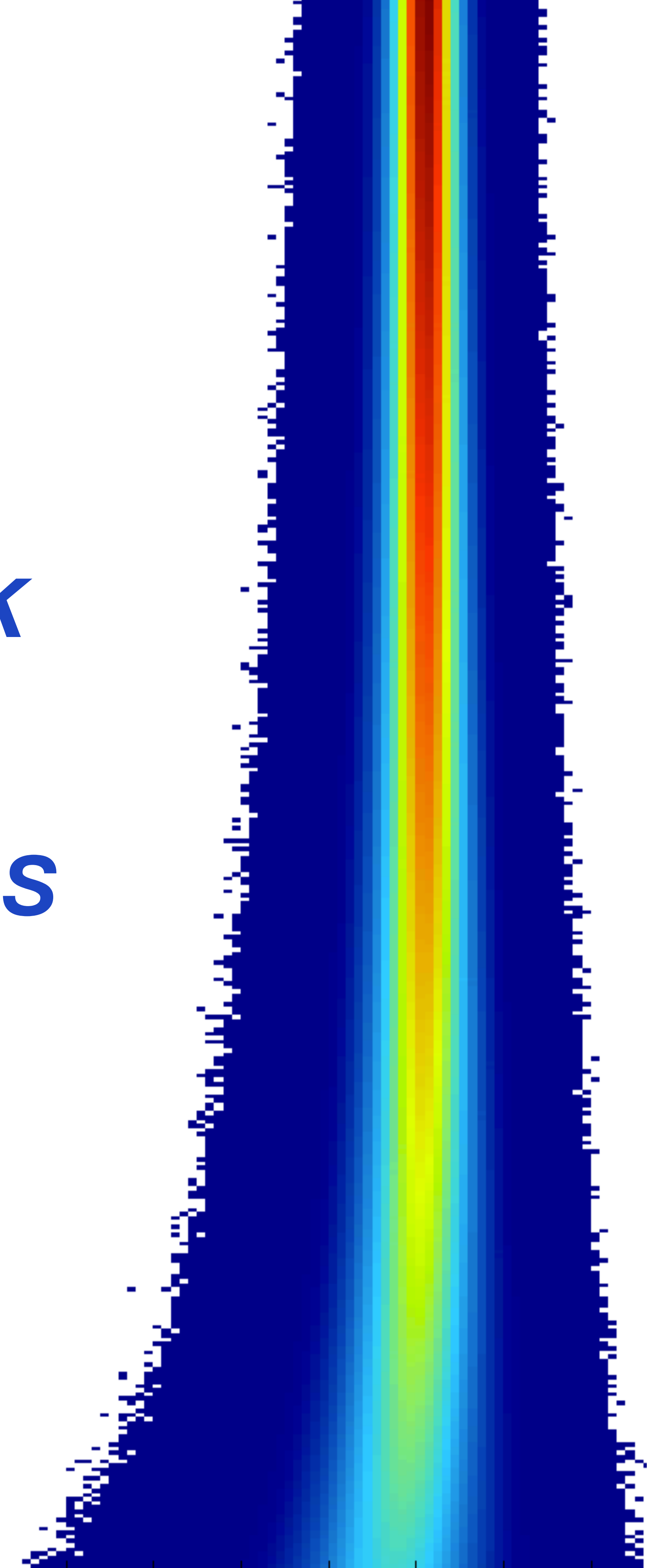
Direct Searches for Dark Matter with DarkSide: Results and Perspectives

Paolo Agnes
University of Houston

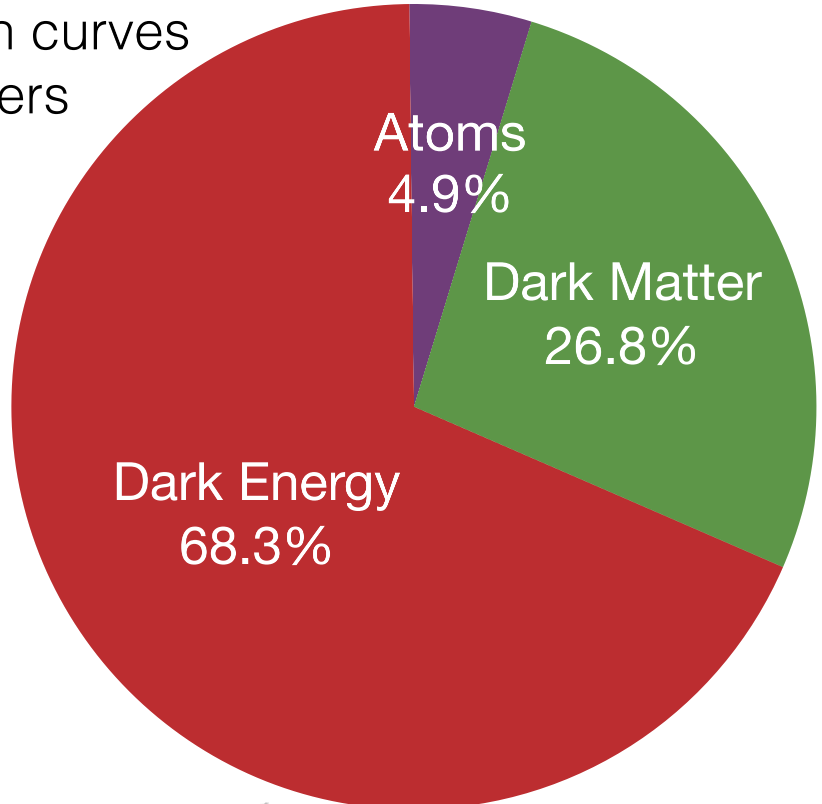
7th February 2019
Queen Mary University of London

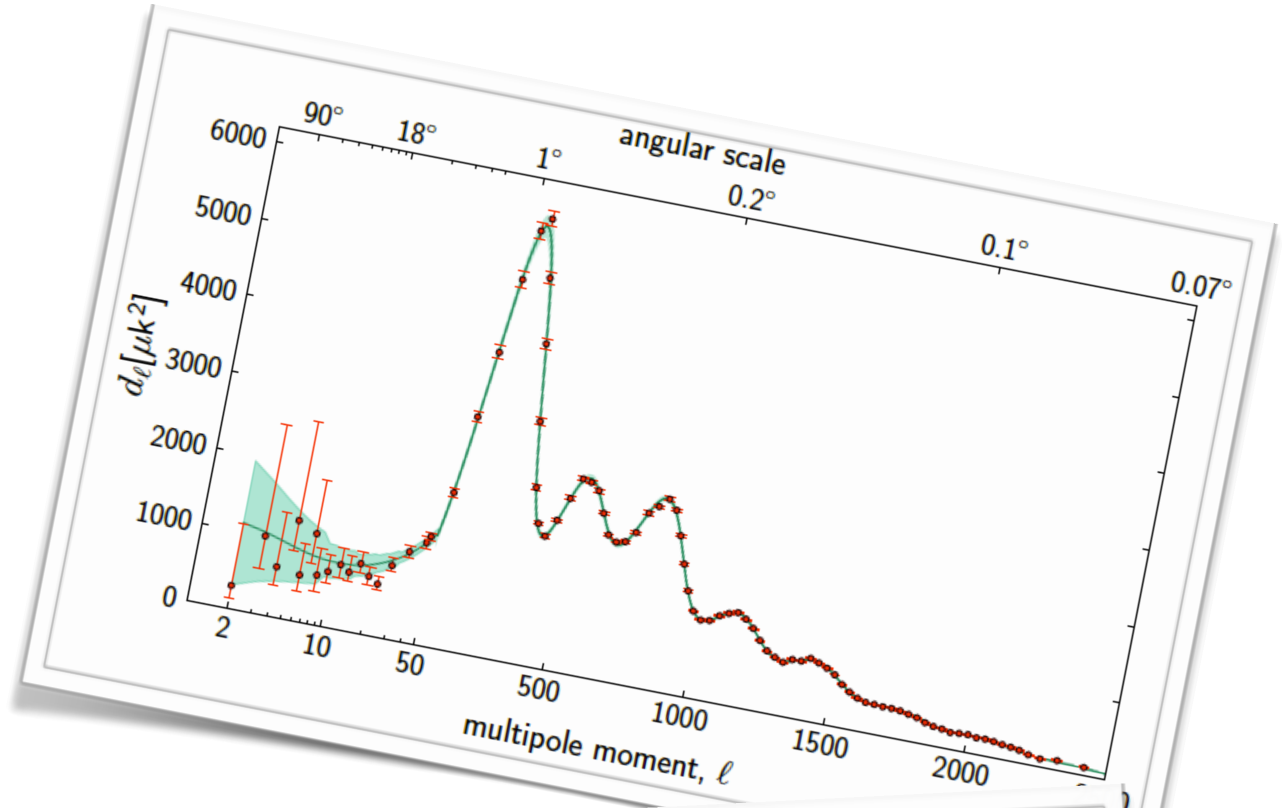


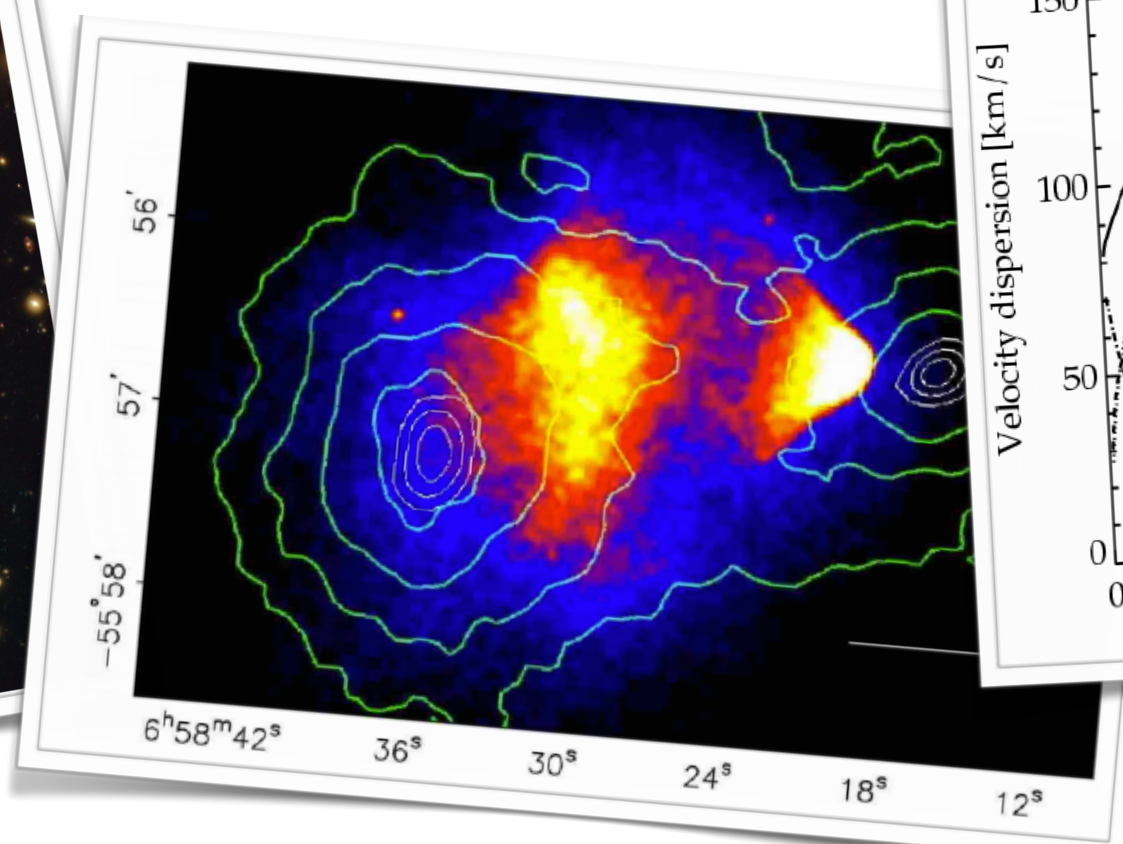
Dark Matter

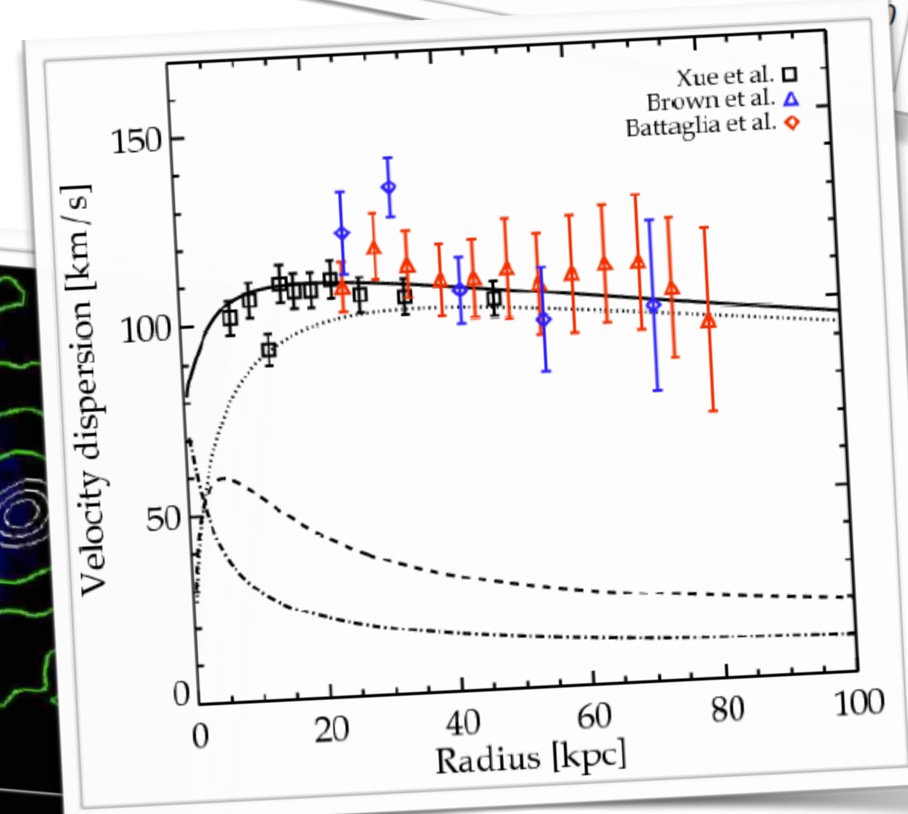
Several indirect observations:

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







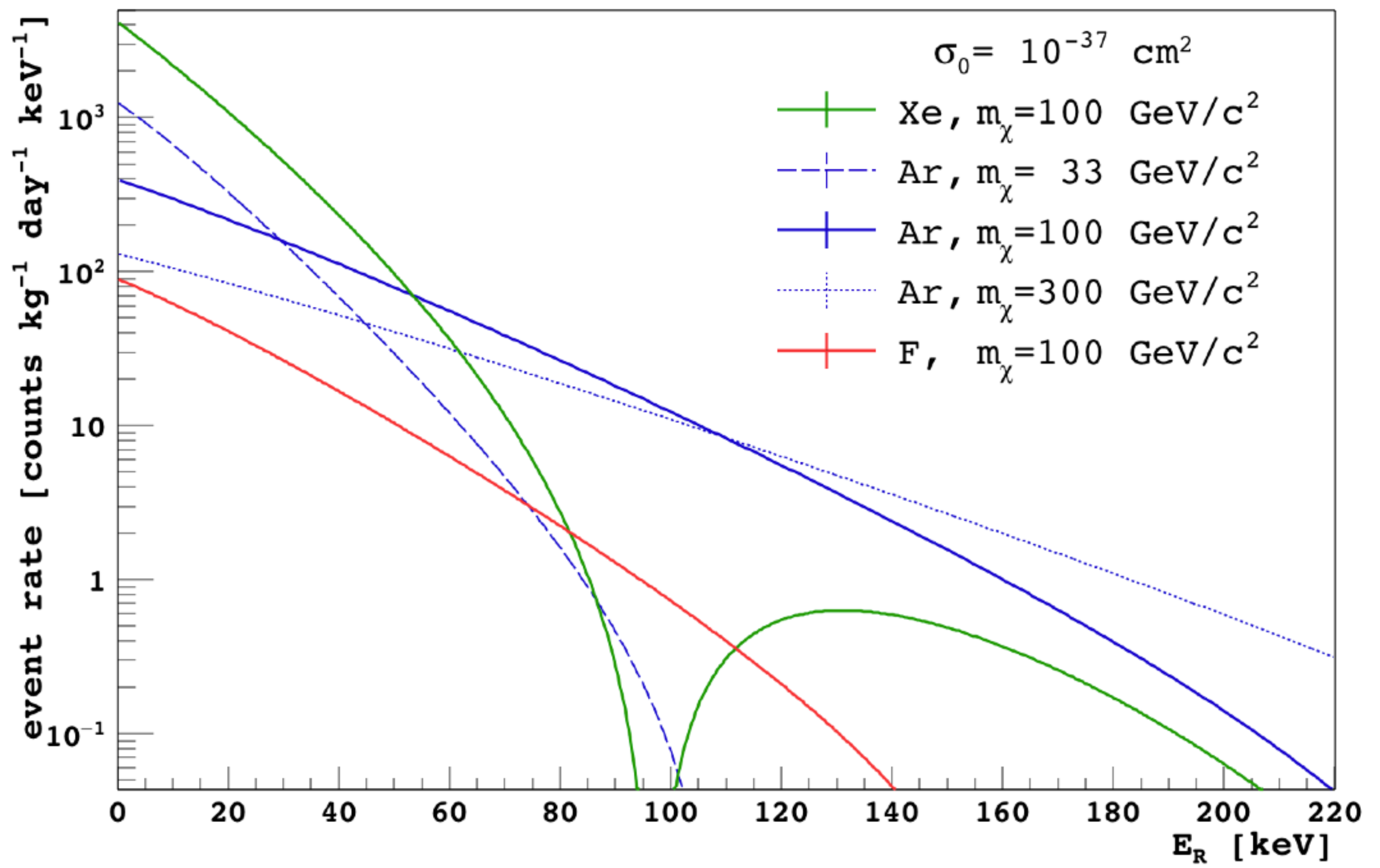


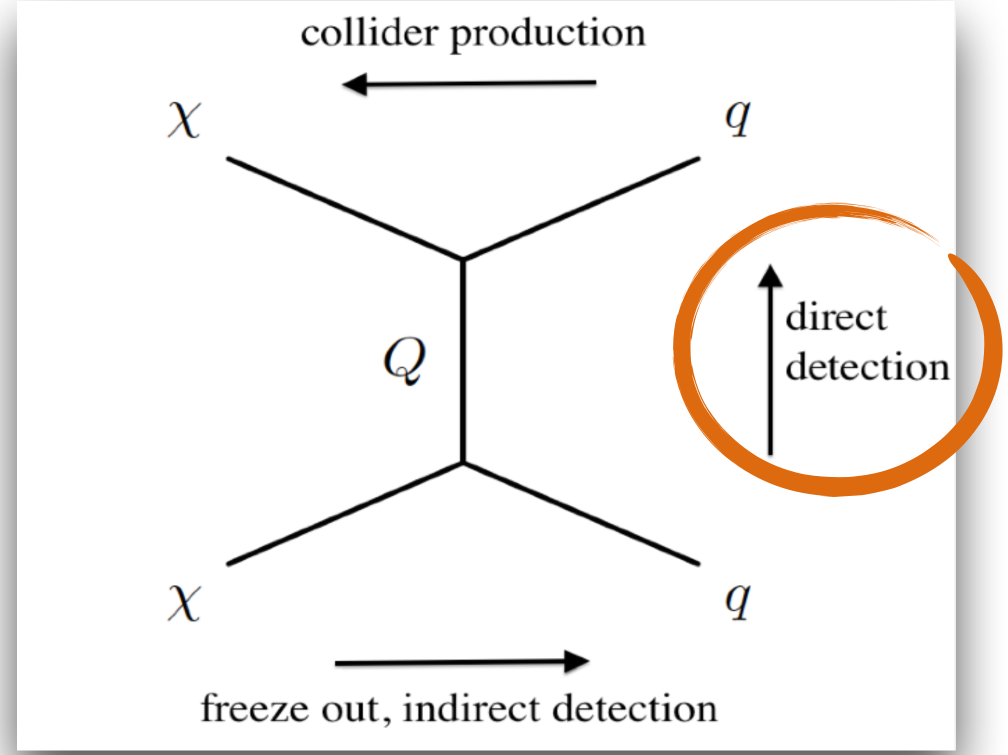
The search for WIMPs

Dark Matter particles:
- are massive
- are stable
- non relativistic
- interact gravitationally
- electromagnetically neutral

WIMP:
Weakly Interacting Massive Particle

Expected signal for DD: **low-energy nuclear recoil**

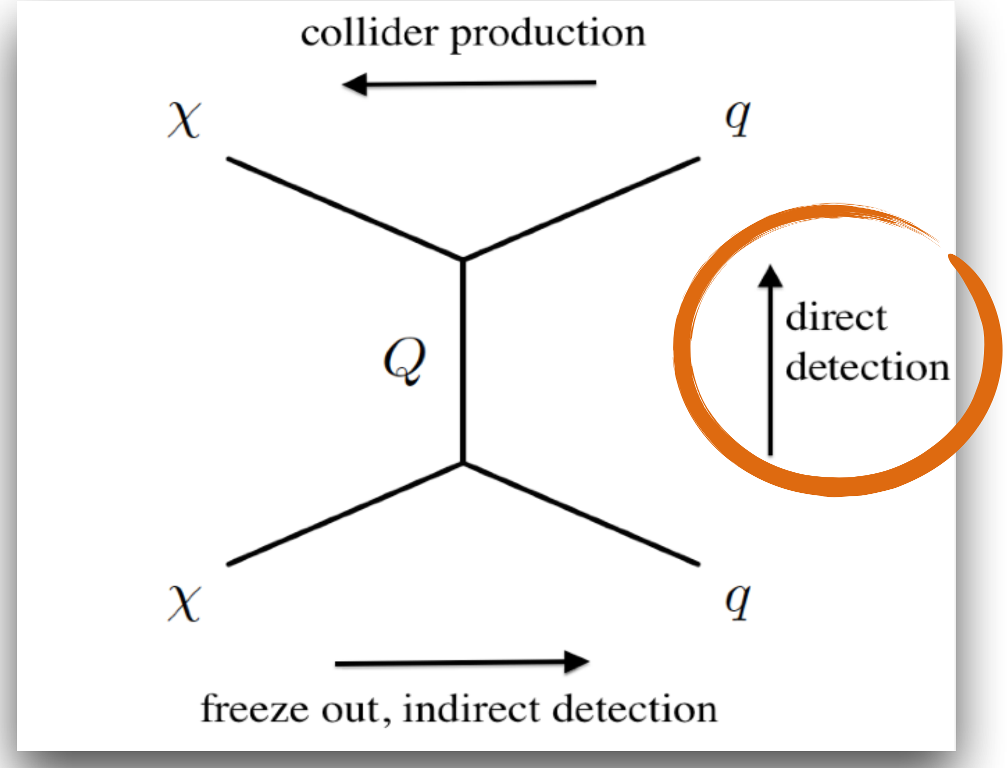




The search for WIMPs

Dark Matter particles:
- are massive
- are stable
- non relativistic
- interact gravitationally
- electromagnetically neutral

WIMP:
Weakly Interacting Massive Particle

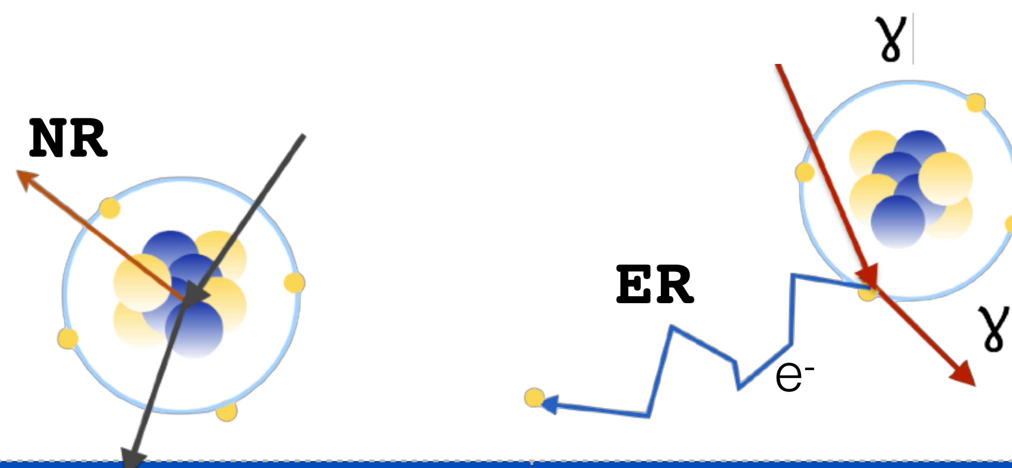


Expected signal for DD: **low-energy nuclear recoil**

- Low energy threshold
(E < 100 keV)

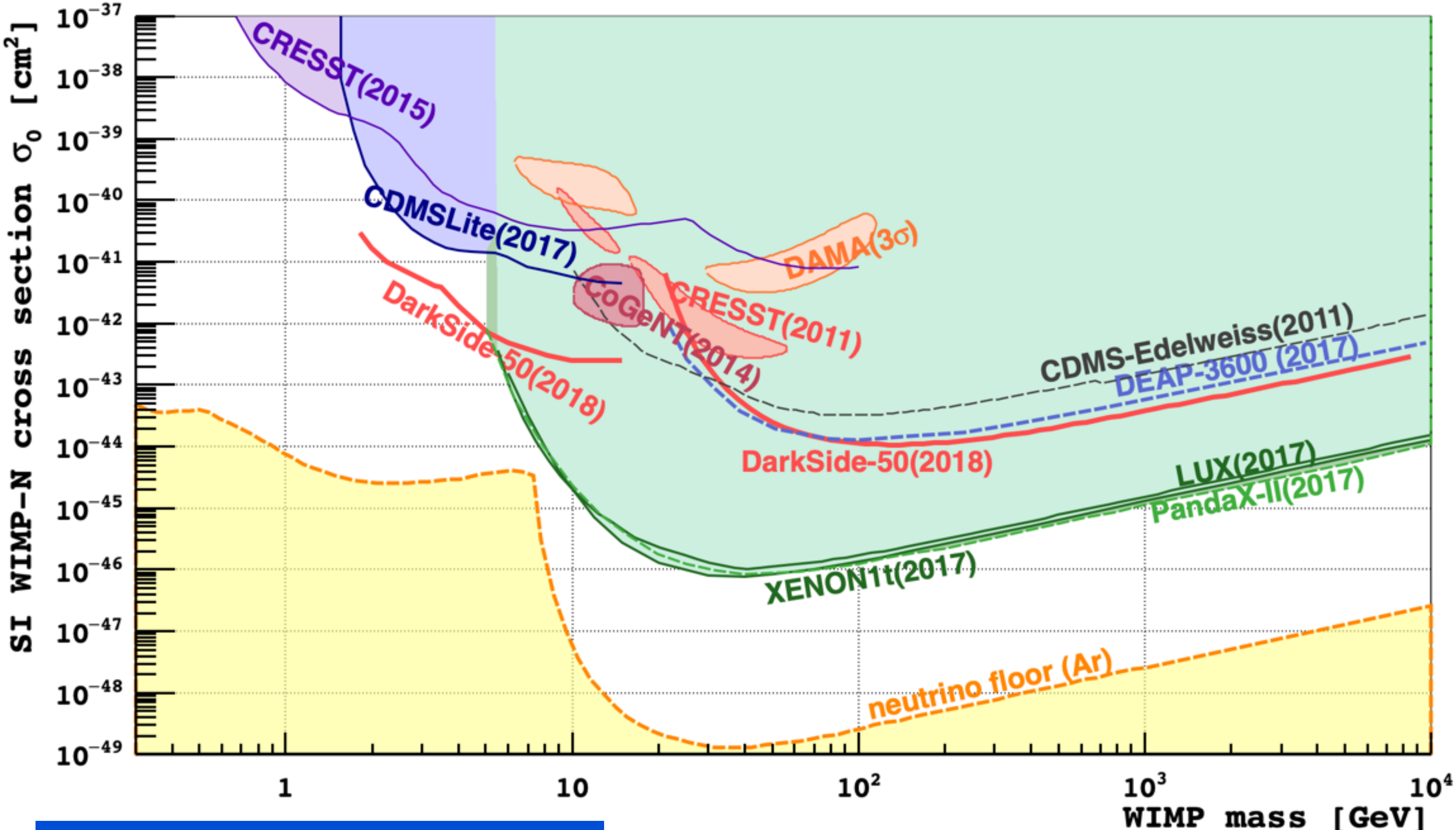
- Large mass
(~ 1 event/tonne/yr @ 10^{-47} cm^2 in noble liquids)

- 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

Direct detection of dark matter (SI)



Potential of LAr for low-mass WIMP !

