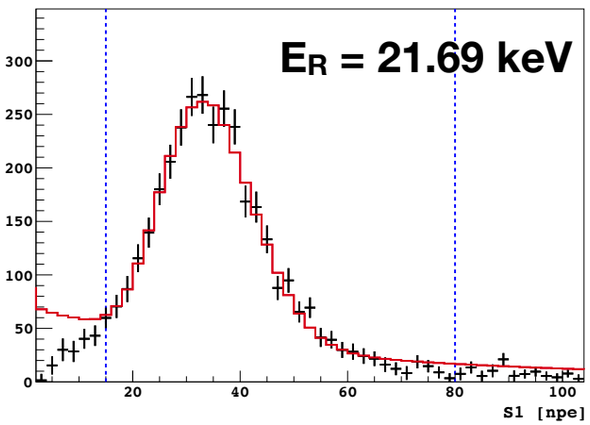

Data
Background
Subtracted Data
S1 [pe]

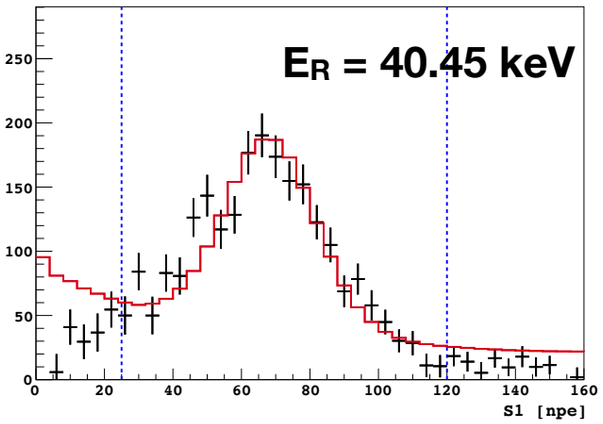
ARIS neutrino

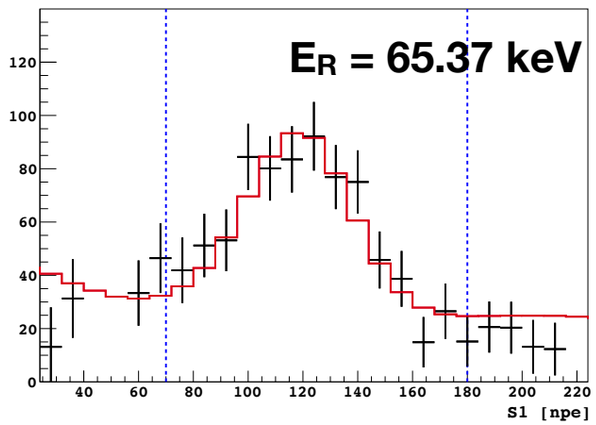


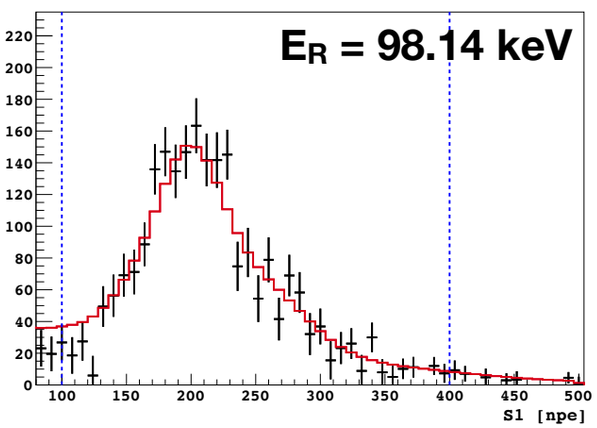


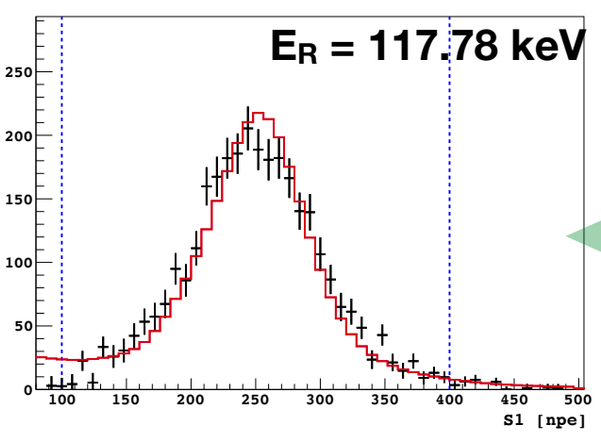




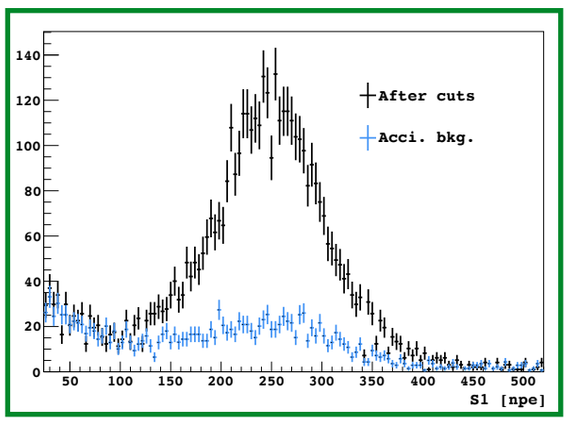




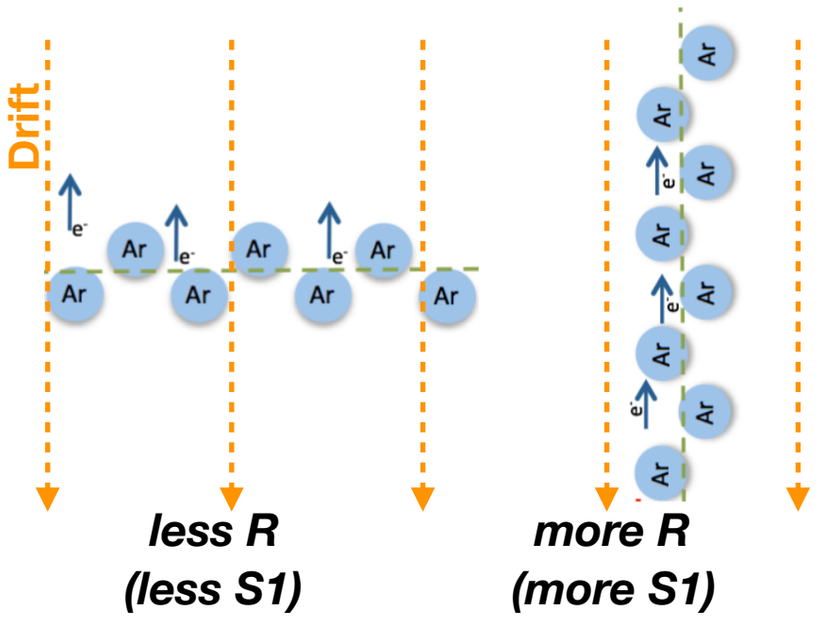




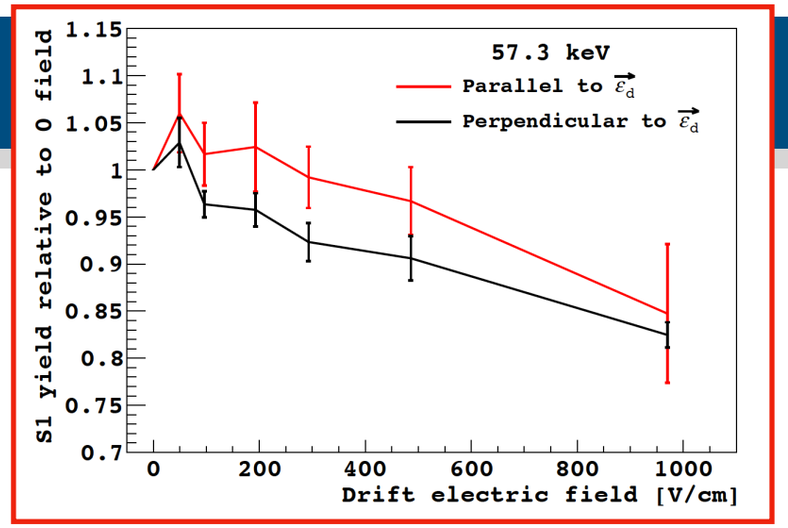
A7 before bg subtraction:

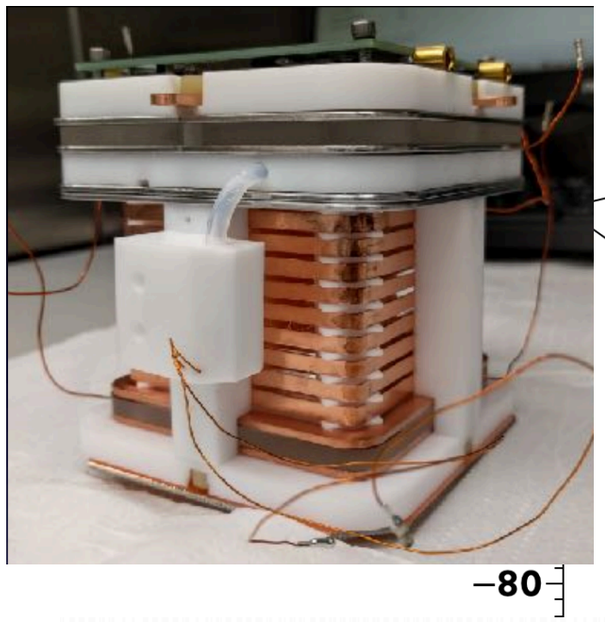


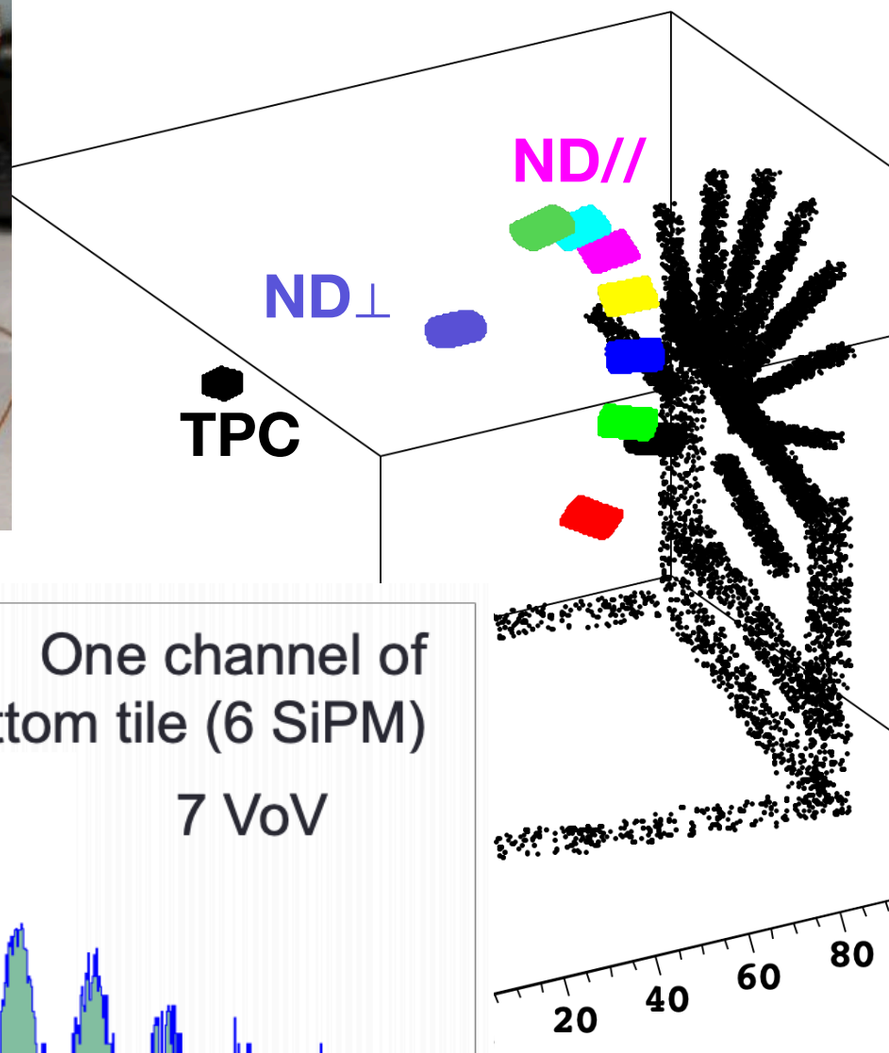
Directionality



SCENE
PhysRevD.91.092007



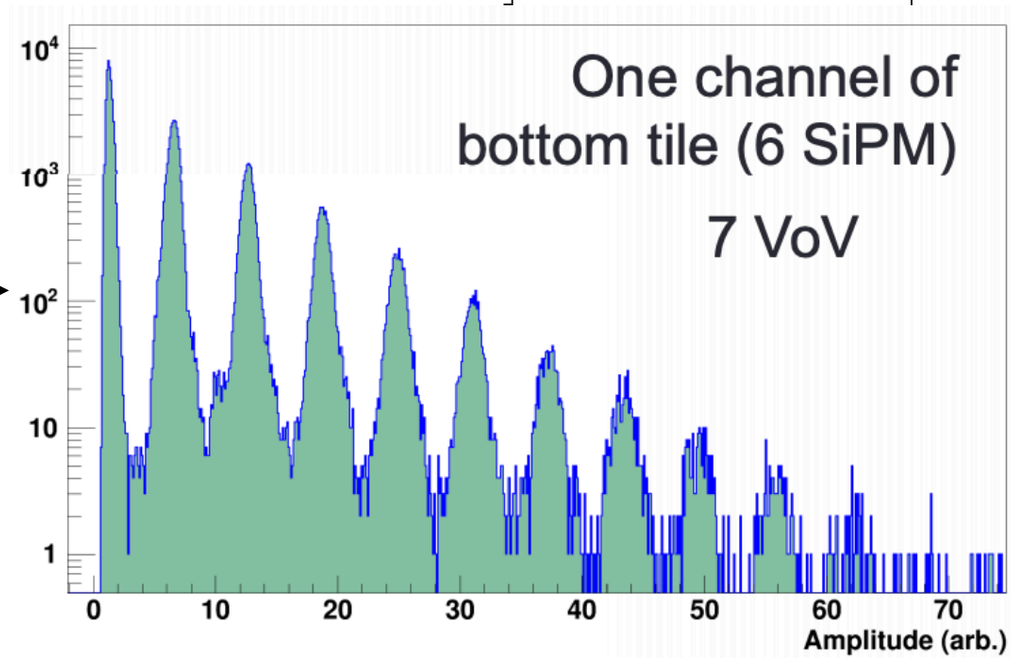




Operative

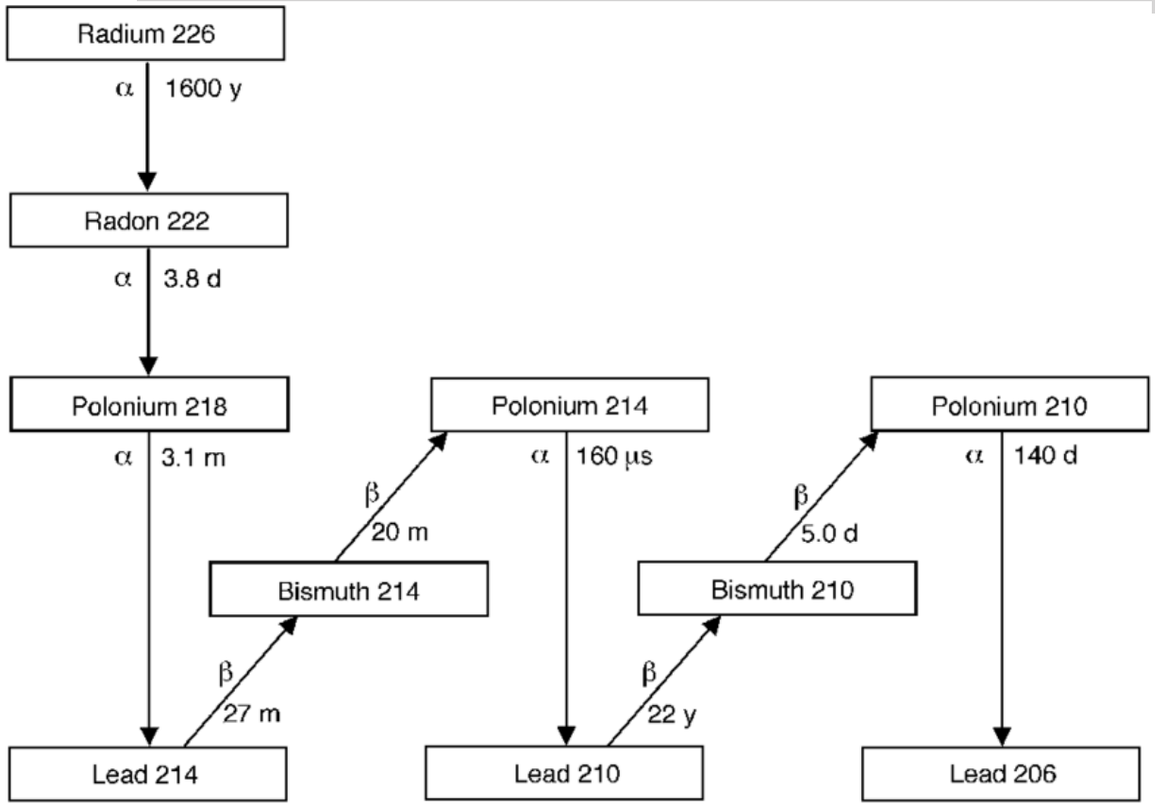
ARIS-like setup (ND select same energy but **different angles**)

