The Data Acquisition System for the DarkSide-20k Detector

WNPPC Virtual Conference

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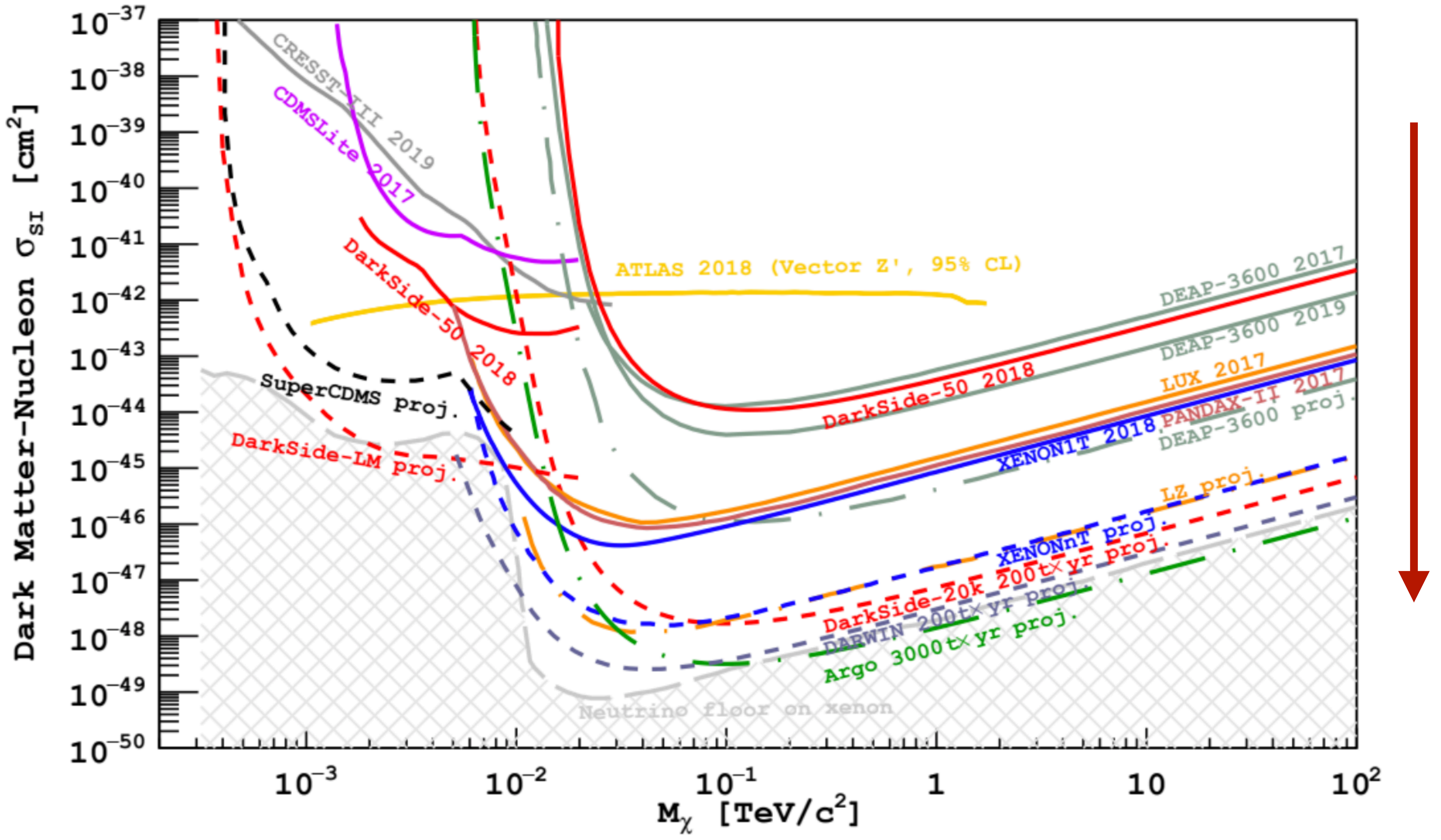
DarkSide-20k

Physics Reach

- Experiment designed to observe low energy nuclear recoils induced by WIMP dark matter-nucleus elastic scattering
- Large target mass, ultra-low background radioactivity & efficient background rejection/veto systems key to unlocking further sensitivity to WIMPs