Noble liquids will cover the high-mass WIMP region

Noble liquids

Noble liquids are suitable targets:
- ☑ dense, inexpensive, easy to purify
- ☑ large ionization/scintillation yields (W~10 eV)
- ☑ ER recoil background discrimination

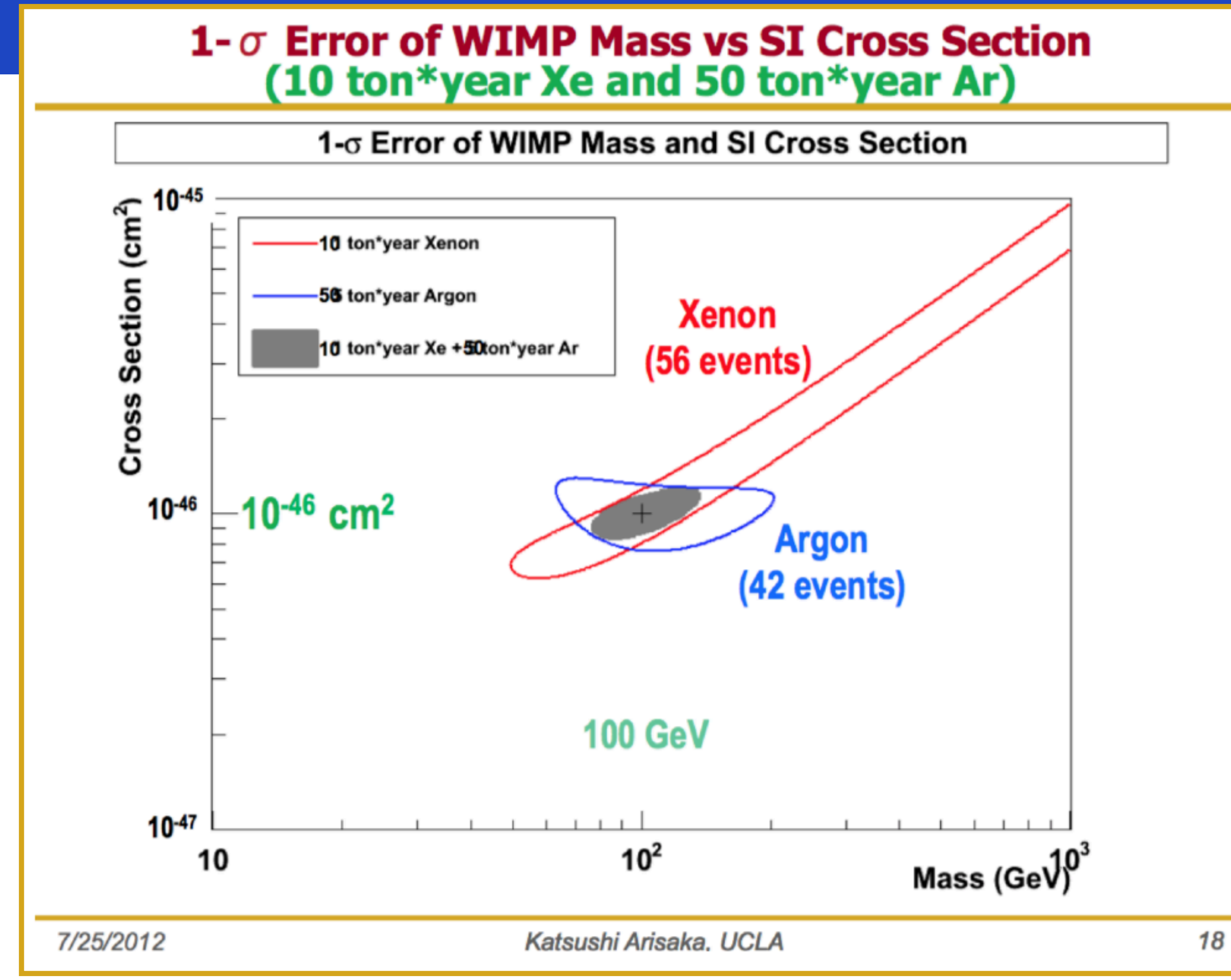
Liquid Xenon
- σ goes as A^2
- radio-purity

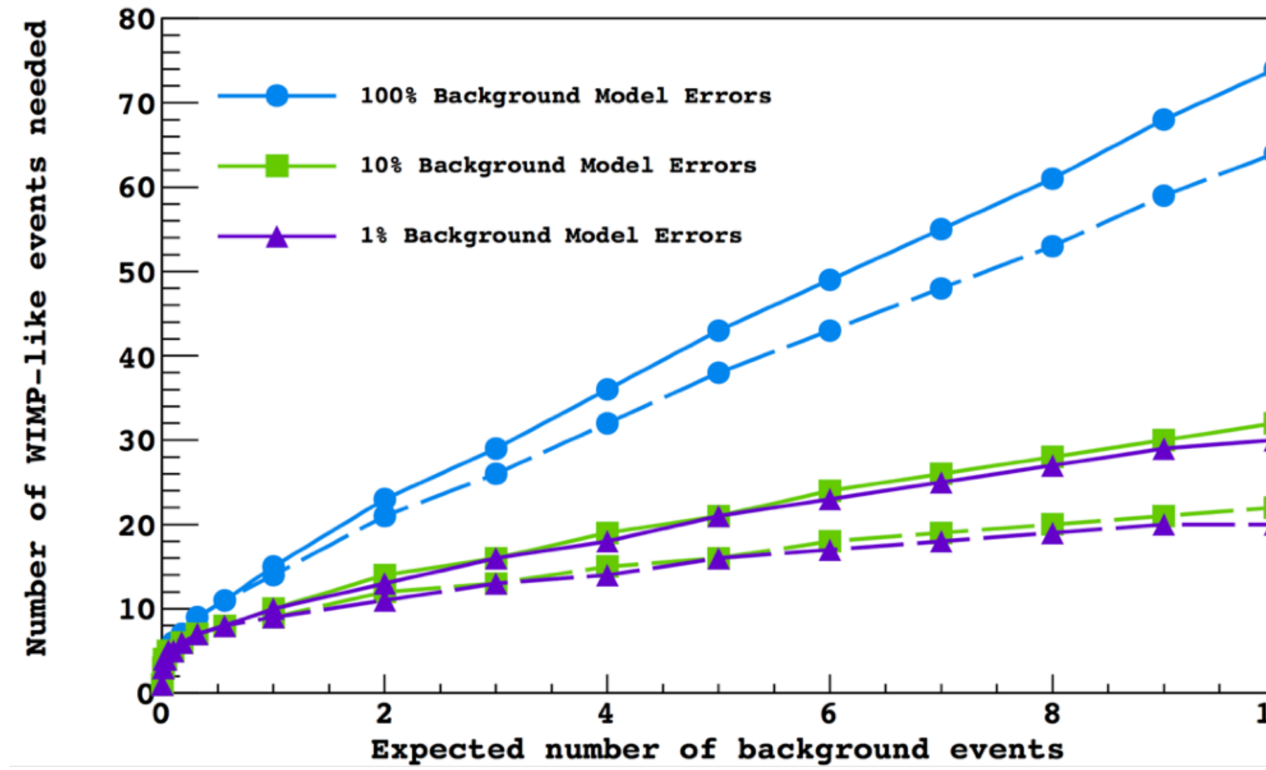
=> most sensitive searches

Liquid Argon
- **Complementarity: great value in case of an excess**
- **Pulse Shape Discrimination: ~10^8 ER rejection** operate a detector in a background-free mode

- **1 Bq/kg from ^{39}Ar in atmospheric argon (AAr),** limiting factor for **dual-phase** layout

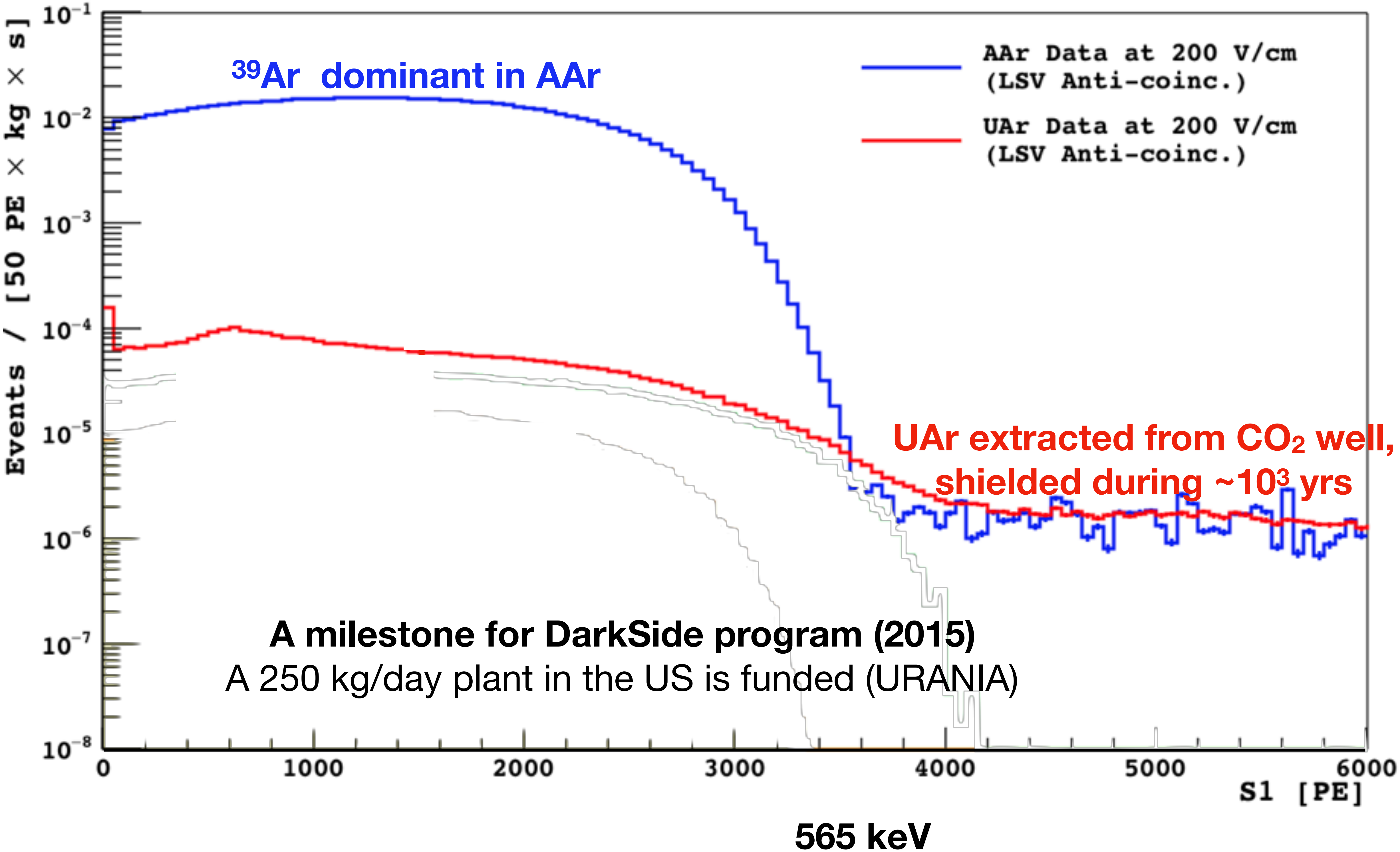
=> Need to work out a solution for the ^{39}Ar problem!





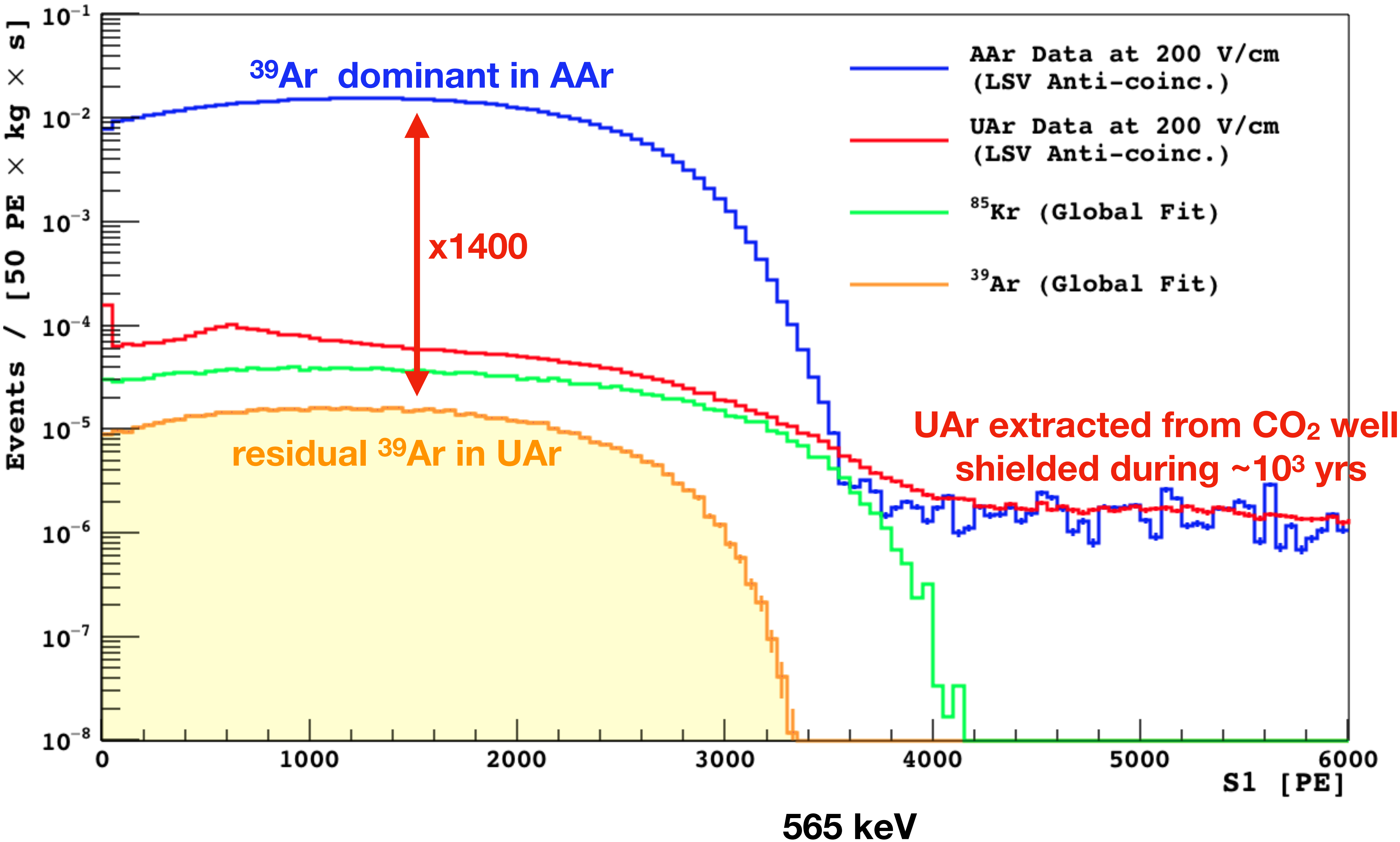
Underground Argon

^{39}Ar is produced in atmospheric argon by **cosmogenic activation**. Beta emitter with endpoint at 565 keV and half life of 269 y. Nominal **activity of atmospheric argon: ~ 1 Bq/kg.**

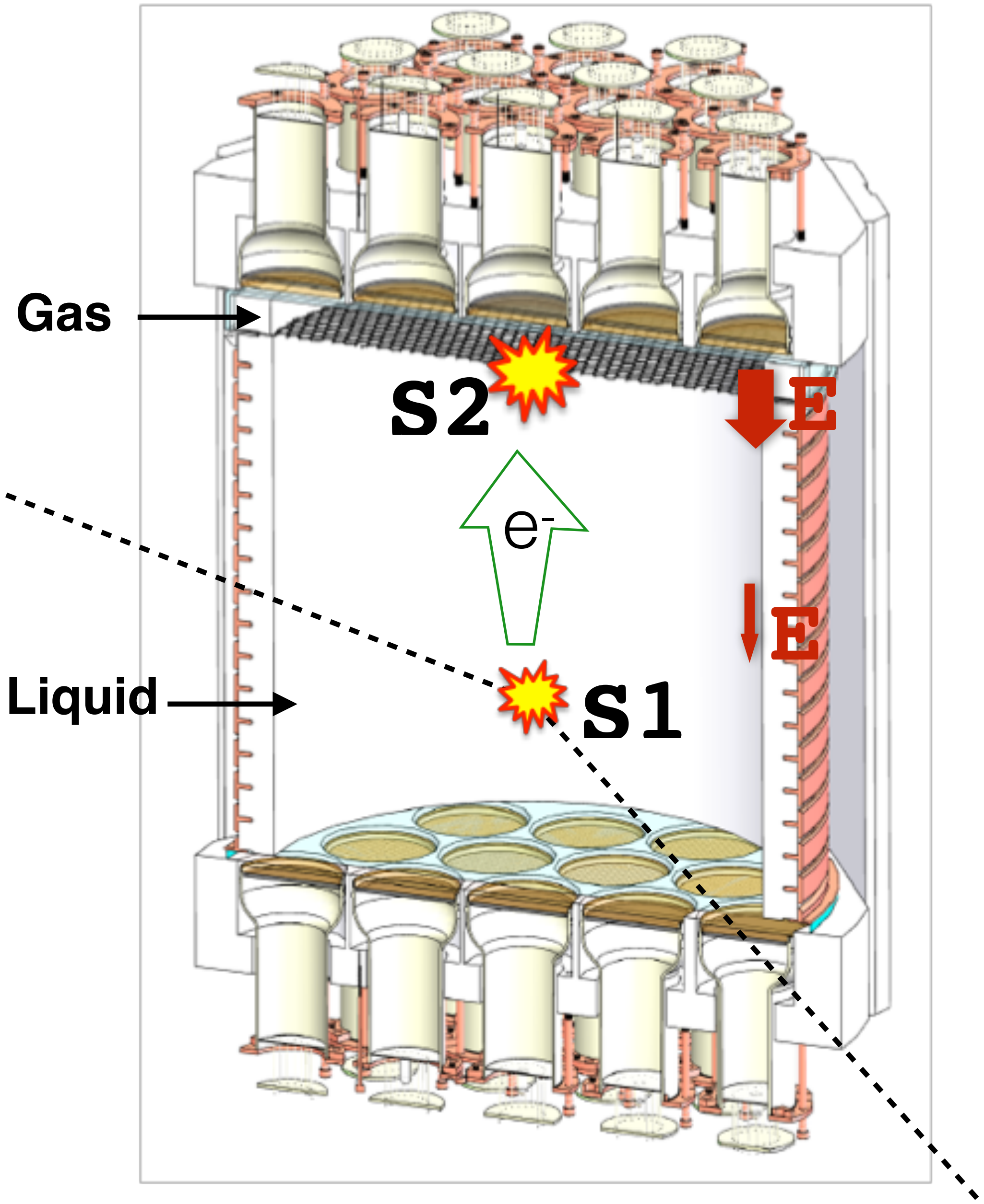


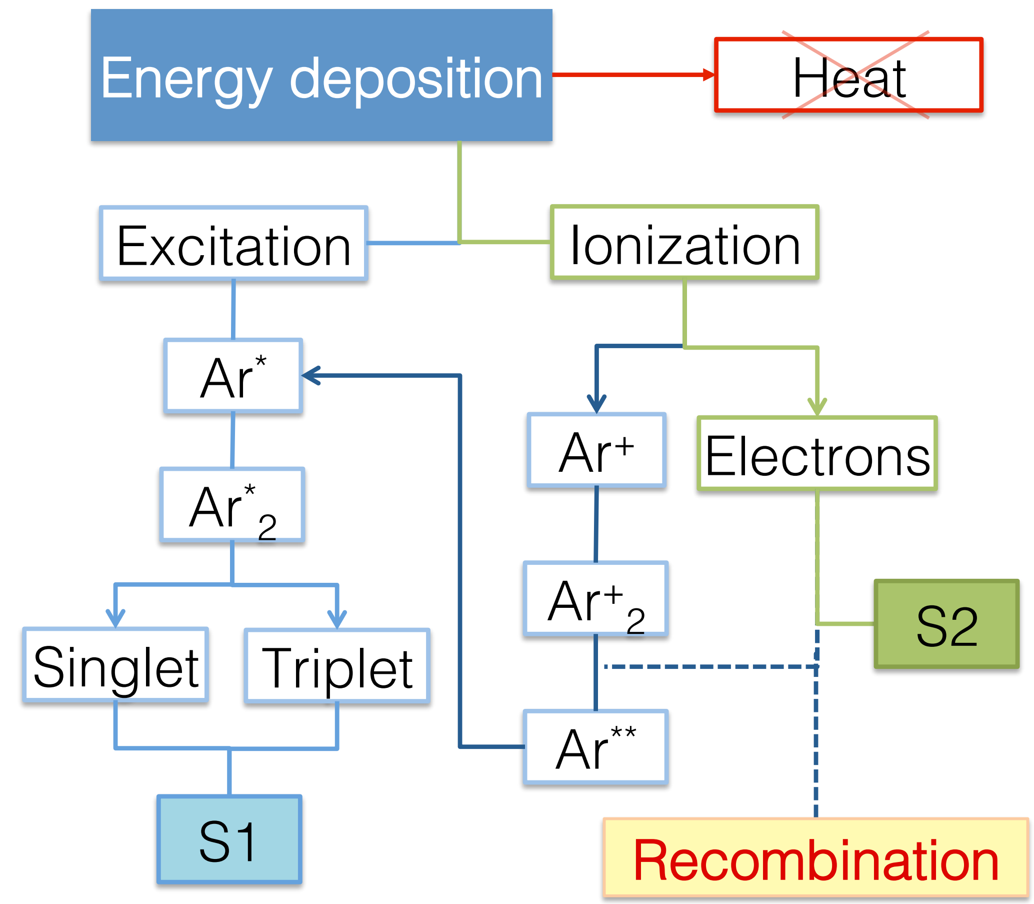
Underground Argon

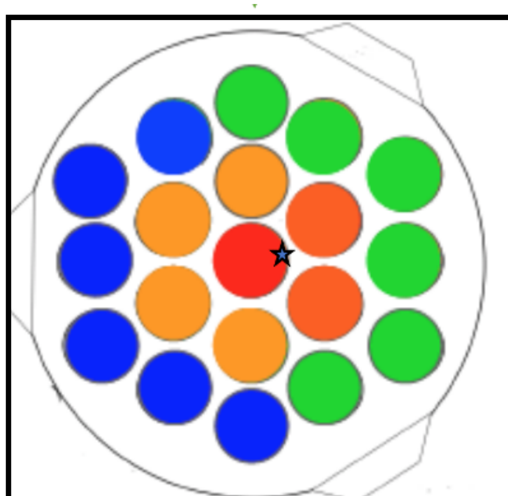
^{39}Ar is produced in atmospheric argon by **cosmogenic activation**. Beta emitter with endpoint at 565 keV and half life of 269 y. Nominal **activity of atmospheric argon: ~ 1 Bq/kg.**



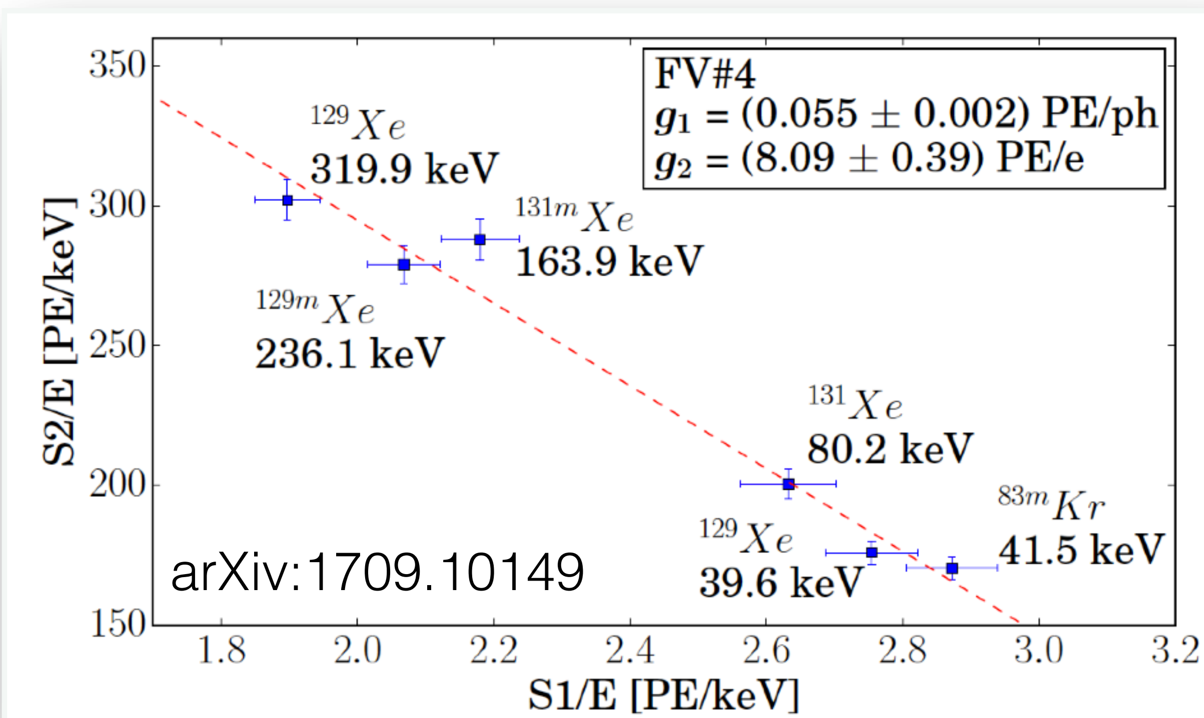
Dual-phase TPC



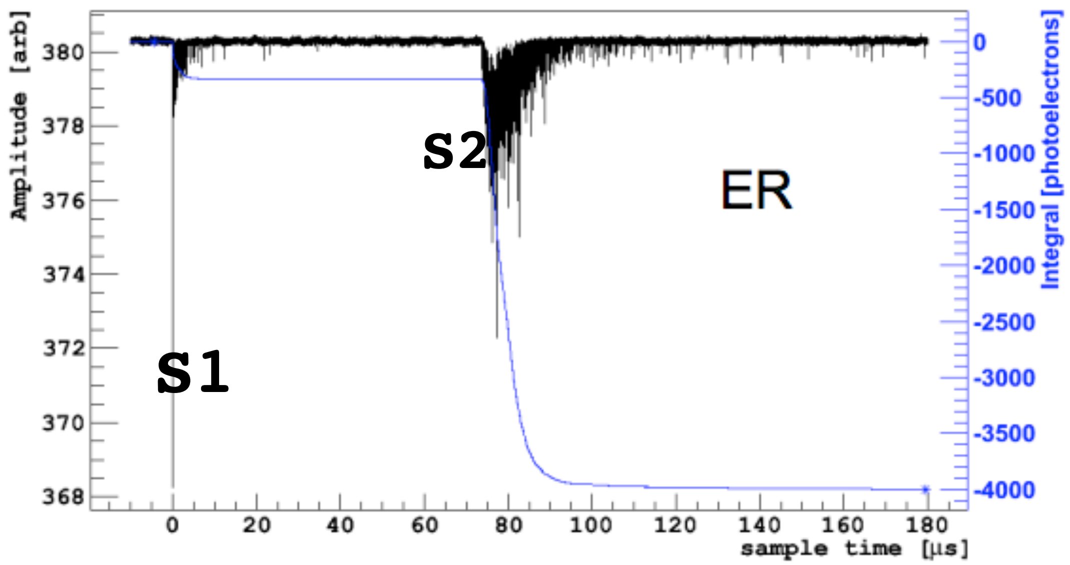


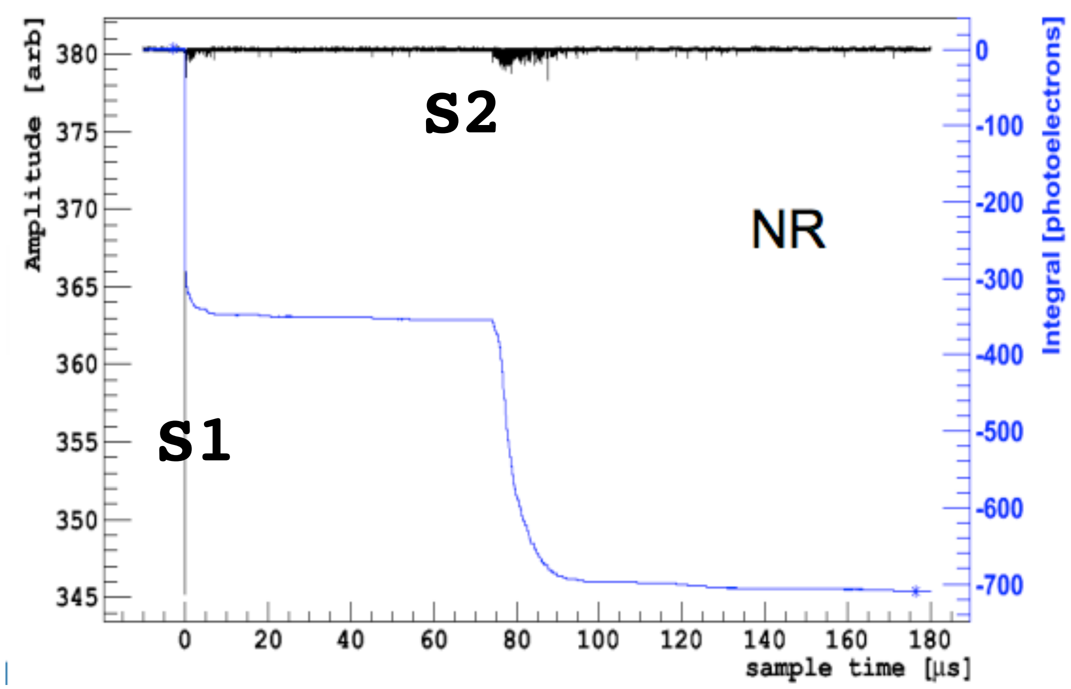


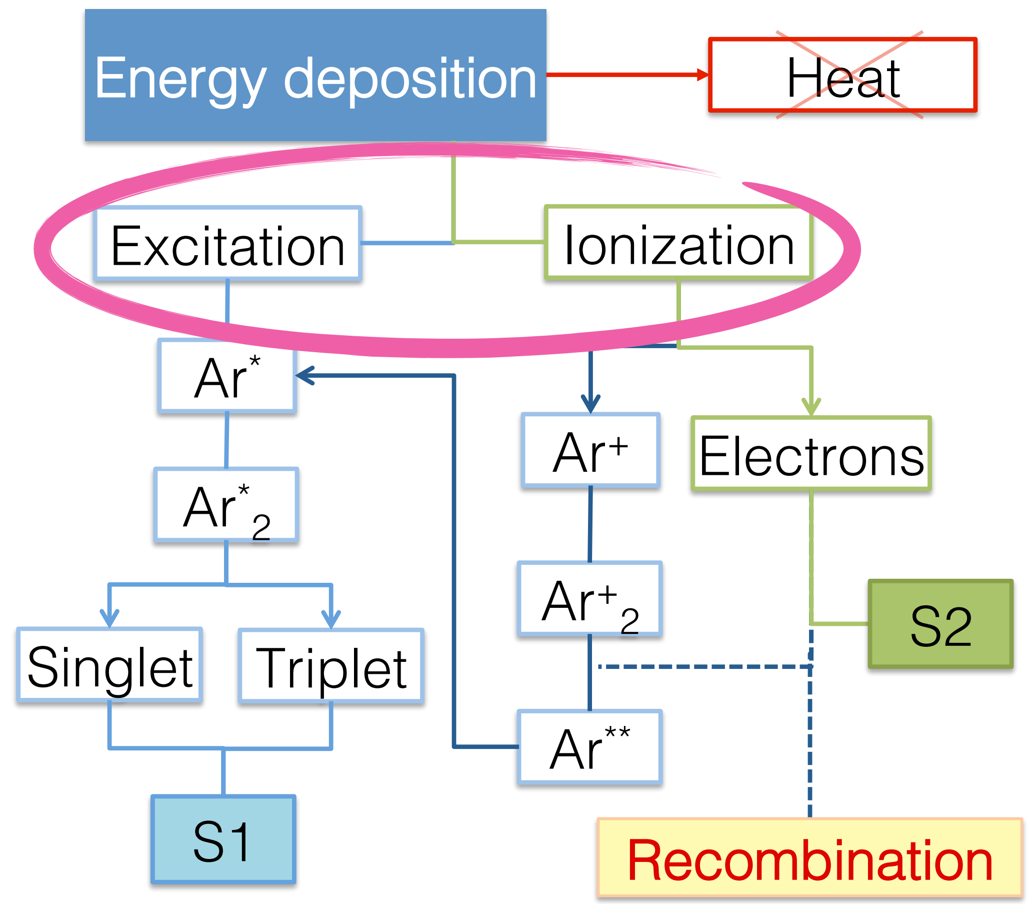
drift time
+
S2 light pattern
=
3D vertex reconstruction