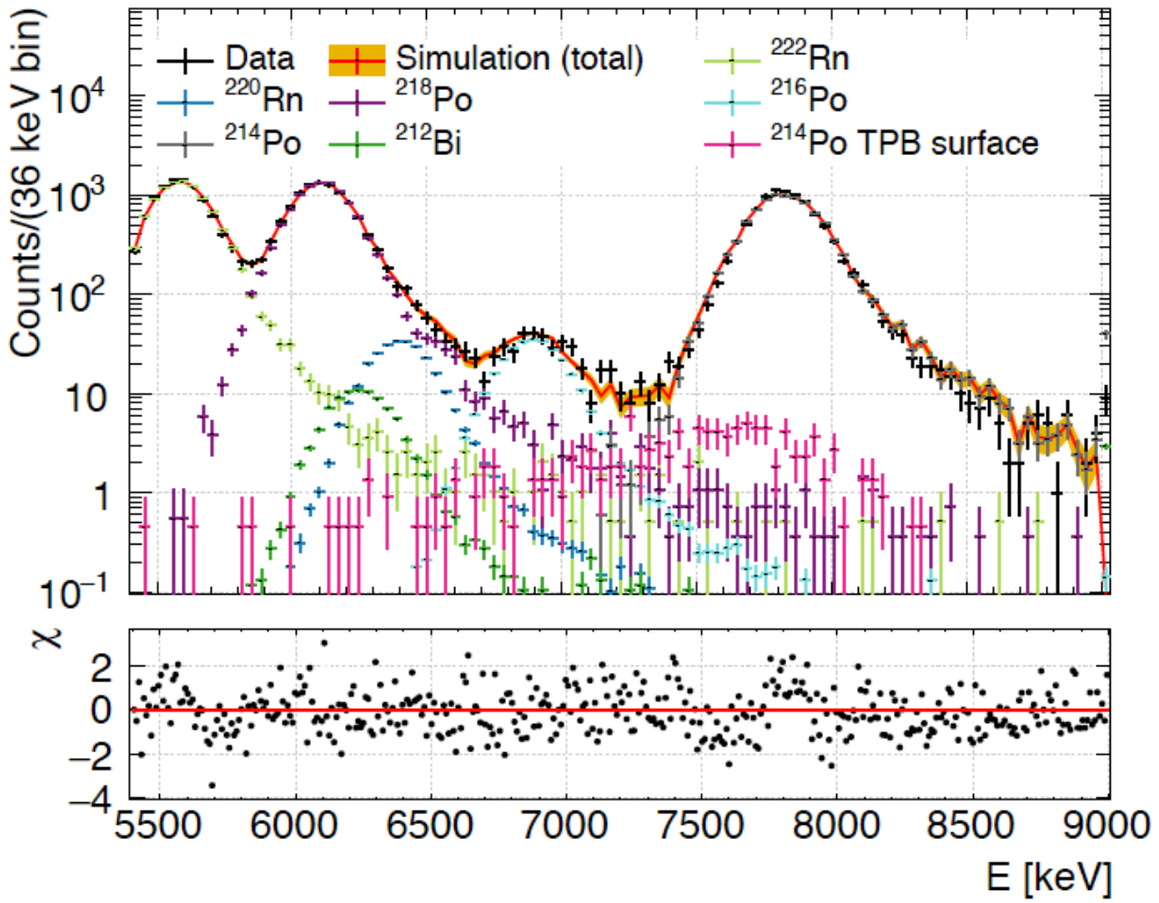
First operation of tiled SiPM array (segmented 4+24 channels).

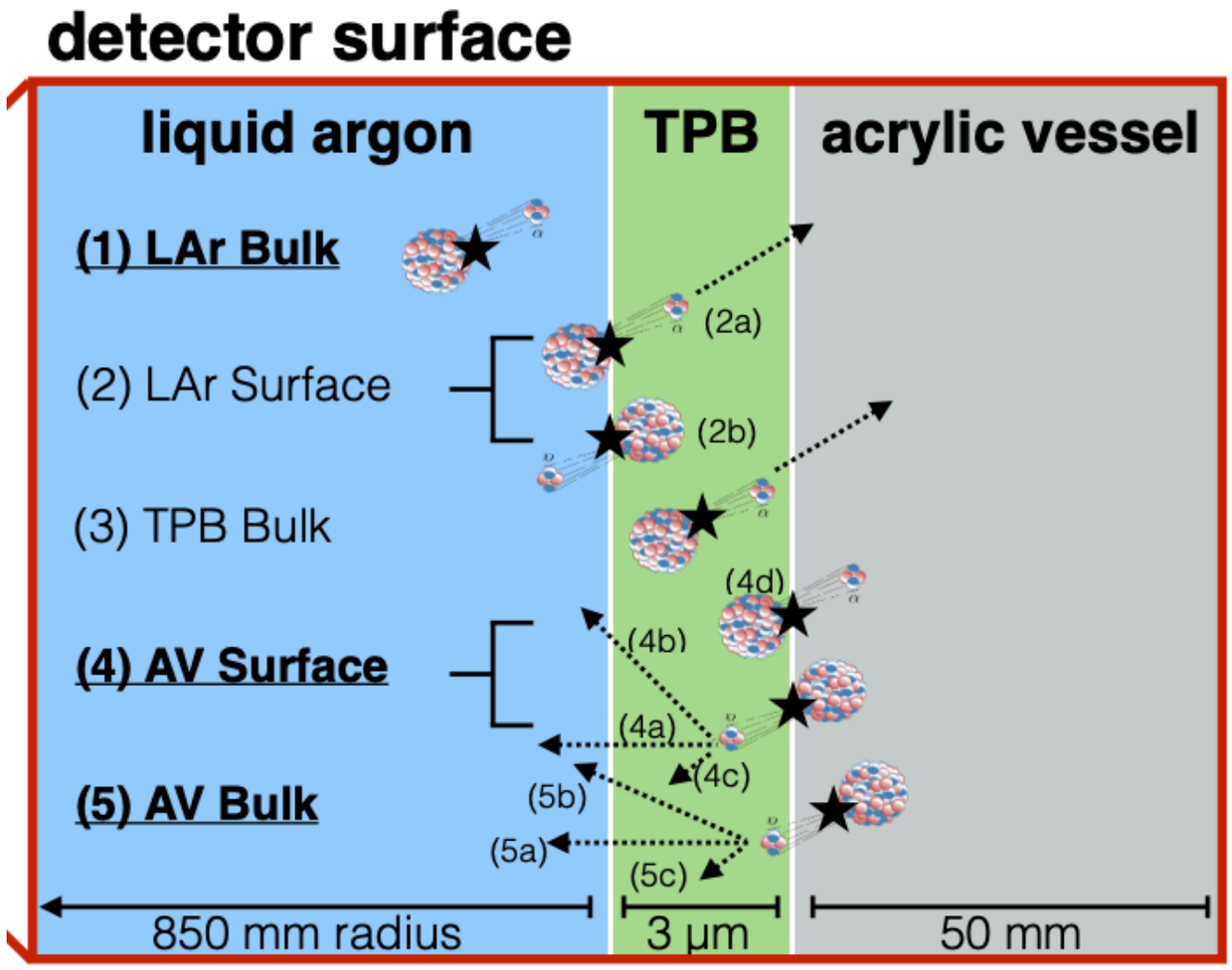


Directionality will be the only handle to distinguish WIMPs from neutrinos (CEvNS)