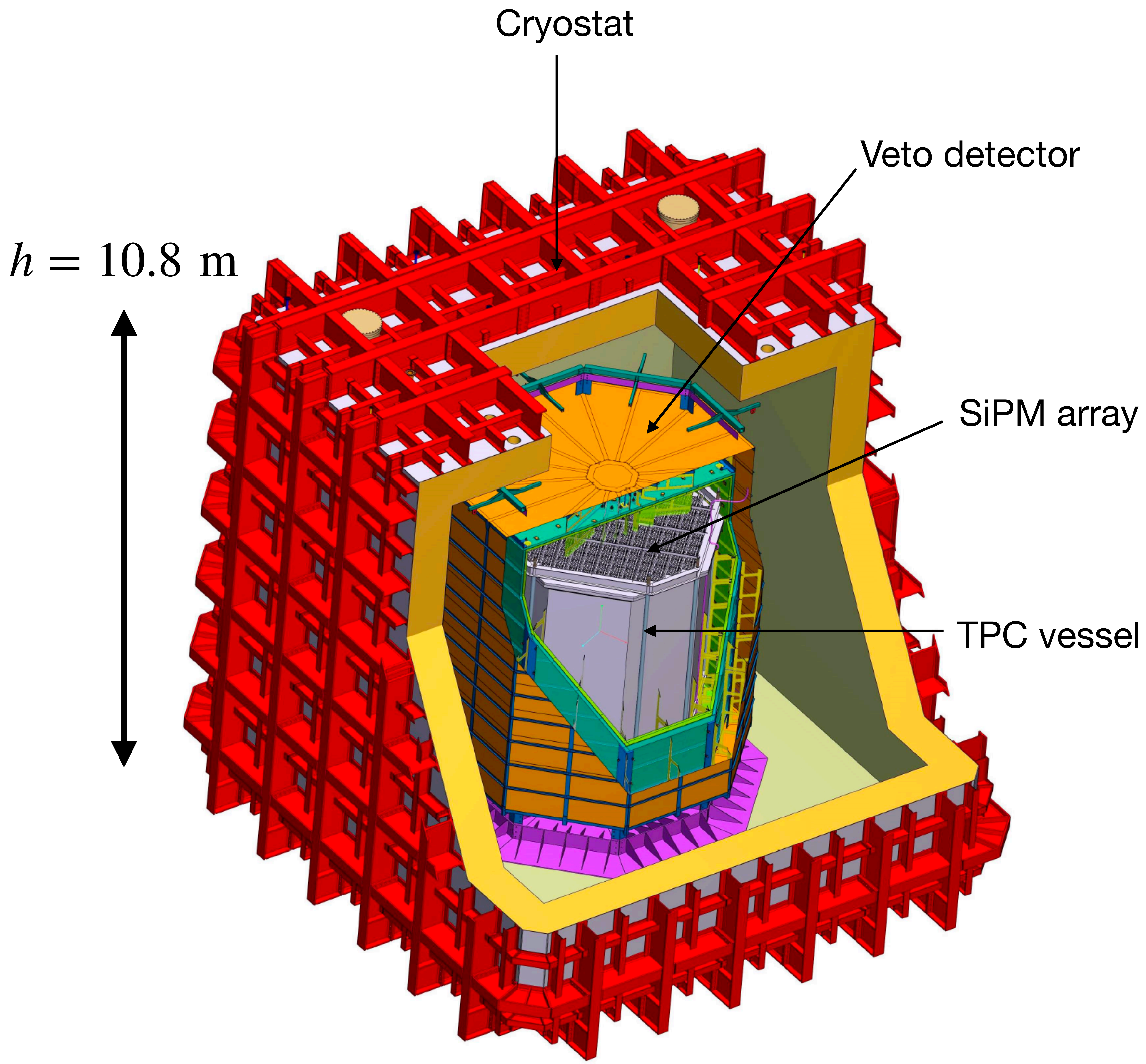


The further down these lines go, the more parameter space we exclude and the closer we come to finding dark matter!