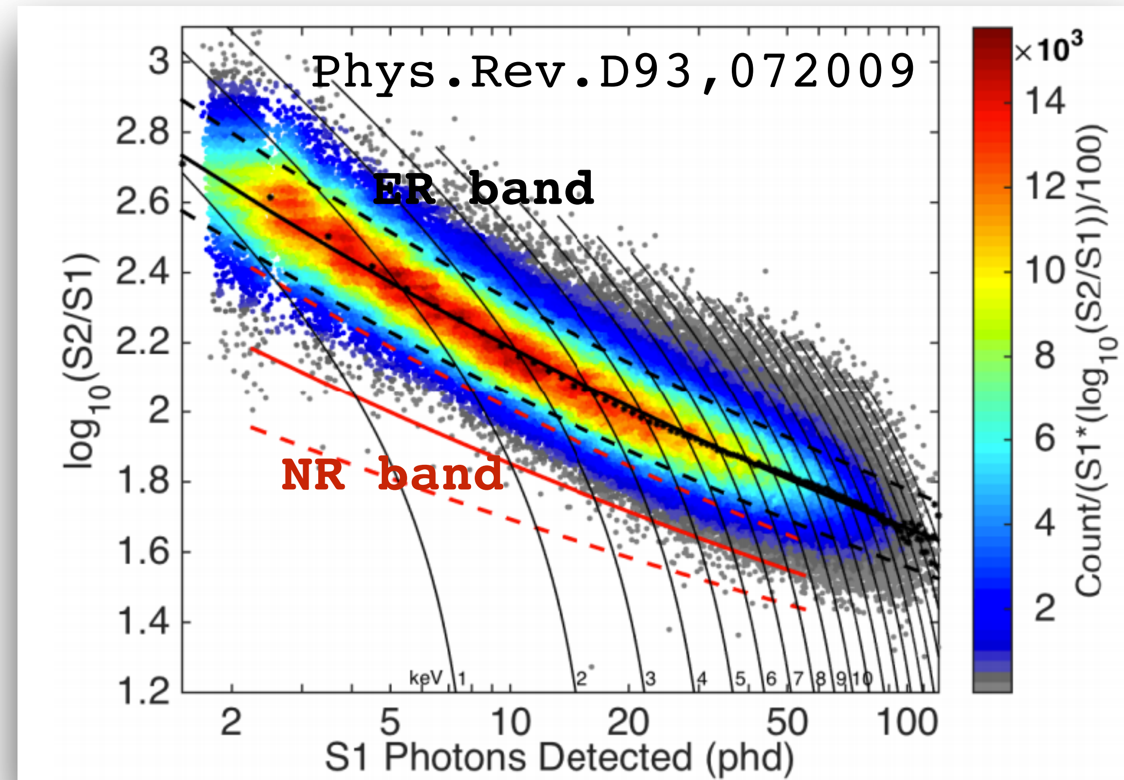


Rejection by Ionization/Scintillation





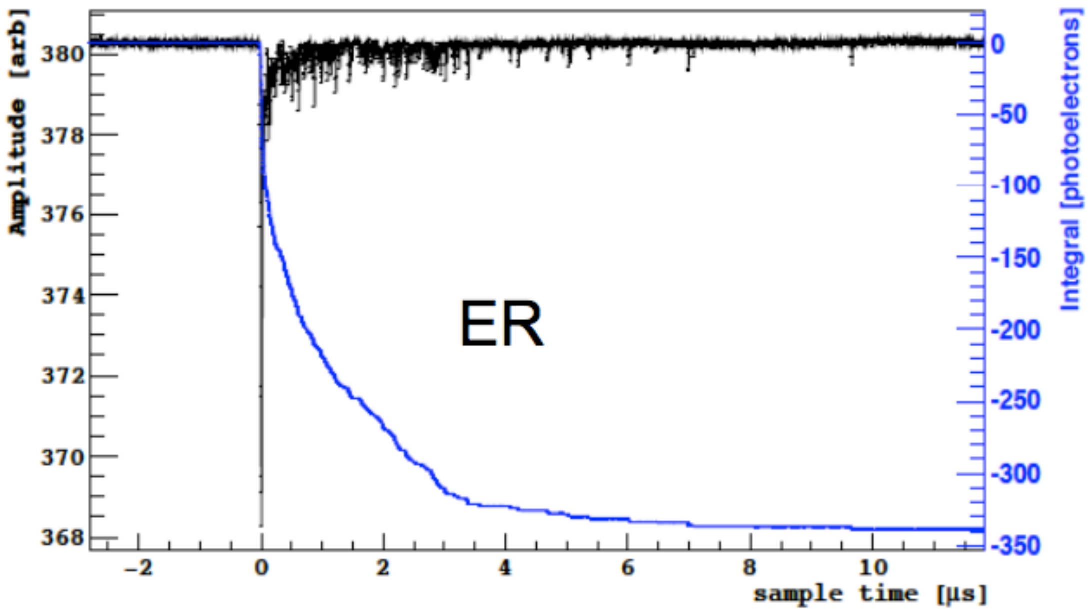


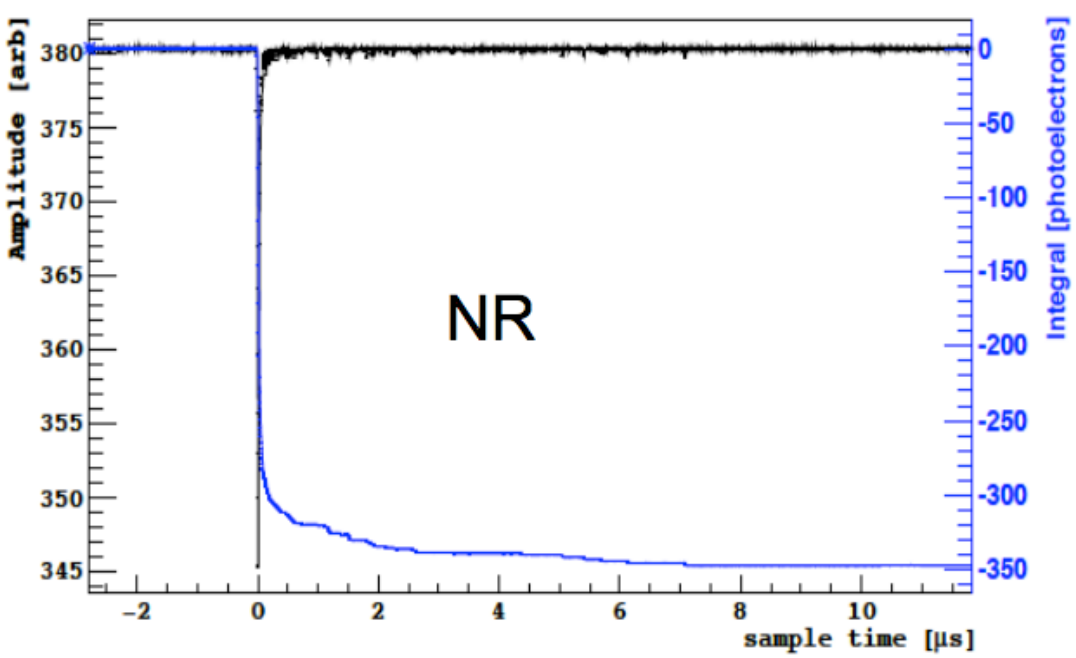


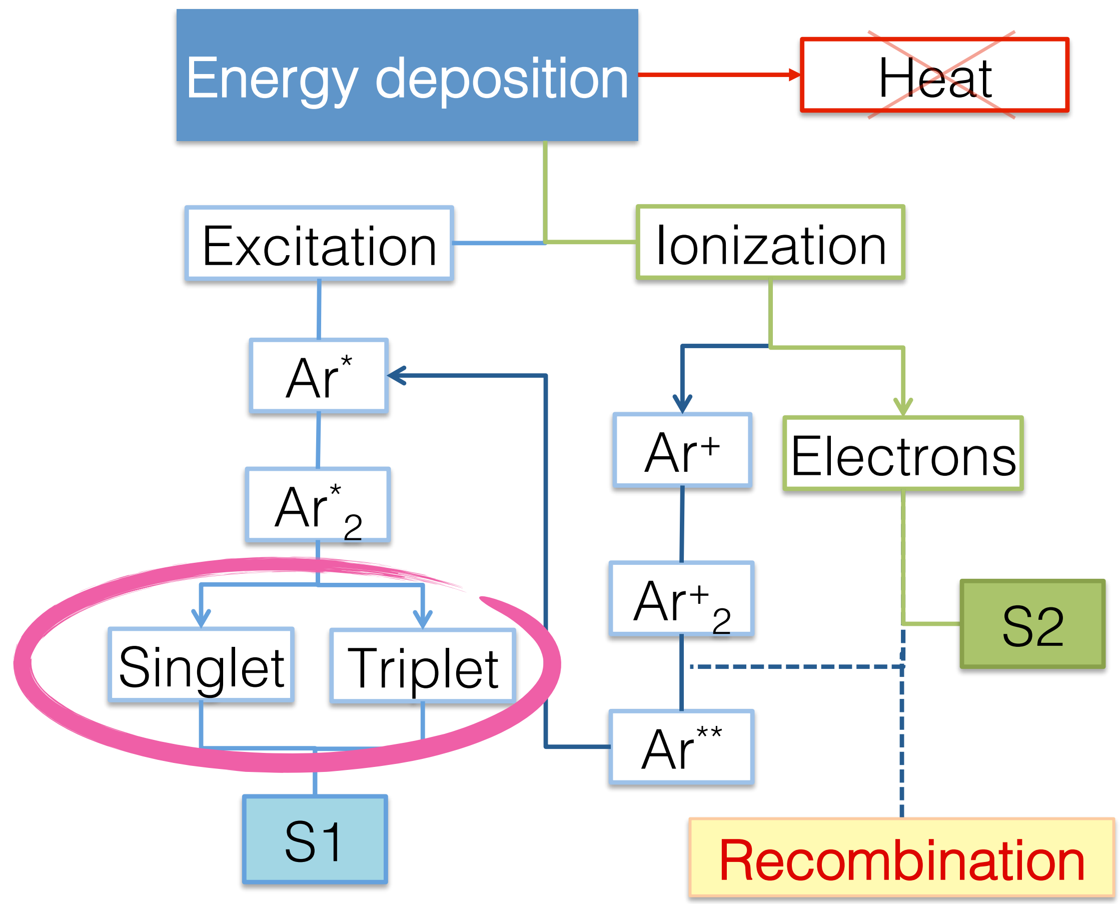
ER Rejection factor: 10^2 - 10^3

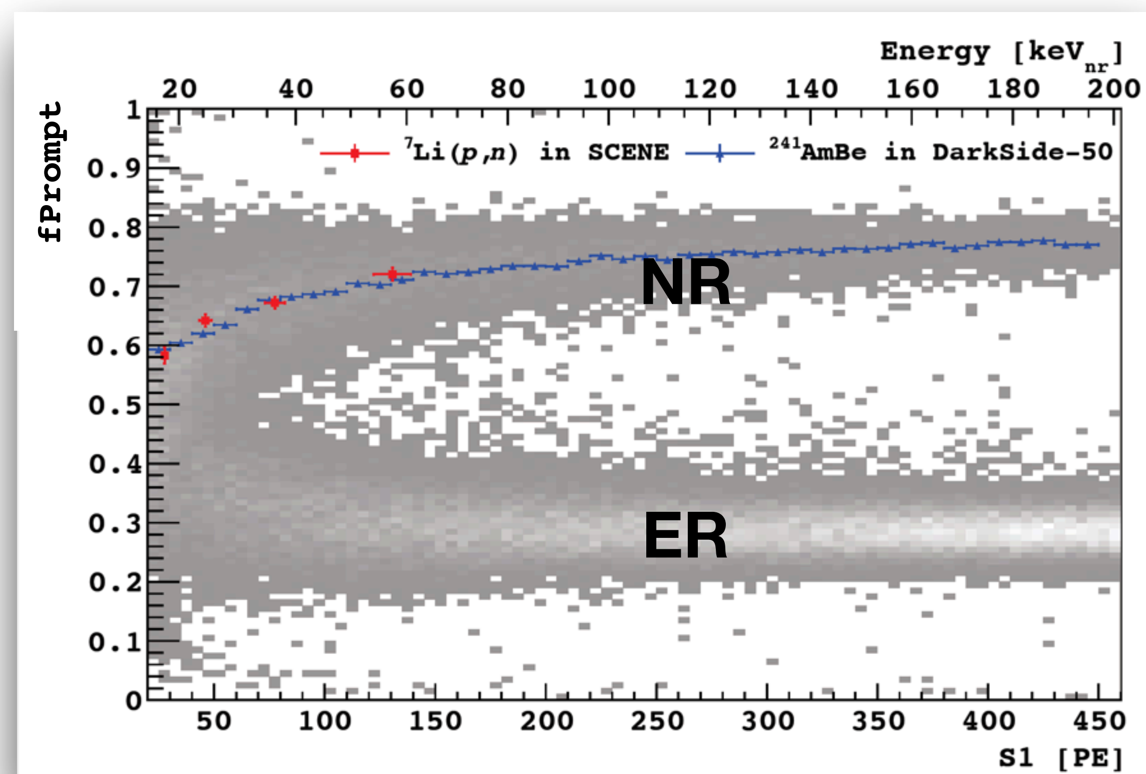
LUX: 99.75% rejection efficiency

Rejection with Pulse Shape Discrimination









ER Rejection factor: ~ 10^8 in LAr

τ_{fast} ~ 6 ns, τ_{slow} ~ 1.6 μs

The DarkSide Program

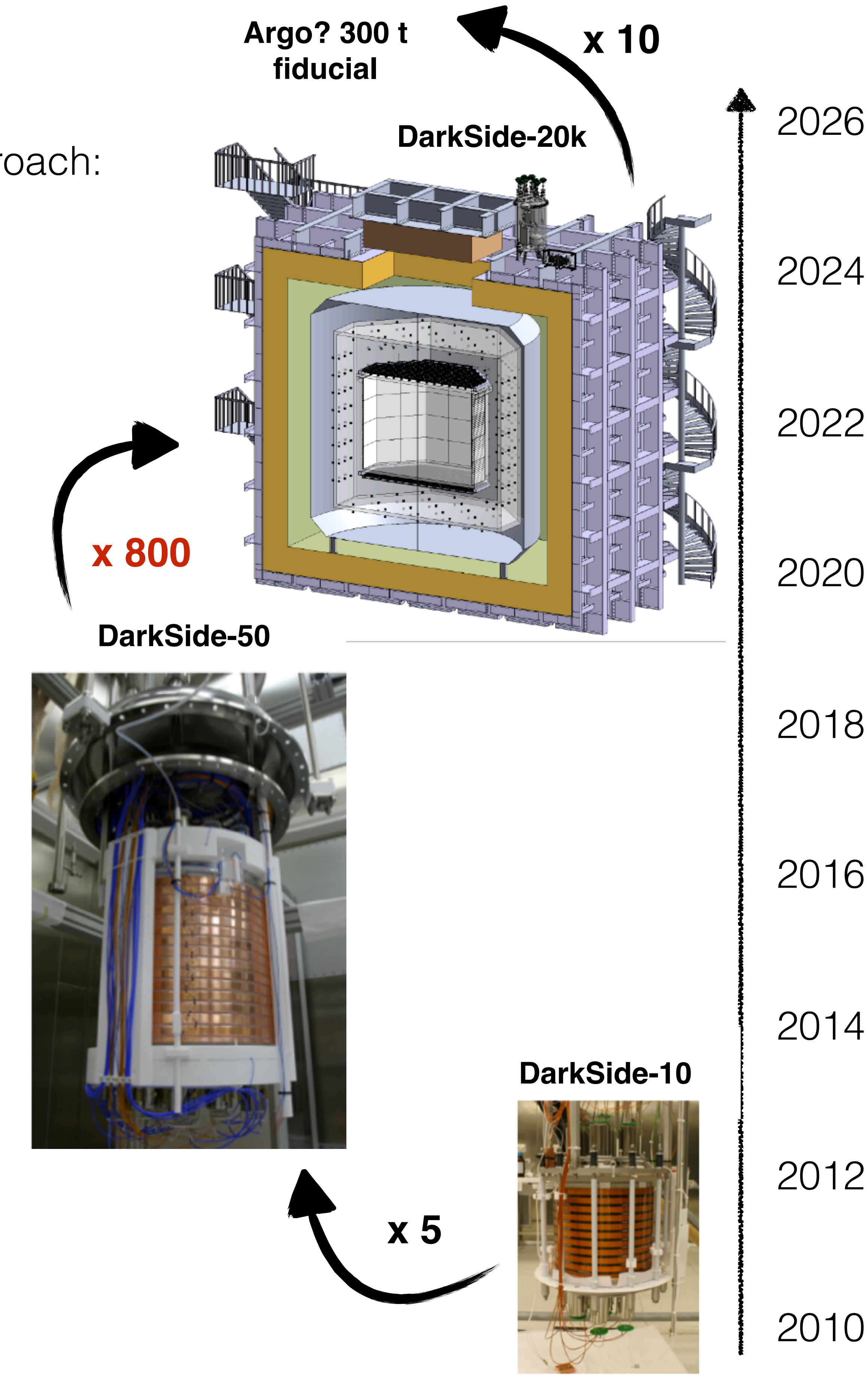
Dual phase liquid argon TPC, through a **staged** approach:

Background suppression
- Ultra-low background materials
- **Depleted Liquid Argon**
- Low background photo-detectors
- Low background material components

Background identification
- **Pulse Shape Discrimination** (PSD)
- Ionization/scintillation ratio
- Position reconstruction
  (surface events)
- Multiple scatters within the TPC

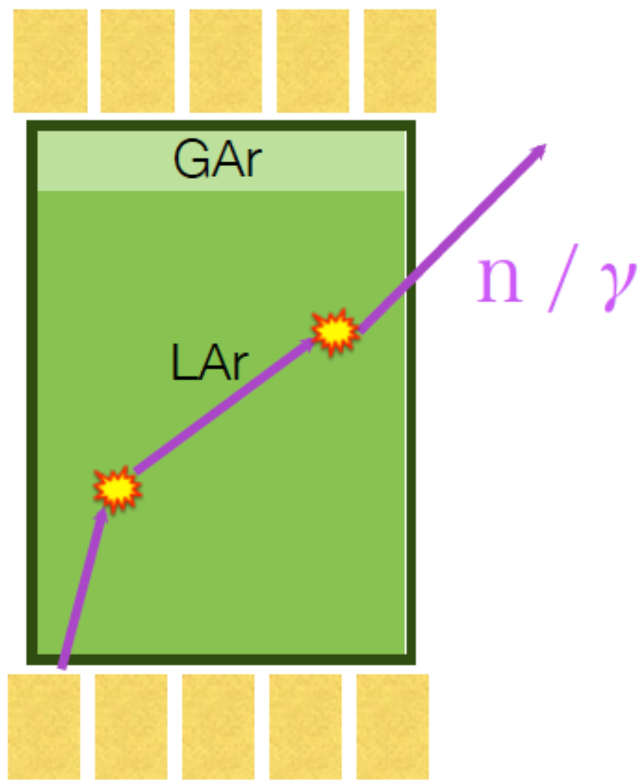
Active Shielding
- **Active Neutron Veto**
- Water Cherenkov against muons (WCD)

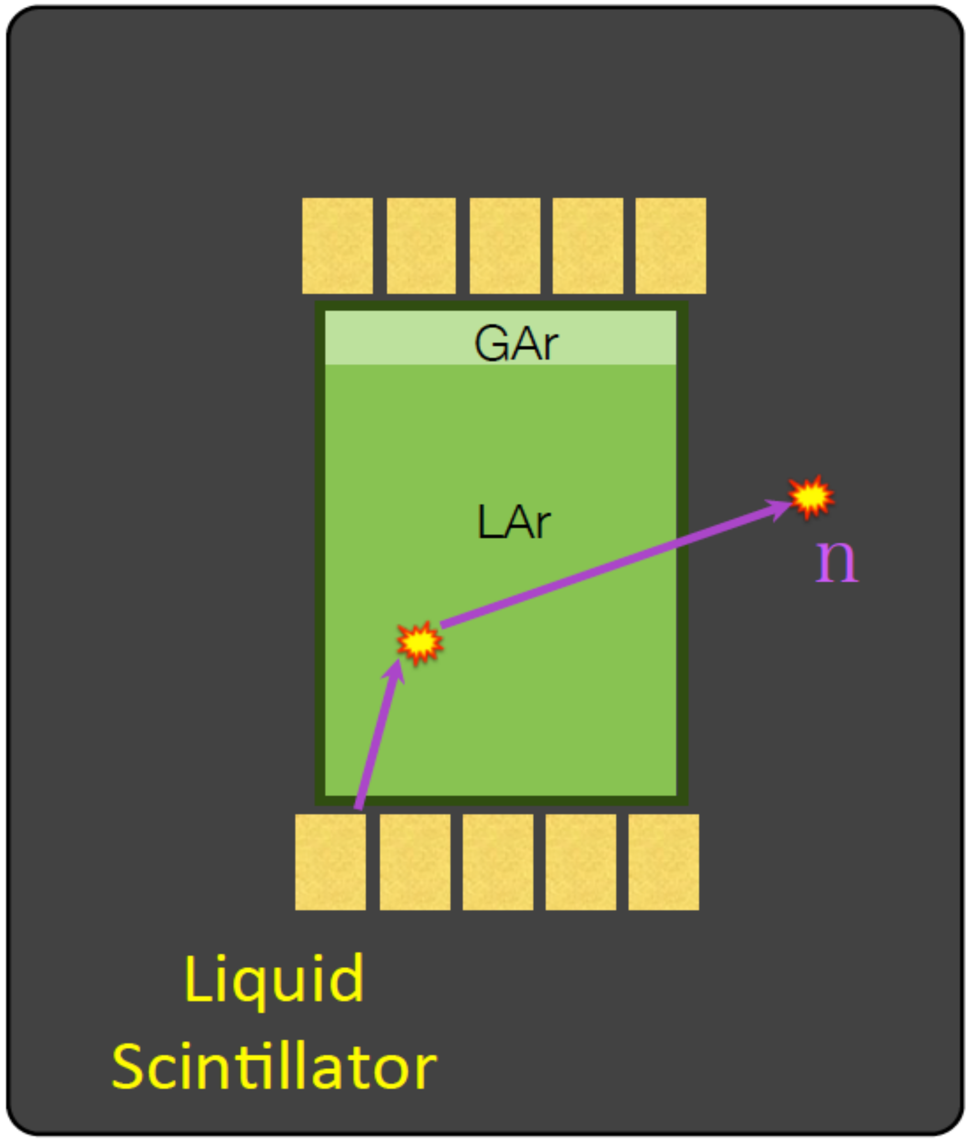
Main goal: background-free exposure



Neutron Background Rejection

Multiple S2 signal





DarkSide-50 Liquid Scintillator Veto: 30 tons of PC loaded with TMB.
The n capture produces a localized alpha (heavily quenched) and a gamma (BR>90%)

$$^{10}\mathrm{B} + n \to \begin{cases} ^{7}\mathrm{Li}\ (1015\ \mathrm{keV}) + \alpha\ (1775\ \mathrm{keV}) & (6.4\%) \\ ^{7}\mathrm{Li}^{*} + \alpha\ (1471\ \mathrm{keV}),^{7}\mathrm{Li}^{*} \to^{7}\mathrm{Li}\ (839\ \mathrm{keV}) + \gamma\ (478\ \mathrm{keV}) & (93.6\%) \end{cases}$$

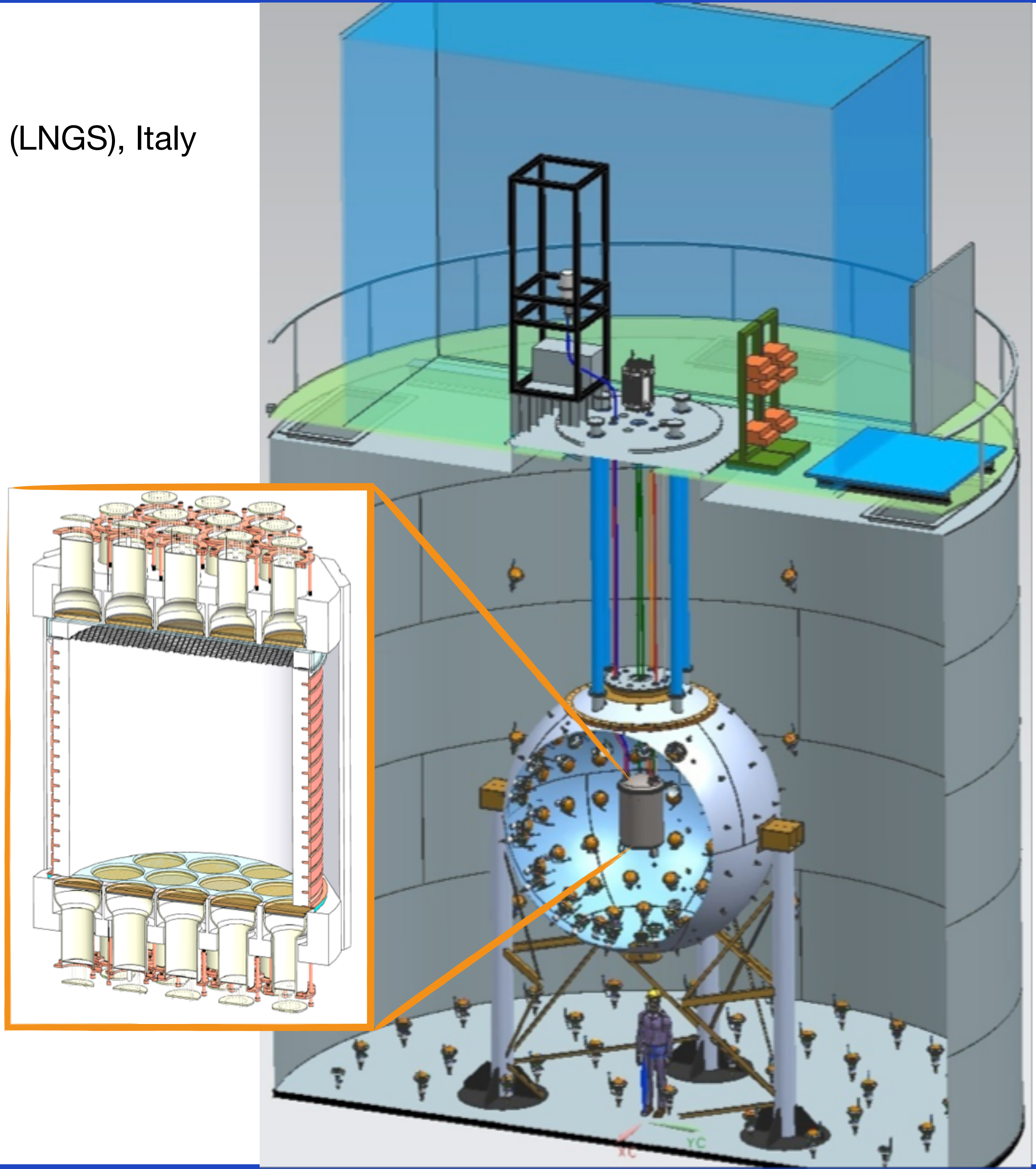
The DarkSide-50 experiment

At *Laboratori Nazionali del Gran Sasso* (LNGS), Italy

Liquid argon TPC
- **50 kg LAr**
- **19 + 19 3" PMTs**
- Reflectors and TPB coating

Liquid Scintillator Veto (LSV)
- 30 tons, 2 m radius
- 110 PMTs (LY = 0.5 pe/keV)

Water Cherenkov Detector (WCD)
- 1 kt water, 5.5 m radius
- 80 PMTs



DarkSide-50 operations

Oct 2013: first data with AAr fill
- **S1 LY of 8.0 PE/keV** (@41 keV null-field)
- excellent electron lifetime (>5 ms)

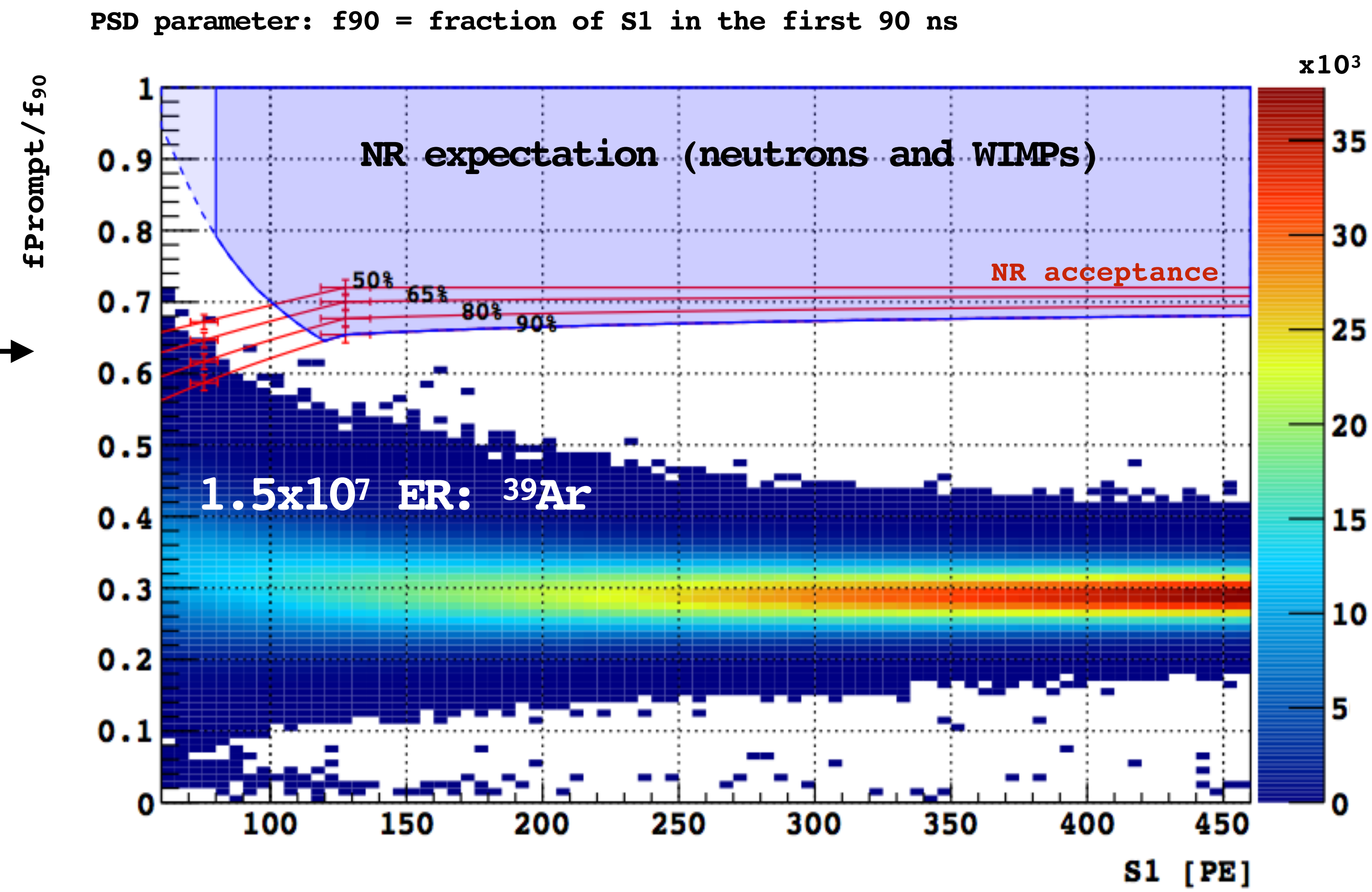
Feb 2014: first null result (50 days)
- **rejection power of PDS in LAr**

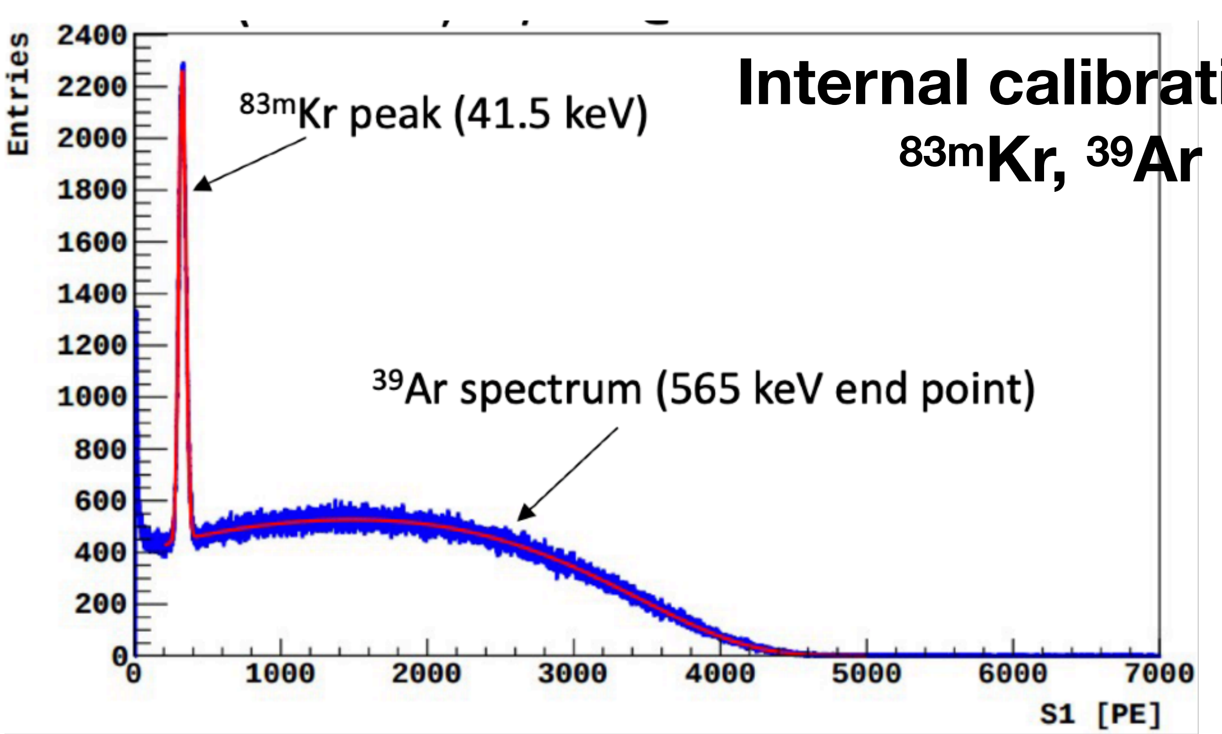
Apr 2015: filling with UAr

Jul 2015: end of **70 days campaign**
- **first use of UAr**

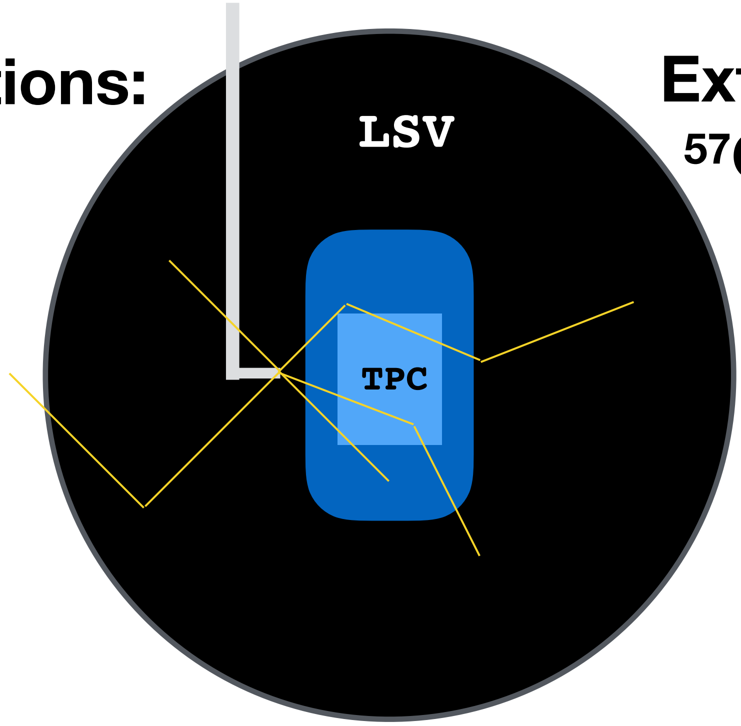
'15-'17: **blind data taking** and analysis

2018: null results at High- and Low- Mass



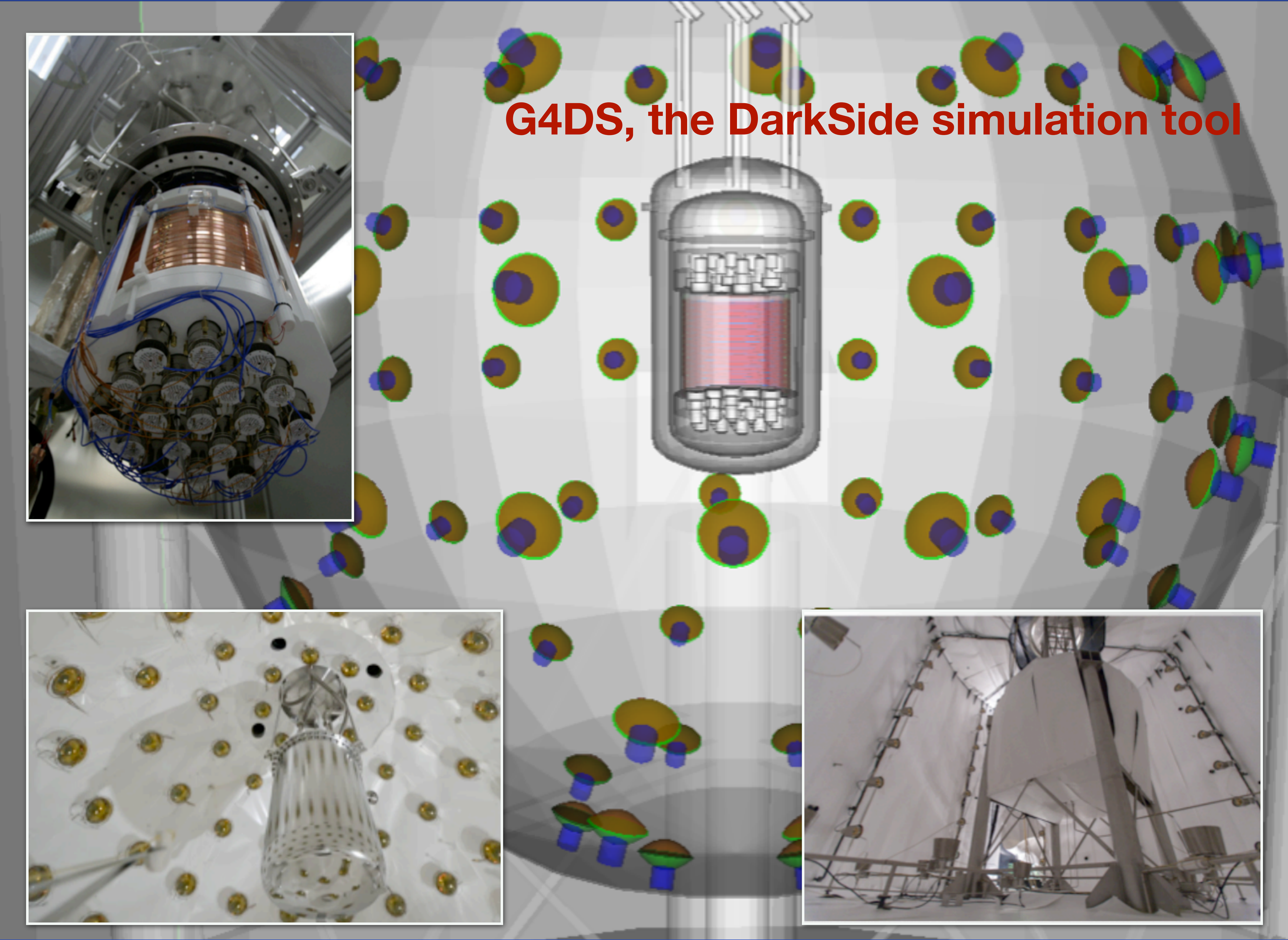


Internal calibrations:
^{83m}Kr, ^{39}Ar



External calibrations:
^{57}Co, ^{133}Ba, ^{137}Cs (γ)
AmBe, AmC (n)