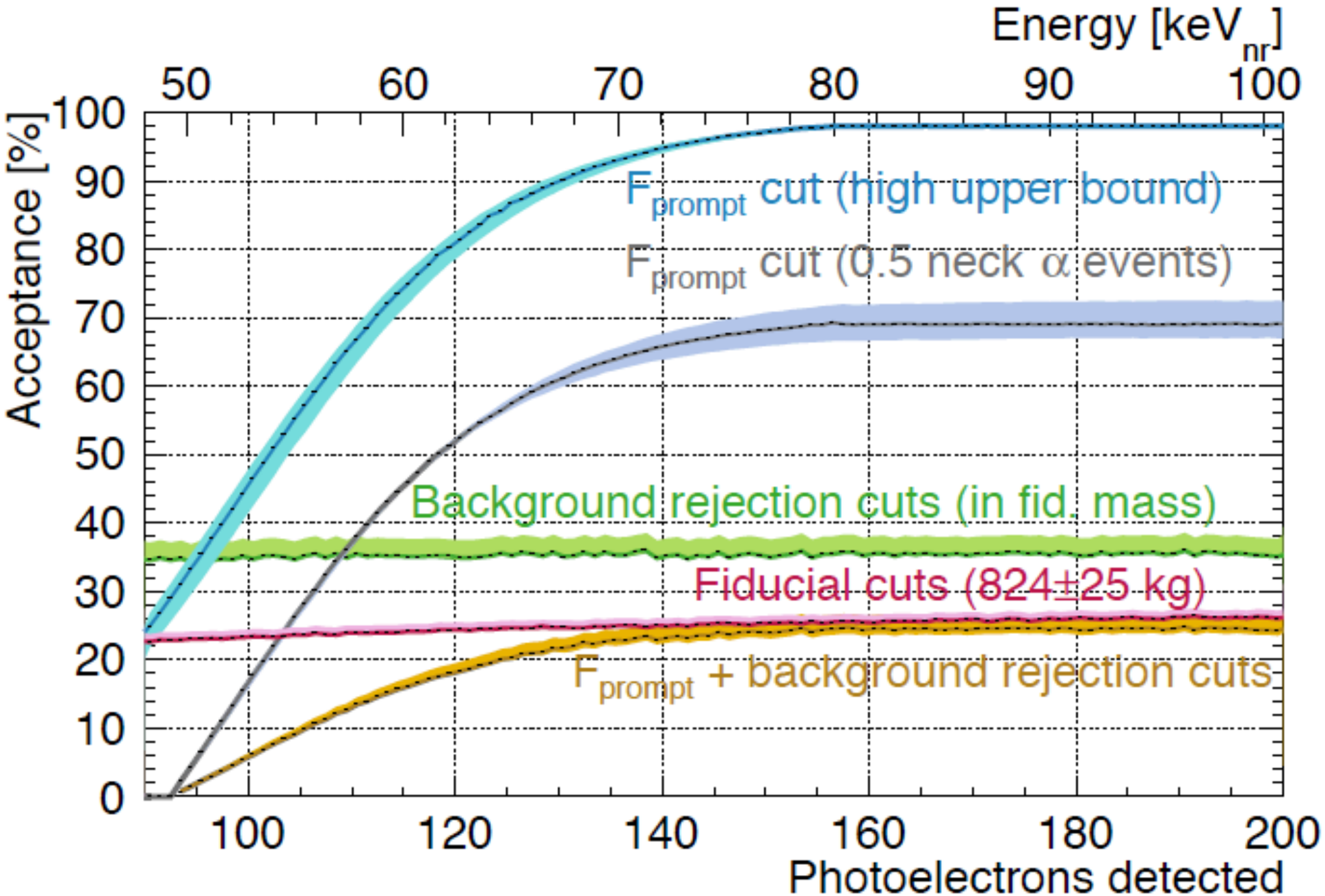
222Rn decay chain and surface alphas



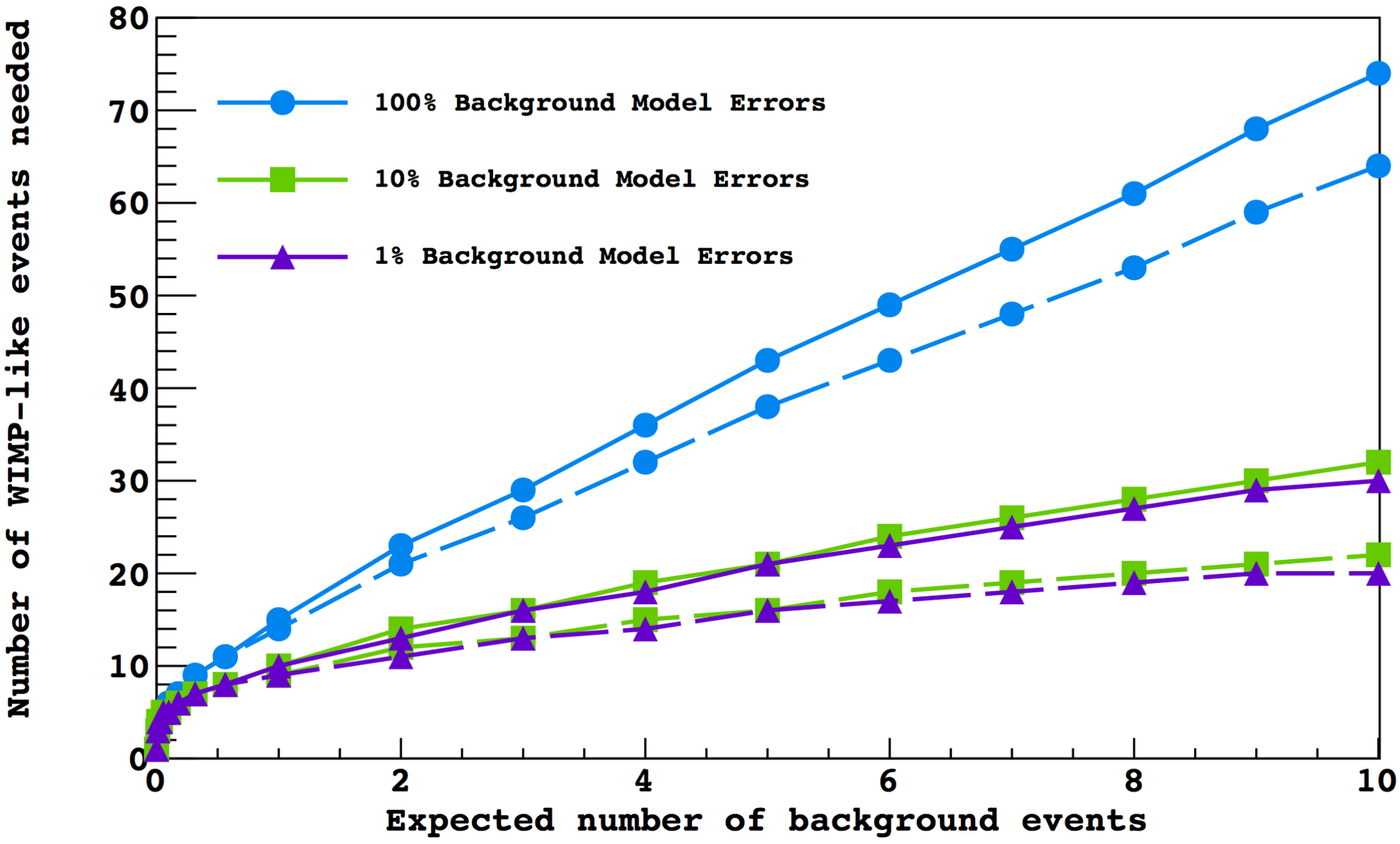




DEAP acceptance



bg-free condition

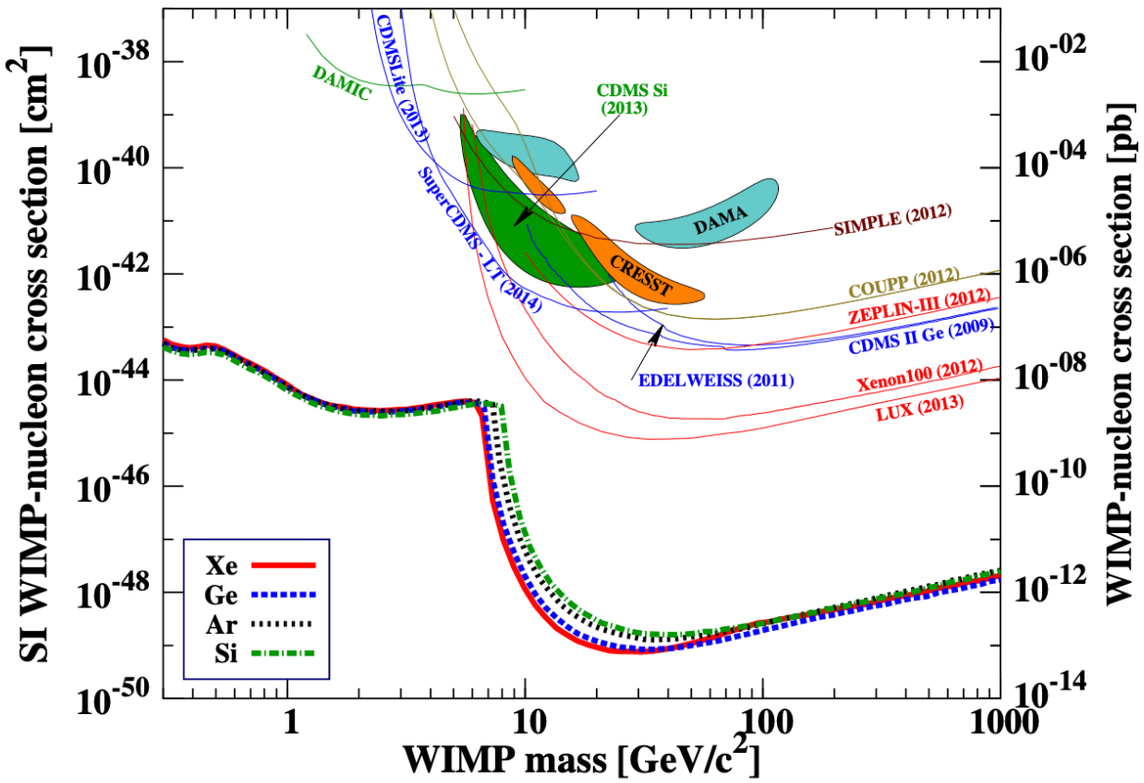


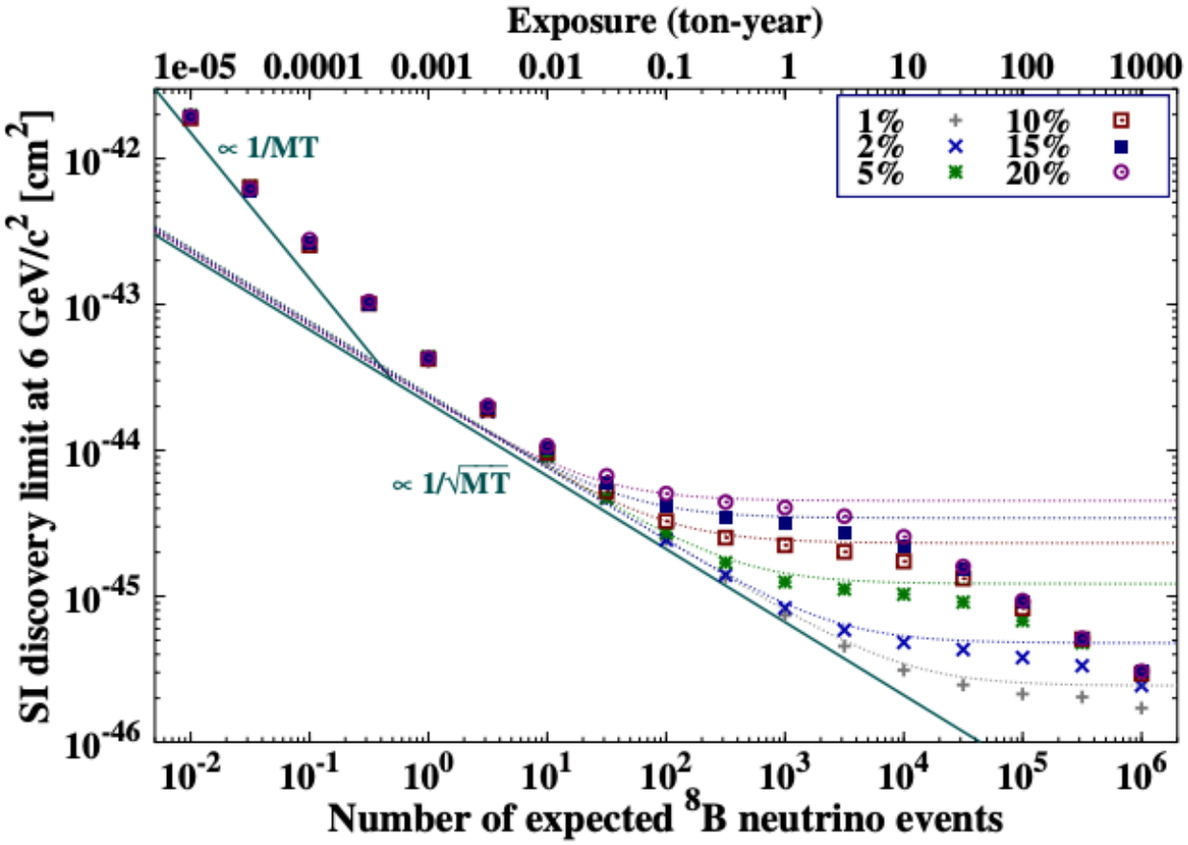
For 3 sigma claim

Next generation of Xenon experiments:
LZ (6 ev in 18 t.y), XENONnT (2 ev in 4 t.y - Radon dominated)
in DarkSide, CNNS neutrinos (a signal, actually): 1.6 in 100 t.yr

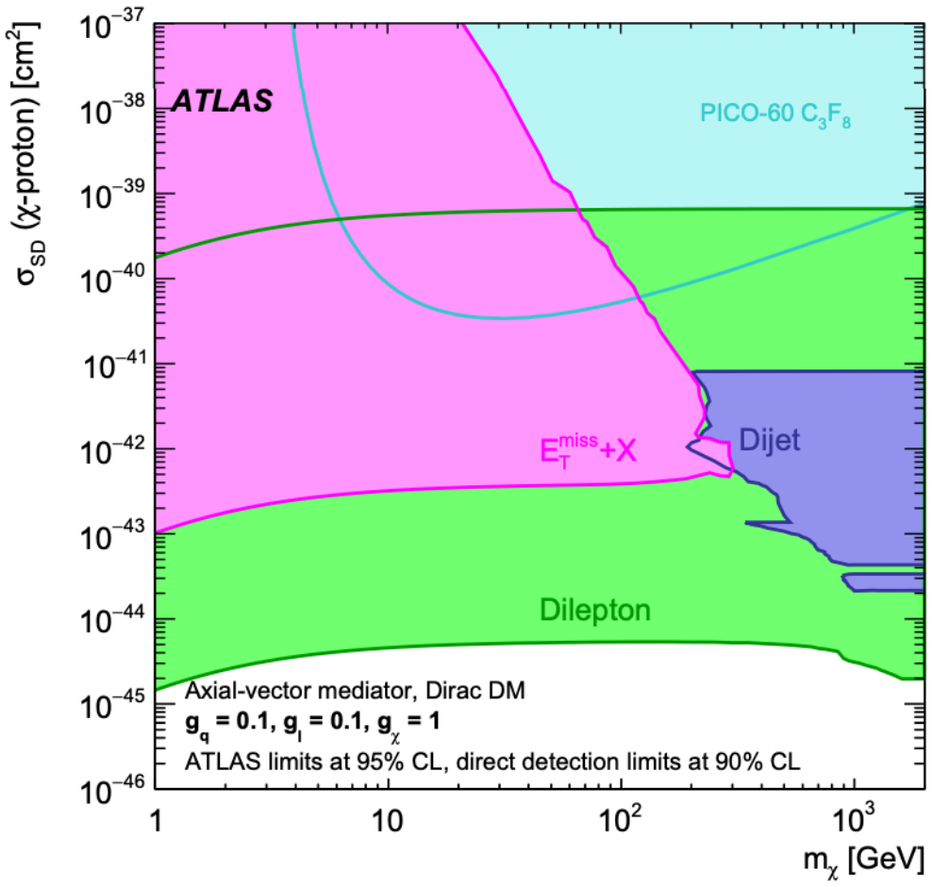
A discovery limit fixes a WIMP-nucleon cross section such that if the true WIMP-nucleon cross section is higher than this value then the considered experiment has a 90% probability to detect a WIMP with at least a 3σ confidence level

Only marginally affected long y axis: both CEvNS and σ0 scale with A^2.
There is however some difference in the kinematics: the vertical

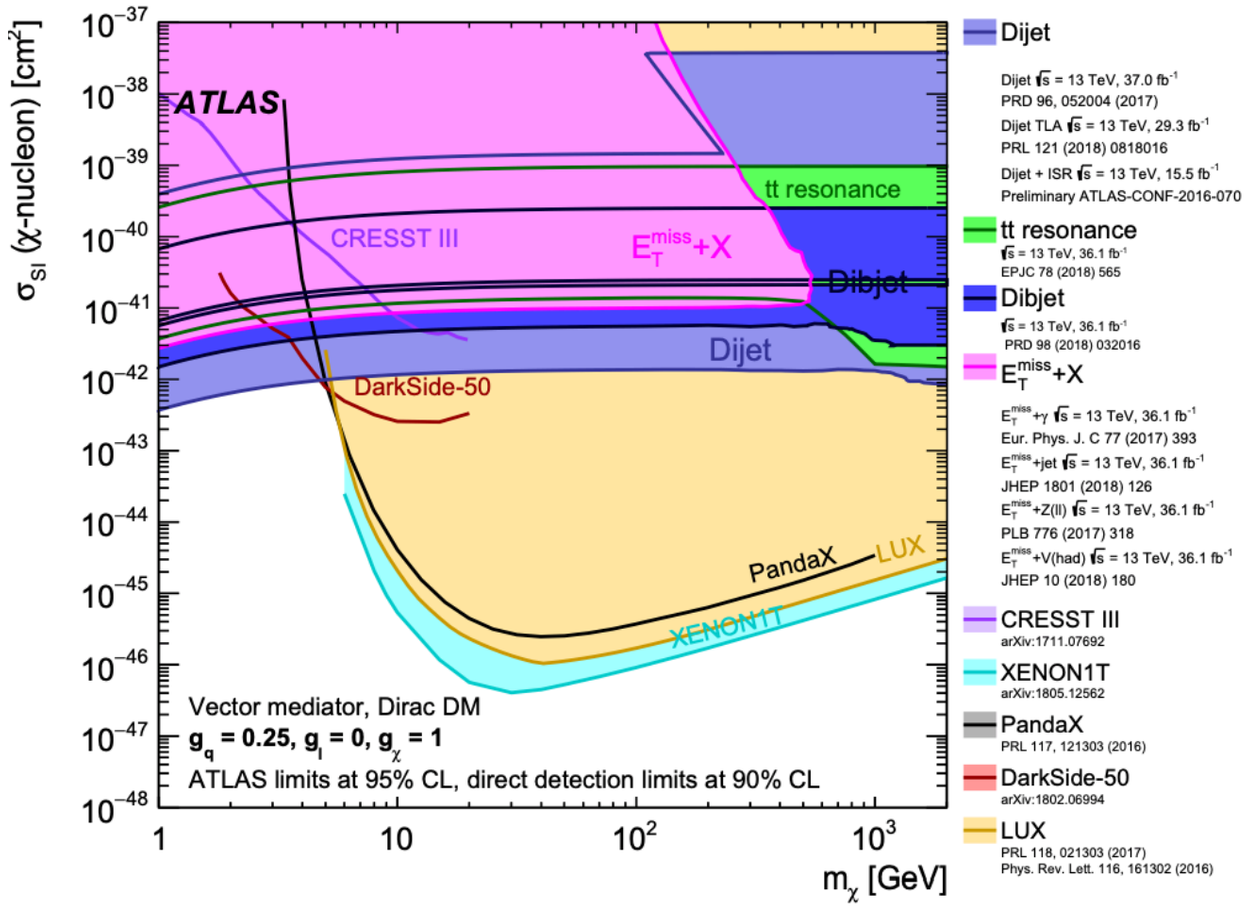




Uncertainty on neutrino fluxes: B ~ 5%, DSNB ~20%?, atm ν 10% ?