DarkSide-20k: Introduction

Detector Overview

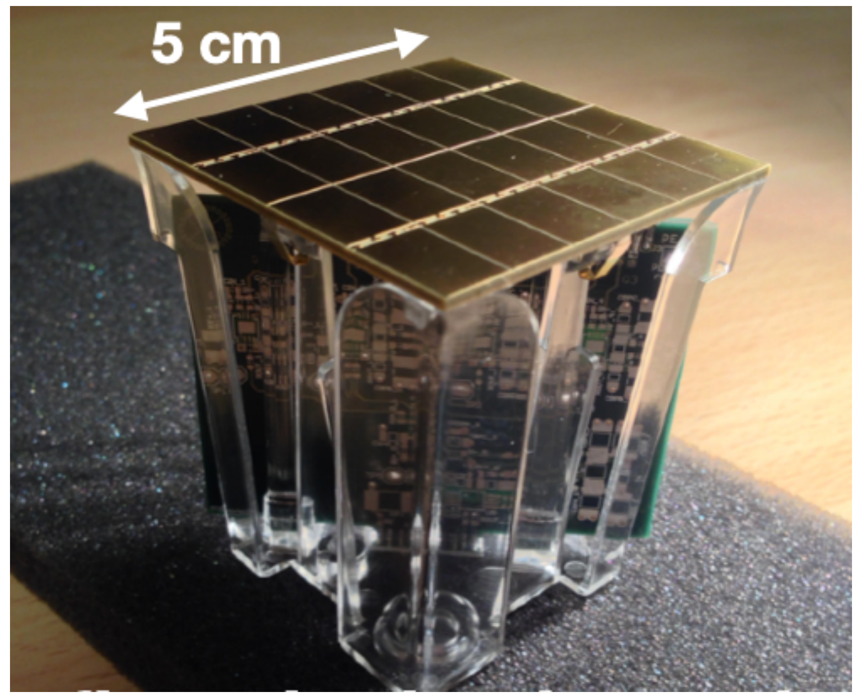
- Dual-phase liquid argon time projection chamber (LAr TPC) containing 55 tonnes (20 t fiducial) of low-radioactivity underground argon (UAr)
  - ➡ Particle interactions in Ar generate scintillation light via excitation and ionisation of argon atoms
  - ➡ Scintillation light collected by Silicon Photomultiplier (SiPM) devices arranged on top/bottom of TPC vessel
  - ➡ Scintillation "S1" signals used to discriminate between nuclear and electronic recoils using pulse-shape discrimination (PSD)
  - ➡ Uniform electric field applied across TPC so that ionised electrons that do not recombine are drifted to top of TPC vessel towards gas pocket; in GAr phase extracted electrons produce secondary scintillation photons through *electroluminescence* generating a secondary "S2" signal
  - ➡ S2 signal measured by the SiPM arrays Δt after S1 signal
- TPC surrounded by veto detector
  - ➡ Gadolinium-loaded plastic sheet for neutron captures