G4DS, the DarkSide simulation tool



G4DS

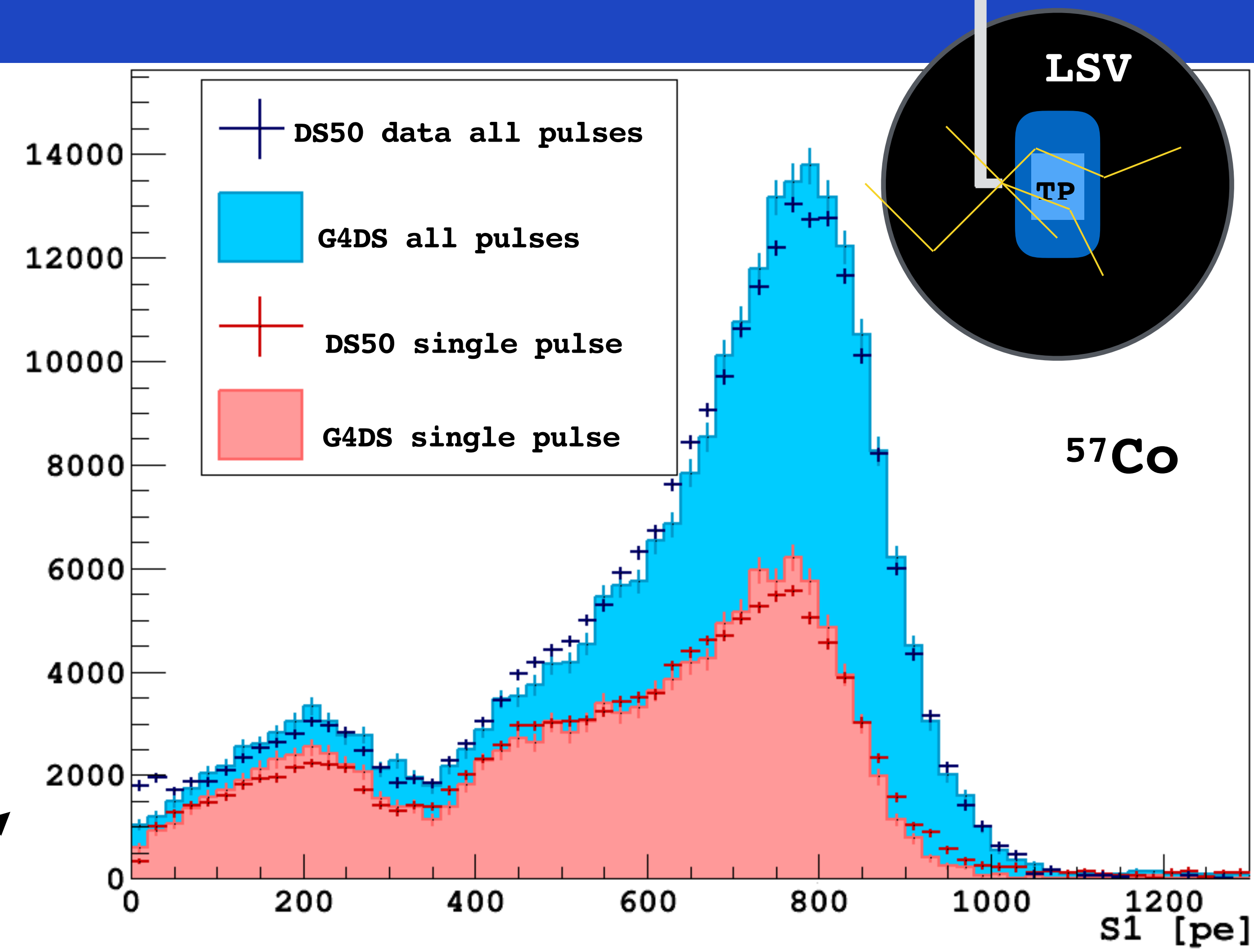
- Optical tuning: TPC response

- Scintillation time characteristic for PSD

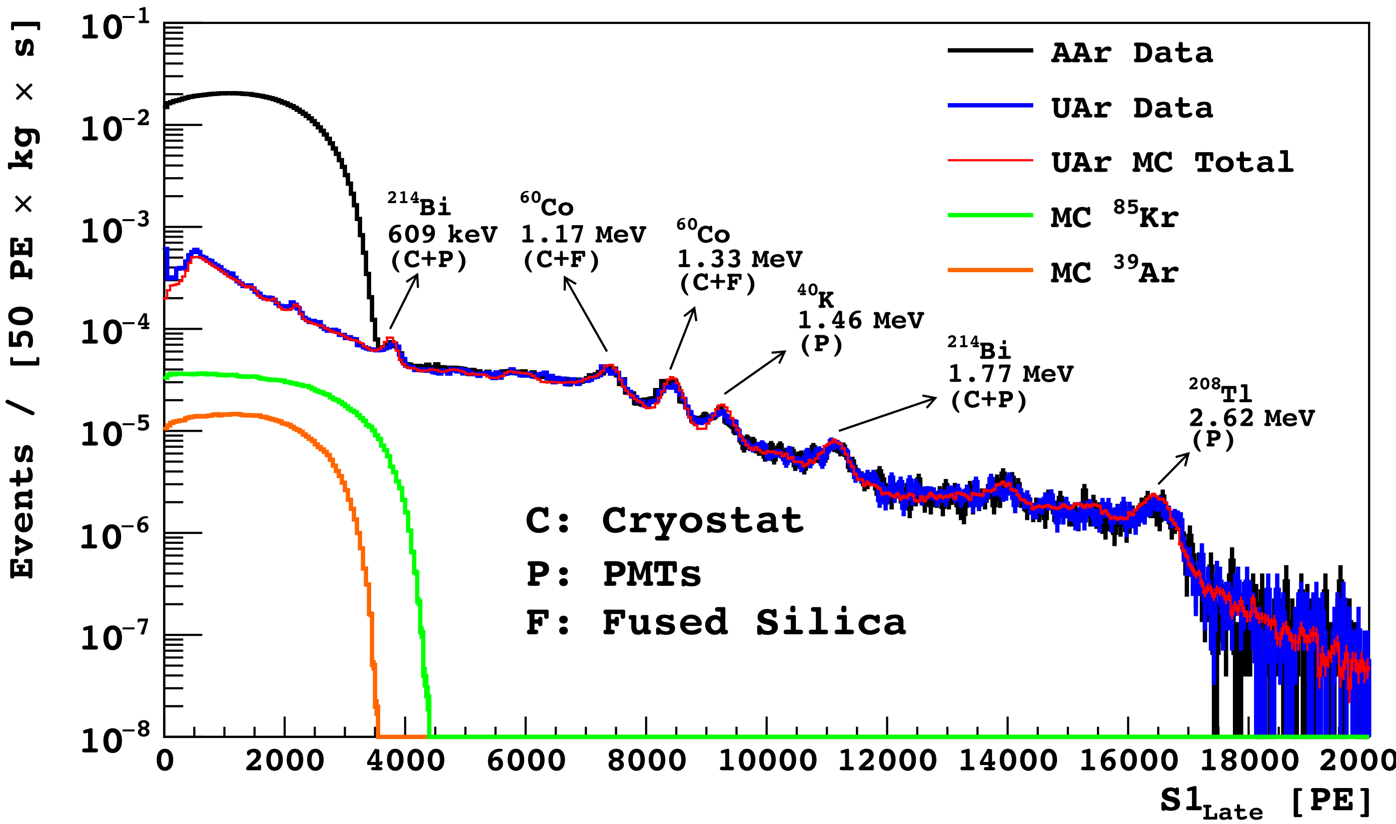
- Simulation of reconstruction

- **Energy scale for ER**: effective model based on extraction of recombination probability

Cross checked with external calibrations:



Multivariate fit, exploiting energy and topology of ER events:



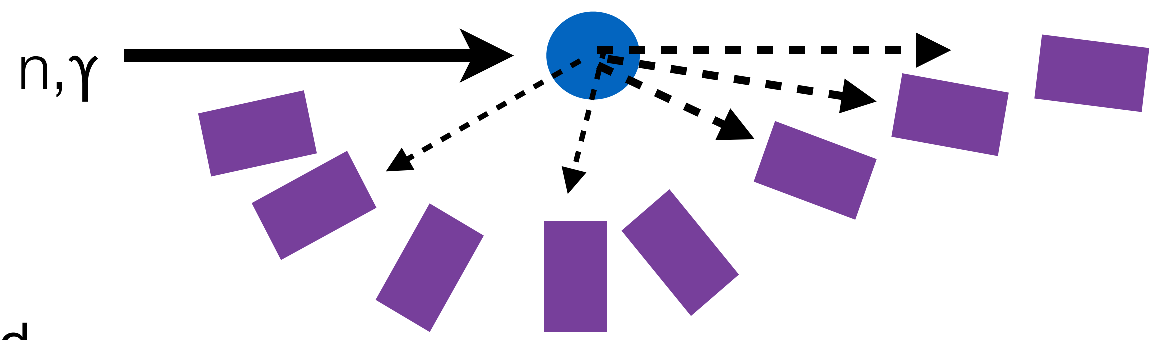
MC spectra from detector materials

Good agreement with screening measurements

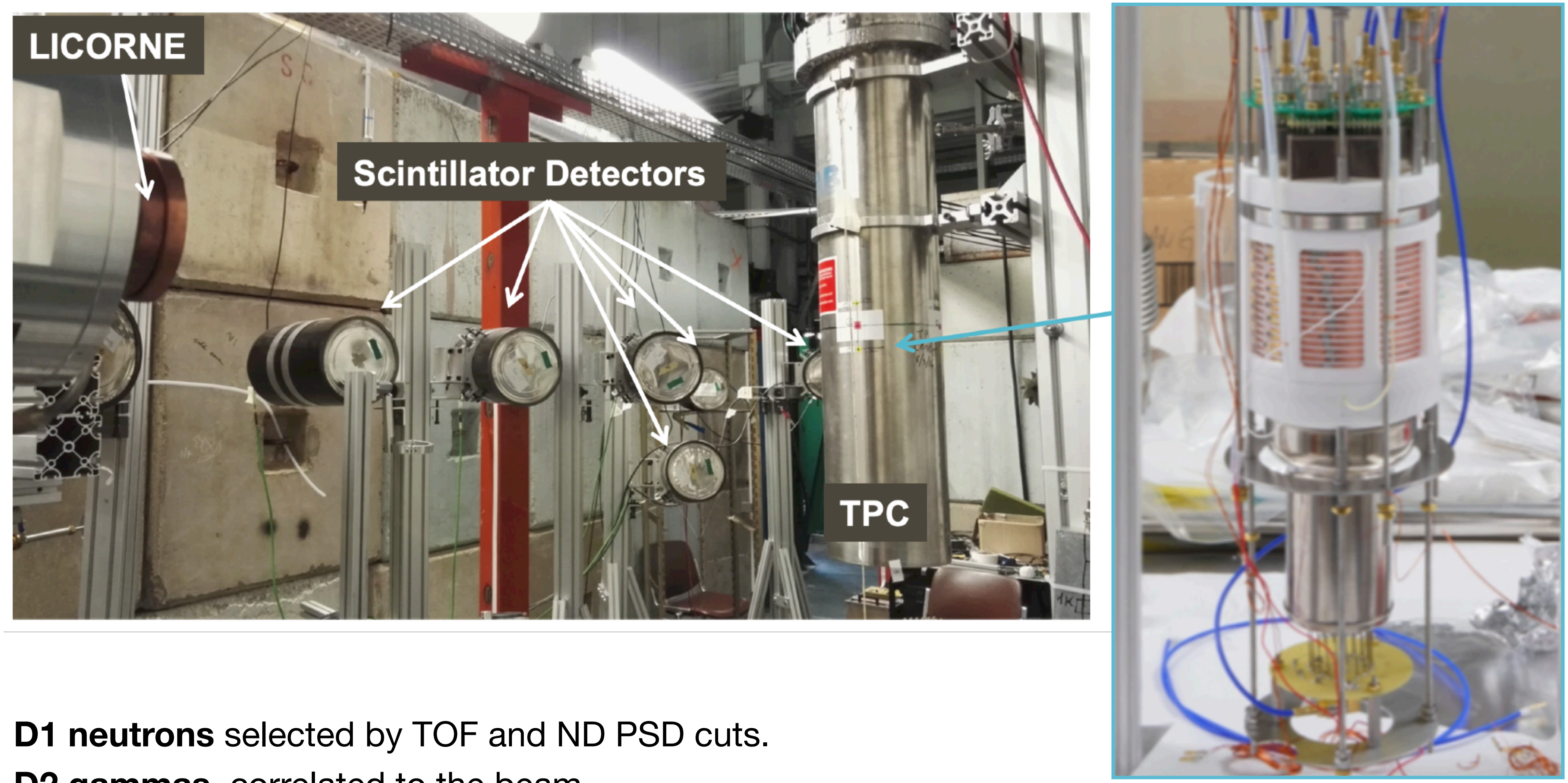
Measure ^{39}Ar content in UAr and ^{85}Kr

NR calibration: the ARIS experiment

Main goal: L_{eff} at low energy (scintillation efficiency of NR's)



Expose a small scale TPC to a **pulsed**, **collimated**, **mono-chromatic** neutron beam (LICORNE @IPNO, Paris), coupled with 8 neutron detectors, to fix NR energy by kinematics.

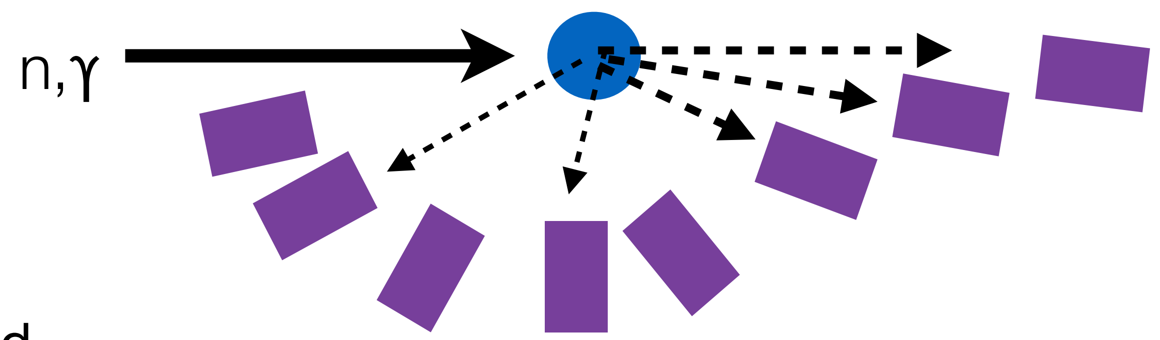


D1 neutrons selected by TOF and ND PSD cuts.

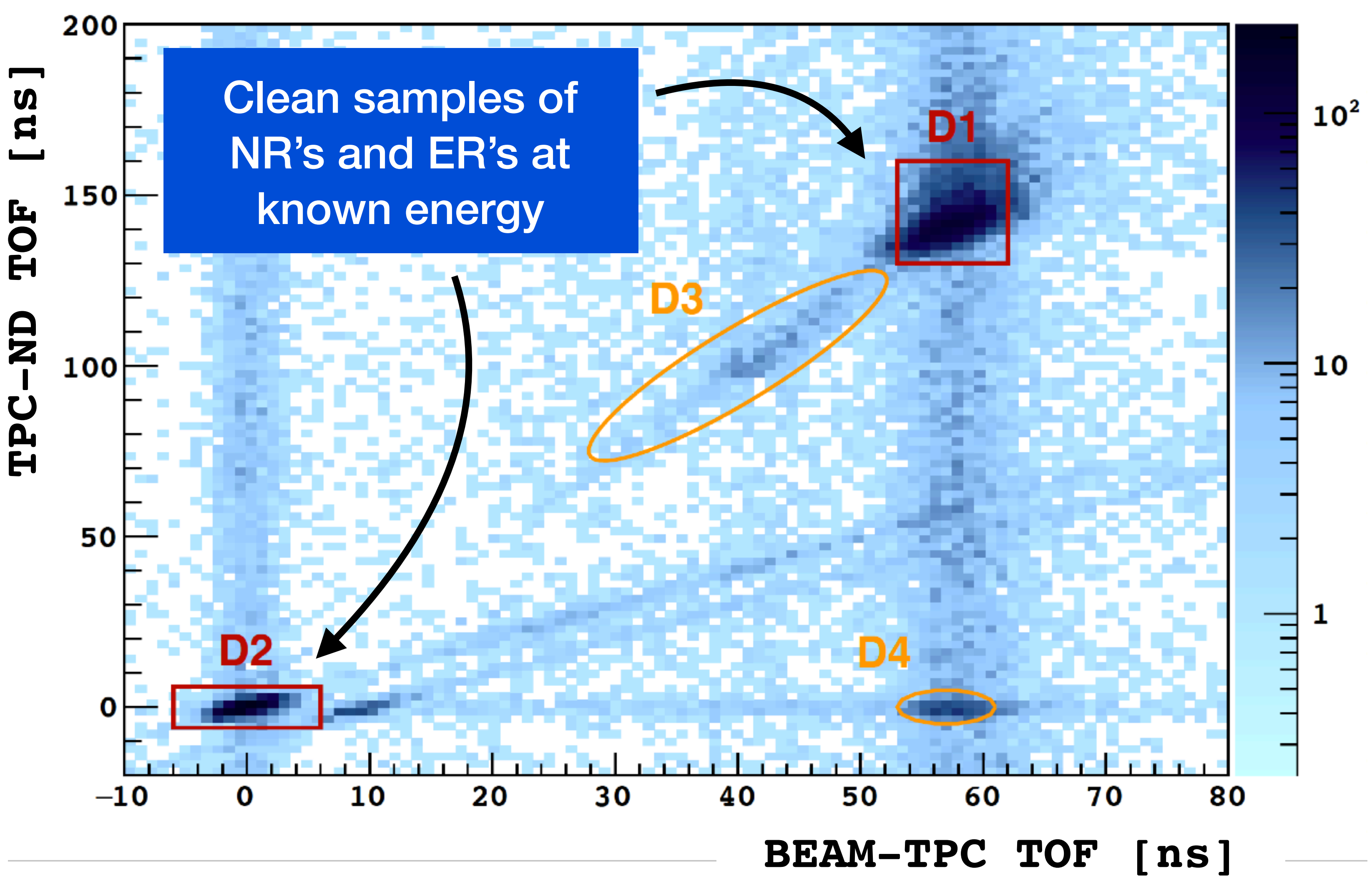
D2 gammas, correlated to the beam.

NR calibration: the ARIS experiment

Main goal: L_{eff} at low energy
(scintillation efficiency of NR's)



Expose a small scale TPC to a **pulsed**, **collimated**, **mono-chromatic** neutron beam (LICORNE @IPNO, Paris), coupled with 8 neutron detectors, to fix NR energy by kinematics.

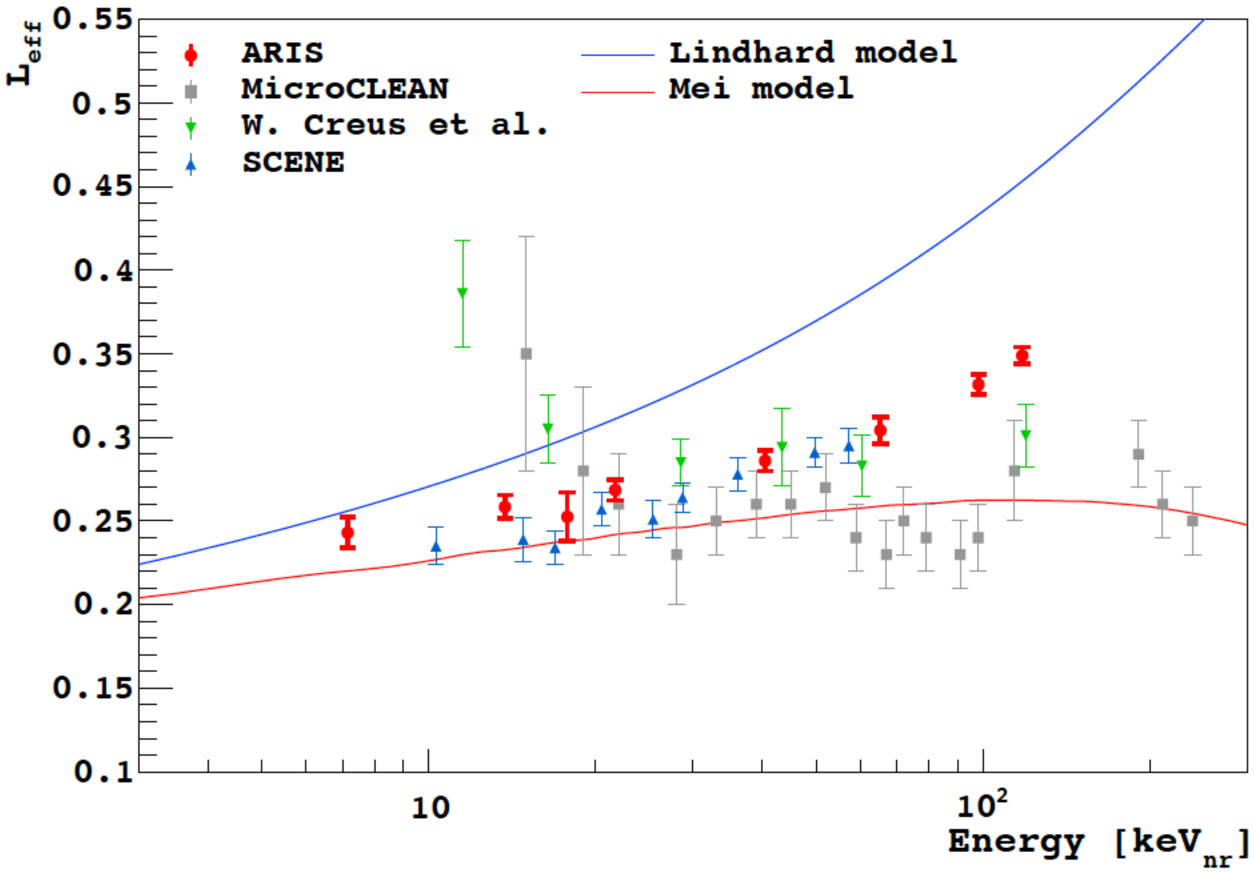


D1 neutrons selected by TOF and ND PSD cuts.

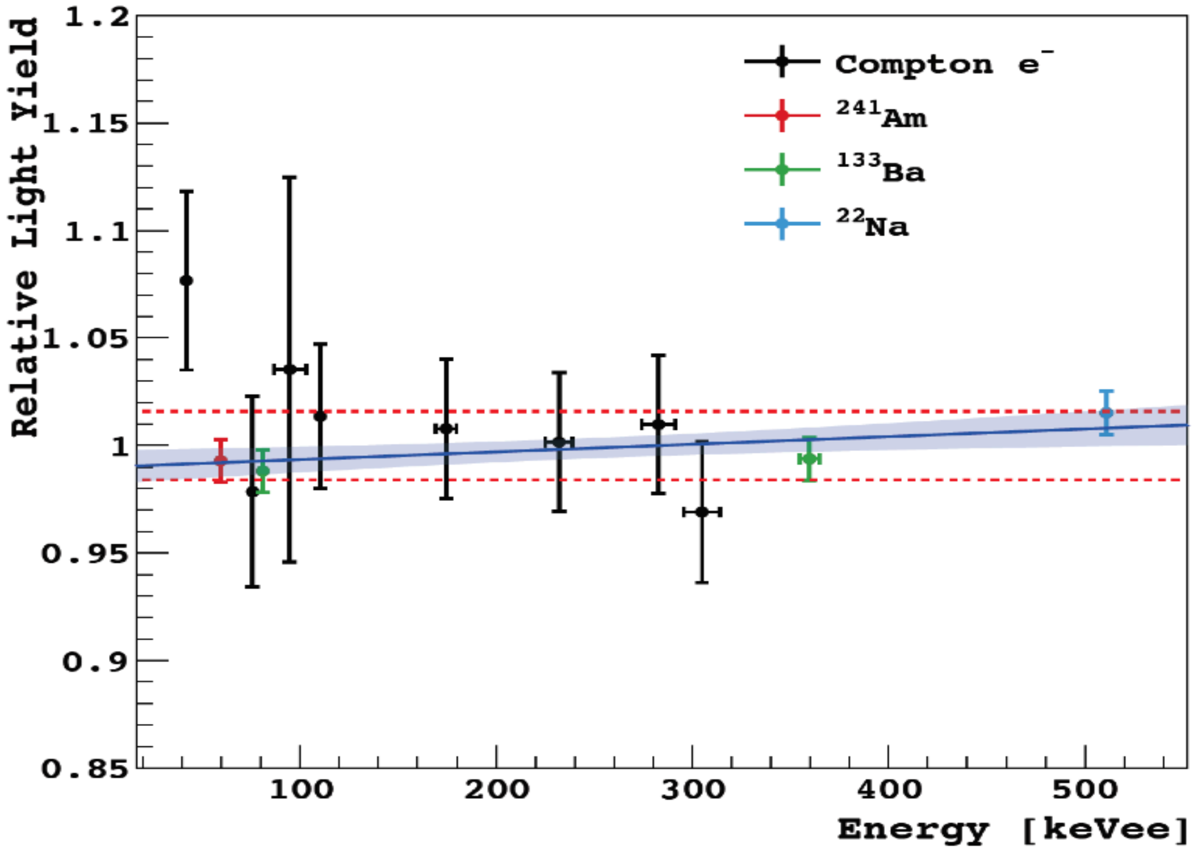
D2 gammas, correlated to the beam.

The ARIS results

Precision L_{eff} at low energy



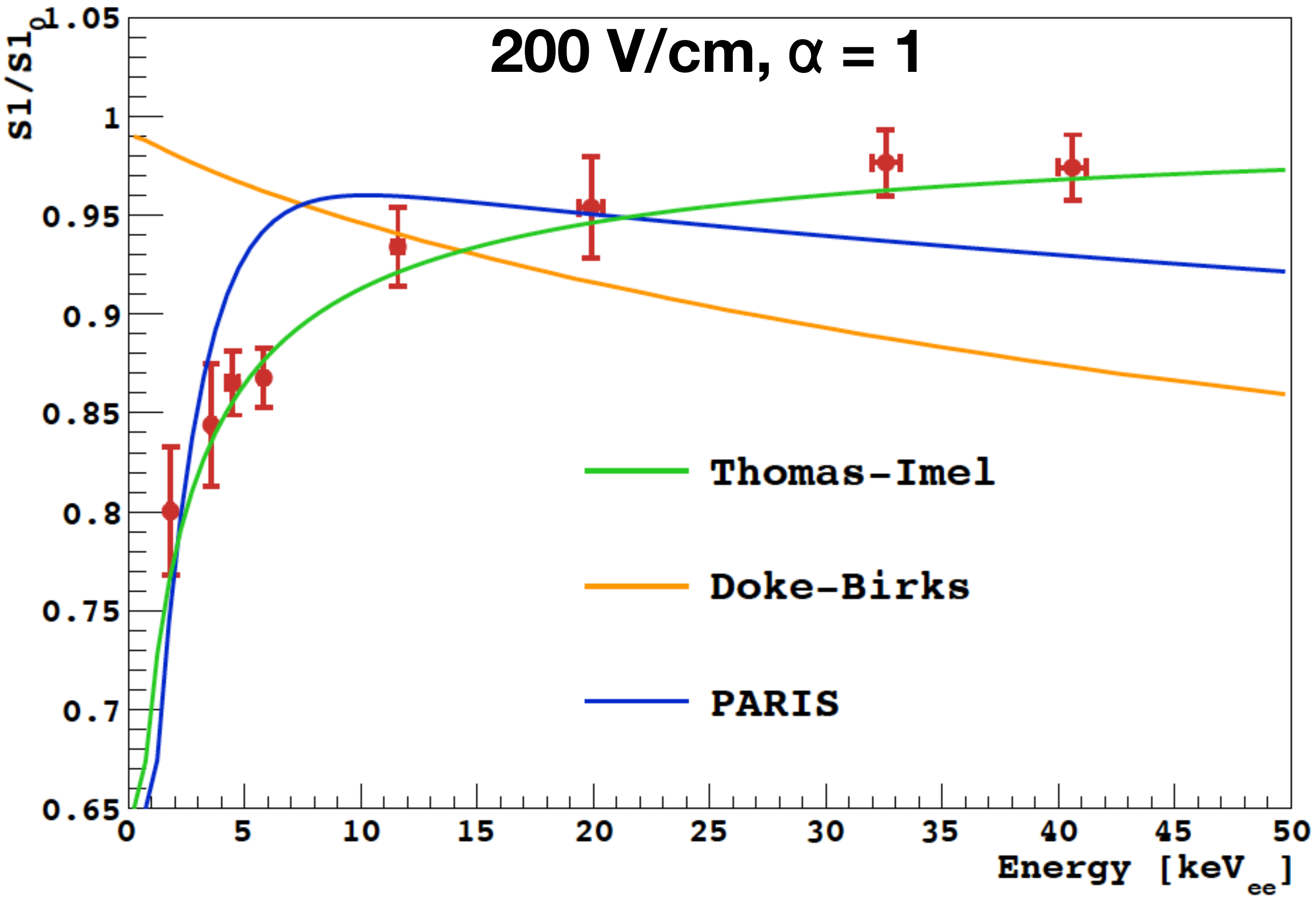
LAr ER linearity

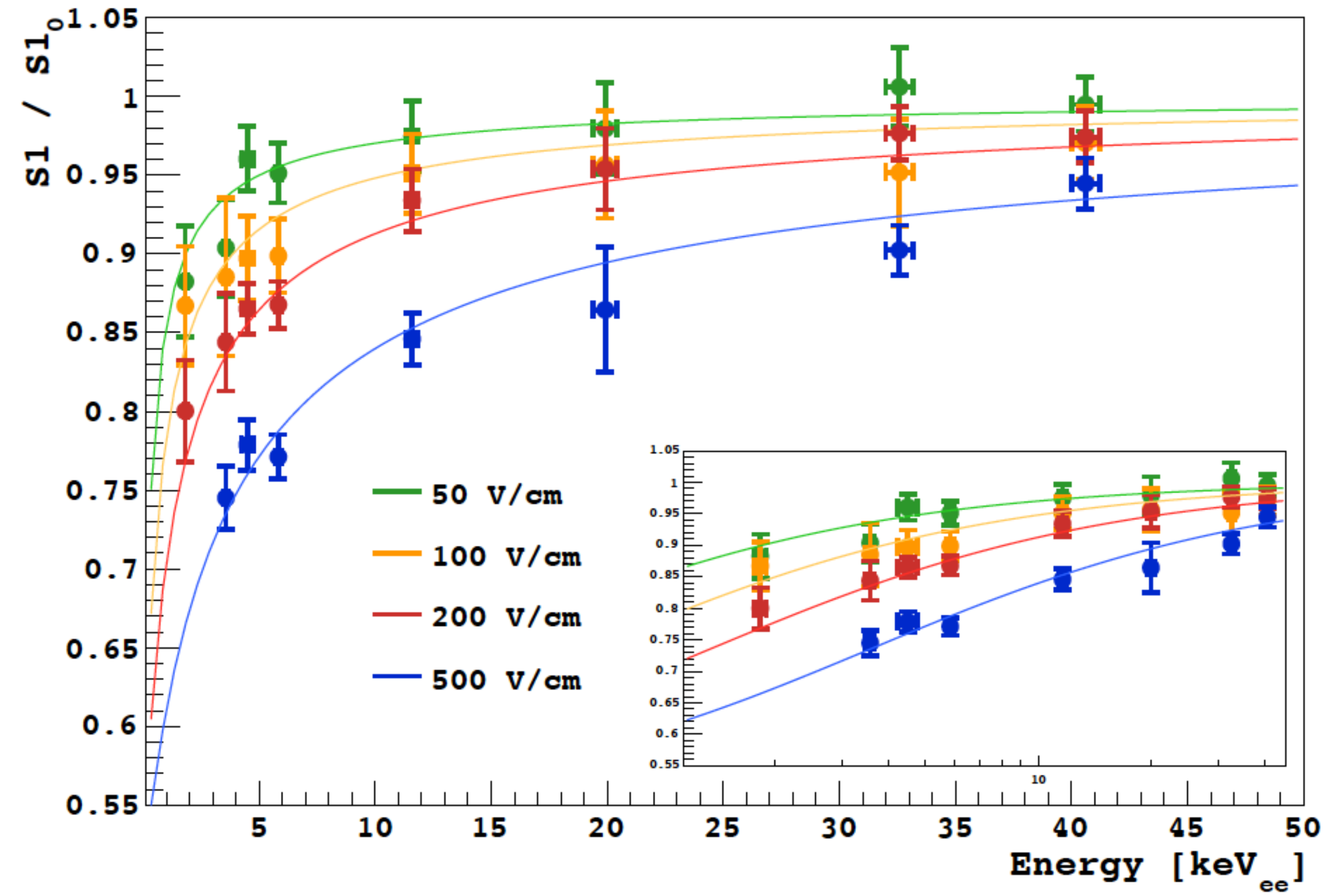


Precise measurement of L_{Eff} parameter down to 7.1 keV_{NR}.