(b)



(a)

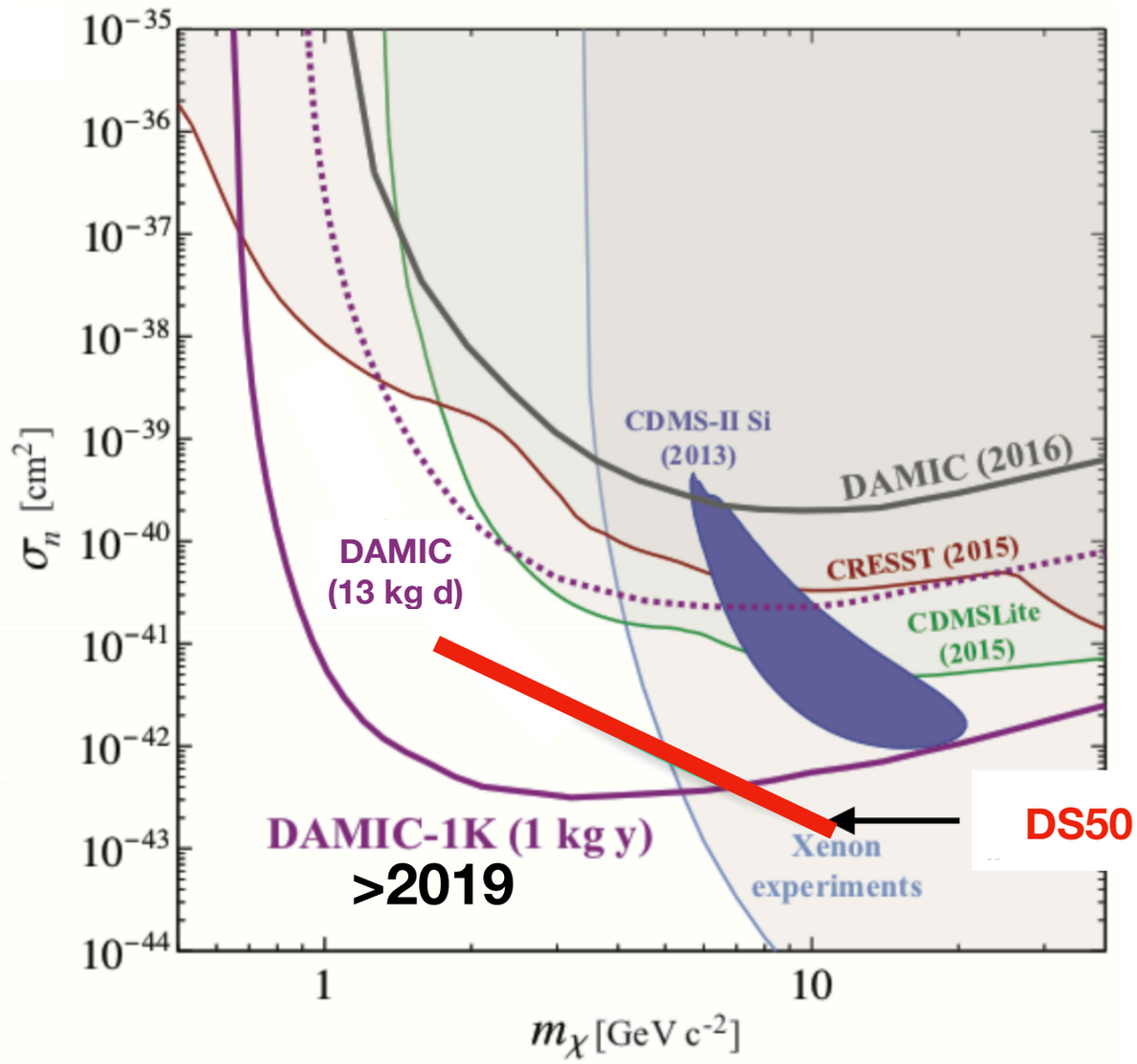
Not trivial to compare DD (DM mass & X-sec) and LHC searches.

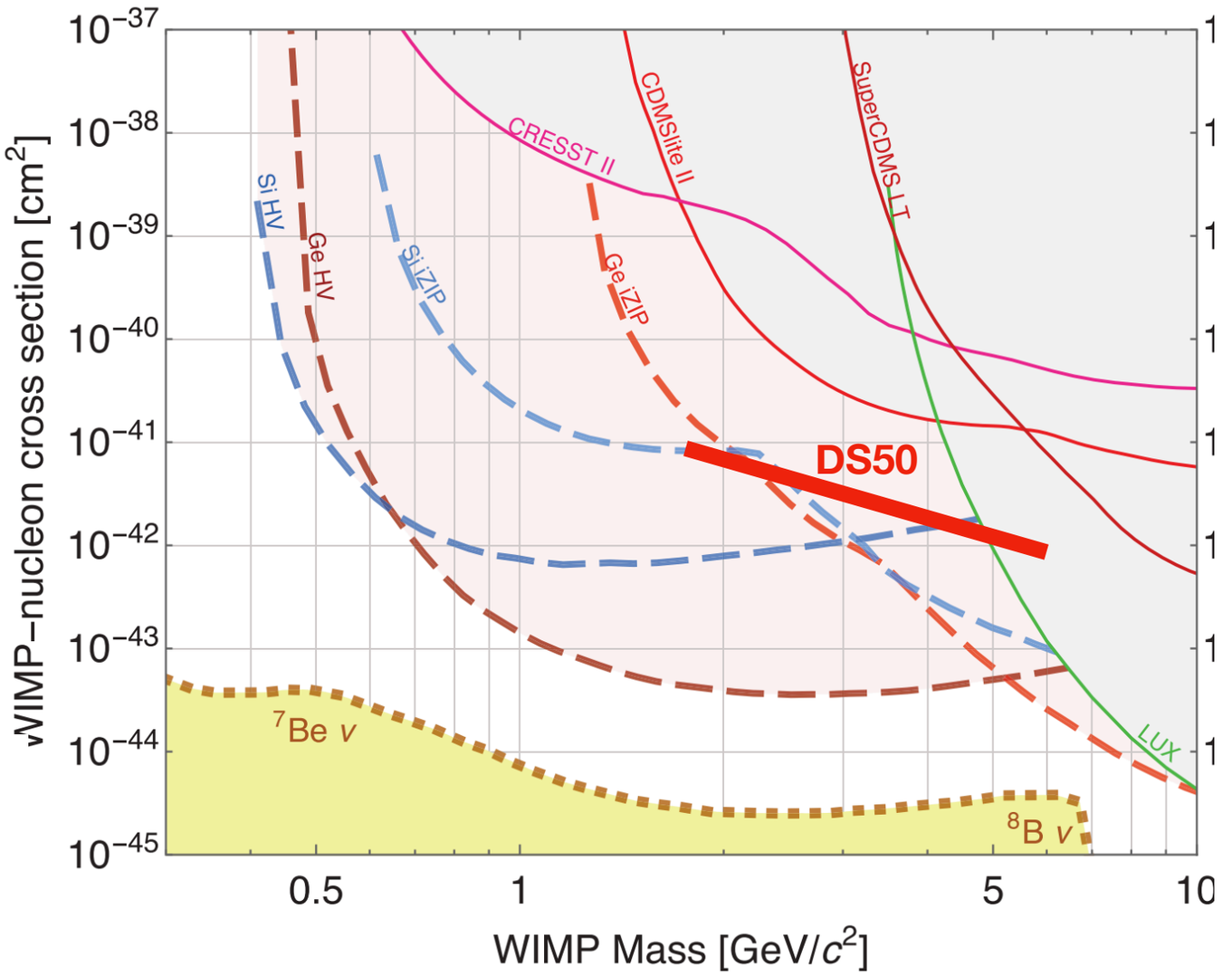
LHC search exclusion depends on (**SIMPLIFIED MODELS**):
- DM mass (limited energy in CM)
- Mediator Mass
- g_{DM} (mediator coupling to DM)
- g_g (mediator-gluon coupling)

Caution with EFT theories: heavy mediator >> q

LHC: high-q
DD: low-q

Comparing EFT collider limits with those of DD searches gives a misleading representation of the relative sensitivity of the two search strategies, especially for weaker coupling scenarios and m_{DM} > 300 GeV





DAMIC-1k at LSM

Thick CCD (1 mm), low noise and low-thrsh
1 kg target expected end 2018 (20 CCDs)
Skipper readout to reduce noise (**SENSEI**)
Target rate in bulk: <1 dru (now 2 to 5)

SuperCDMS at SNOLab

CD3 review passed, construction started
HV: lower thrsh (80/40 eV), no discrimination
iZIP: thrsh at 170/270 eV, bg rejection (10^6)
Background levels: ~0.2 dru for all, after cuts
Assumed exposure: 5 yr

Solar neutrinos in Argo

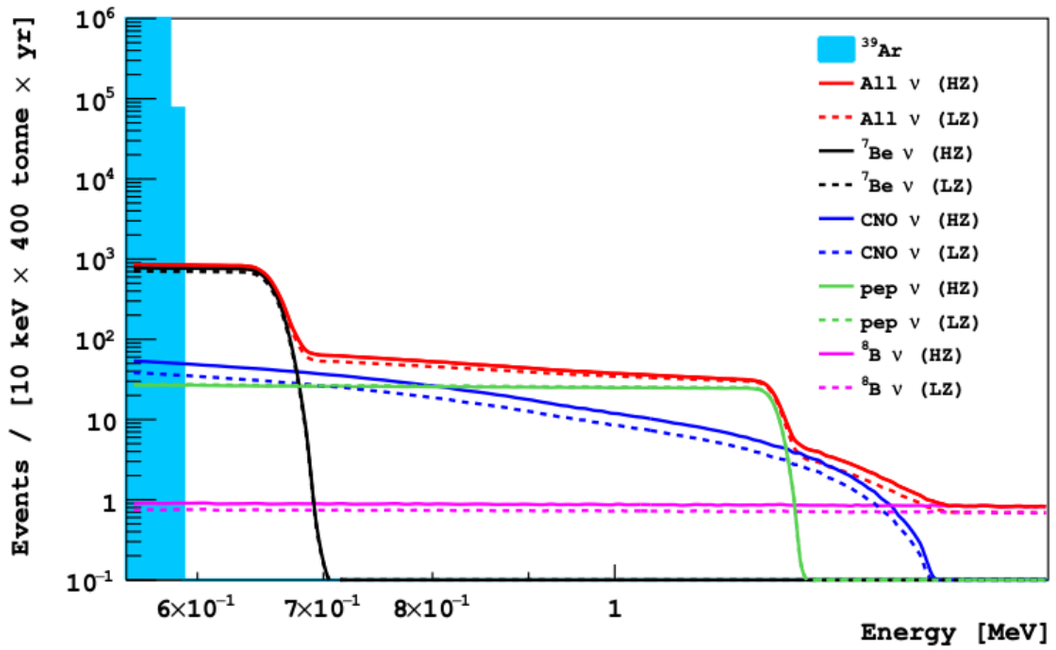
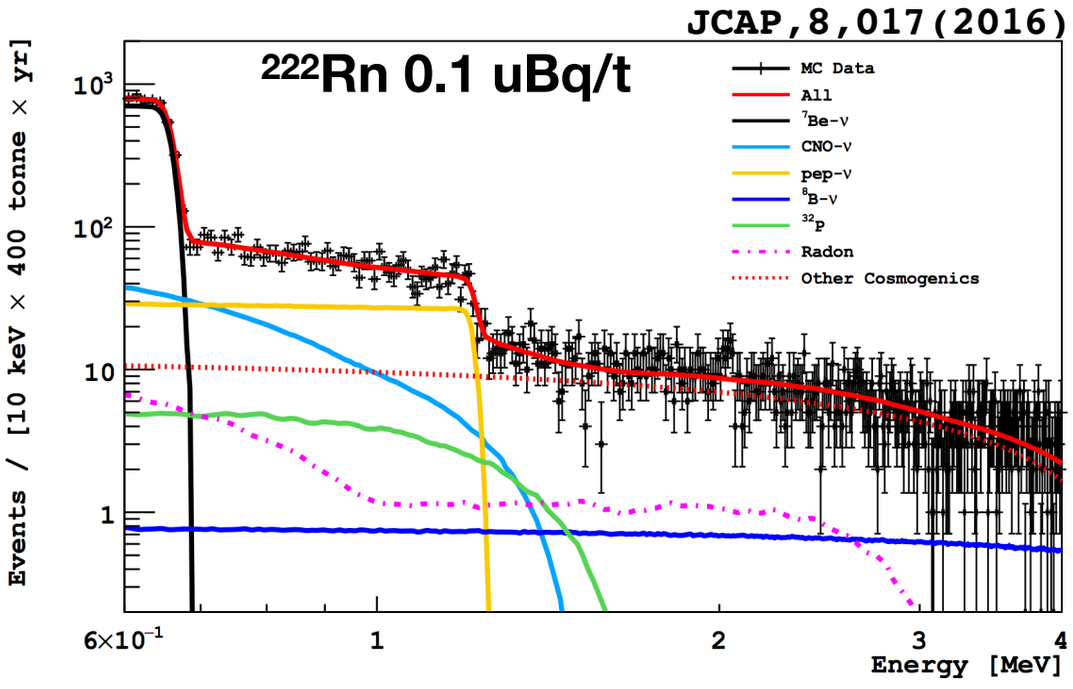


Figure 1: Simulated solar neutrino spectra in a 400 tonne-yr LAr TPC exposure, assuming σ =1.3% energy resolution at 1 MeV, corresponding to a PE yield of 6 PE/keV. The blue shaded area represents the tail of the ^{39}Ar contamination, intrinsic to underground LAr.

Solar neutrinos with 1000 t yr exposure

After **DS20k**, solar neutrinos in the ER channel
Fit in [0.6,1.3] MeV range (above ^{39}Ar, flat bg)
Could resolve CNO shape feature (if Rn is low) and provide hints to solve the *solar metallicity problem* (HZ vs LZ).