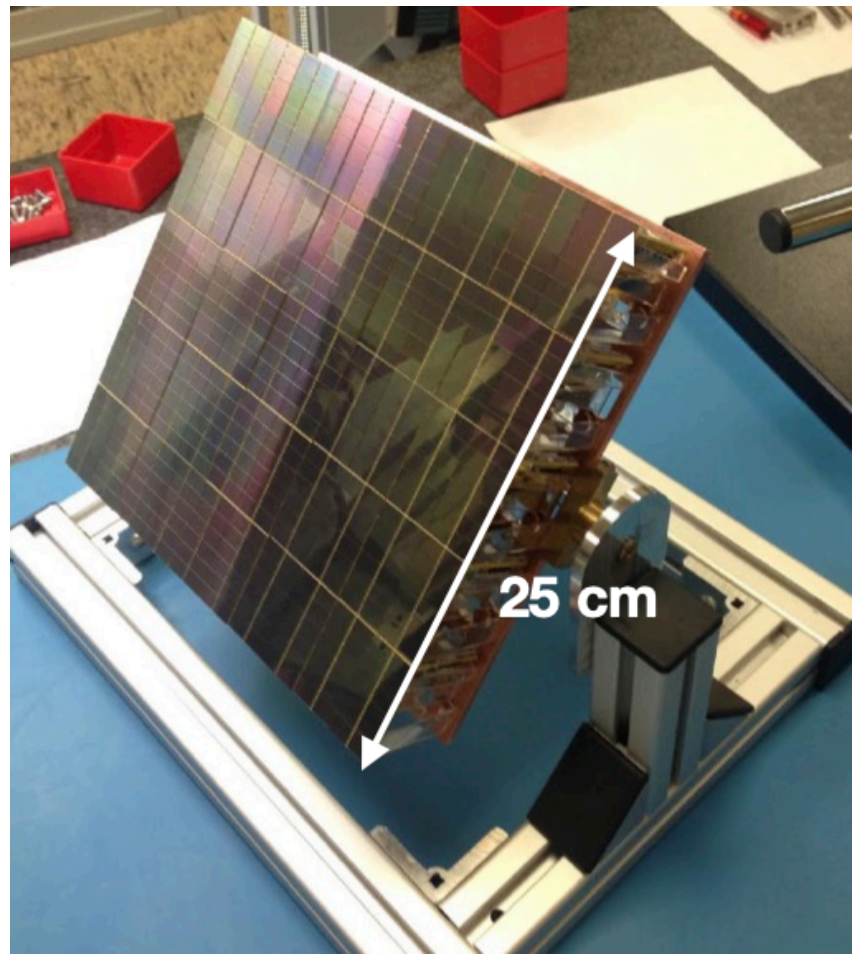
DarkSide-20k: Introduction

Silicon Photomultipliers (SiPMs)

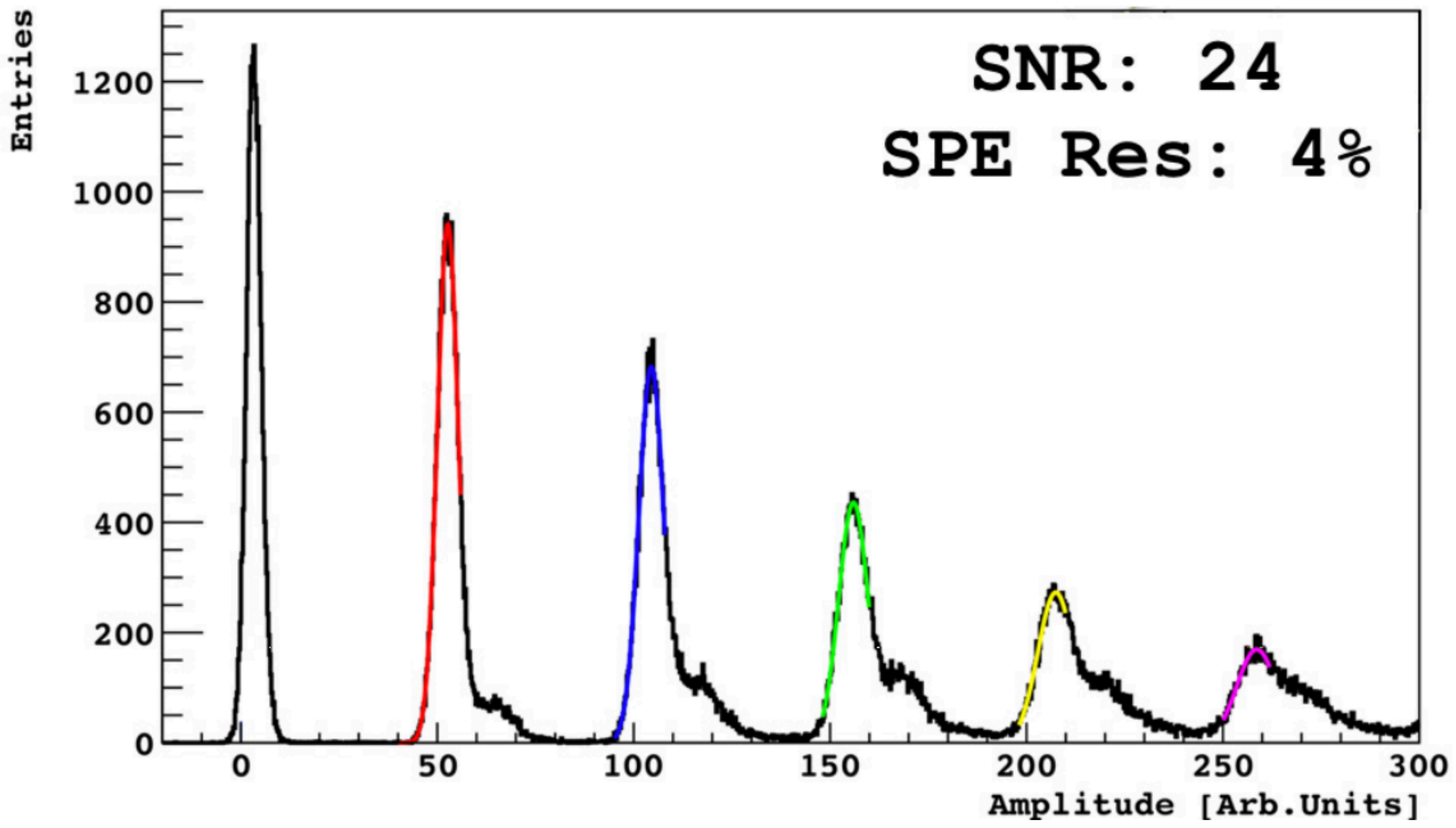
- SiPMs are extremely sensitive, single-photon solid-state photodetectors
- Compared to traditional photomultiplier tubes (PMTs) typically employed in direct detection experiments, SiPMs…
  - ➡ May have a lower radioactivity
  - ➡ Have a significantly better single photon resolution
  - ➡ Have a higher photon detection efficiency (> 40%)
- Photodetector modules (PDMs) each comprised of 24 SiPMs
- Each motherboard comprised of 25 PDMs
- Dark count rate (DCR) of < 250 Hz/PDM