Linearity of LAr response to ER at null field assessed within 1.6% using the Compton induced single ER and external calibration sources

ARIS: Field dependence, NR





S1^F/ S1^0 (E) = (α + R(E)) / (1 + α)

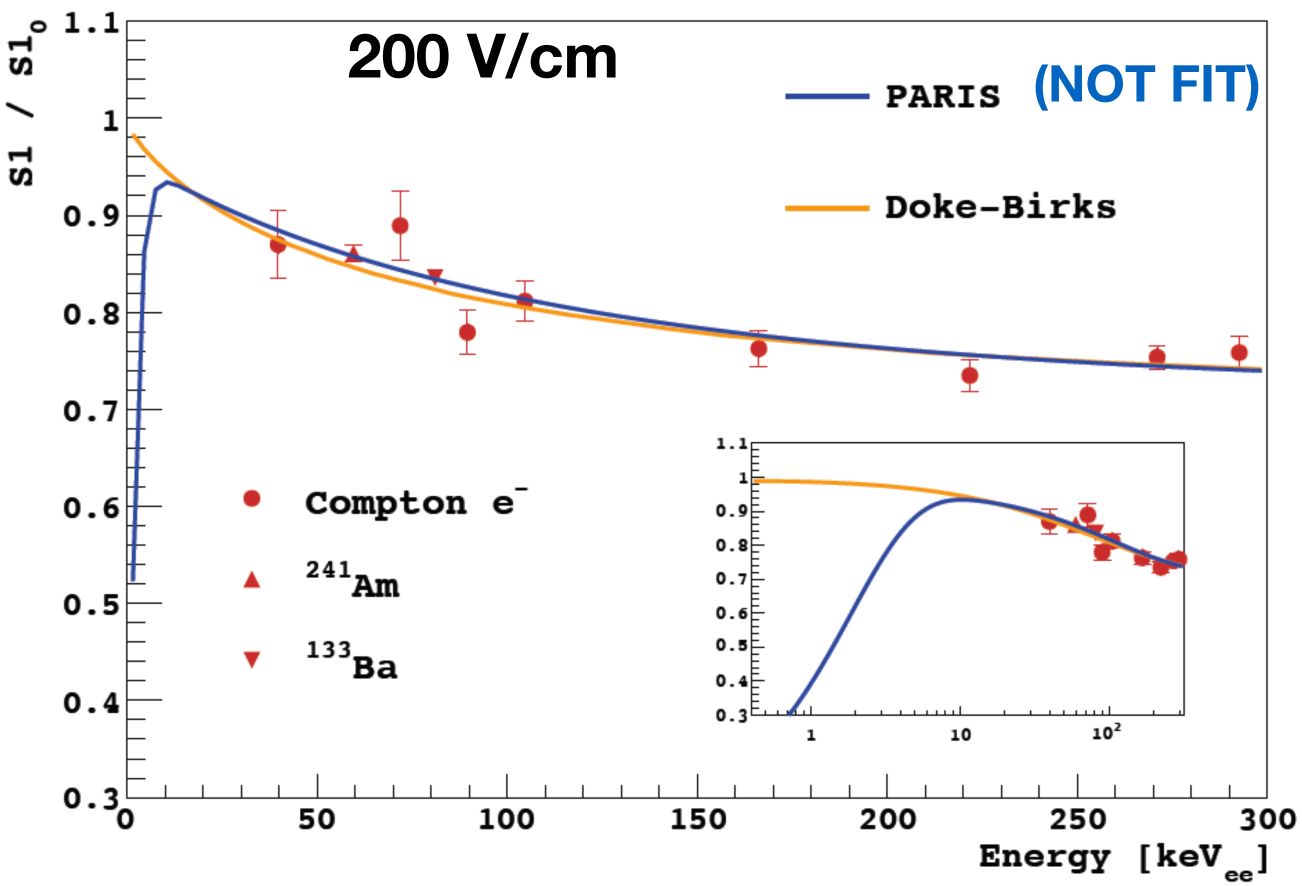
Fixing α = 1 to break the degeneracy between **R** and **α** (do not measure charge).
The Thomas-Imel model is favored
Thomas-Imel also describes the field induced scintillation quenching with **b ~ 1** and **C ~ 18.5**.
N_i is number of free ions.

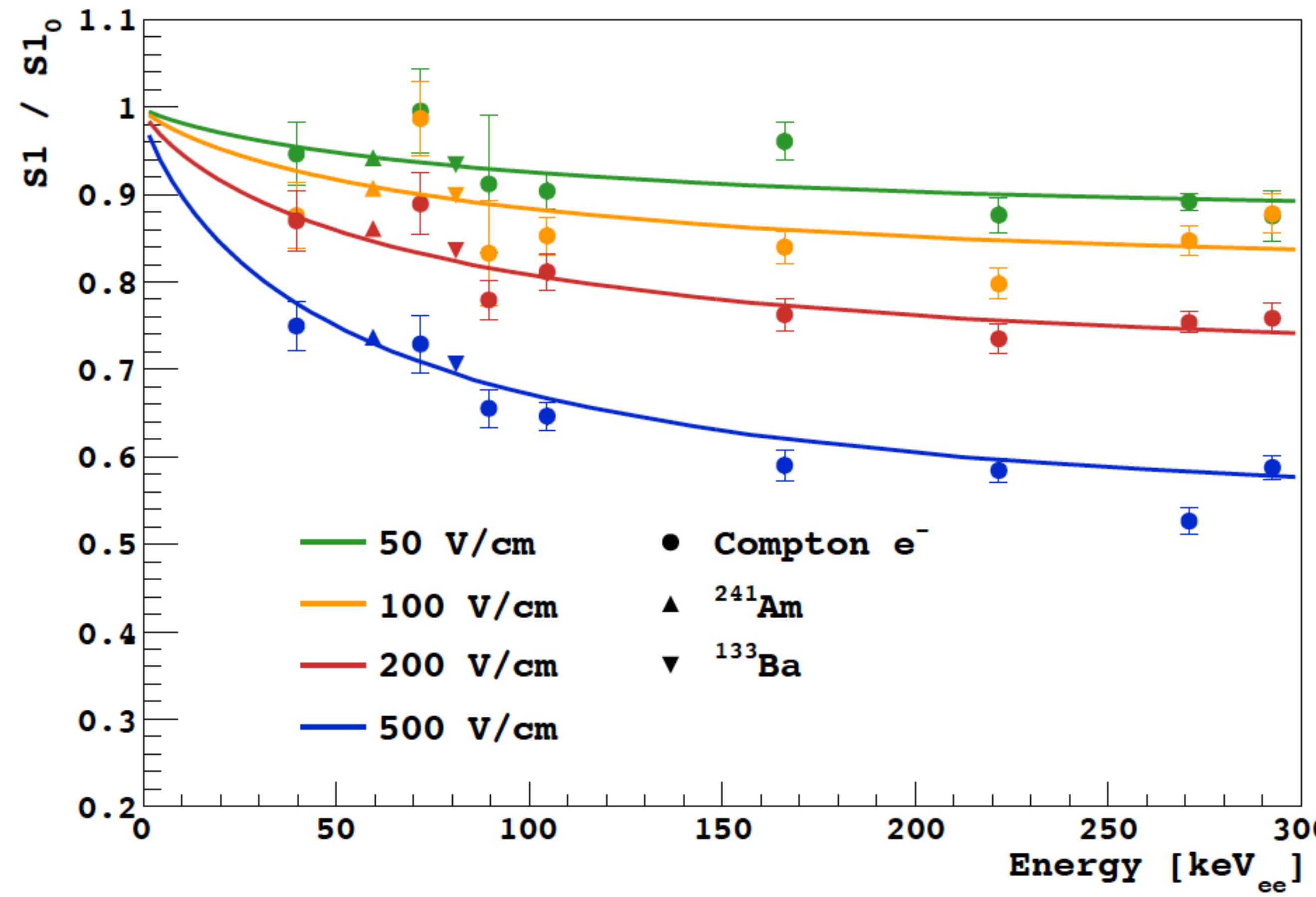
$$\boxed{R = 1 - \frac{ln(1+\xi)}{\xi}}$$

$$\xi = C_{box}\frac{N_i}{F^{\beta}}$$

F: field

ARIS: Field dependence, ER





$$S1^F / S1^0 (E) = (\alpha + R(E)) \;/\; (1 + \alpha)$$

Testing the **model** developed for **DarkSide**.
For **E >20 keV, Doke-Birks** model fits well (fails at low E) and describes field dependence.

$$\boxed{R = \frac{A\ dE/dx}{1 + B\ dE/dx} + C e^{-D \times F}}$$

A ~ 2.5E-3 cm/MeV
C ~ 0.77
B ~ A/(1-C)
D ~ 3.5E-3 cm/V

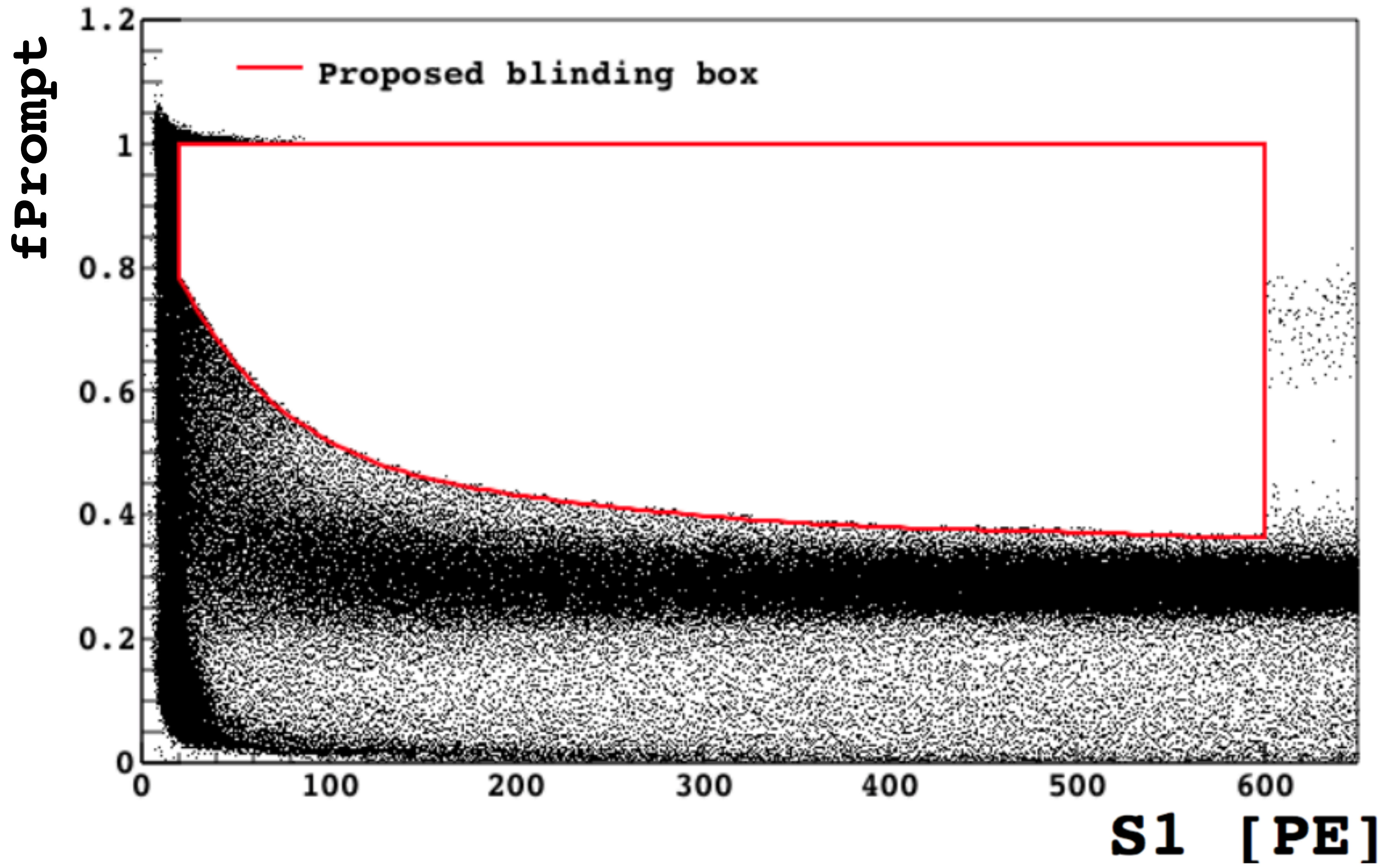
dE/dx: e- StP
F: field

A comprehensive effective model for the response of LAr to **ER** and **NR** is available in the energy range of interest for **WIMP searches**

High-mass analysis

532 days exposure, **blind analysis.** Goal: draw the contours of WIMP search region

by requiring 0.1 surviving bg events in the full exposure

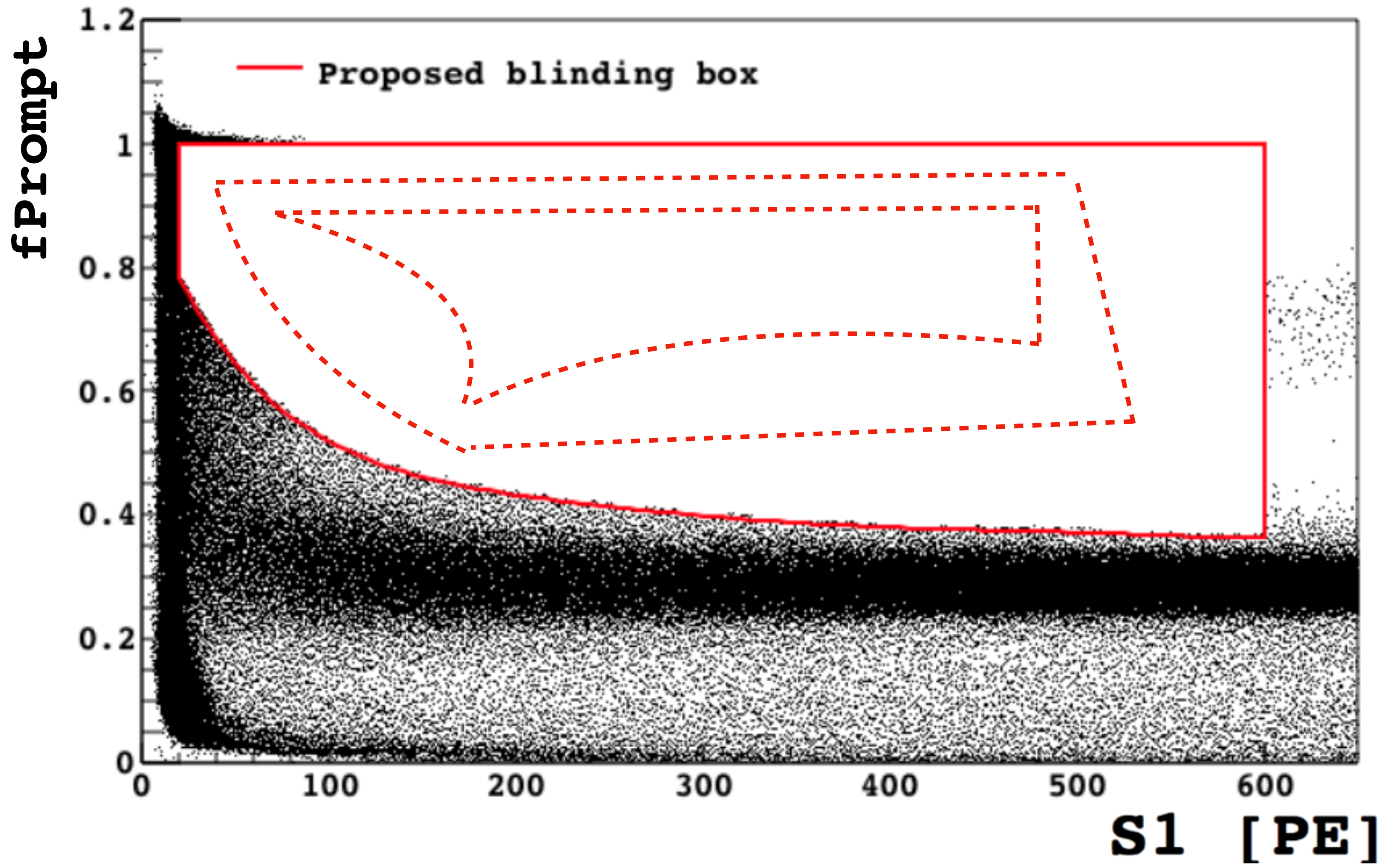


single sited events

500 days dataset

High-mass analysis

532 days exposure, **blind analysis.** Goal: draw the contours of WIMP search region **by requiring 0.1 surviving bg events in the full exposure**

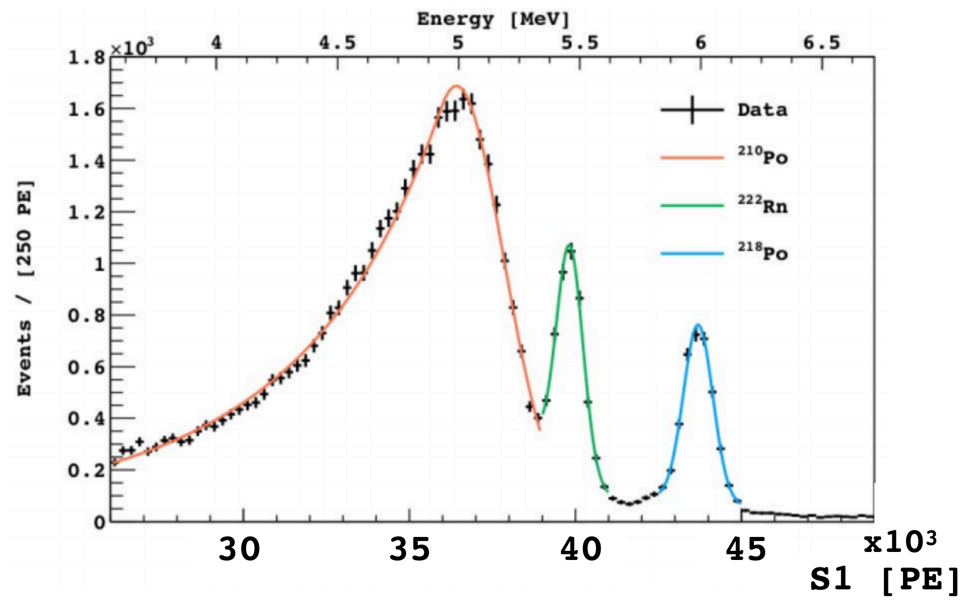


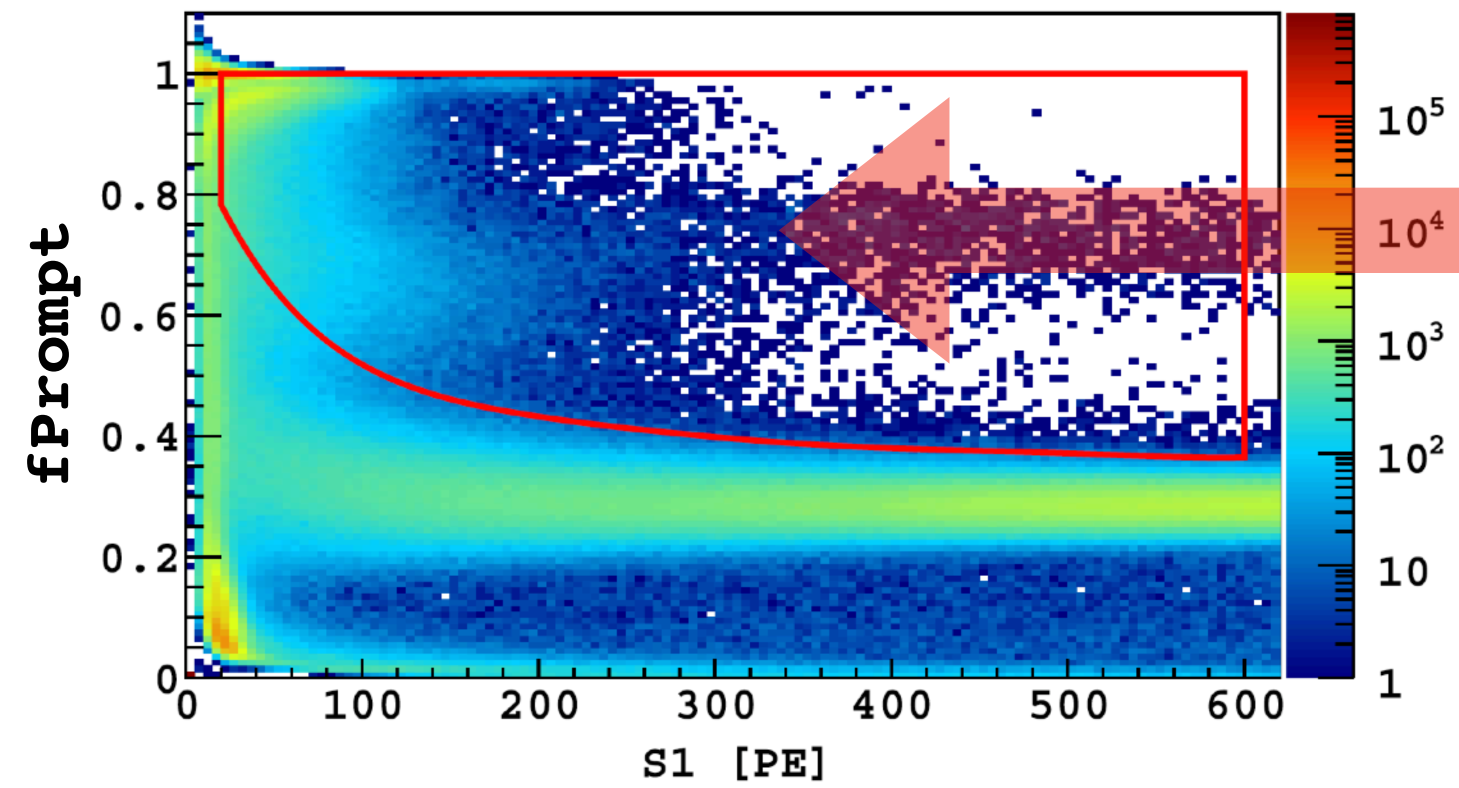
Tune models and MC on open:
- 70 days UAr dataset
- 50 days AAr dataset
- calibration data

Main backgrounds are:
internal and external β and γ's
surface α's
cosmogenics and radiogenic neutrons
γ + Cherenkov

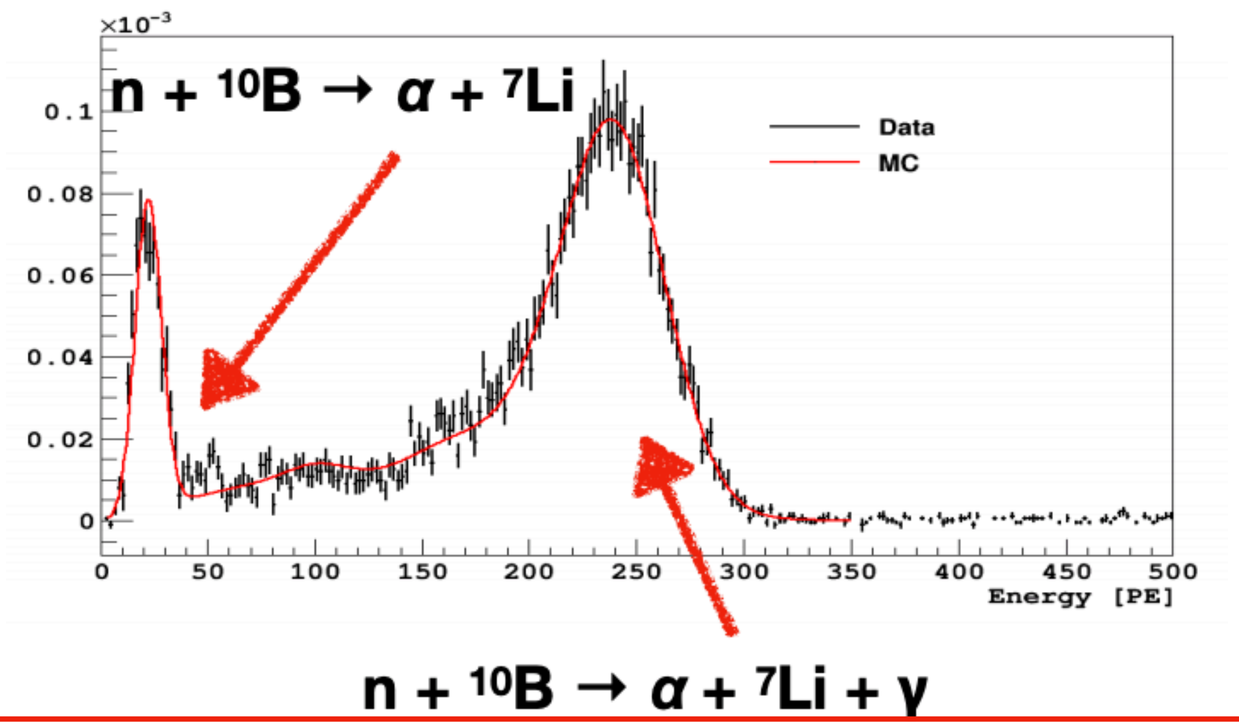
High-mass analysis - NR background

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

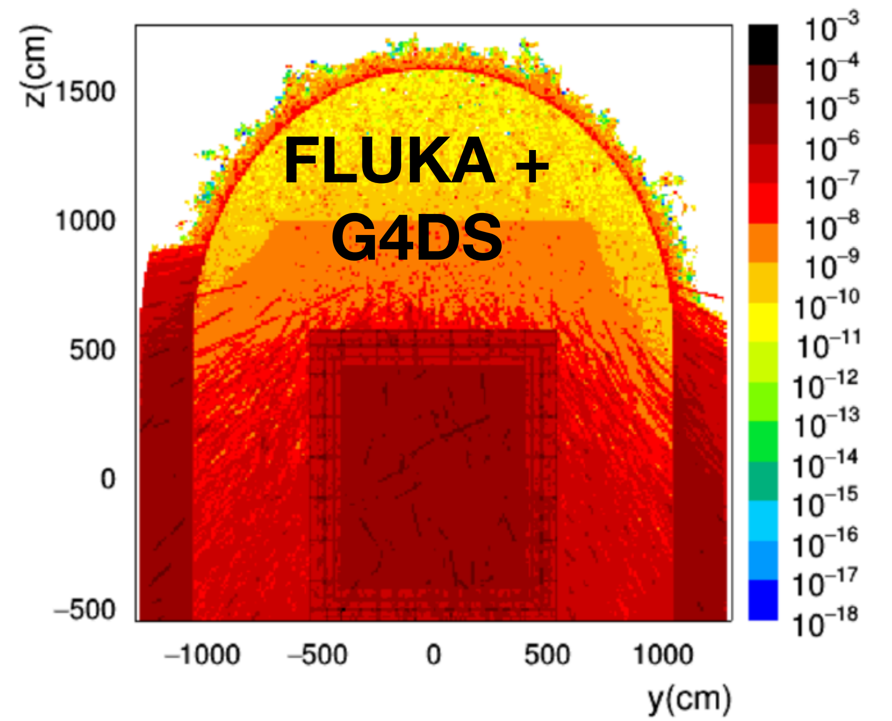




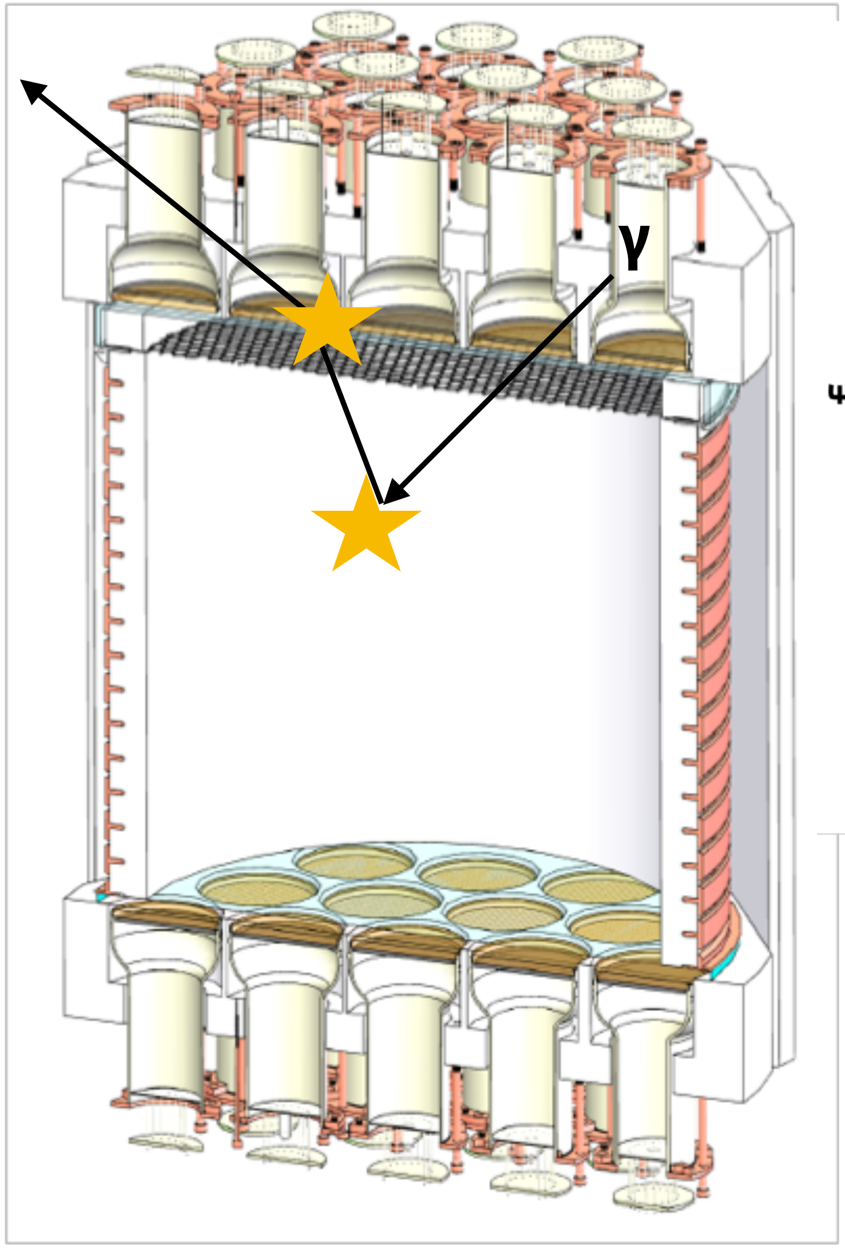
Radiogenic neutrons tagged by the veto.
Efficiency: estimated with G4DS and measured with external n sources