Could lead to measurement of CNO component at 15% if ^{222}Rn is <1 uBq/t



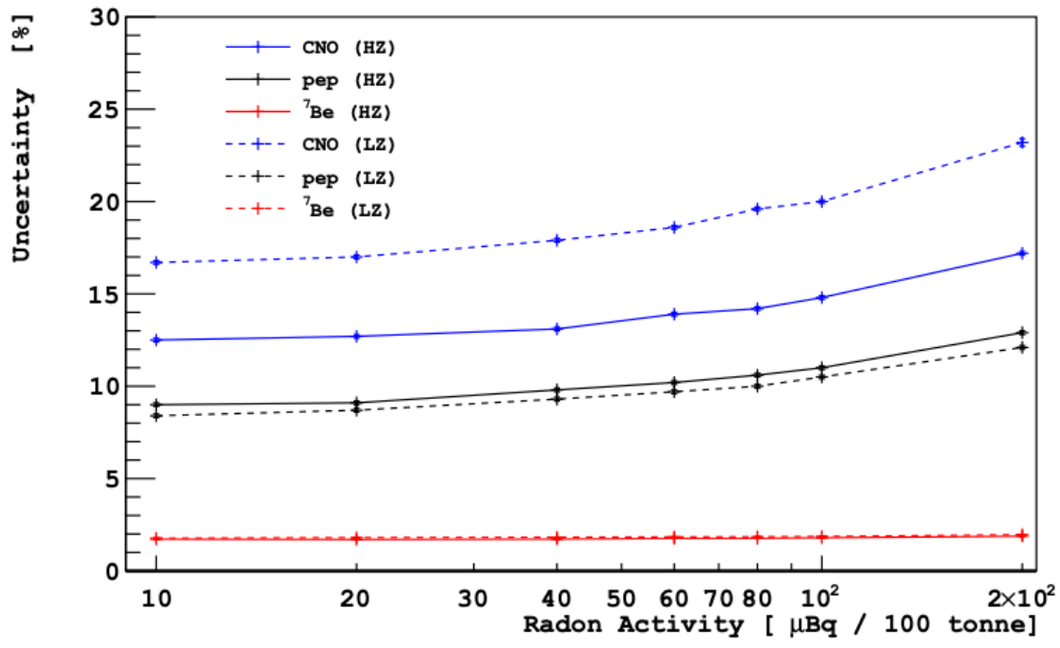
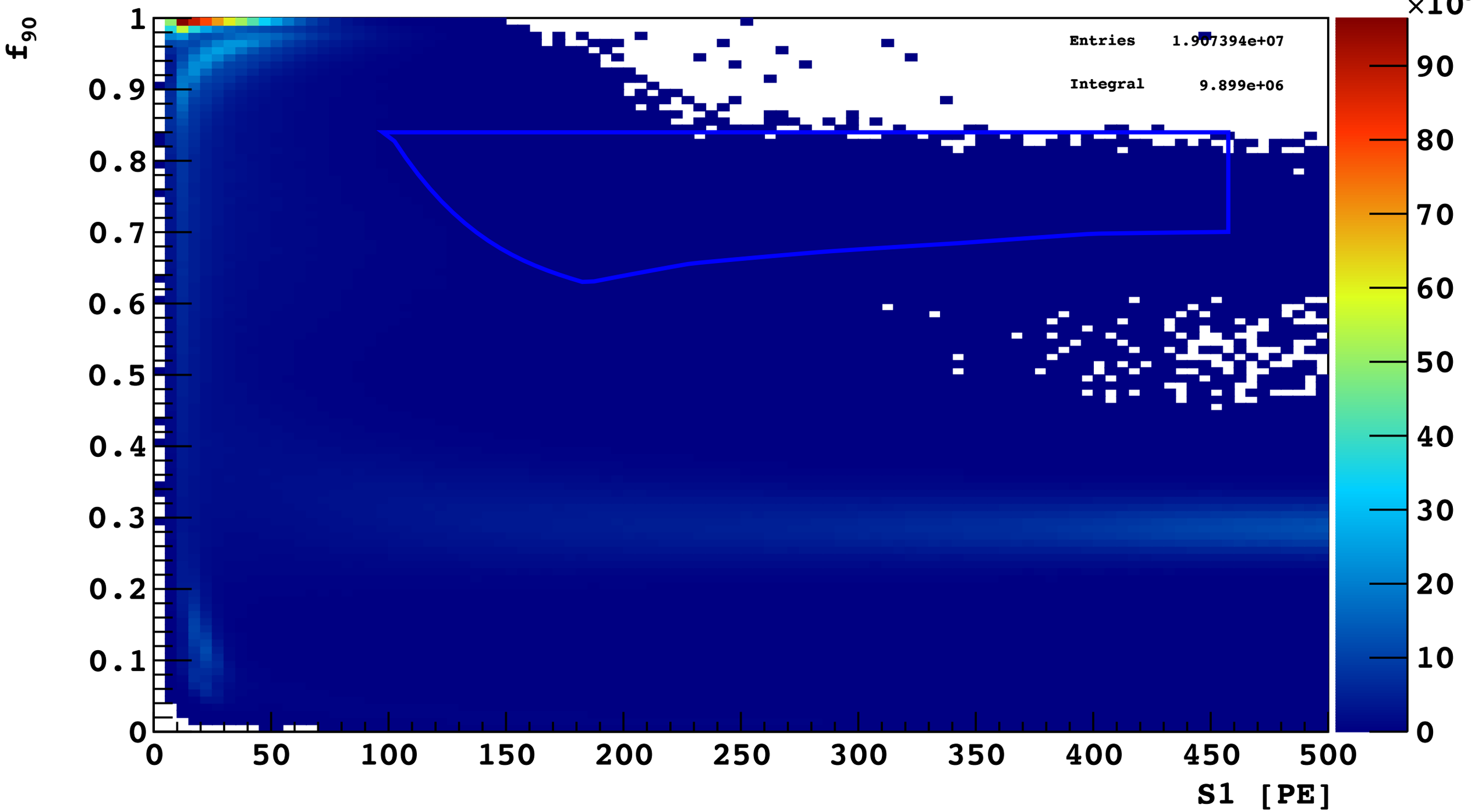
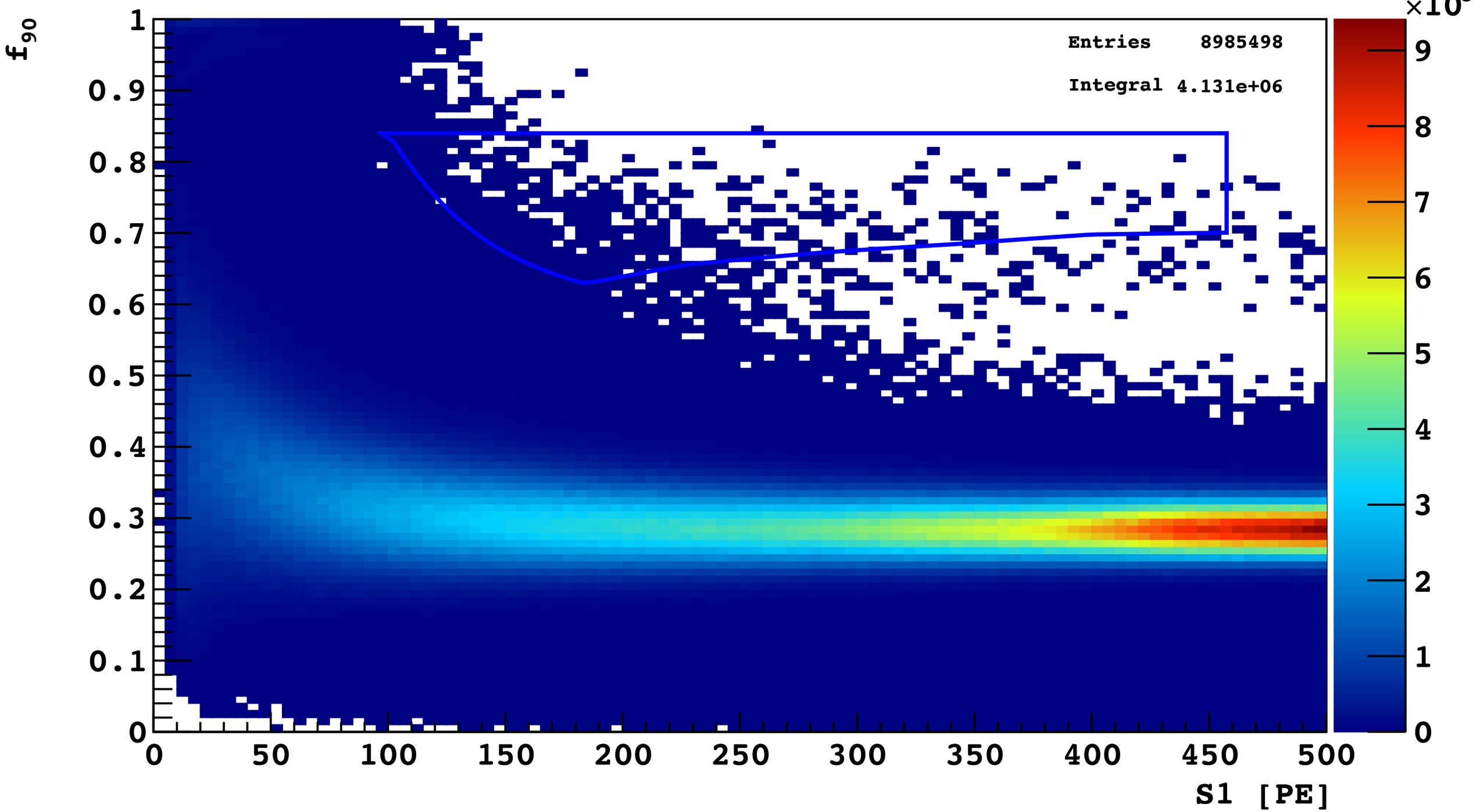


Figure 7: Statistical uncertainties on the solar neutrino components, as a function of the radon activity.

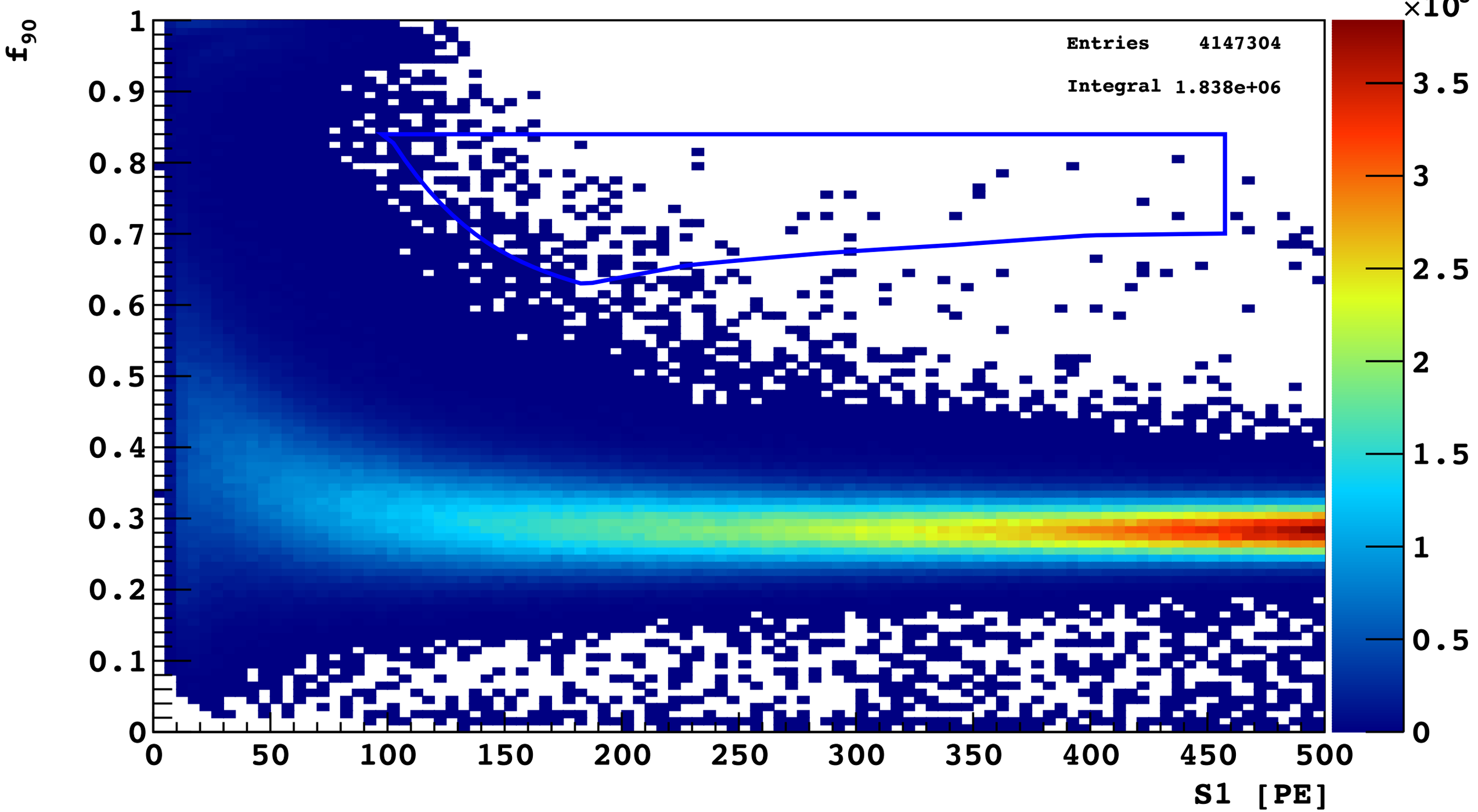


- Trigtime: the first pulse is within expected trigger time window
- S1sat: S1 pulse is not saturated