24 SiPMs/PDM



25 PDMs/
motherboard



Typical single channel energy response (superseeded version of the FBK SiPM matrix): http://www-kam2.icrr.u-tokyo.ac.jp/indico/event/3/session/40/contribution/60/material/slides/0.pdf

DarkSide-20k: Data Acquisition System

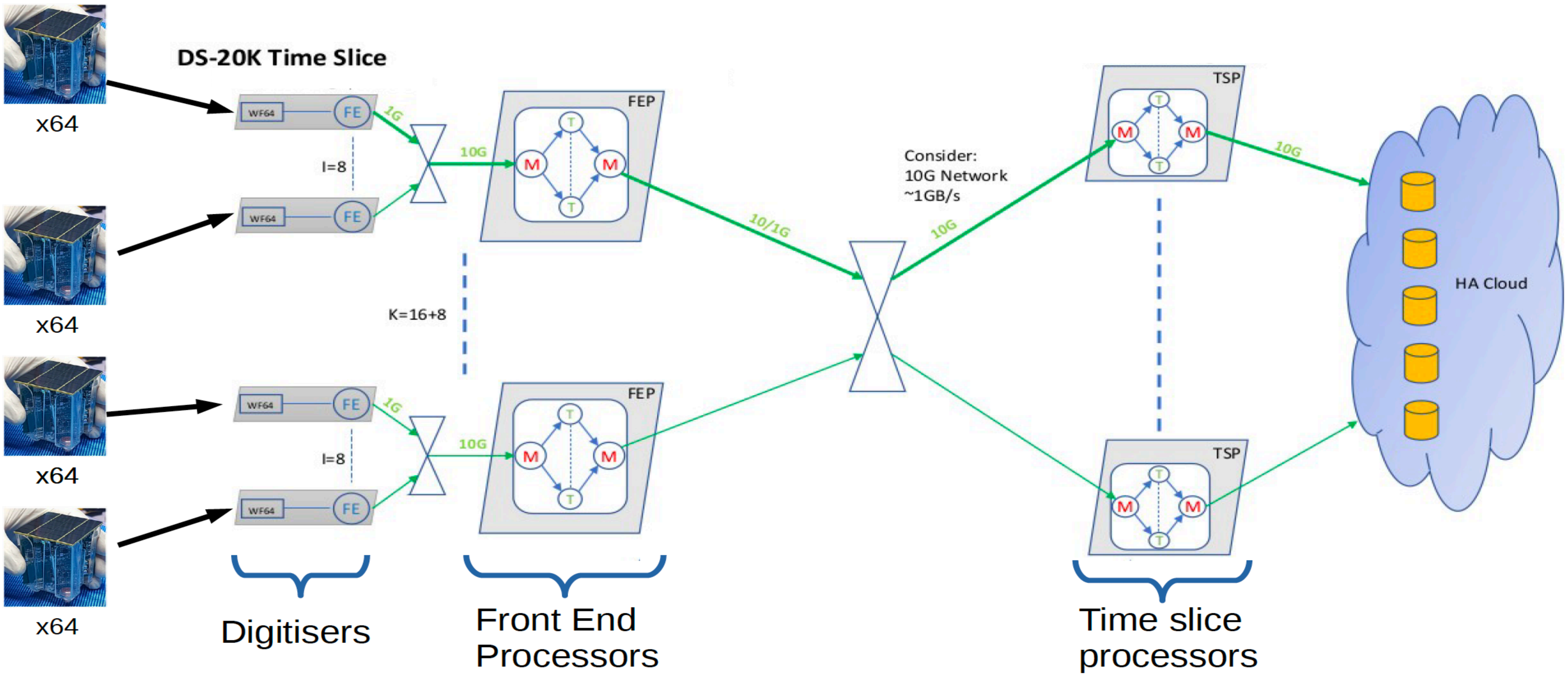
Overview, 1.0

- Current design for the electronics and data acquisition system (DAQ) accommodates both the large number of PDMs and the long drift-time (expected maximum electron drift time ~ 4 ms) of the LAr TPC, and the readout of the veto detector
- Current strategy of DAQ is to readout all activity in the TPC & veto compatible with ≥ 1 PE, deferring any high-level processing & data-reduction schemes until after the (partial) event-building stage
  ➡ Relying on filtering out data rather than completely eliminating events from continuous data stream
- Trigger rate during dark matter search data-taking from three major contributions:
  A. Background events from detector material intrinsic radioactivity
  B. Background events from ^{39}Ar (~ 35 Hz from 50 t active UAr)
  C. DCR (< 250 Hz/PDM)
- DAQ design has to:
  ➡ Be able to correlate activity in the TPC with activity in the veto detector
  ➡ Have a detection threshold < 1 photon at channel level
  ➡ Handle large background rate in veto detector

DarkSide-20k: Data Acquisition System

Overview, 1.1

Courtesy of P. Amaudruz, M. Stringer



DarkSide-20k: Data Acquisition System

Challenges

- Current detector design envisions ~ 8280 channels for the TPC & 3000 channels for the veto digitised by 64-channel, 16-bit CAEN digitisers with fast sampling rate of 125 MS/s
- Given expected rates from background and noise, this results in an unfeasible data throughput through the DAQ chain if the full waveforms were to be saved
- Various data reduction schemes need to be implemented at the digitiser and FEP level to reduce data throughput across the system, and at the TSP level to save on disk space