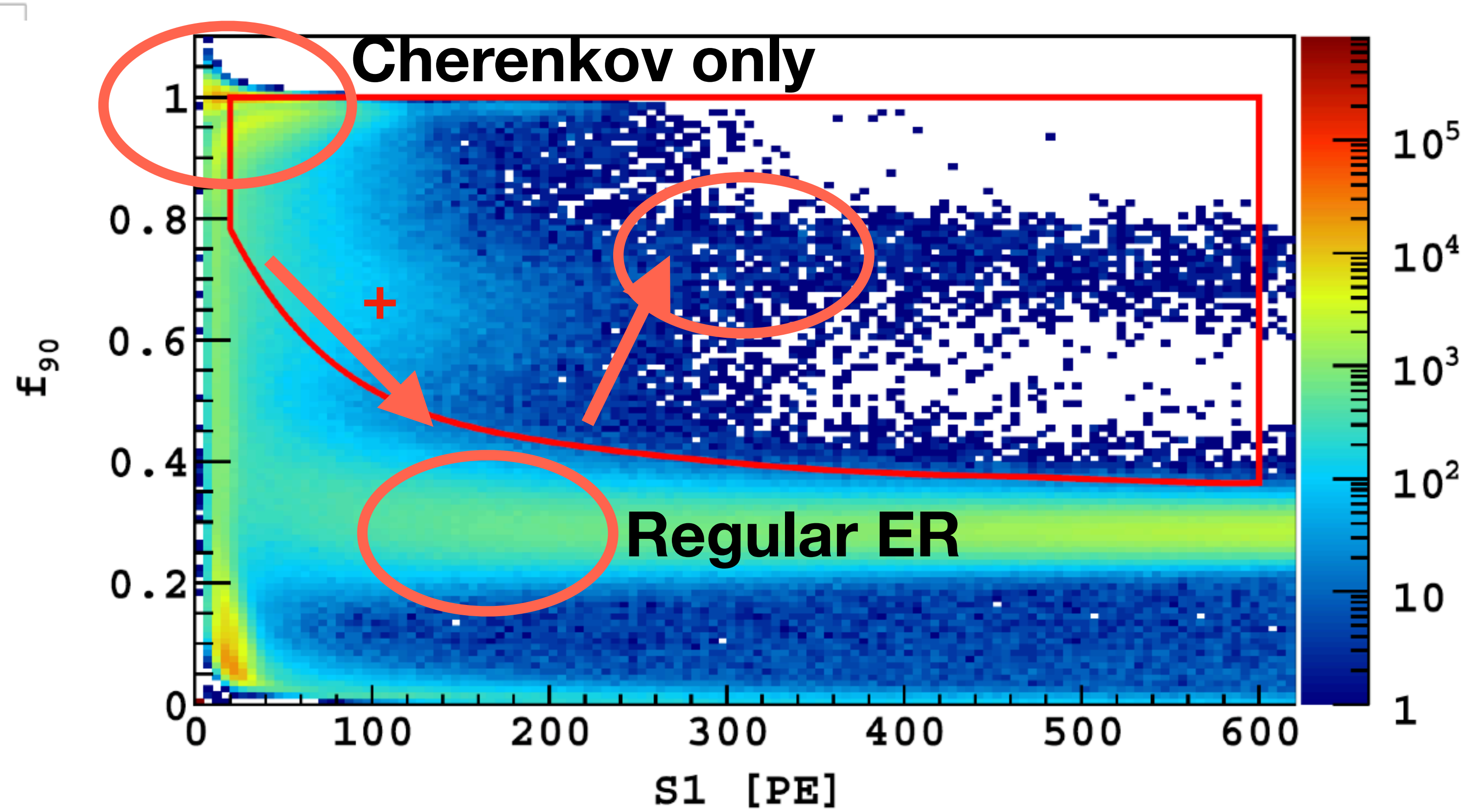


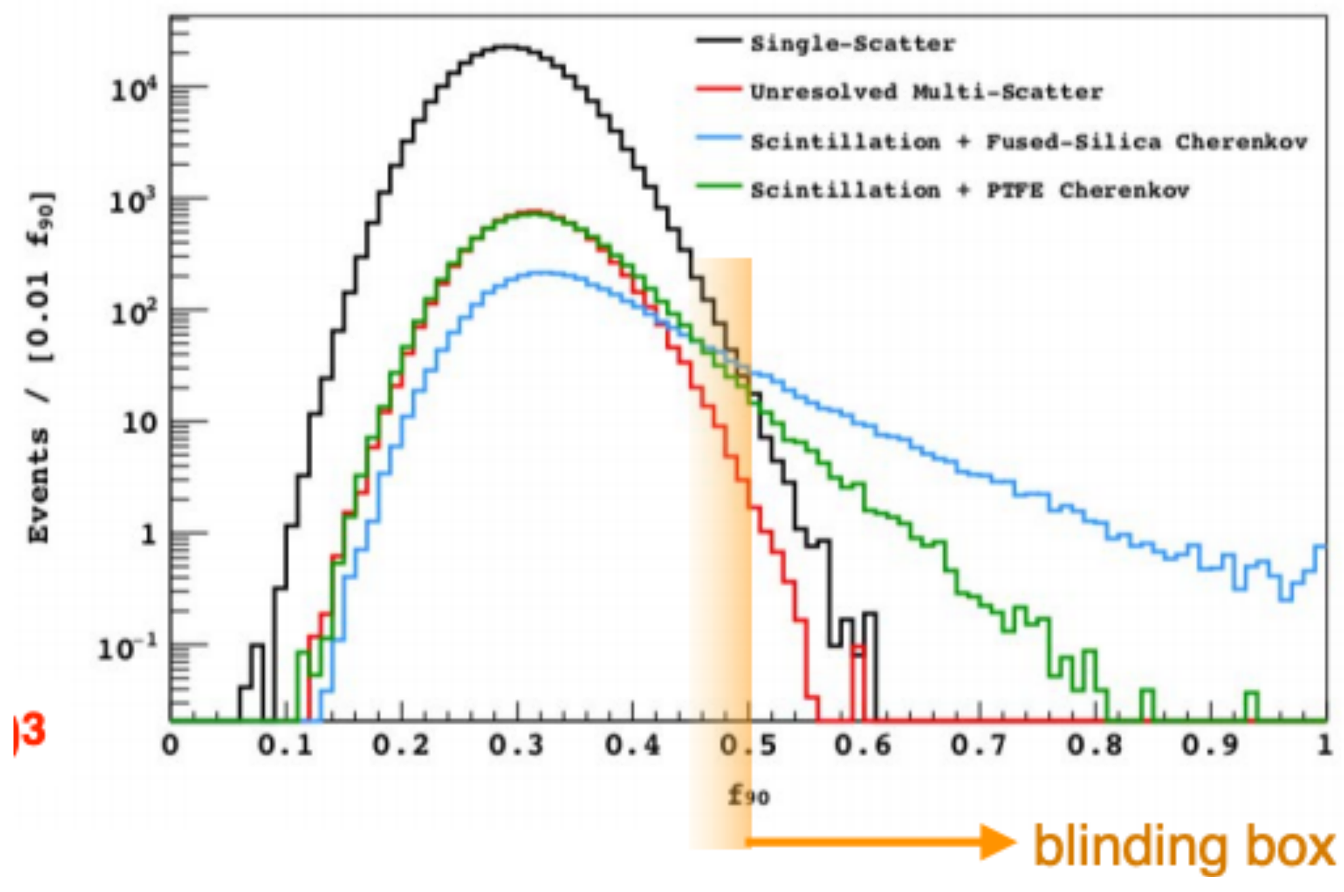
Cosmogenic n background simulated with FLUKA + G4DS. Tagged by vetoes



High-mass analysis - ER background







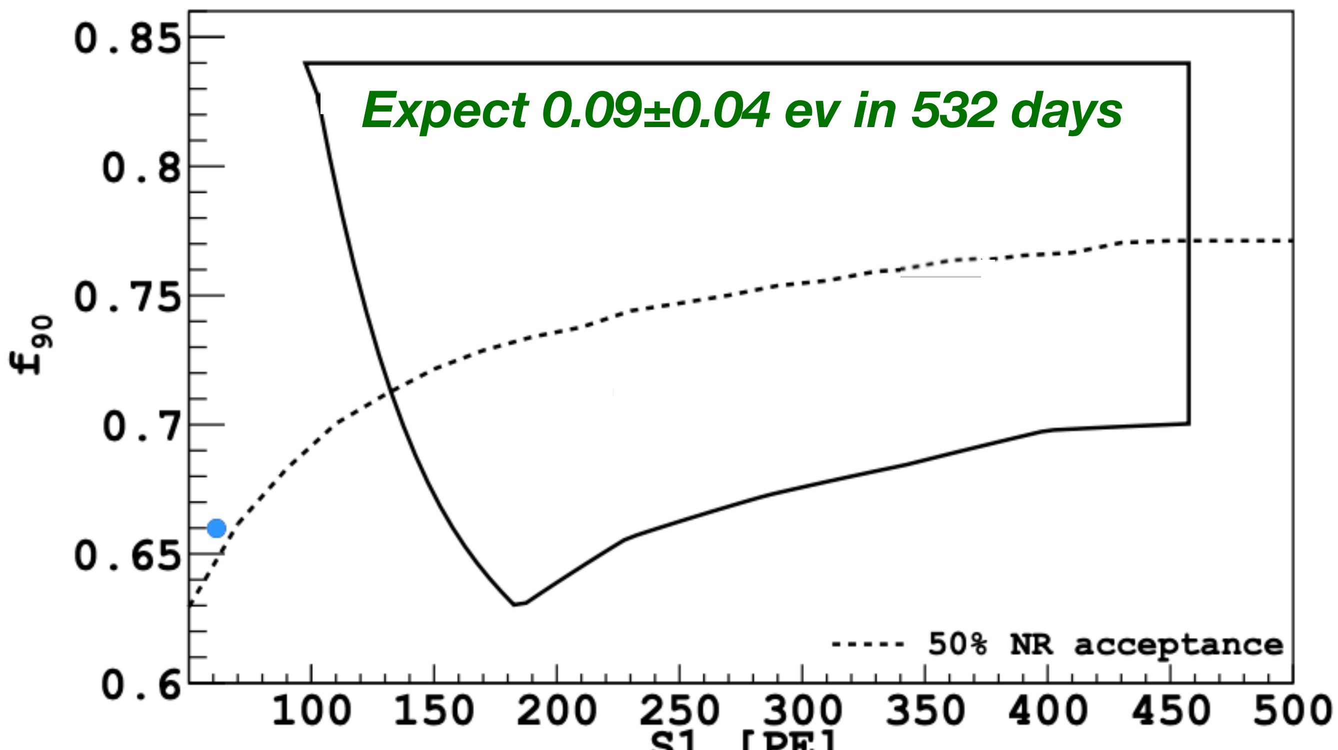
Developed:
- Topological cuts
- dedicated MC

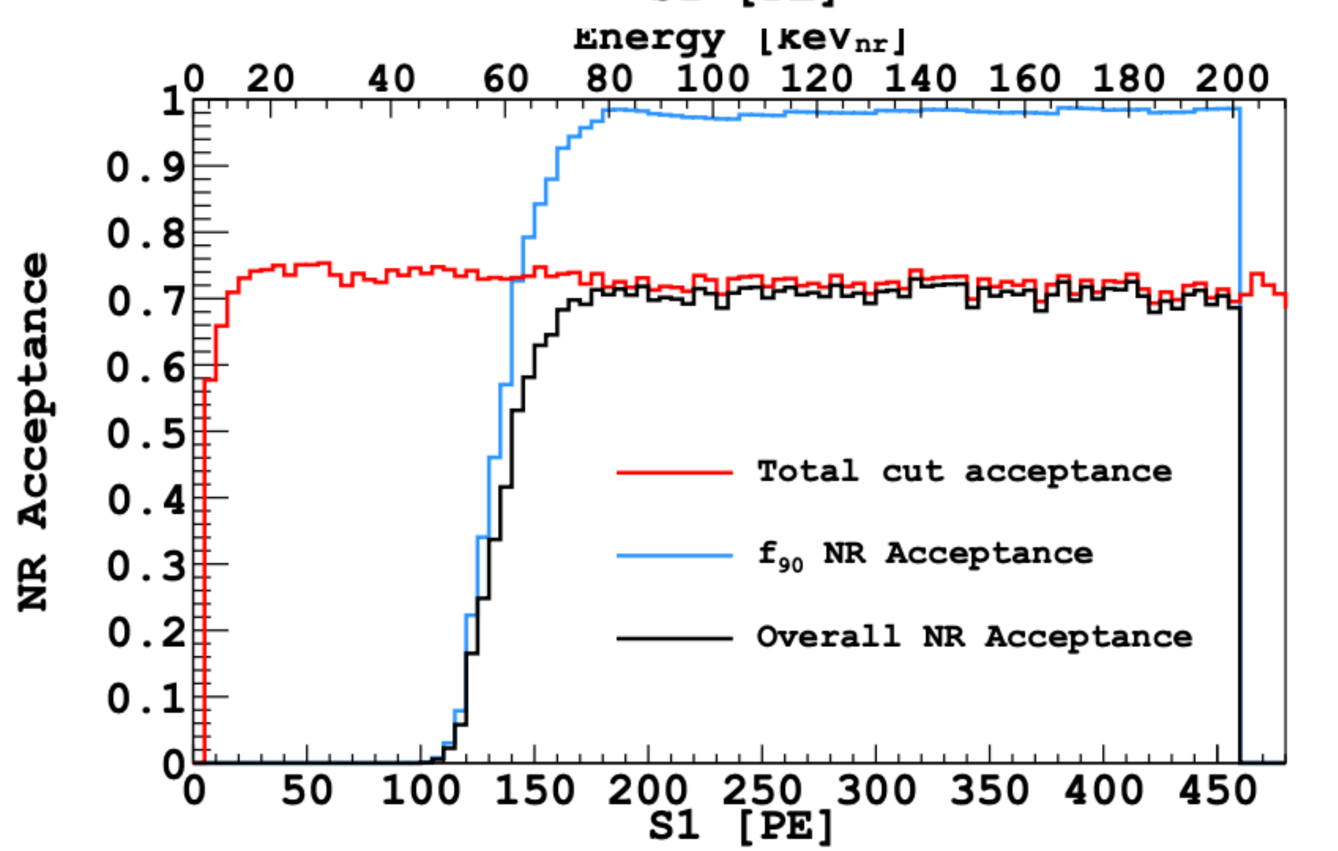
Box opening

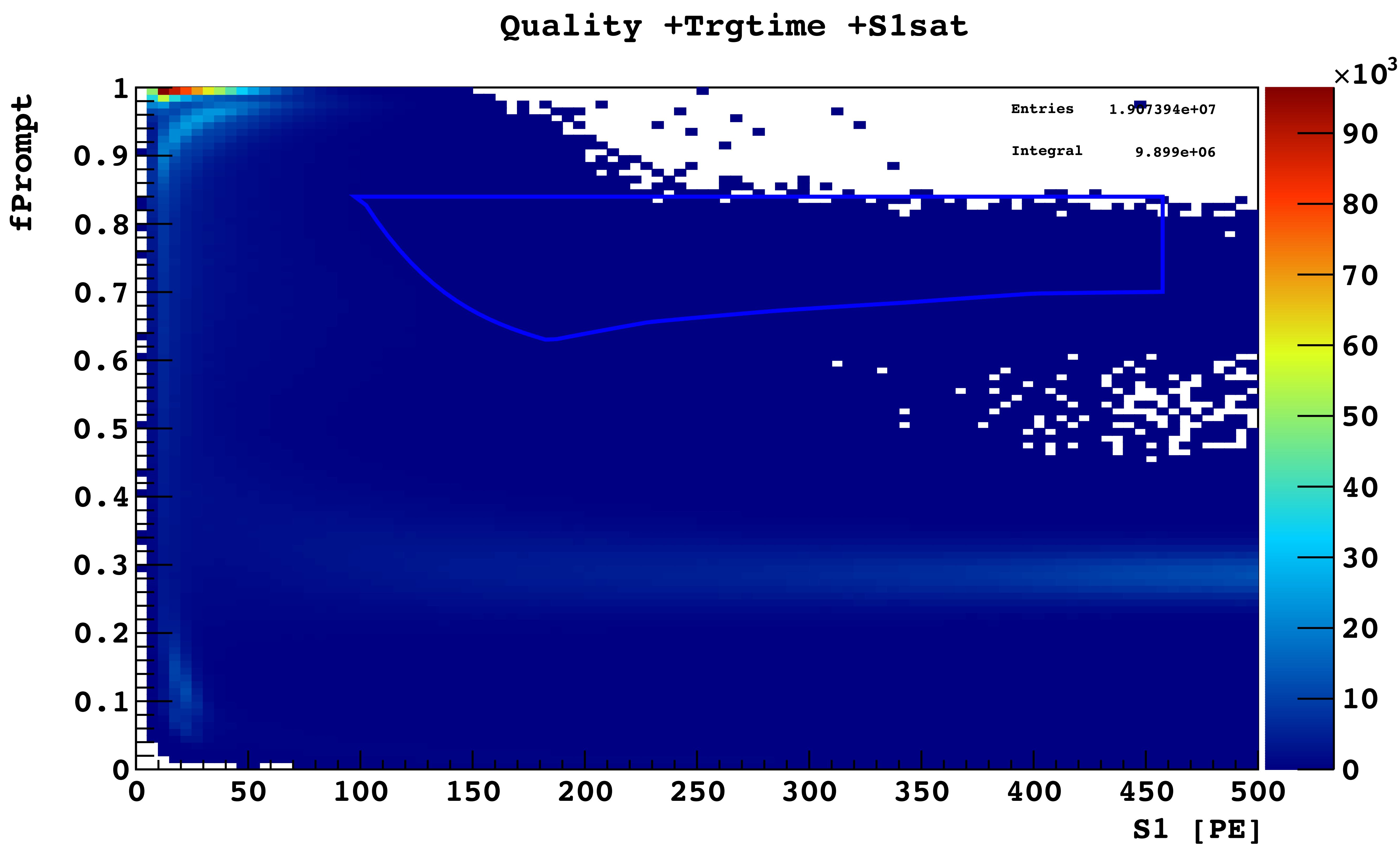
Test box satisfy the requirements:

Background	Estimated survivors
Surface α	0.001
Cosmogenic n	<0.0003
Radiogenic	<0.005
ER	0.08
Total:	**0.09±0.04**

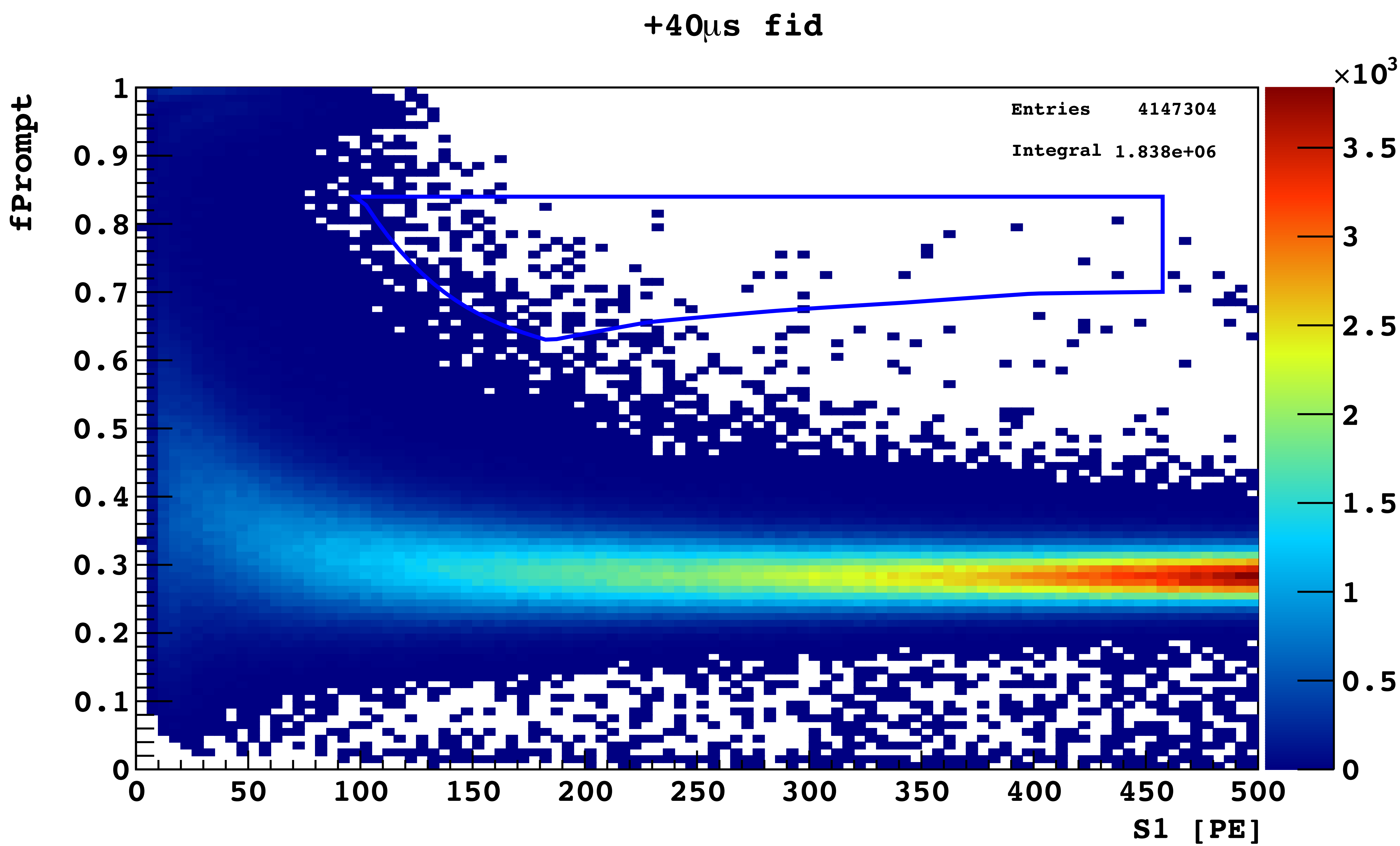
NR acceptance is 70% at 80 keV$_{NR}$
Fiducial mass is 31 kg (47 kg active)



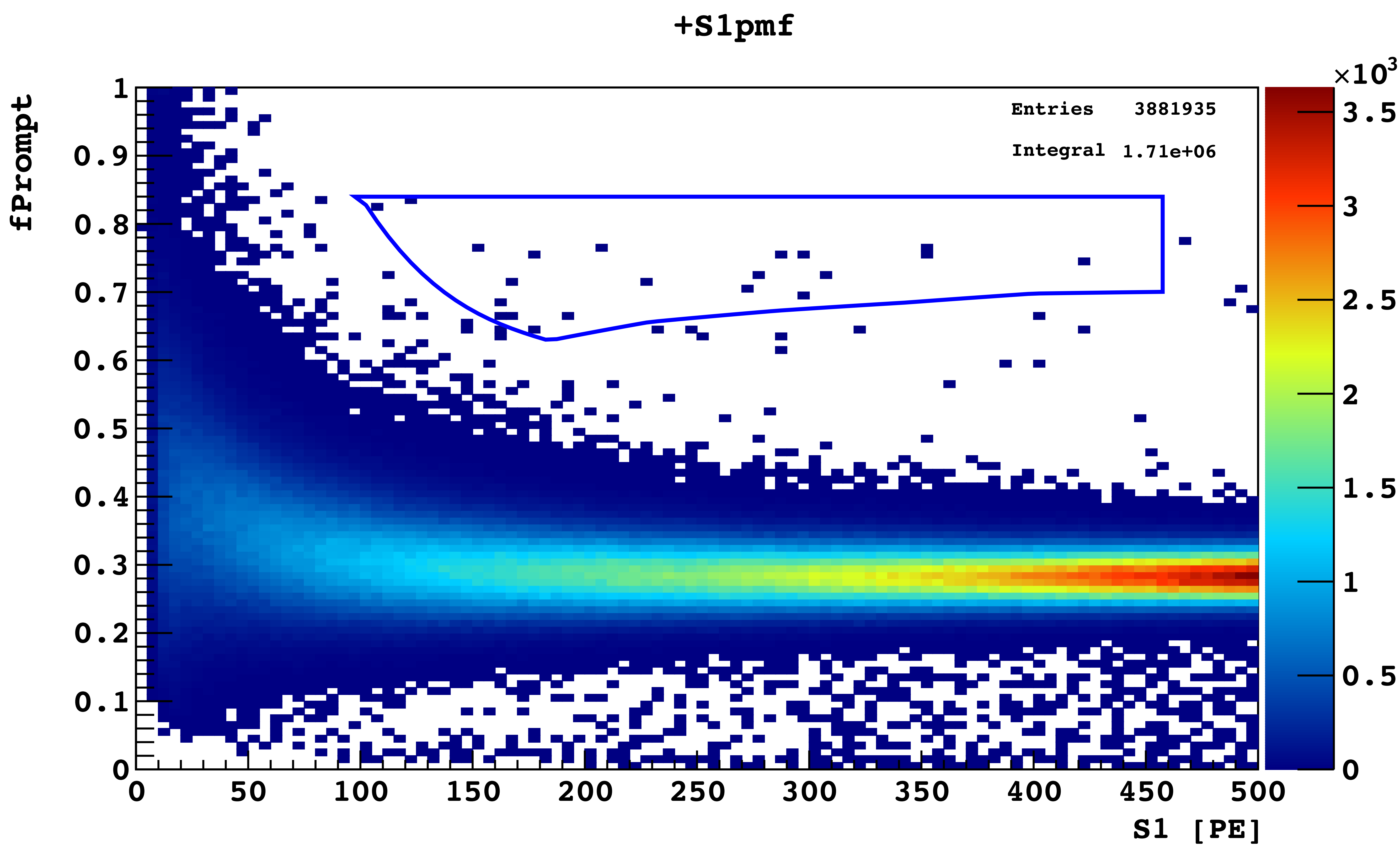




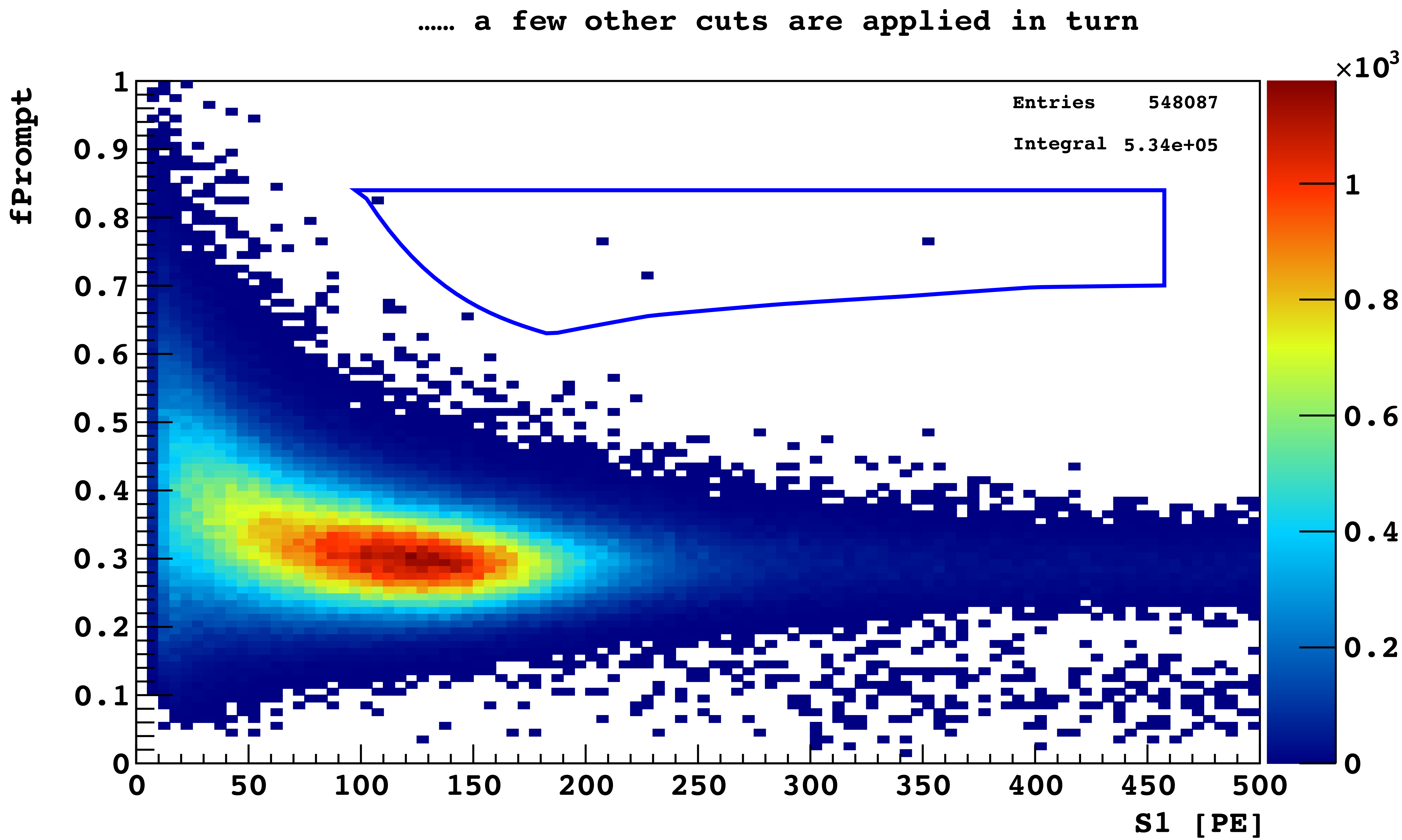
- Trigtime: the first pulse is within expected trigger time window
- S1sat: S1 pulse is not saturated



- Single S2 Pulse (S1 + S2) and 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

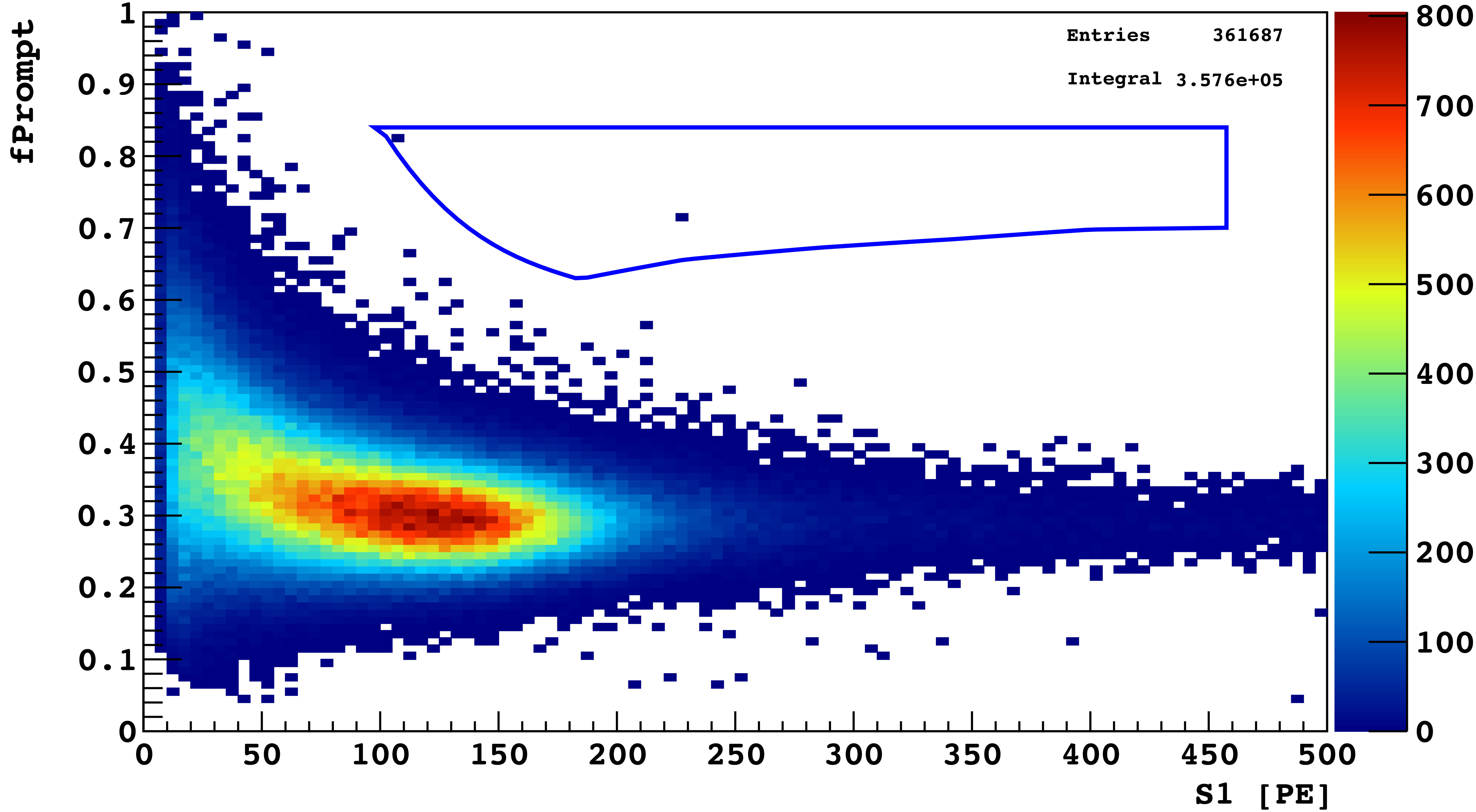


- S1pmf: fraction of prompt light in the maximum PMT is less than a threshold, which is a function of t_drift and S1
- Remove S1+Cherenkov events from fused silica windows

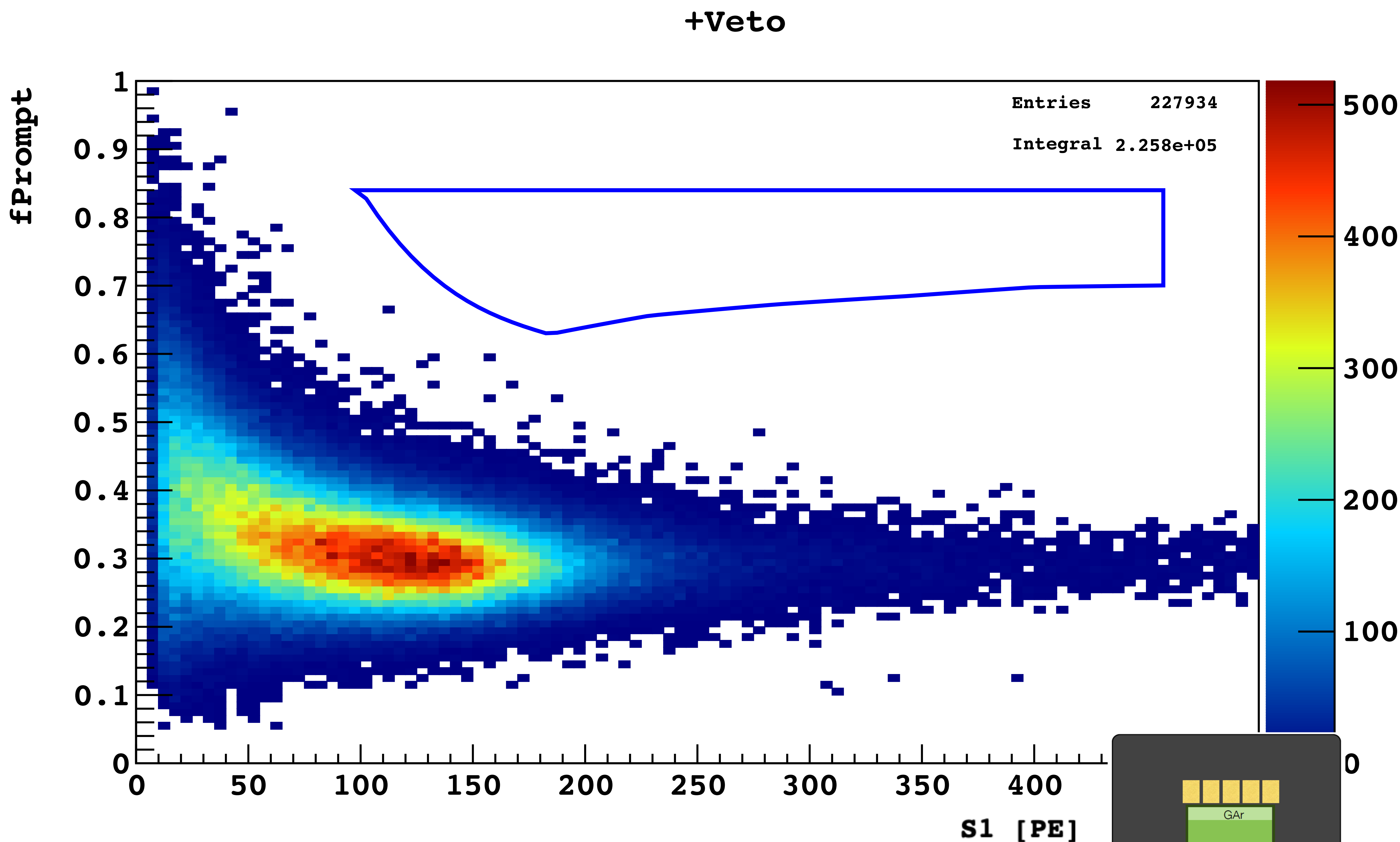


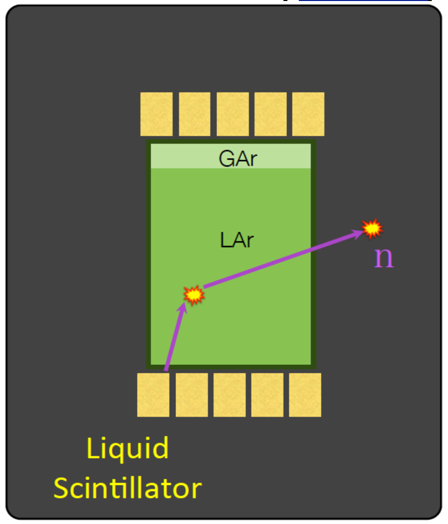
- …… a few other cuts are applied in turn
- Only radial cut is missing