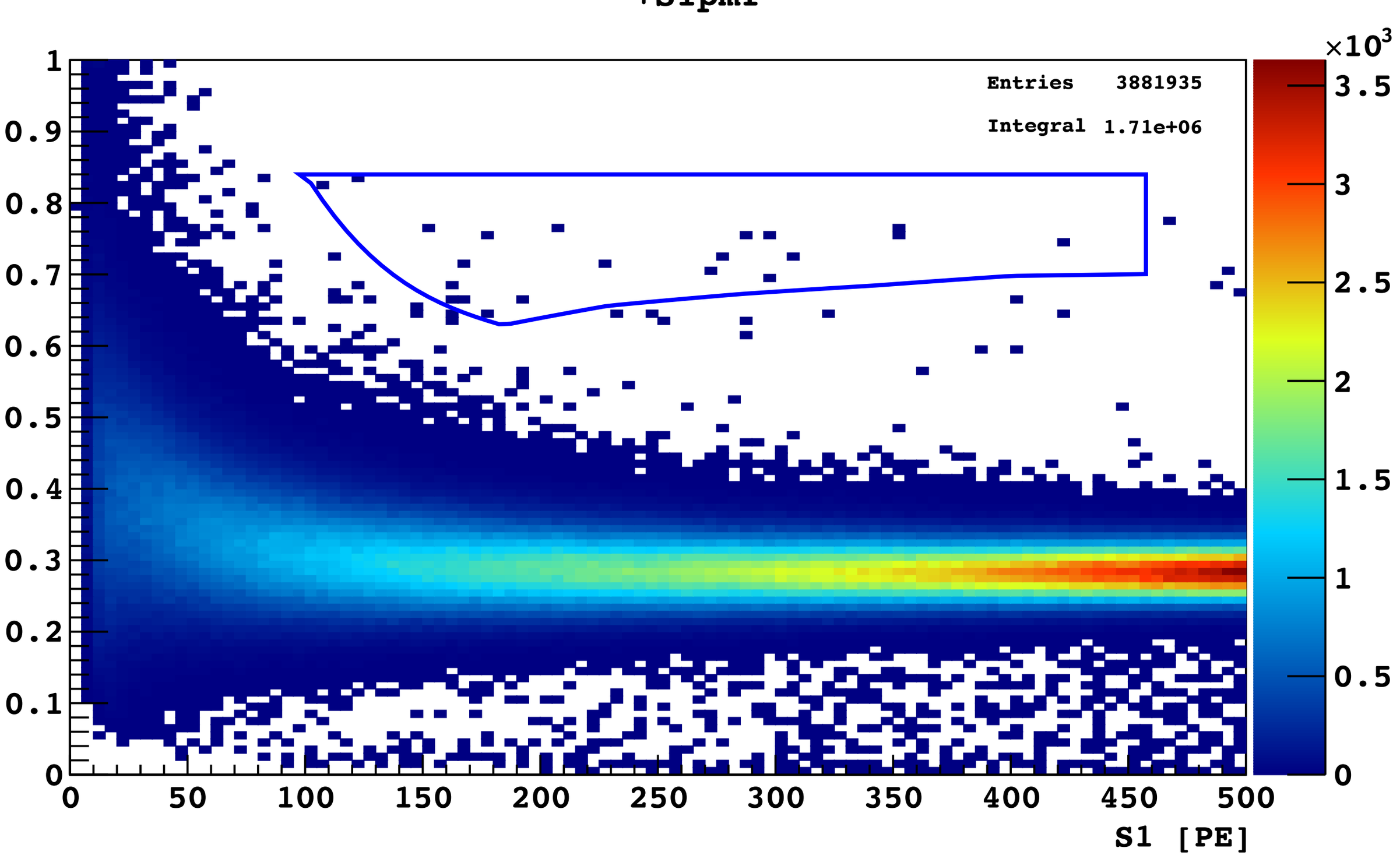
+Npulses



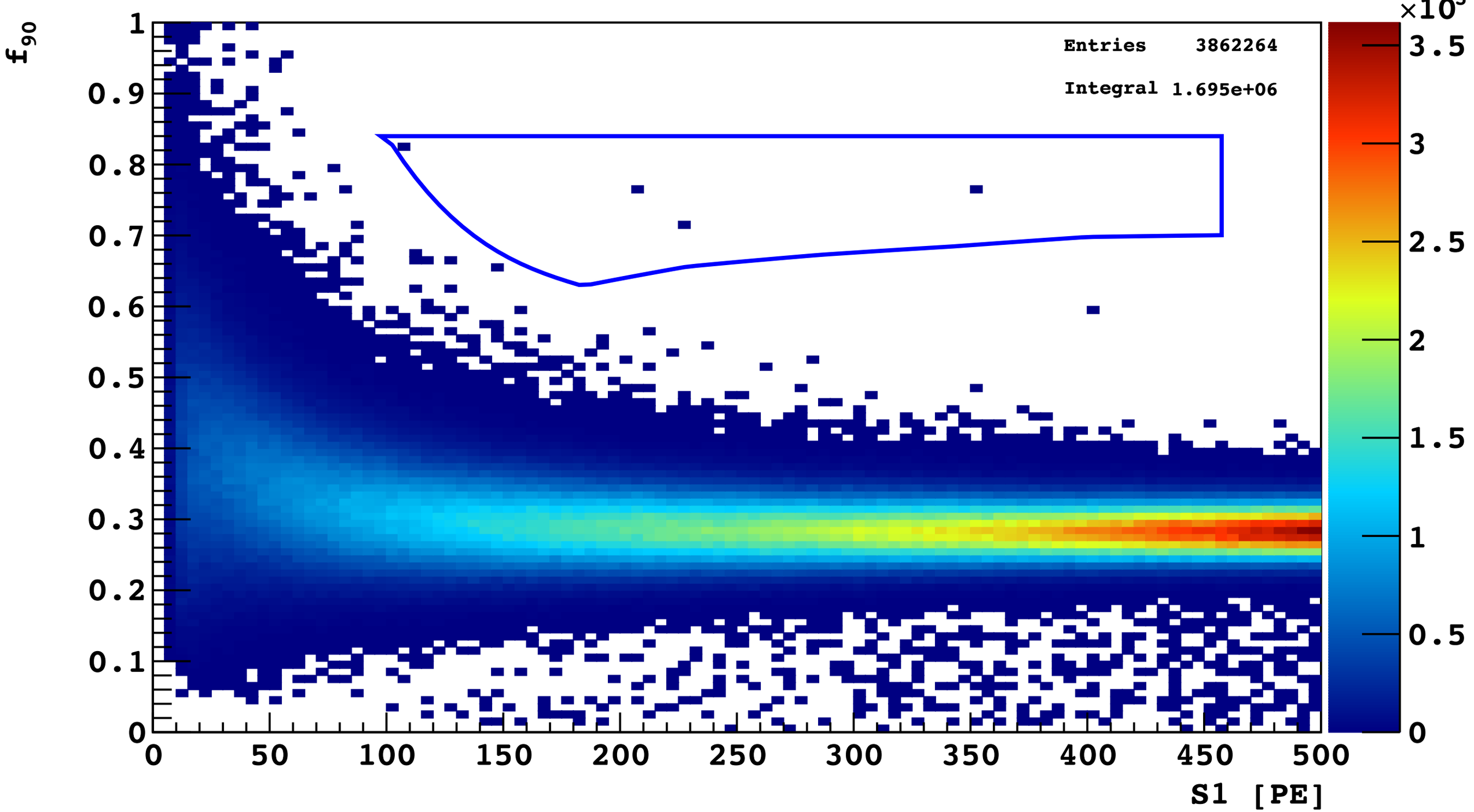
- Npulses: number of pulse is 2 or 3 if there is S3 (echo of S2)
- Most of surface events are gone



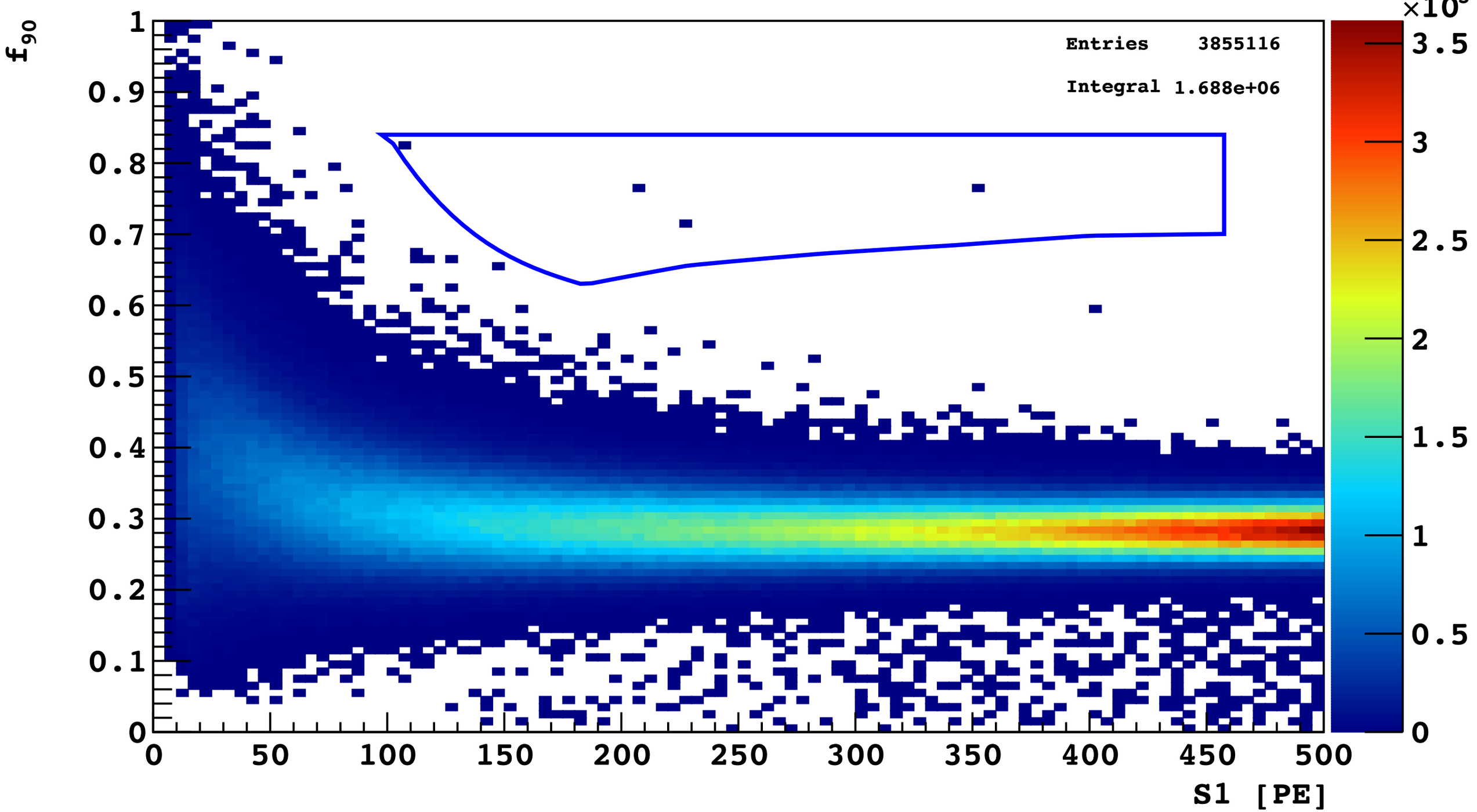
- 40μs fid: remove 40μs from top and bottom in t_drift
- Lots of ɣs from PMTs, unresolved S1+S2 events, and surface close to top are removed



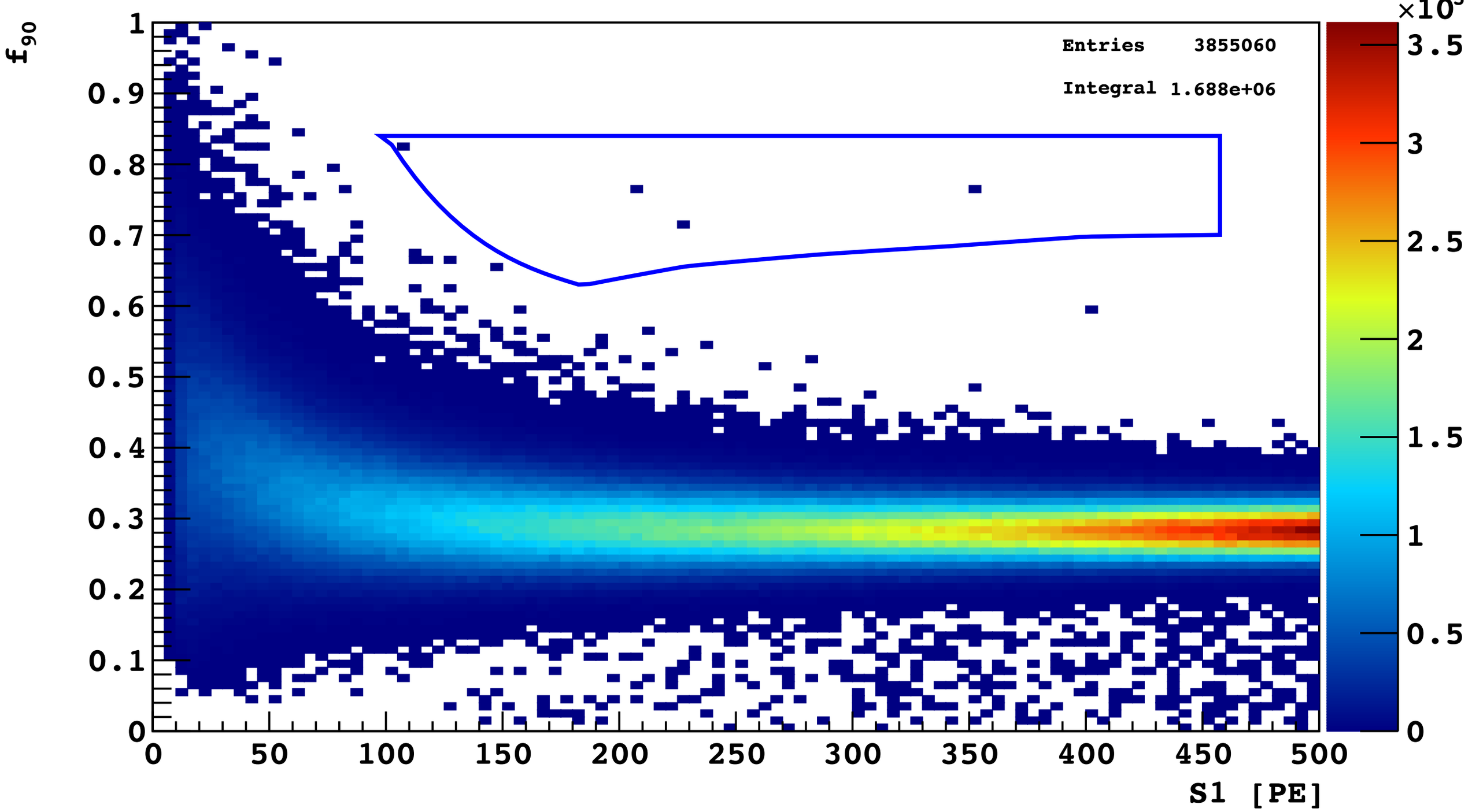
- S1pmf: fraction of prompt light in the maximum PMT is less than a threshold, which is a function of t_drift and S1
- Remove S1+Cherenkov events from fused silica windows



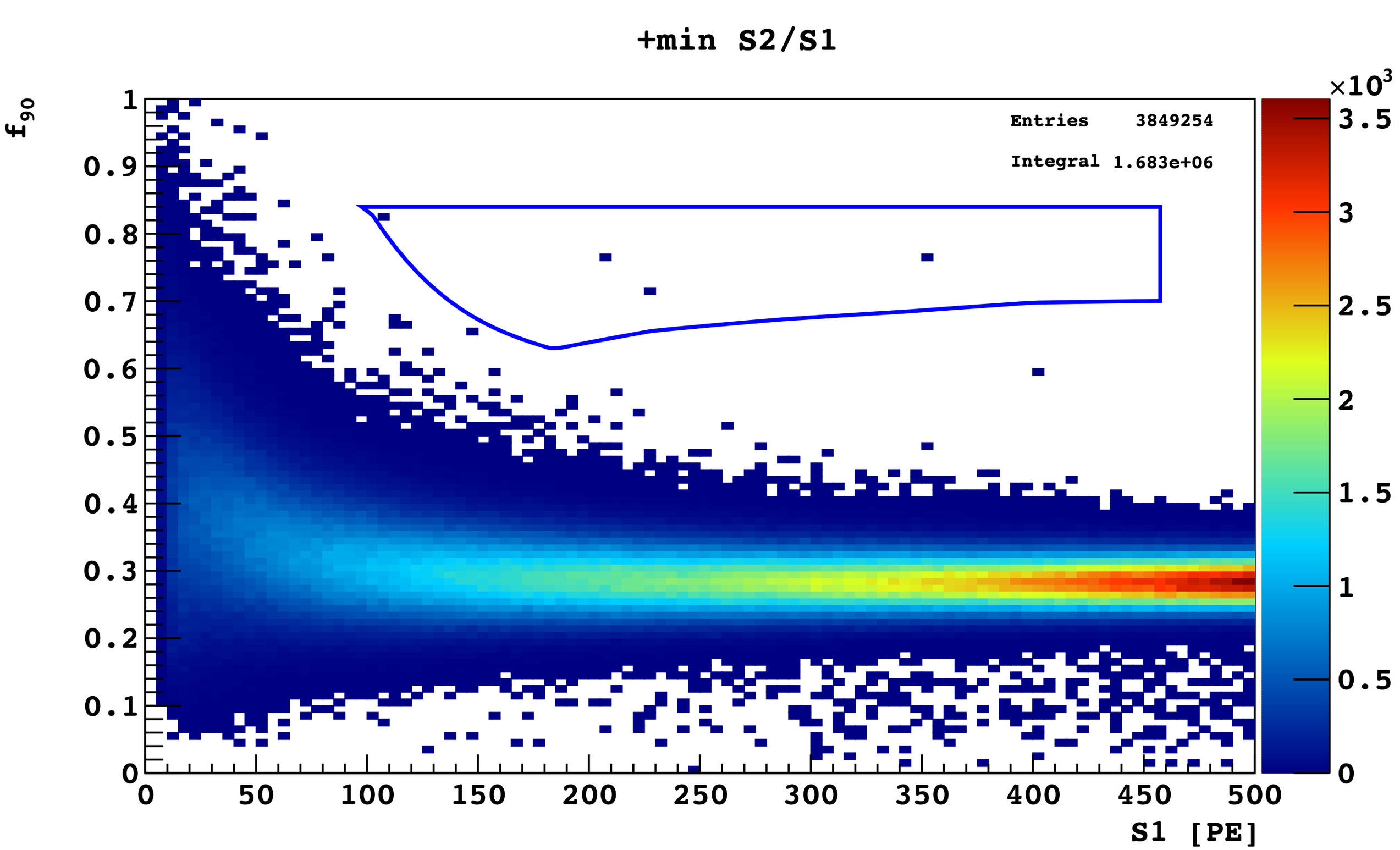
- min S2uncorr: S2≥200 PE
- This is more like quality cut, but remove surface events, which number of electrons are reduced by the surface effect