+R 2

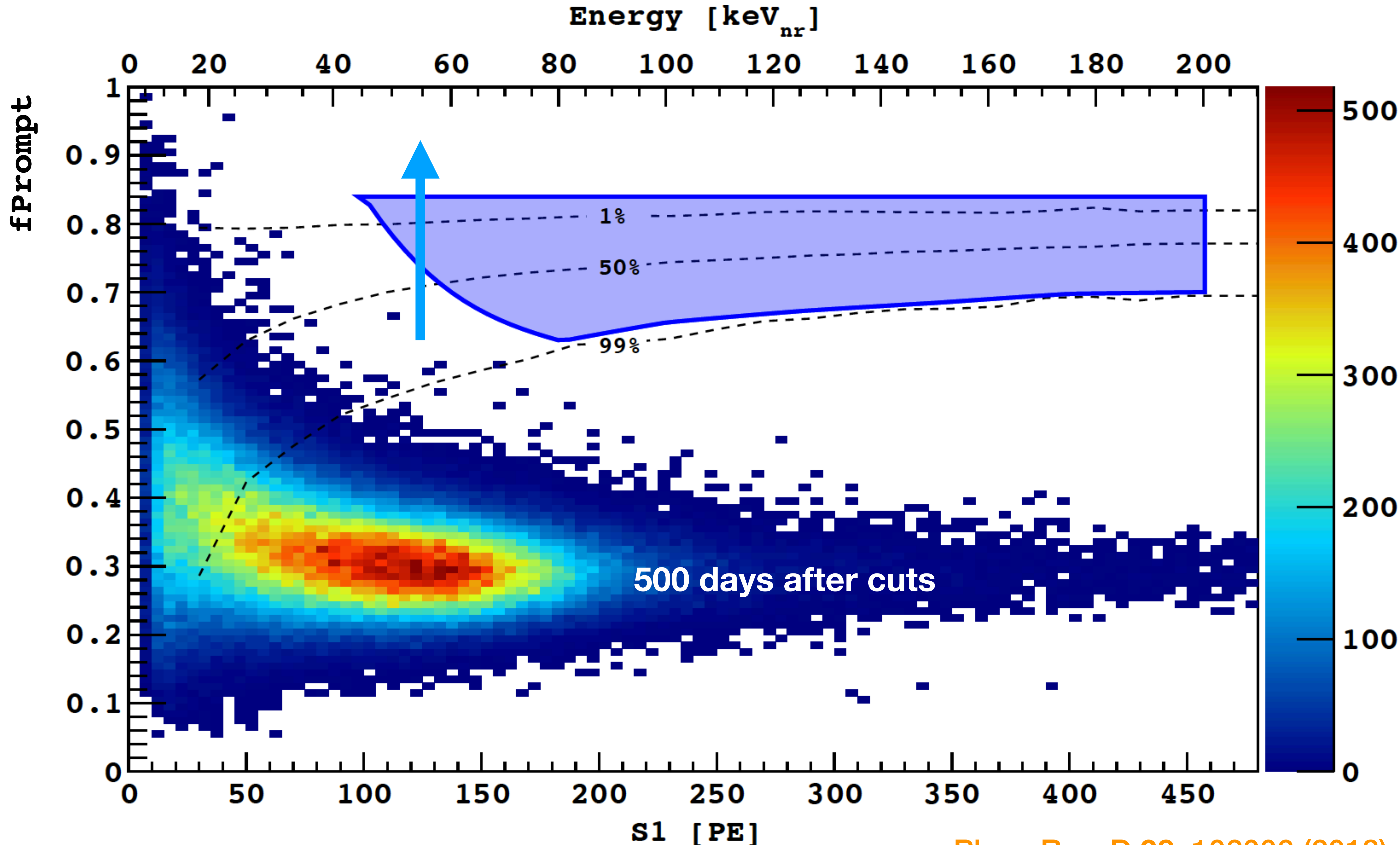


- R 2: Radial cut as a function of t_drift





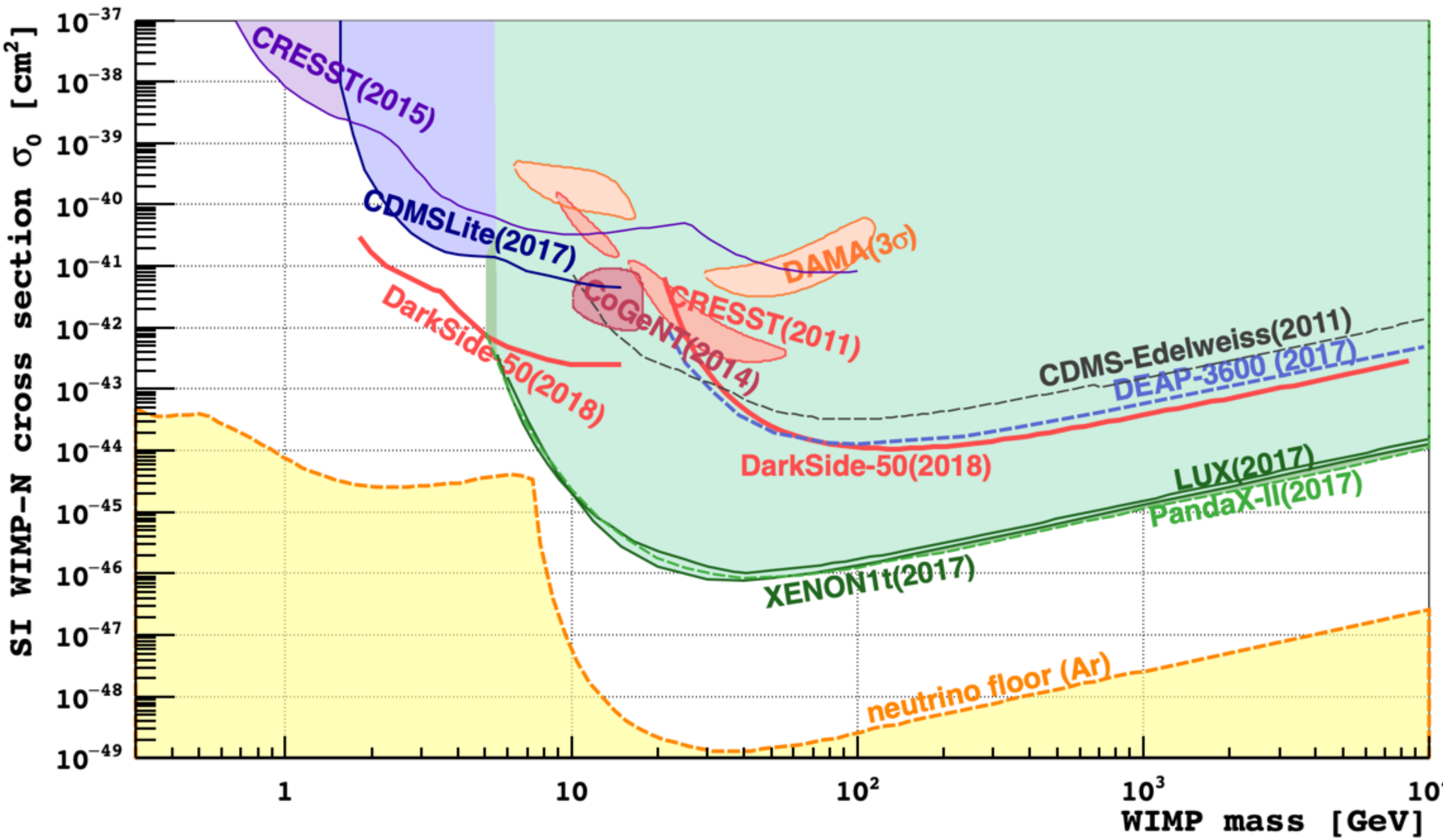
- Veto: all veto cuts
- Remove neutrons



Phys. Rev. D 98, 102006 (2018)

- The threshold at about 50 keV$_{NR}$ is due to the **Pulse Shape Discrimination Effieciency**

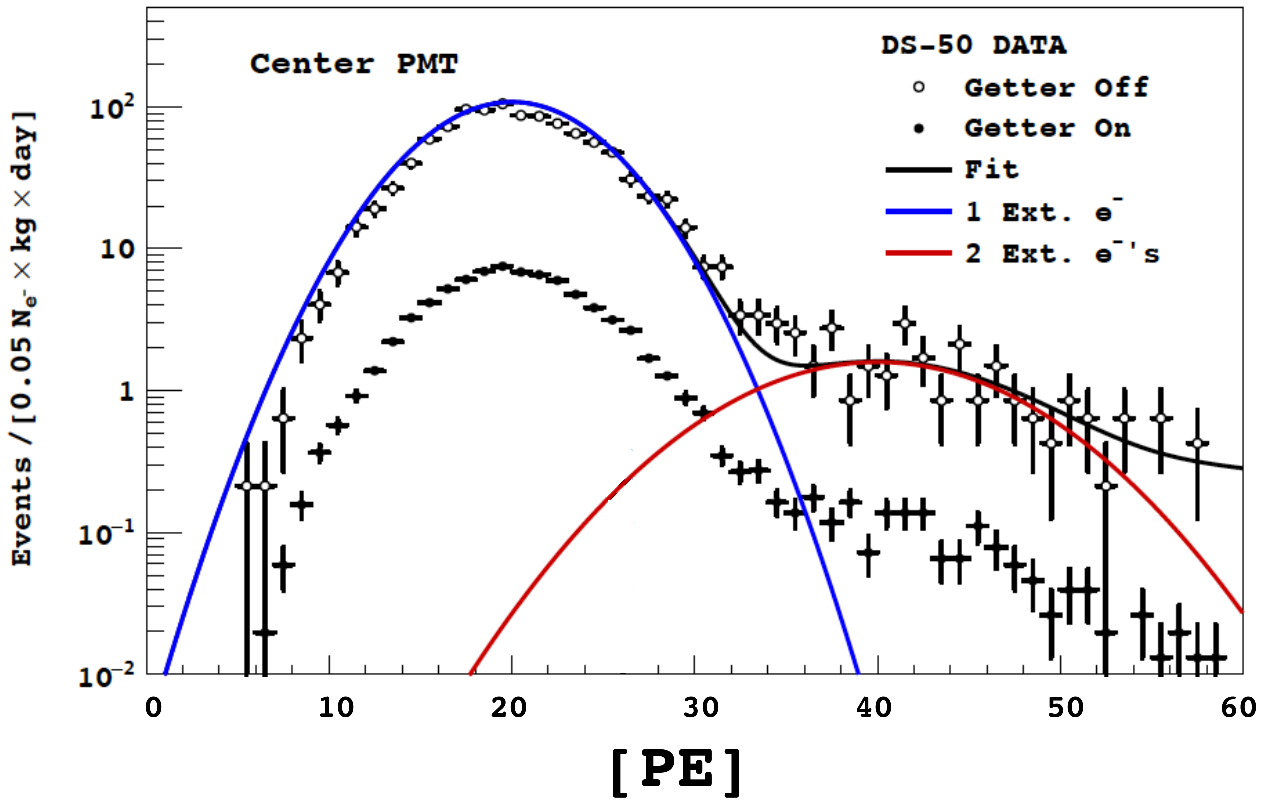
Sensitivity and threshold

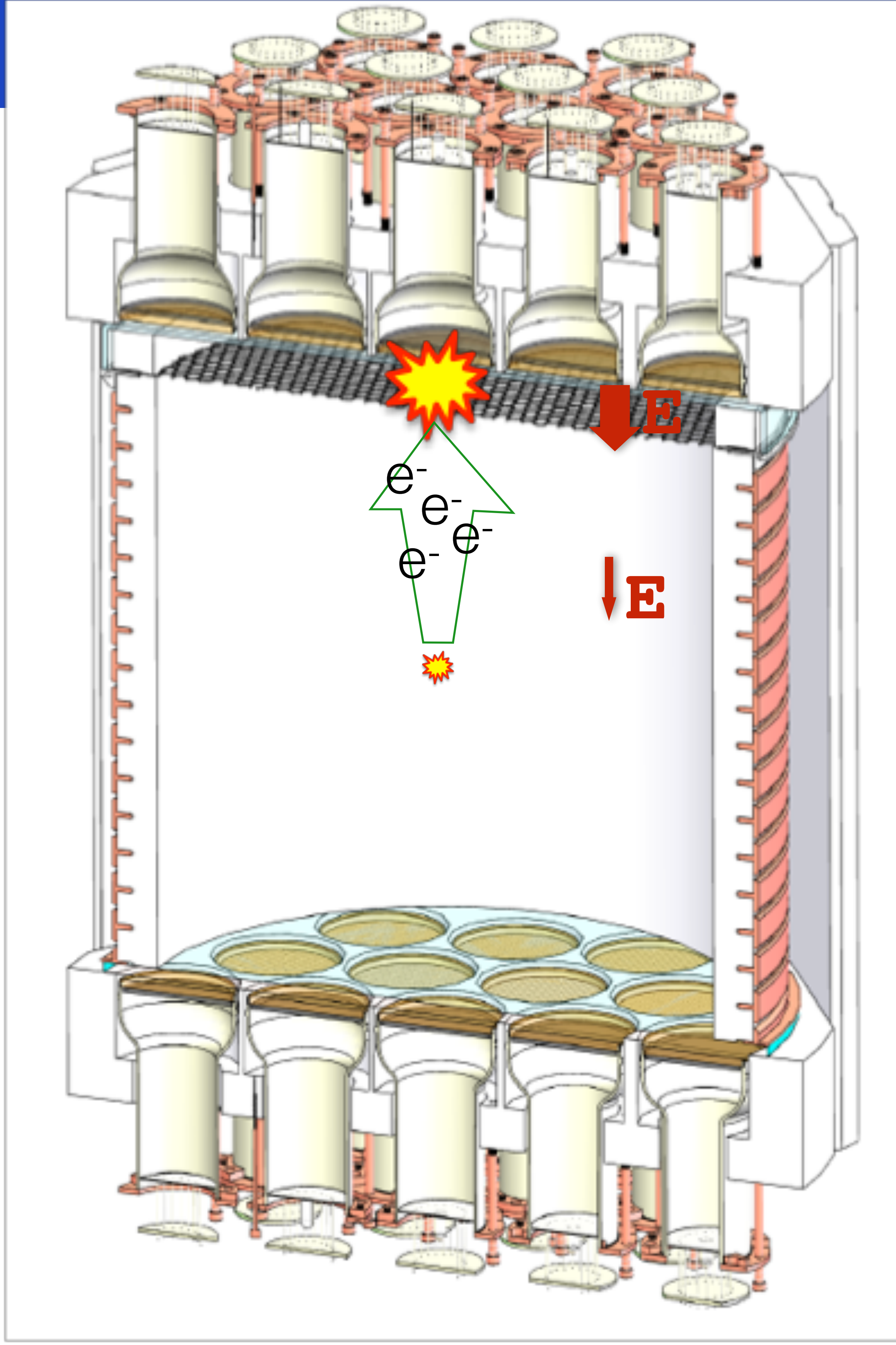


How to lower the threshold?

Look at the **ionization only** spectrum (W_{ion} = 23.5 eV, multiplication in the gas: 23 PE/e^-)

Below 3 keV_{ee}: give up the scintillation signal (too small to trigger the detector), and thus
- **minimal fiducialization** (only radial)
- **no hope for ER/NR discrimination** (nor PSD nor S2/S1)

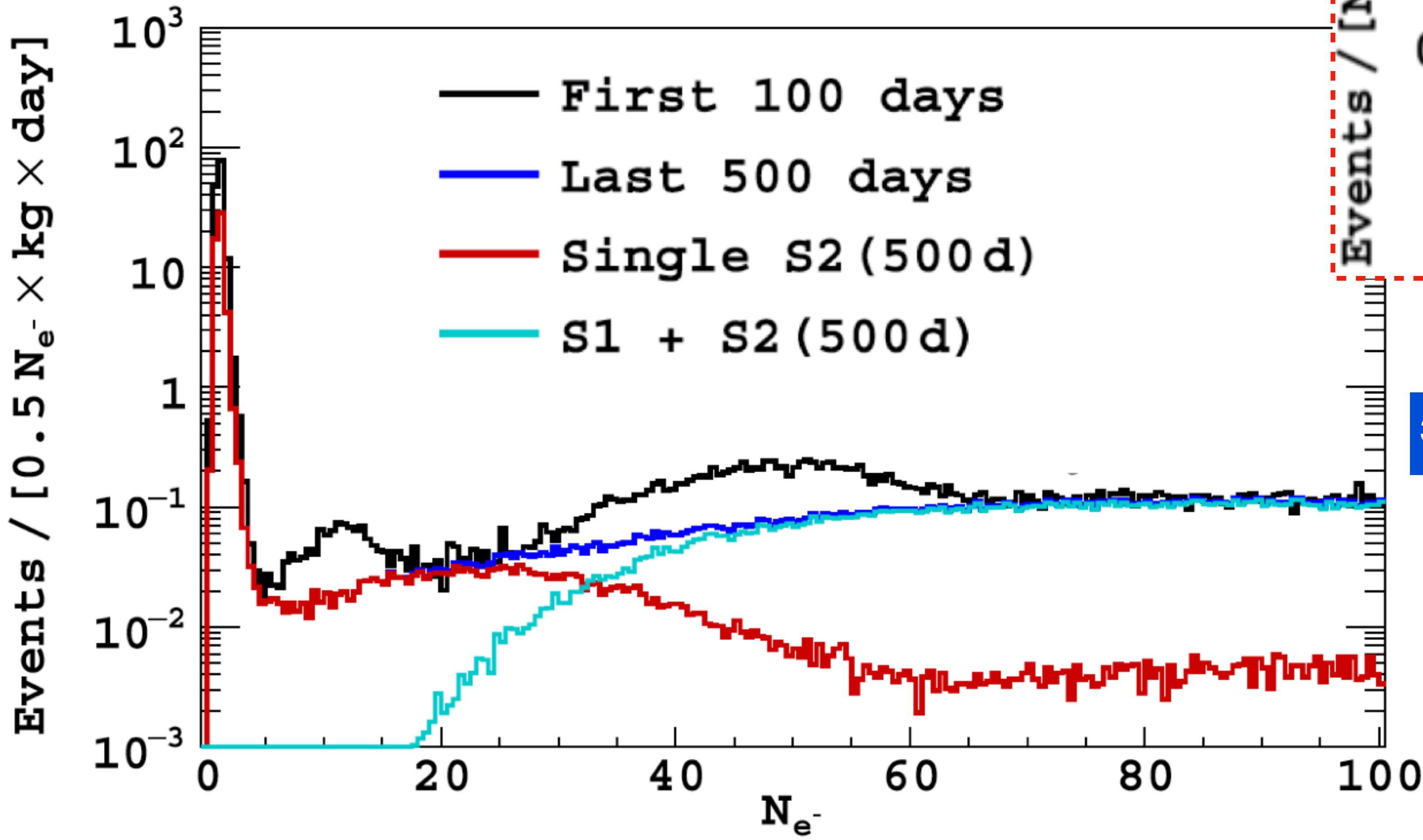




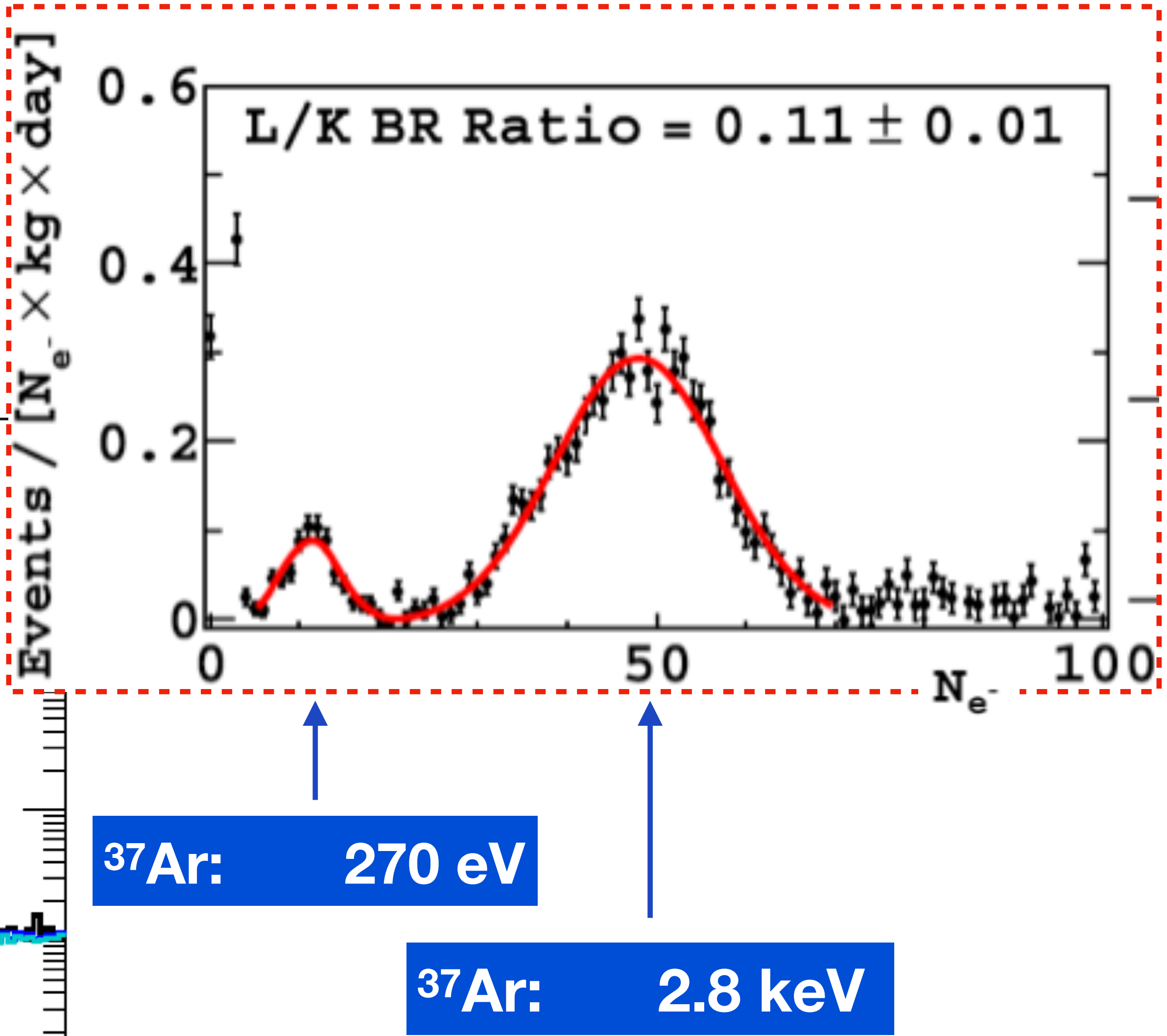
How to lower the threshold?

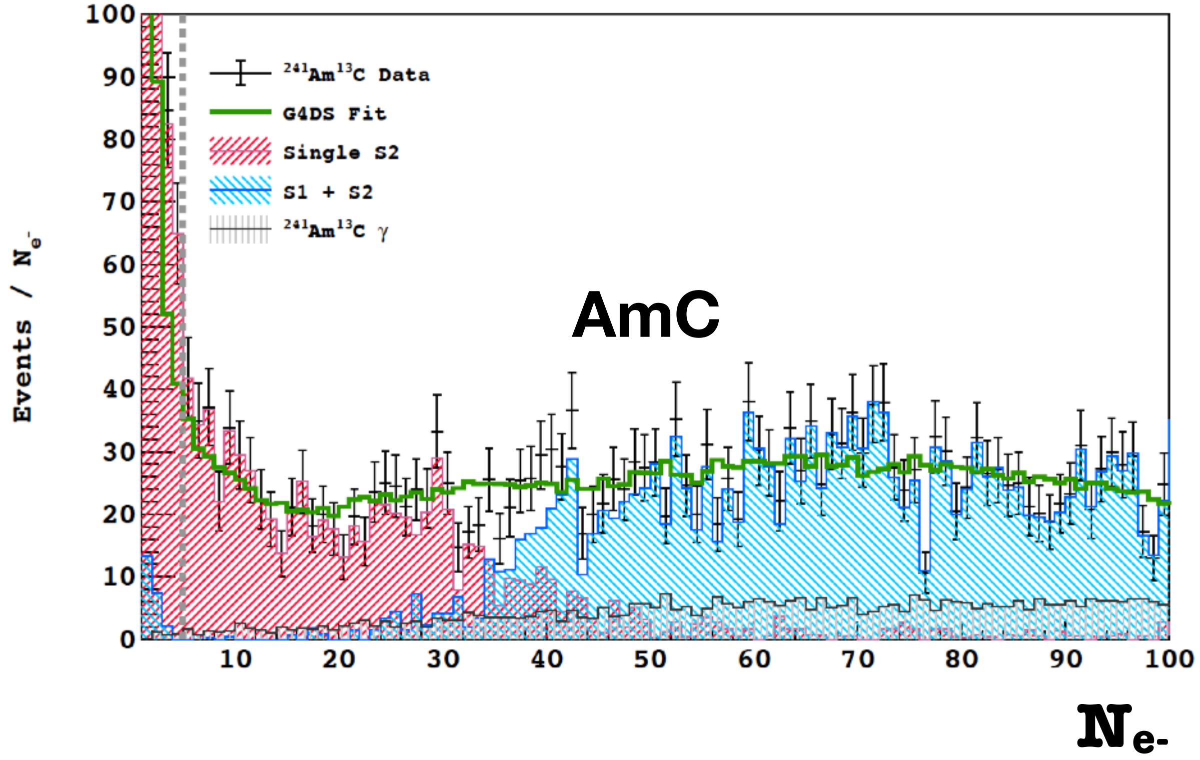
Look at the **ionization only** spectrum (W_{ion} = 23.5 eV, multiplication in the gas: 23 PE/e^-)

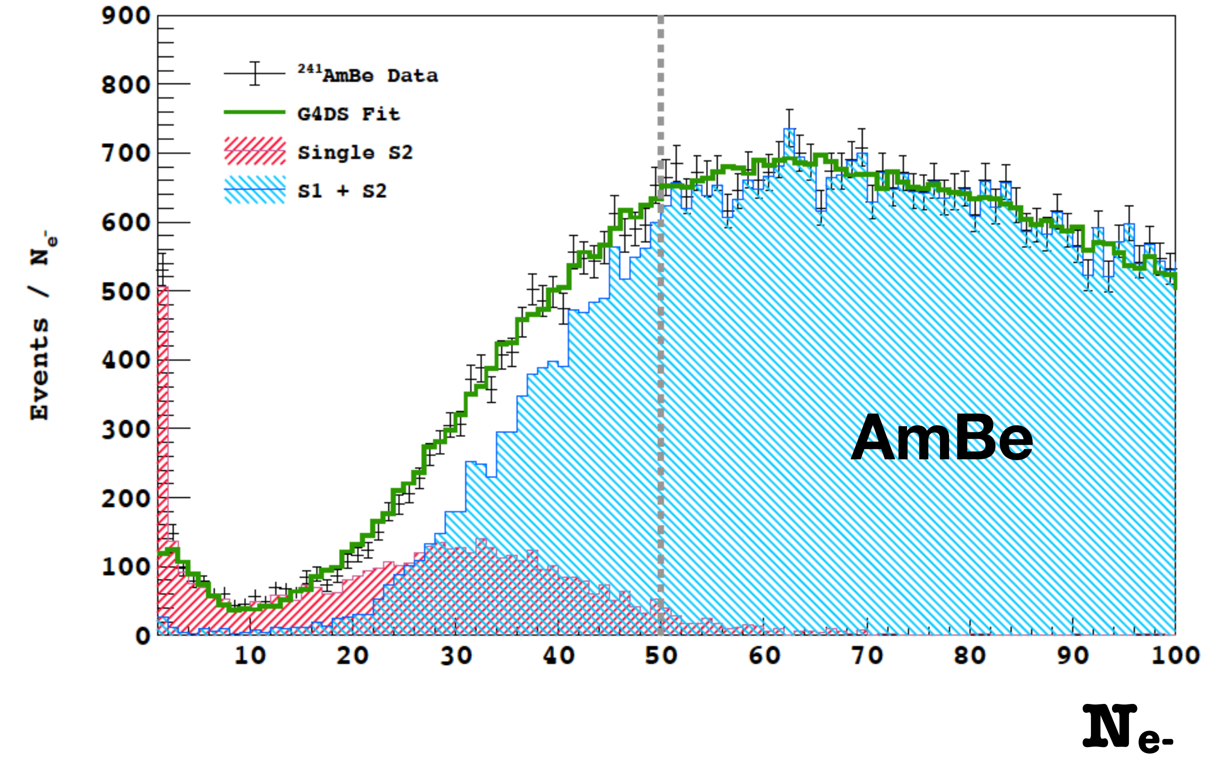
Below 3 keV_{ee}: give up the scintillation signal (too small to trigger the detector), and thus
- **minimal fiducialization** (only radial)
- **no hope for ER/NR discrimination** (nor PSD nor S2/S1)

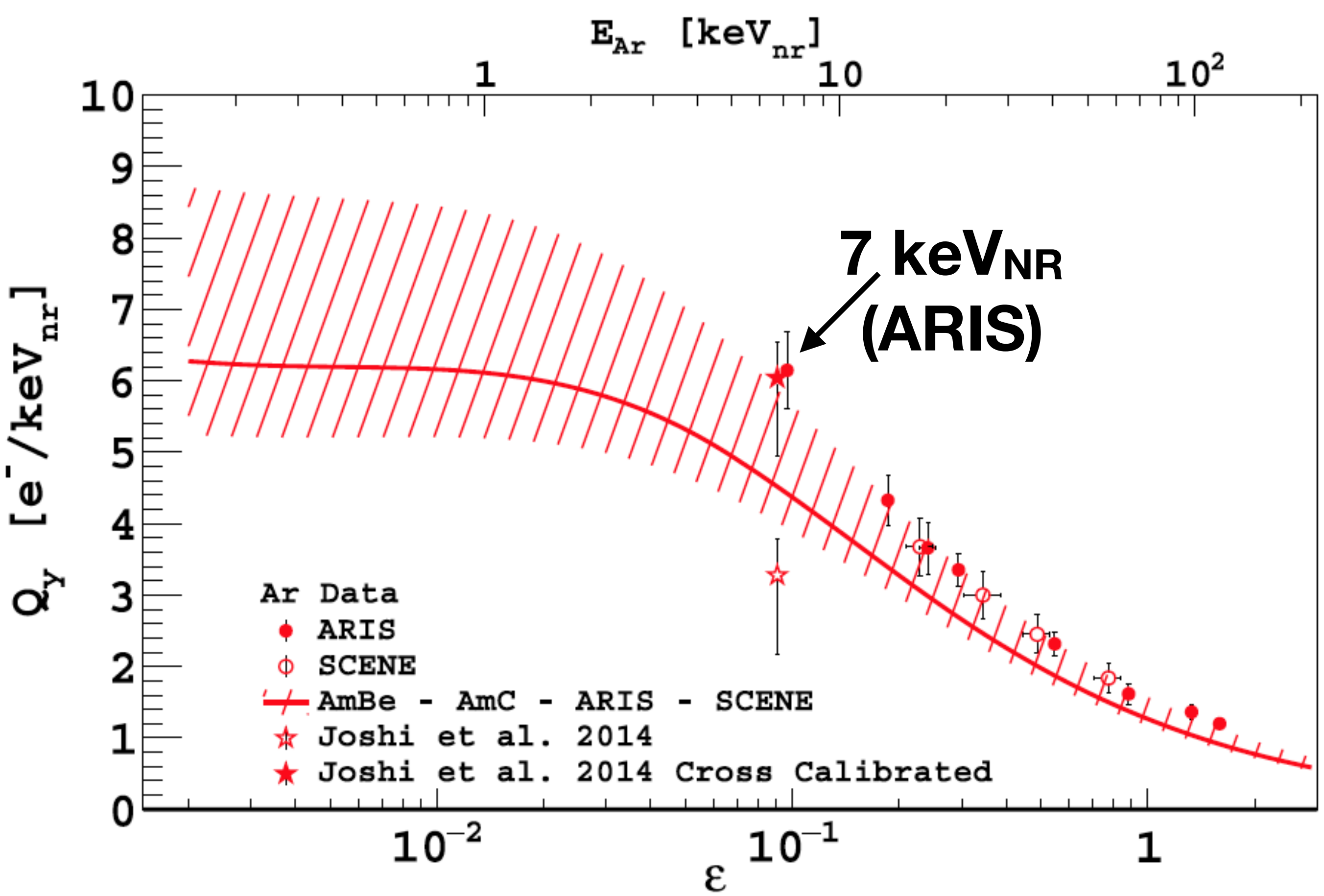


Yet, calibration of ER's with ^{37}**Ar:**









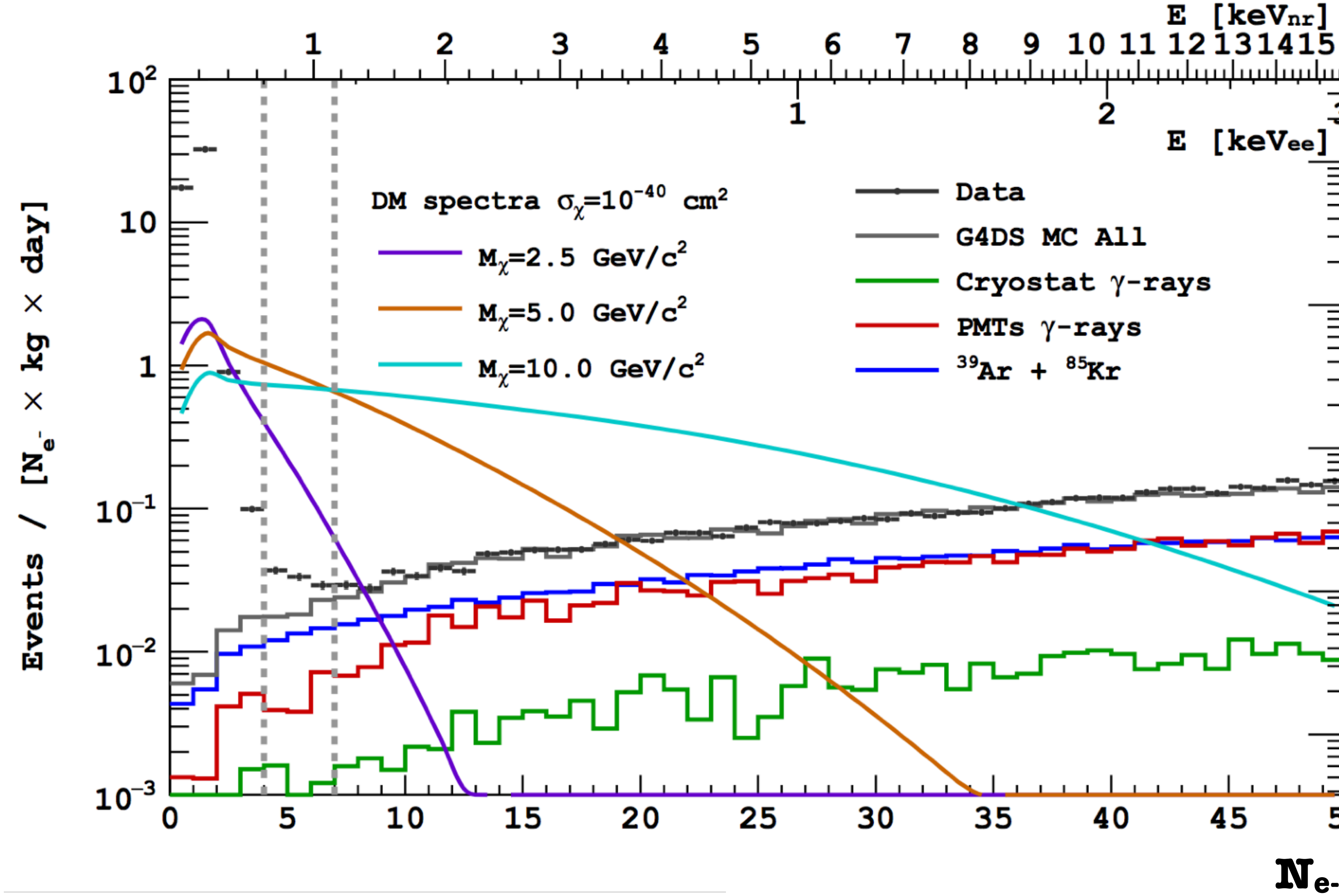
Calibrate NR with **AmC, AmBe** neutron sources

Bezrukov model fit at low energy. Two free parameters to describe quenching and recombination probability of e- / ions.