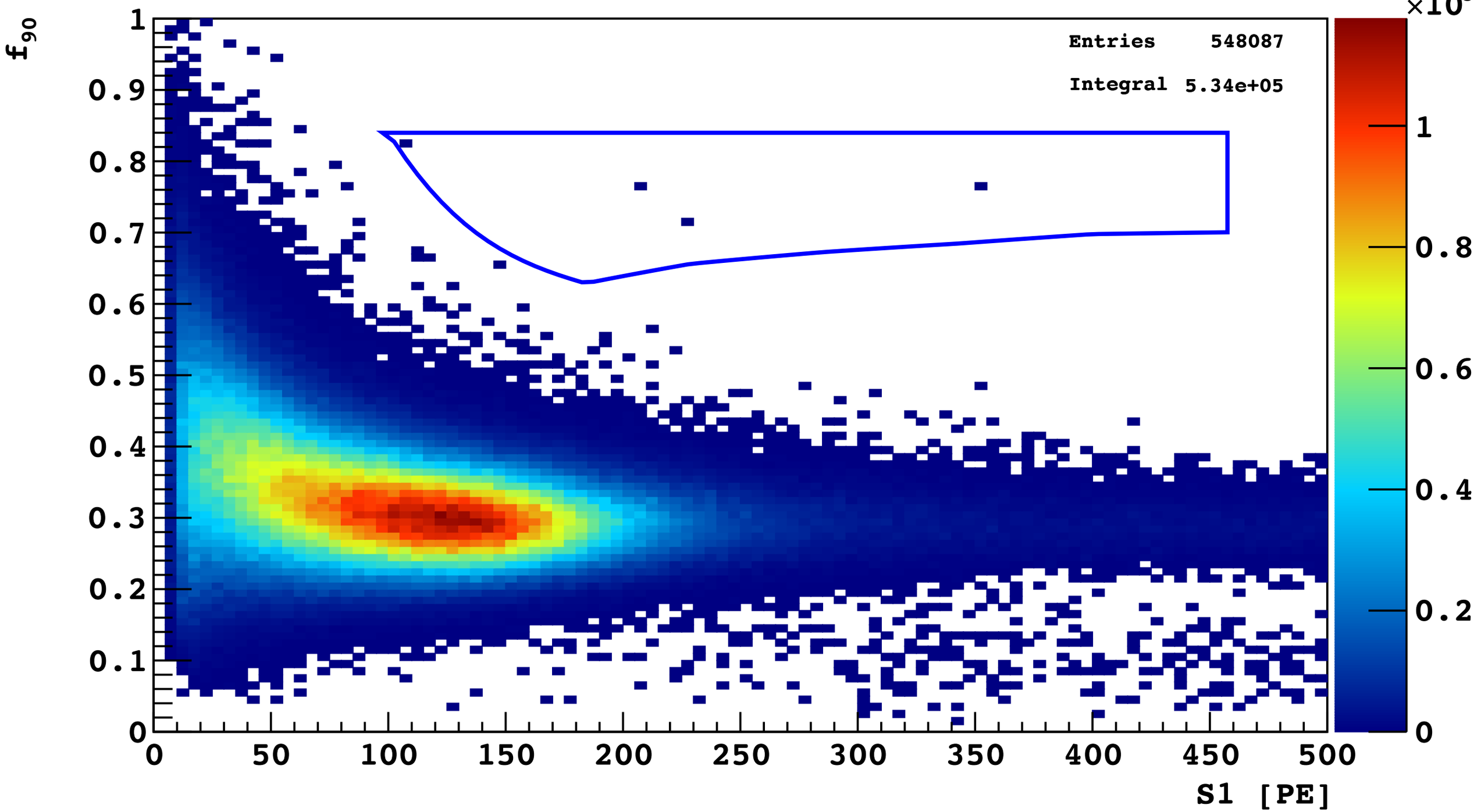
- xy-recon: reasonable x-y reconstructed values



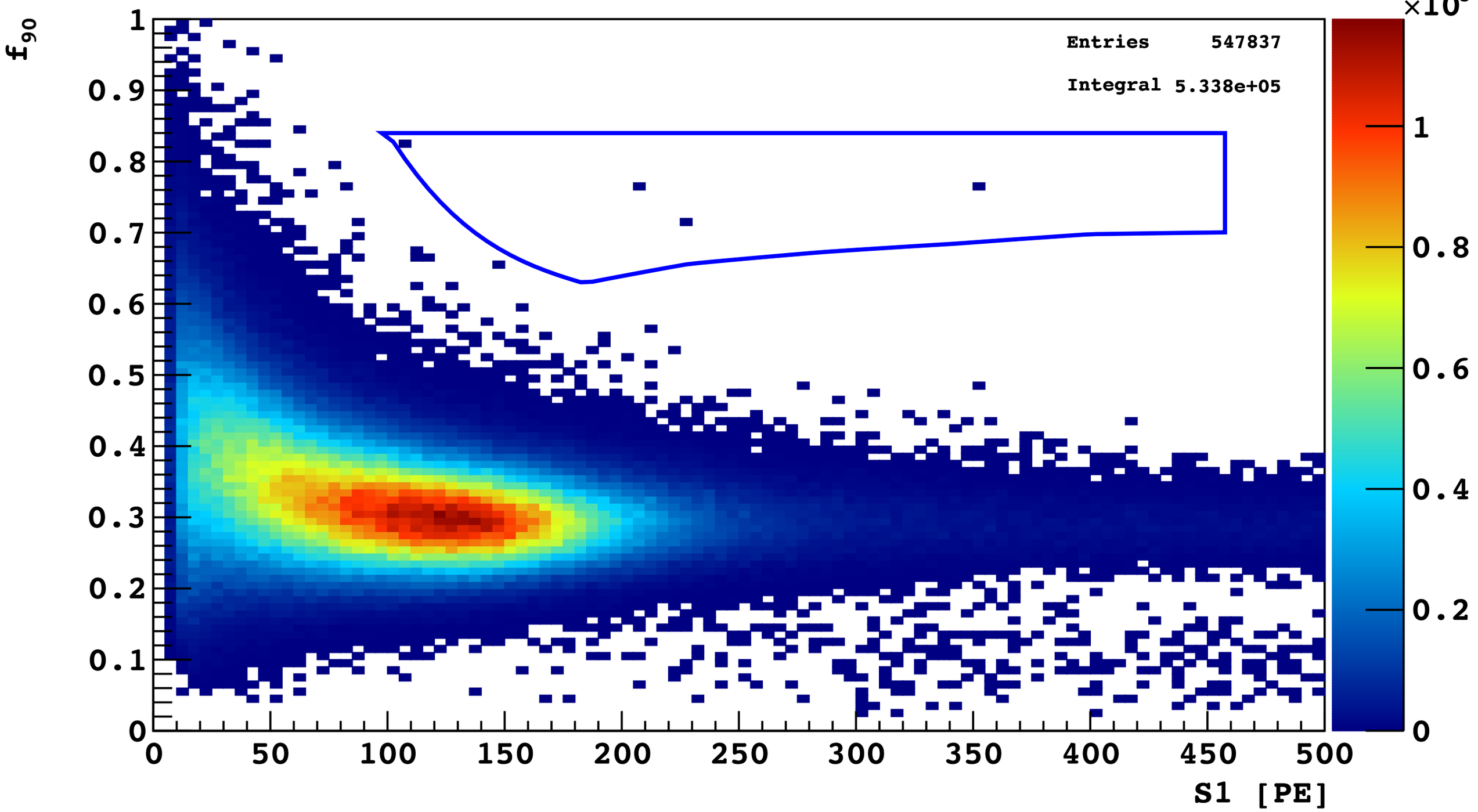
- S2 f90: f90 of S2 pulse <0.20
- Remove S1+S1 pileup events



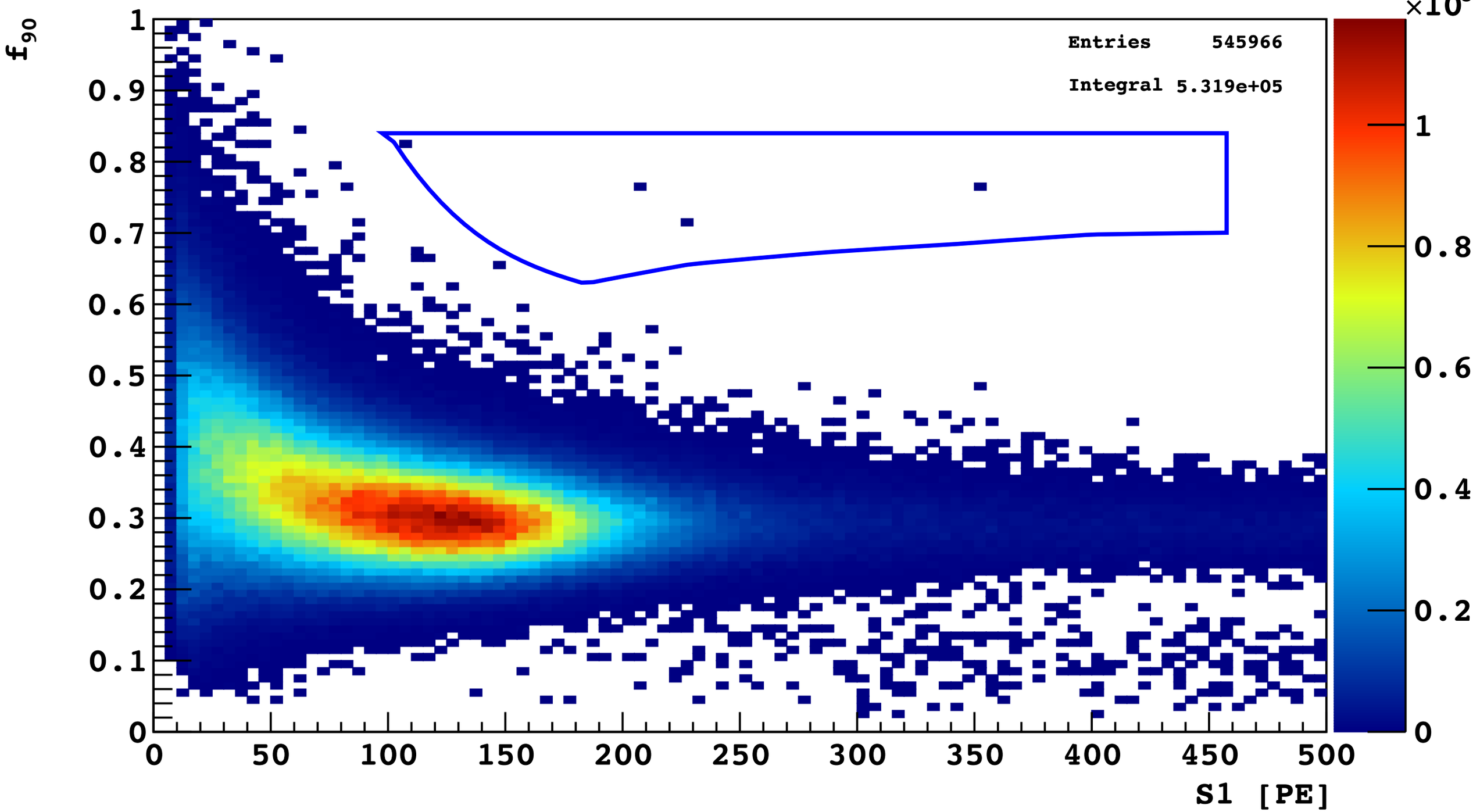
- min S2/S1: S2/S1 need to be above threshold, which is a function of S1
- Remove strangely small S2 events, like surface events



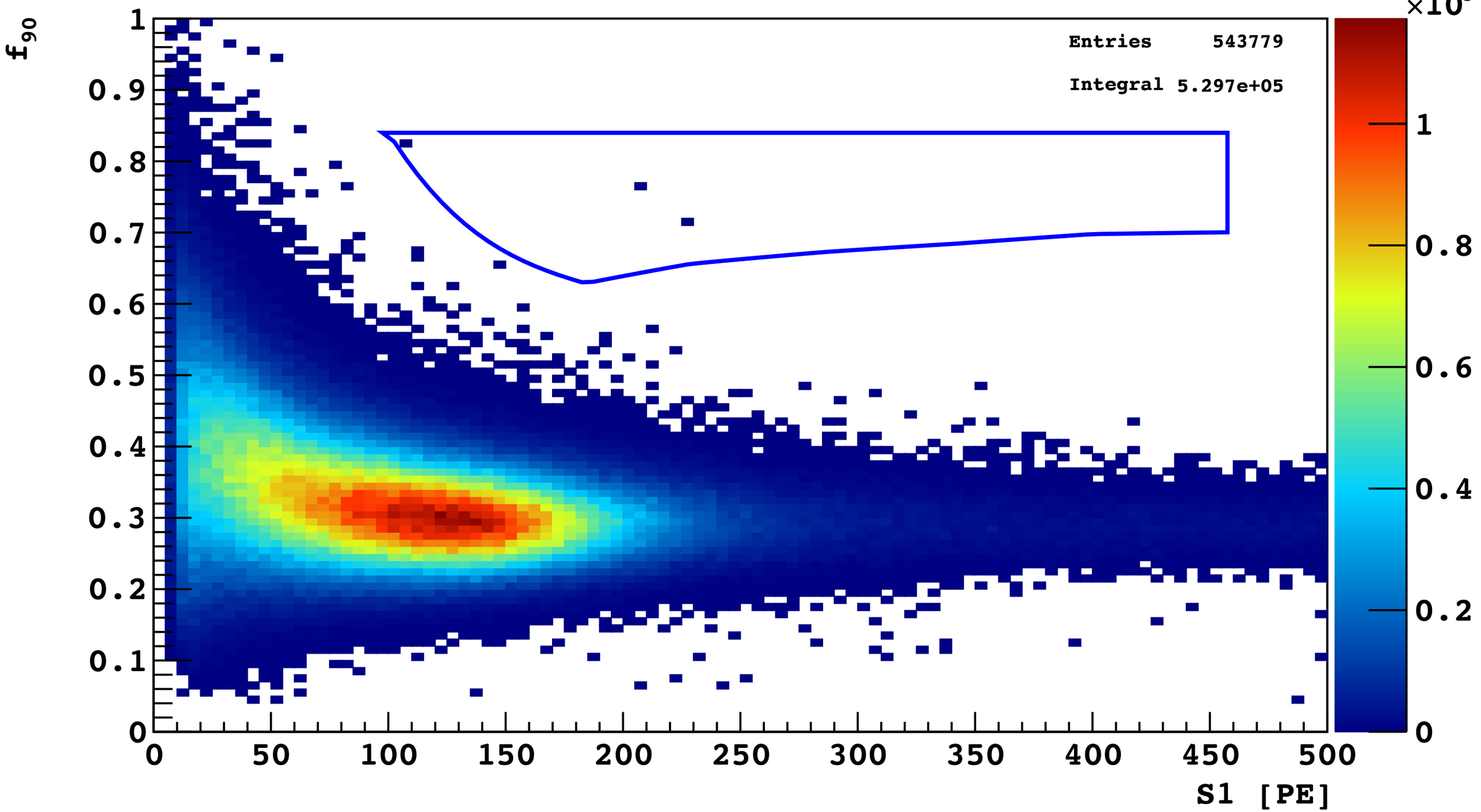
- max S2/S1: S2/S1 need to be below threshold, which is a function of S1
- Remove strangely large S2 events, which we don't expect, but applied as a safety net