Ref: Astropart. Phys. 35, 119 (2011).

Extrapolation at high energy in agreement with ARIS and other datasets

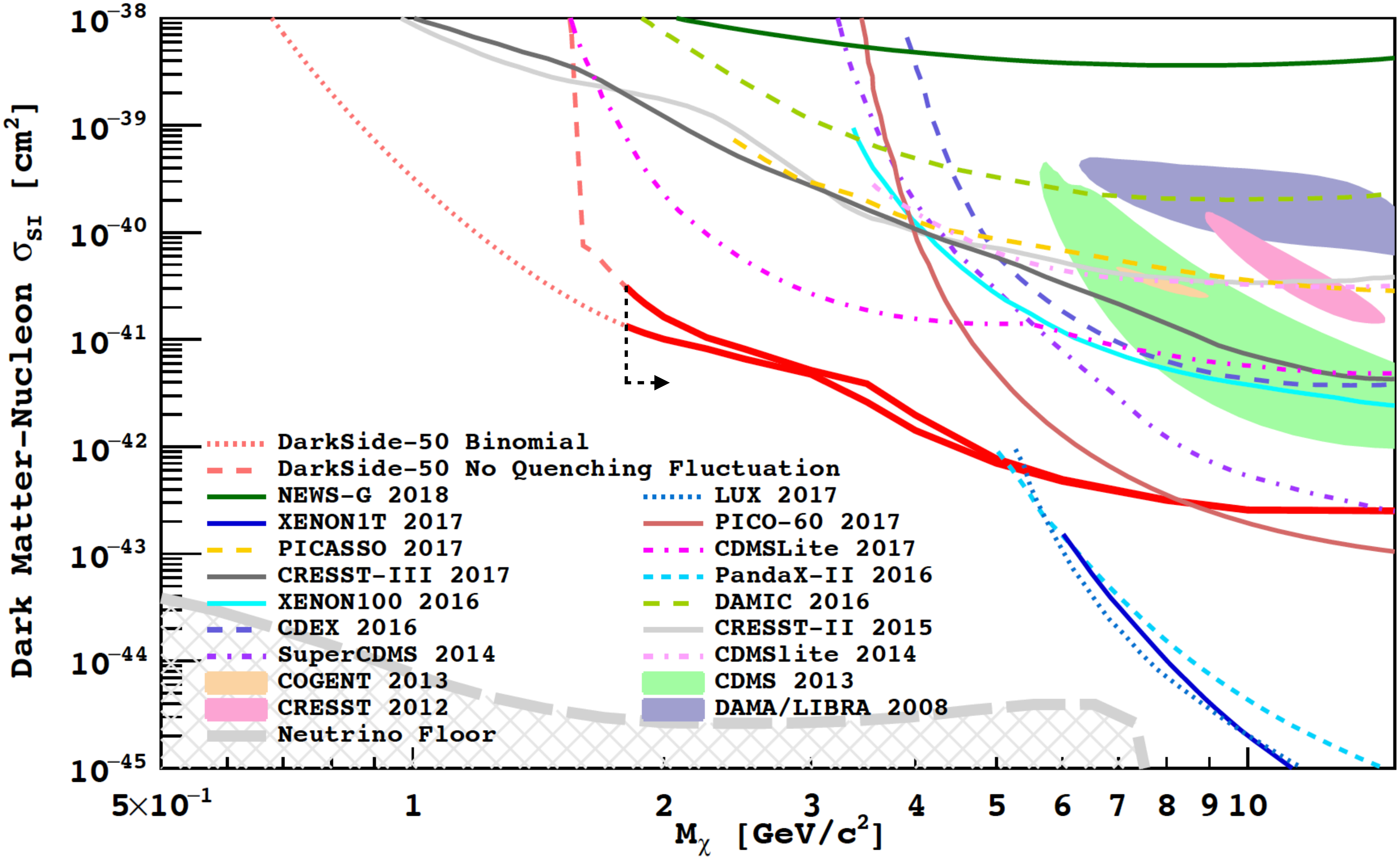
DarkSide for low-mass WIMPs



MC spectra in the low energy region, converted in N_{e-} (ER). **Activities constrained to the results of fit at high energy**.
WIMP induced spectra in N_{e-} (NR); PLL analysis.

Un-modeled component(s) below 7 e^-: impurities (+ radiogenic neutrons?)

The extracted limit(s)



Best limit in [1.8, 6] GeV/c² mass range

Need a measurement to determine quenching fluctuations

Towards DarkSide-20k

1) Shown **potential** of LAr at **low WIMP mass**

2) DarkSide-50 performed a **background-free** WIMP search

- necessary for a **discovery** program
- thanks to pulse shape discrimination (**LAr only**)

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

Towards DarkSide-20k

1) Shown **potential** of LAr at **low WIMP mass**

2) DarkSide-50 performed a **background-free** WIMP search

- necessary for a **discovery** program
- thanks to pulse shape discrimination (**LAr only**)

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

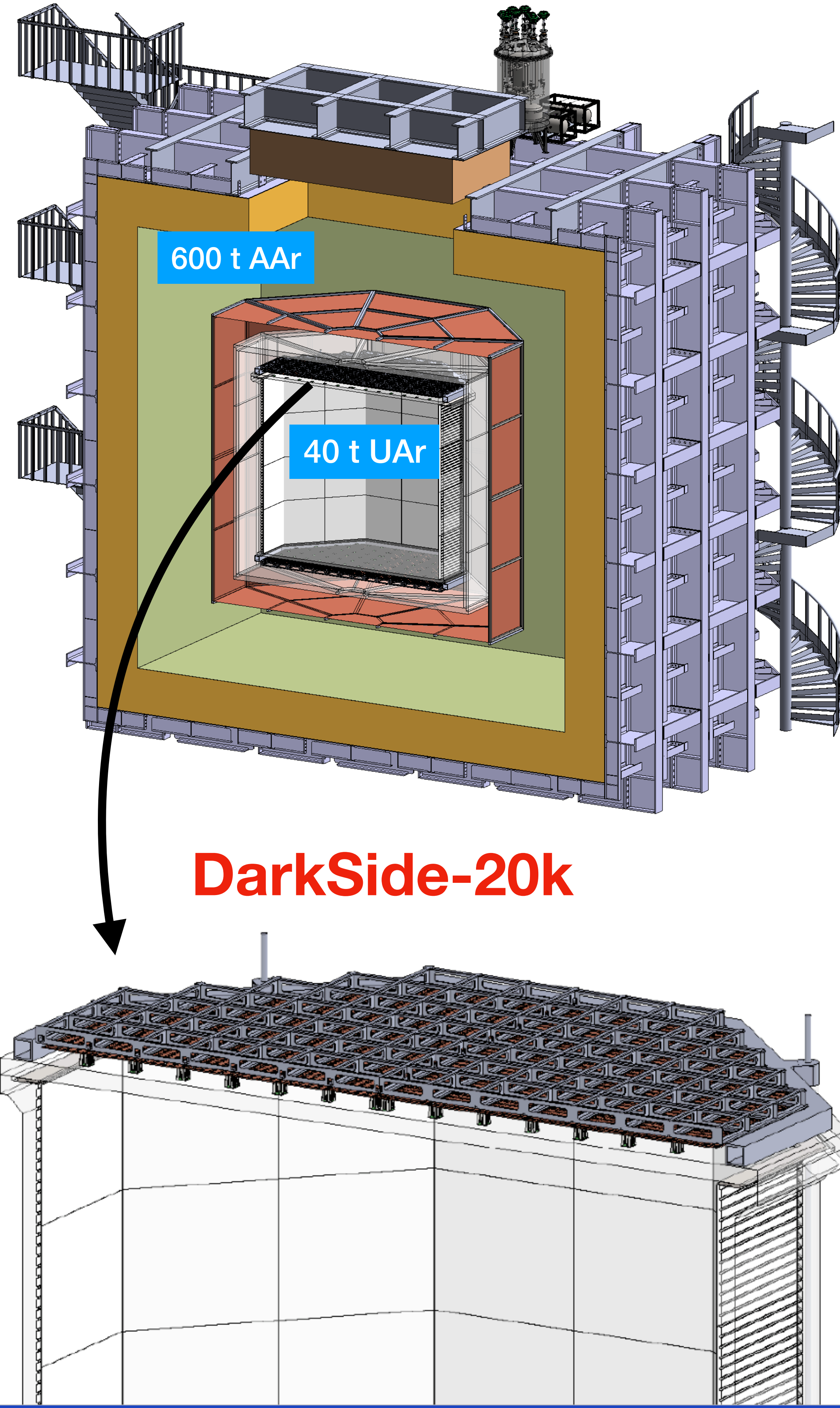
DarkSide-20k is the next step: 40 t (20 t) active (fiducial) UAr

>100 t yr (instrumental) bg free UAr exposure

Expected **1.5 ev in 100 t yr** from **neutrinos** (CNNS).

Based on:

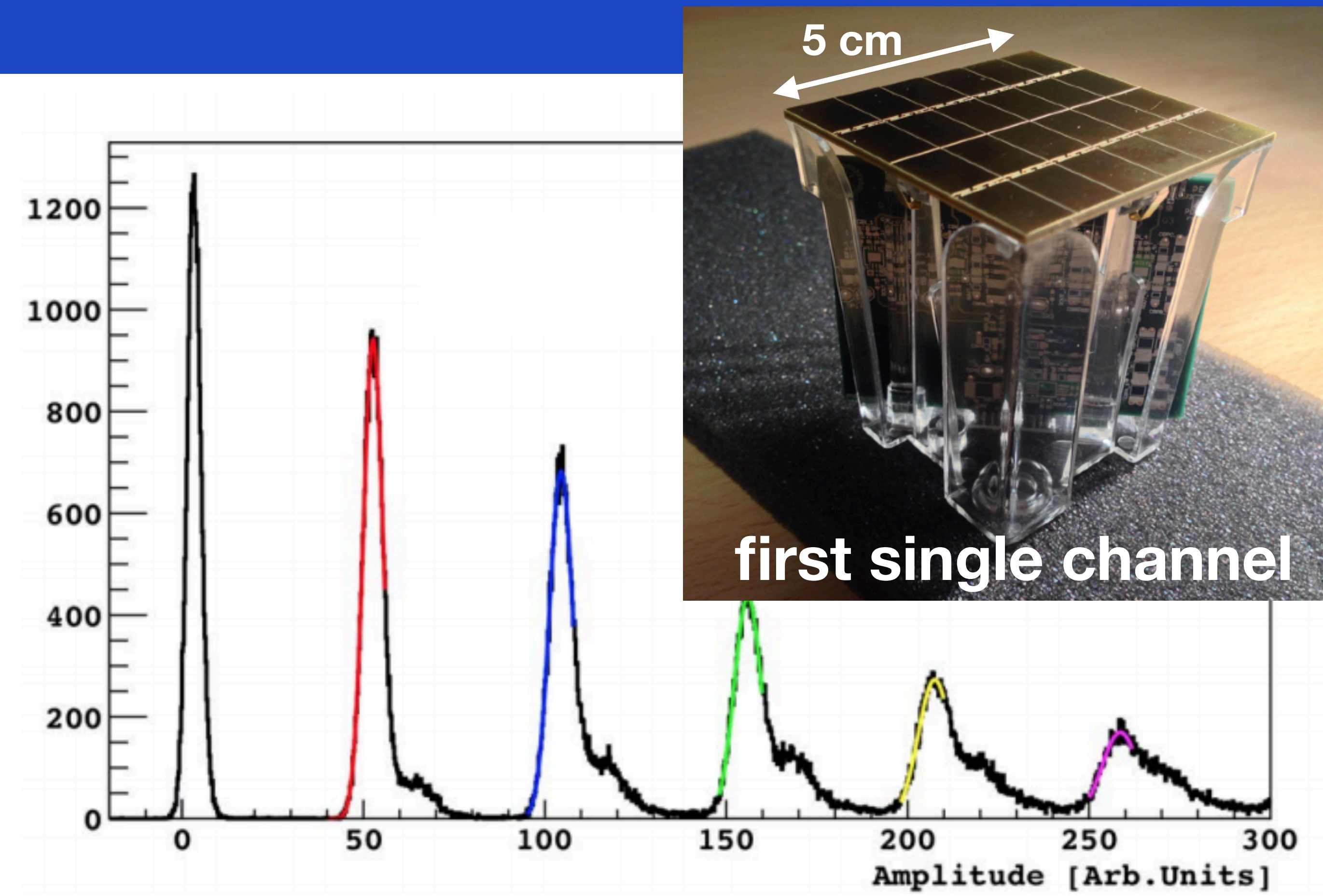
- Extraction of 50 t of UAr
- Hosted in a 700 t LAr **ProtoDUNE cryostat** (move material away from the active volume)
- Instead of PMTs: **SiPM arrays**!



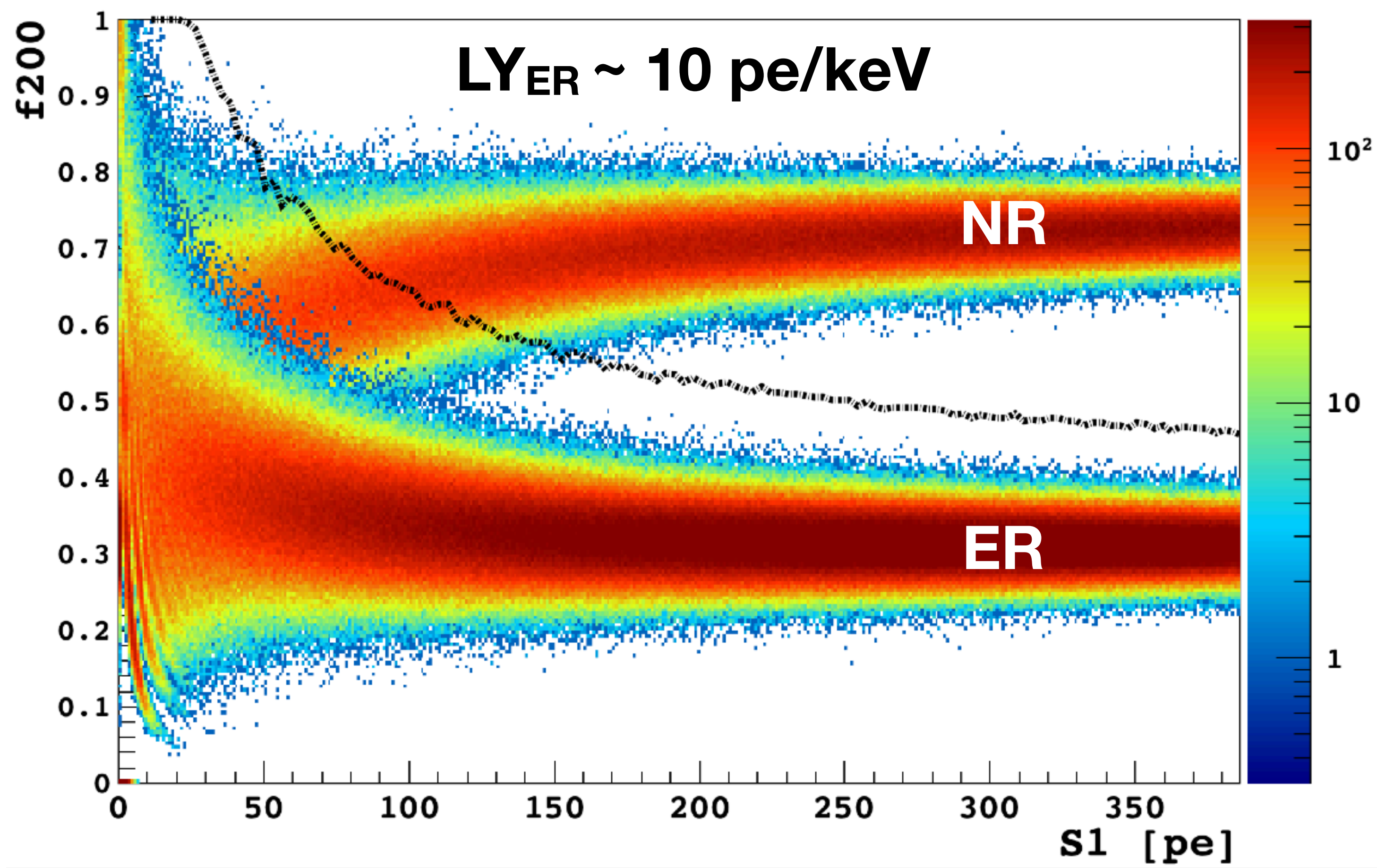
SiPM tiles

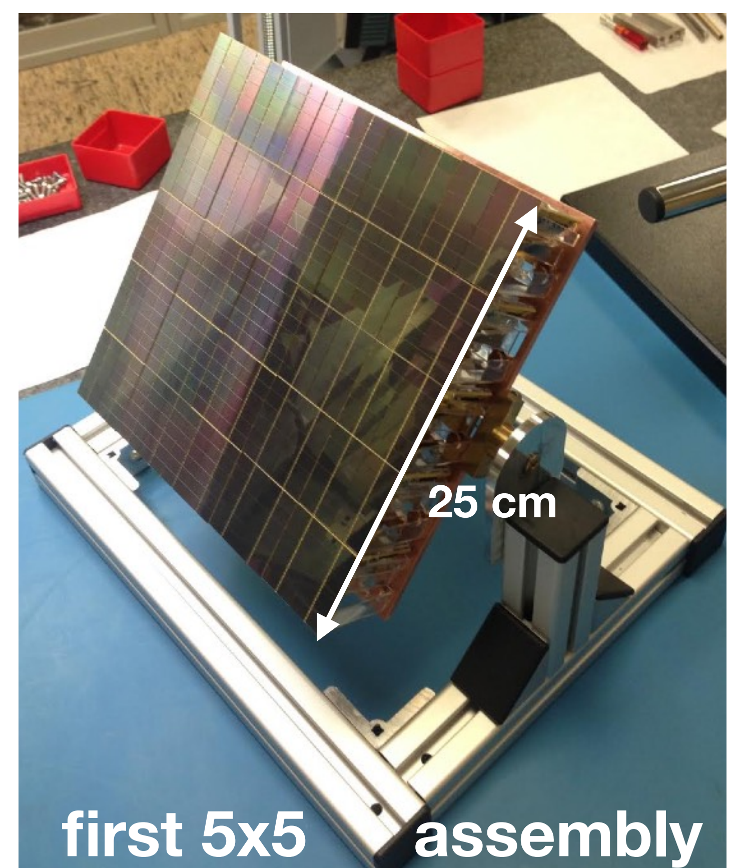
Main novelty: the light readout system **(FBK)**
- intrinsically radio-pure
- improved detection efficiency

PDE > 40%
O(10 ns) timing resolution
<250 Hz dark rate + correlated noise



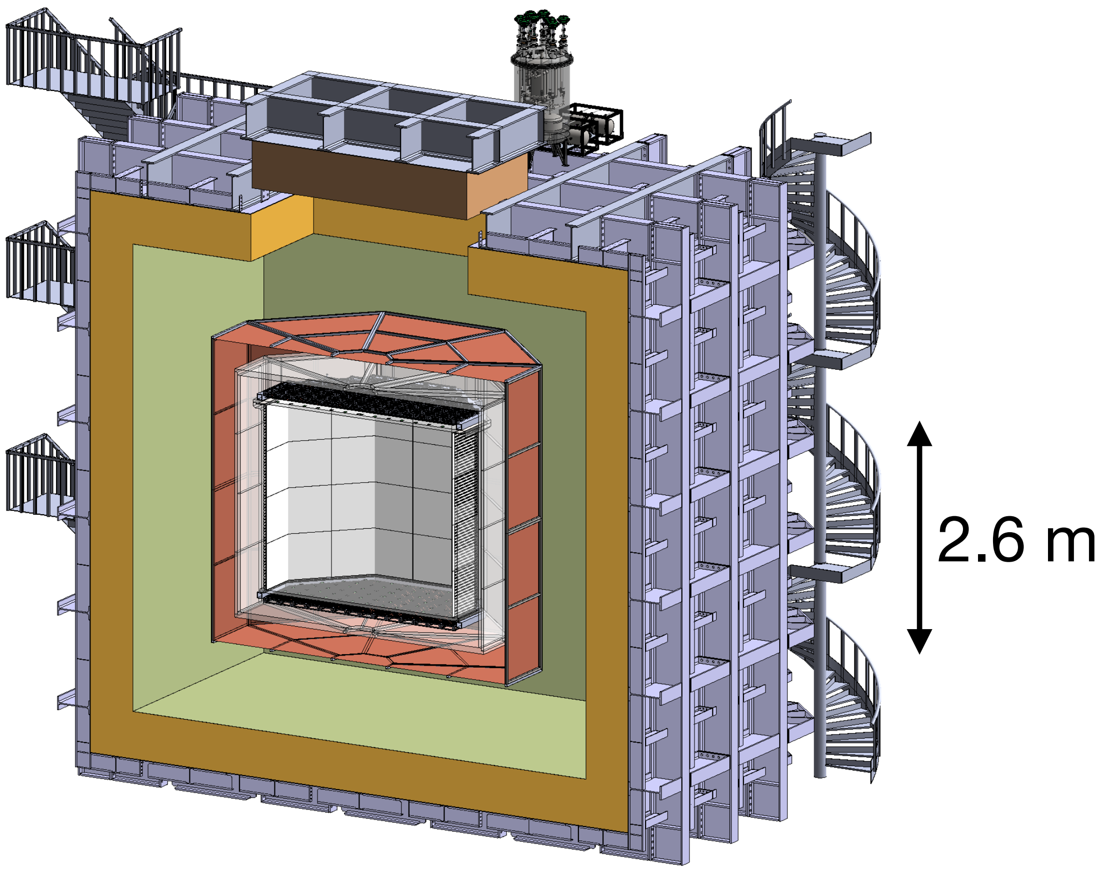
Preliminary G4DS:





Need 350 of these…

DS20k and DS-Proto



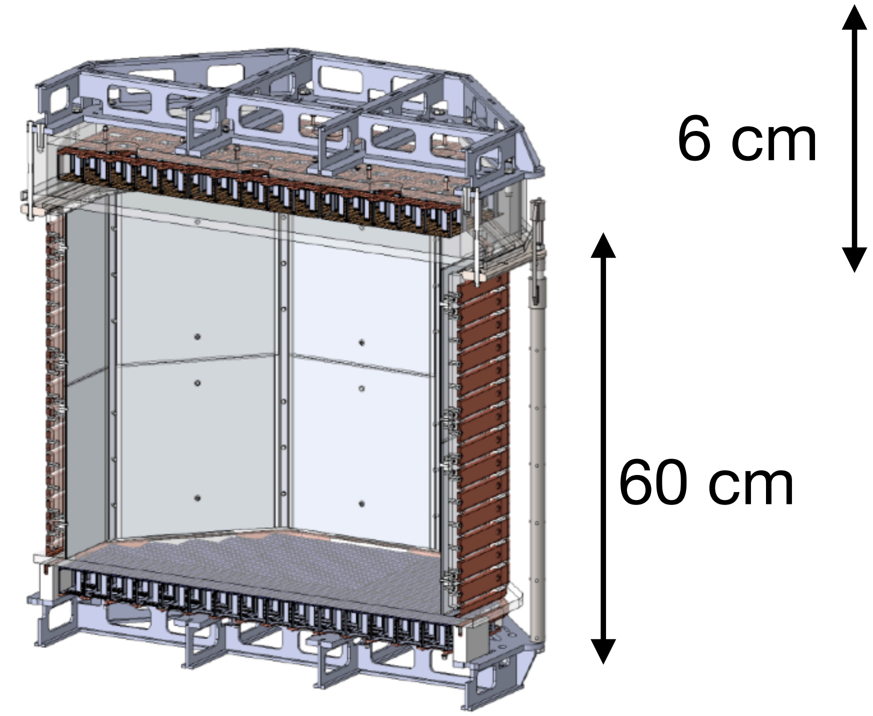
DarkSide-20k

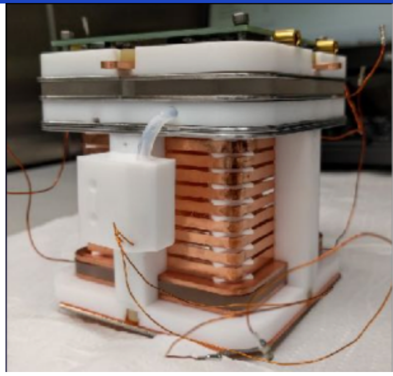
> 25 m² of SiPM required

9000 ch in the TPC and 3000 in the veto

Currently optimizing the **veto geometry** (efficiency to detect neutron capture) and **PE-DAQ** (rate in TPC is ~ 100 Hz, but high digitization rate. Rate in veto is 100 kHz)

Data taking expected for 2022





ReD

DarkSide-Proto

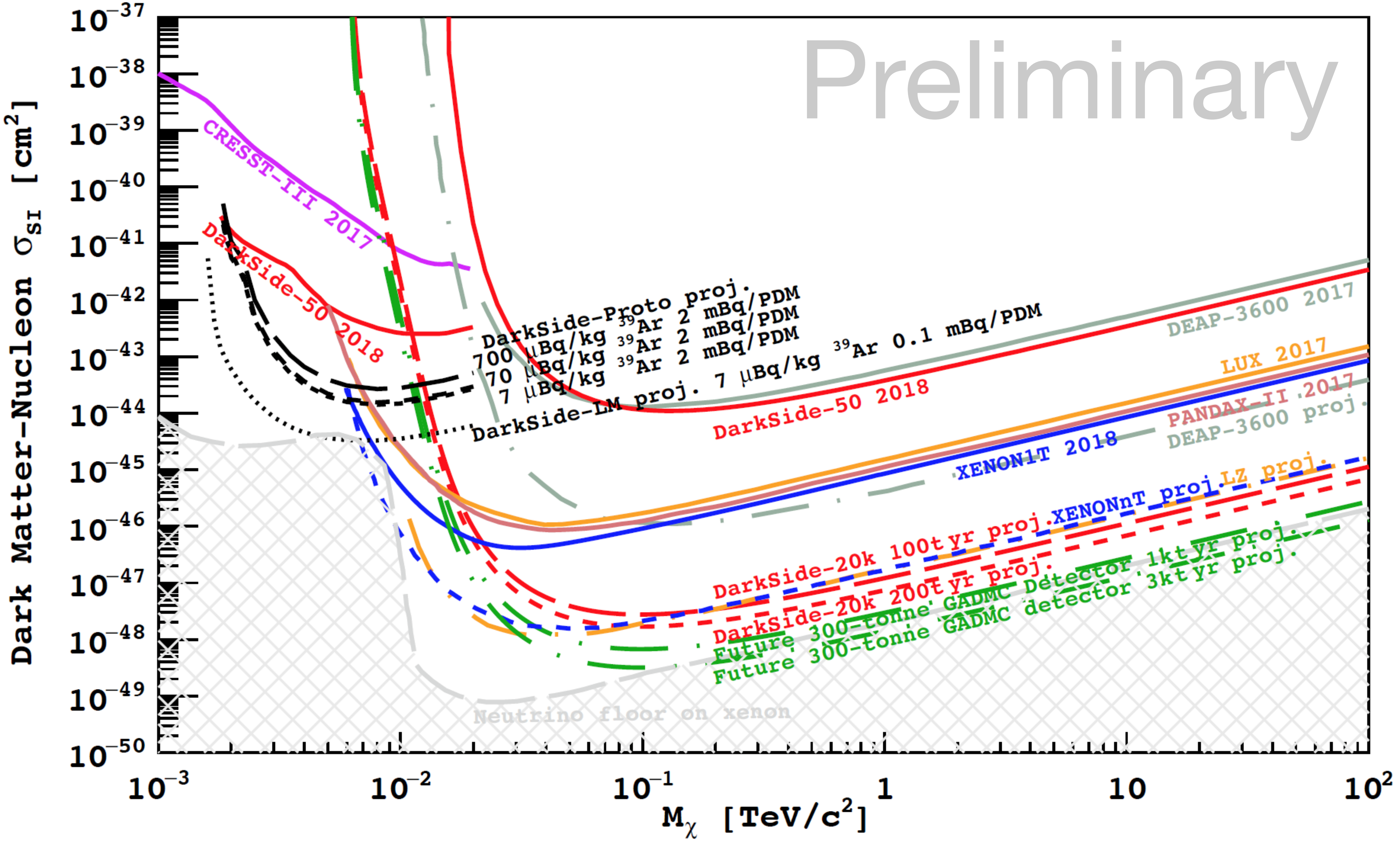
400 channels in the TPC.

Mechanical test at first. Then a fully functional TPC with all the channels (LY, resolution, XY)…

Now: start from this design for low-mass WIMP search? Priority is reduce the internal rate

Start construction in 2019 at CERN

Projection for the future



Conclusions

DarkSide-50 is operated since 2013 and provided interesting results for both low- and high-mass WIMPs.

They:

- asses that the ^{39}Ar content in UAr is sufficiently low to construct a large dual-phase TPC
- demonstrate that a LAr dual-phase detector can be operated in a bg free condition
- show the potential of LAr at low-mass

Those represent important milestones towards the construction of DarkSide-20k (taking data by 2022).

- goal of 100 t yr instrumental background free exposure
- joint effort of the LAr DM community (DEAP, ArDM, CERN NP…)
- novel light readout system (SiPM exciting data are coming soon)