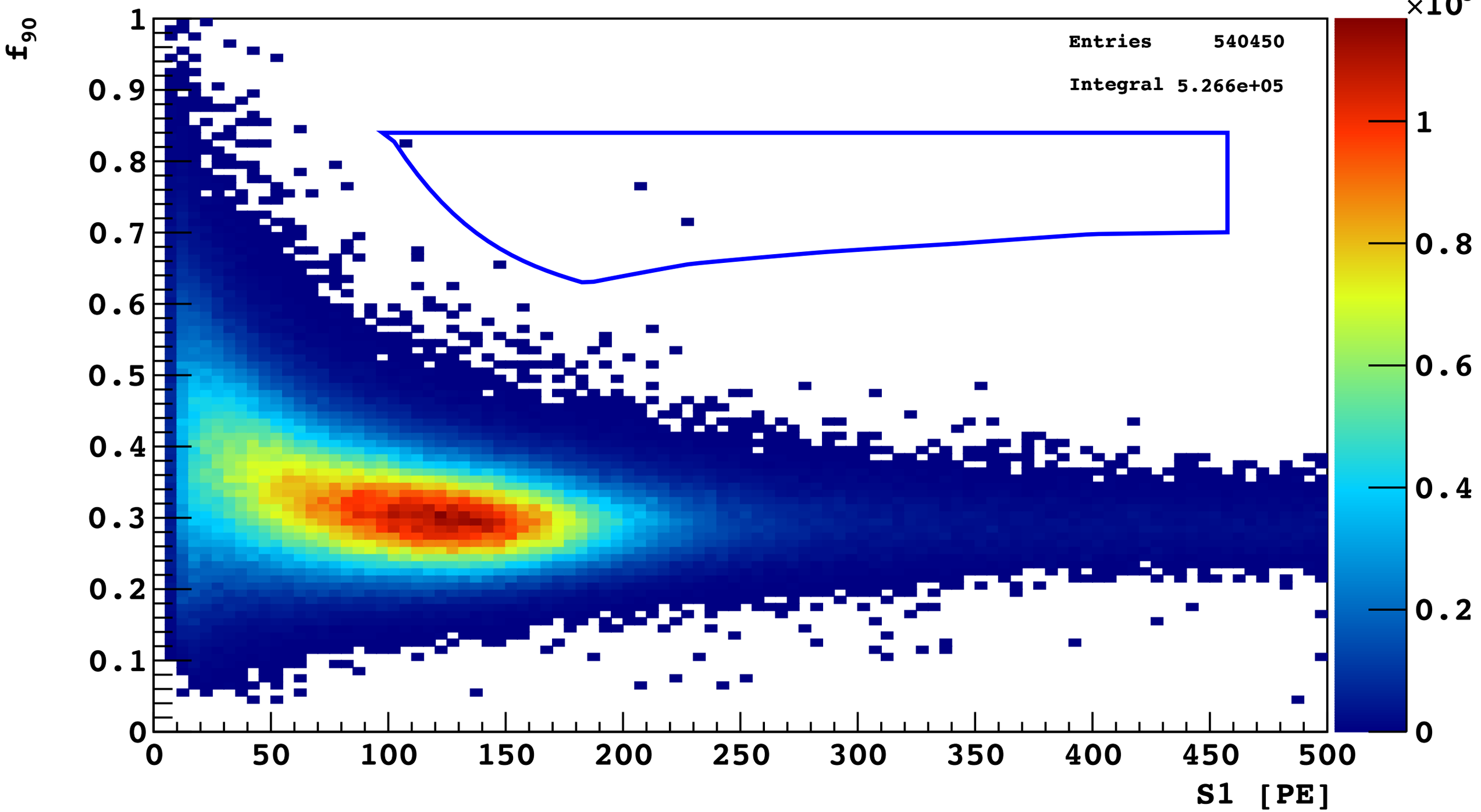
- S2 i90/i1: S2 have reasonable rise time
- Remove events in which S2 is actually S1+S2 pulses



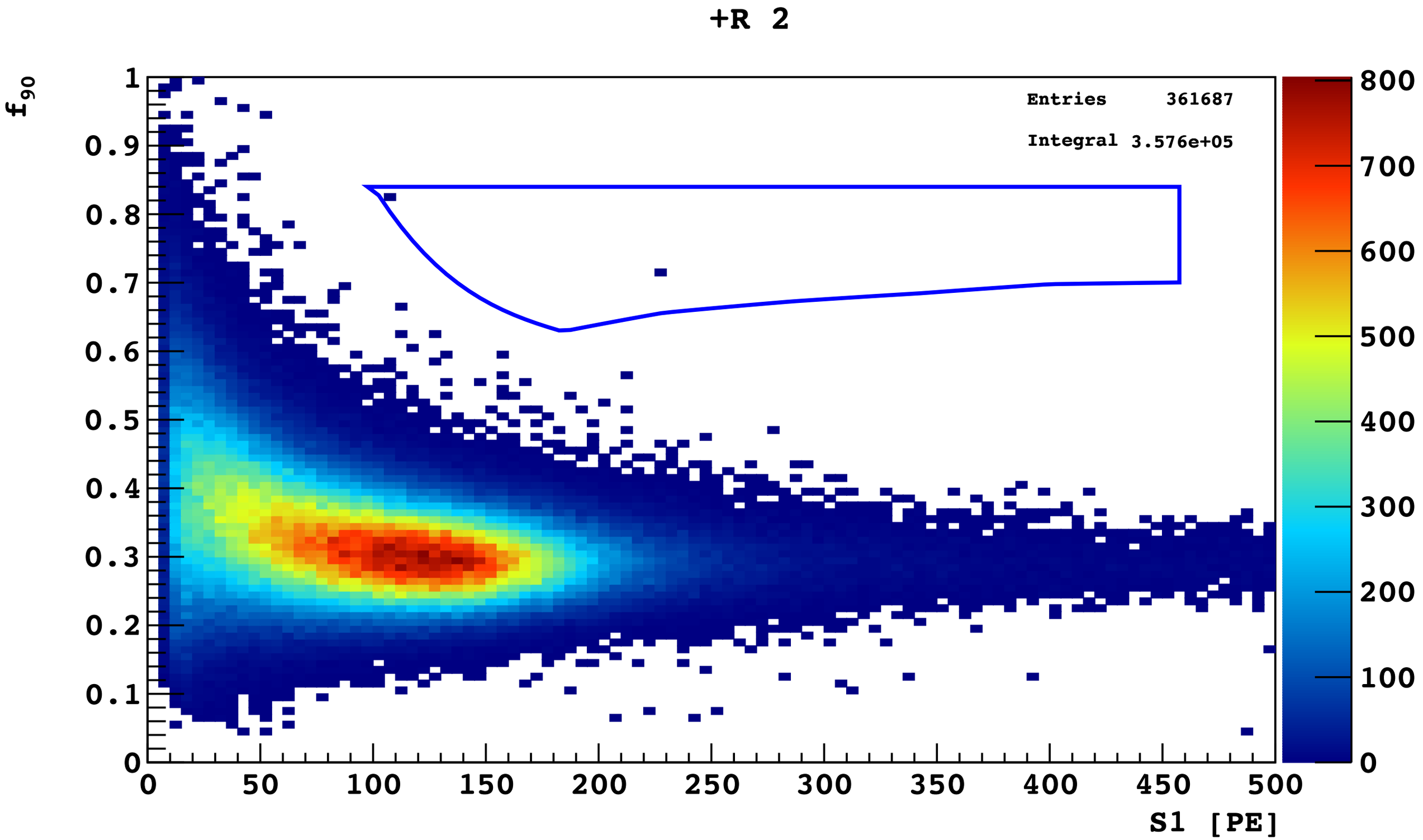
- S1 TBA: z-position from S1 Top-Bottom Asymmetry agrees with t_drift
- Remove random pileup S1 and S2



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

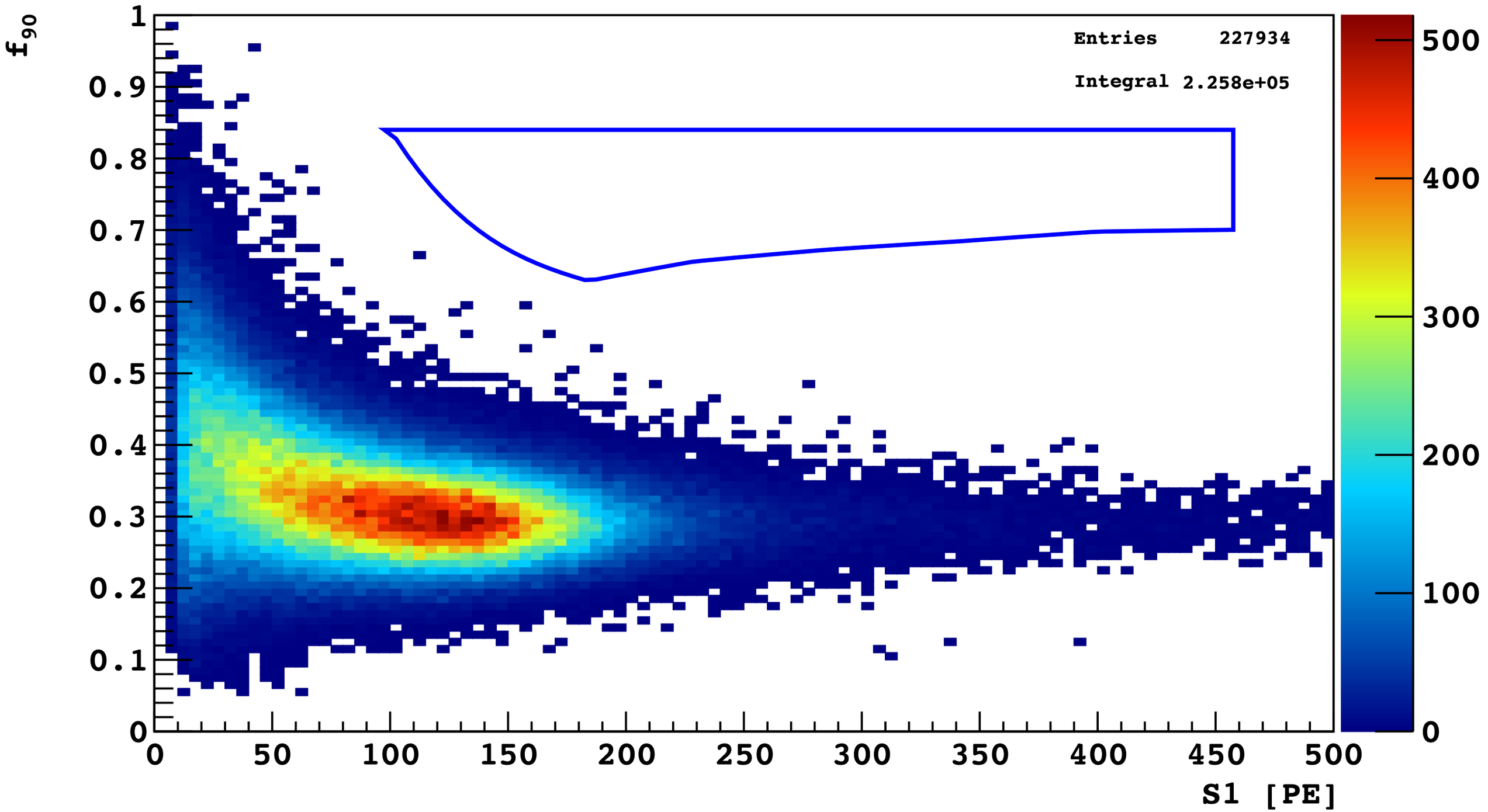


- NLL: Negative Log Likelihood cut, which compare event position from S1 light distribution among PMTs and event position from t_drift and S2 x-y
- Remove S1 + Cherenkov events which deposit energy in separate locations

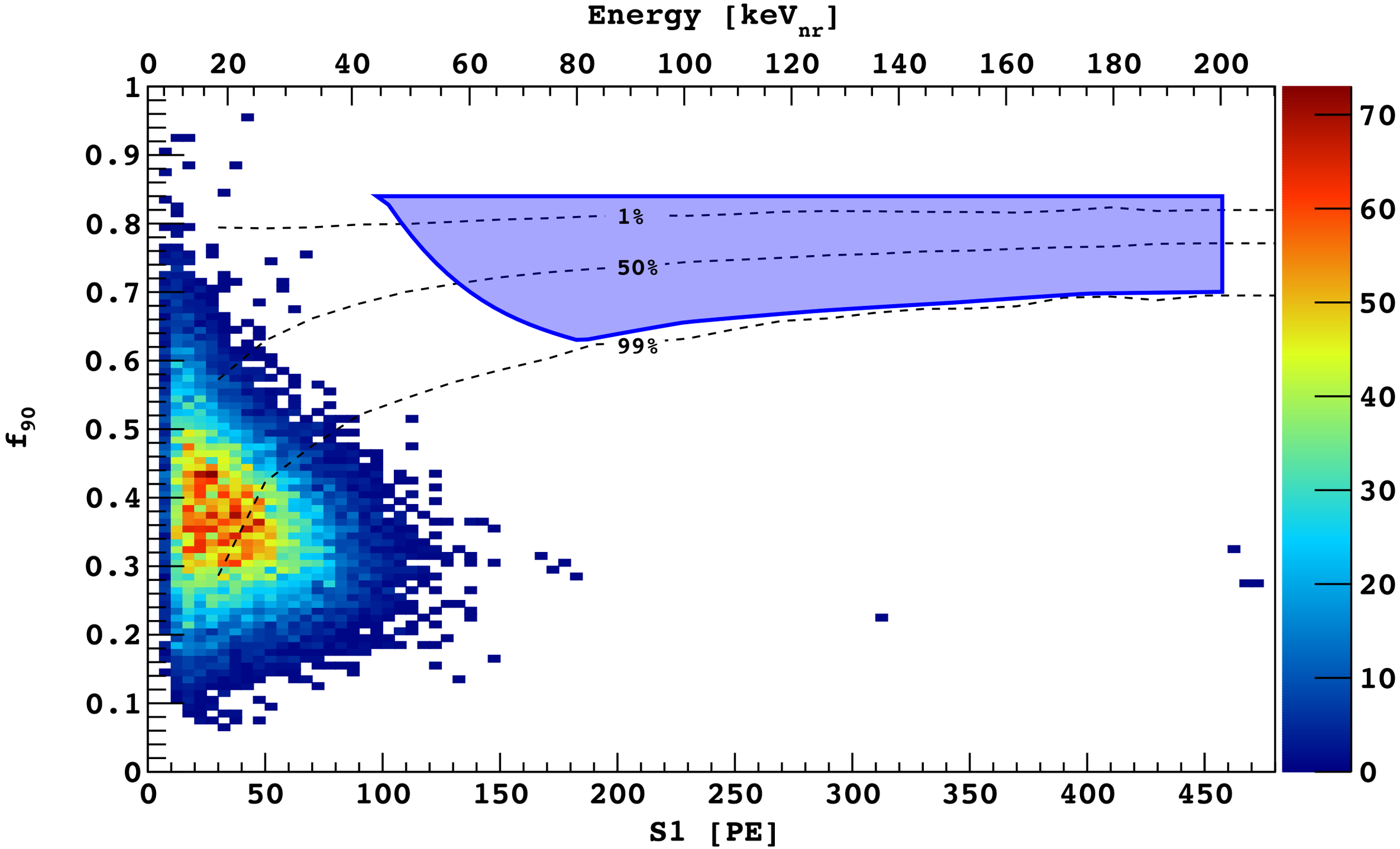


- R 2: Radial cut as a function of t_drift

+Veto



- Veto: all veto cuts
- Remove neutrons



arXiv:1802.07198