DarkSide-20k: Data Acquisition System

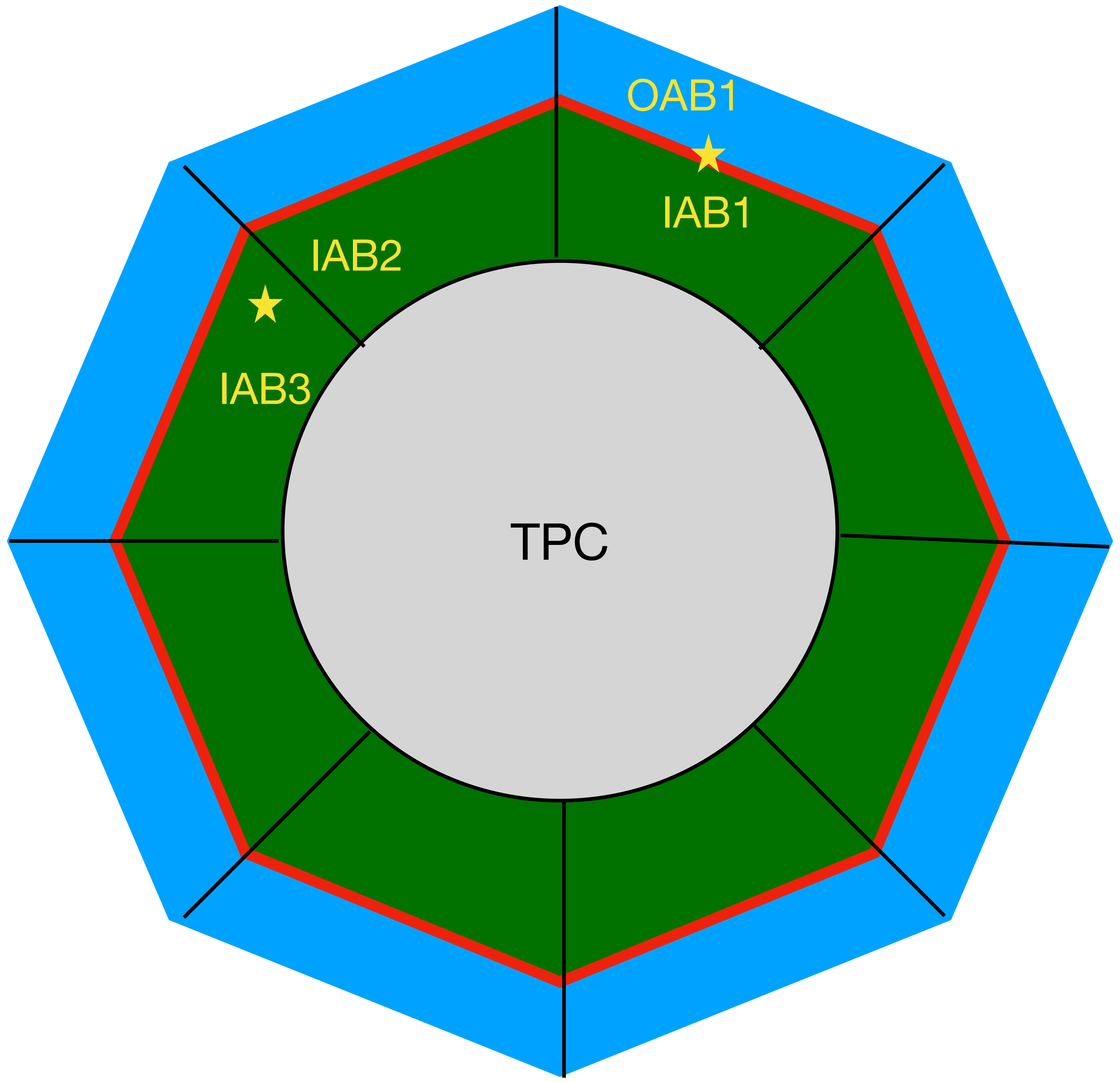
Veto System: Overview

Work-in-progress

- Veto encompasses the TPC vessel and is comprised of three main components:

Inner atmospheric argon (AAr) buffer (IAB) → Gadolinium-loaded plastic → Outer AAr buffer (OAB)

- IAB consists of 45 tonnes LAr, OAB consists of 75 tonnes LAr
- Veto will be used to reject background events from the data collected from the TPC as candidate WIMPs, primarily using neutron-capture signals on the Gd-loaded sheets (~ 50%), on LAr (~24%) and on H (~15%)
- Veto consists of segmented (octagonal) design; separation of segments using acrylic sheets
  - ➡ IAB and OAB divided into 8 "sectors" of roughly equal size
  - ➡ Segmented design reduces rate of ^{39}Ar pile-up, ~ 1 Bq/kg for AAr
  - ➡ Can also use correlation of signals in neighbouring sectors to discriminate between candidate neutron-capture events and uncorrelated, random ^{39}Ar/γ events
- Challenges of the veto from the DAQ perspective:
  - A. High background rate: 5.6 kHz/9.4 kHz per IAB/OAB sector from ^{39}Ar, 30 Hz/23 Hz per IAB/OAB sector from γ's from detector material radioactivity, < 250 Hz from PDM dark noise
  - B. High data throughput (3000 channels envisioned, 2000 for IAB & 1000 for OAB)
  - C. It is **vital** to not miss neutron-capture signals! Require a maximum veto inefficiency of 10%
- Various data reduction schemes need to be implemented at different layers of DAQ chain such that DAQ is not overwhelmed with veto data whilst ensuring all important data is stored



DarkSide-20k: Data Acquisition System

Veto System: Channel & Digitiser Level

Current Readout Proposal: Work-in-progress

- Sample at 12.5 MS/s (factor of 10 in data reduction compared to TPC)
- Timing resolution is not as important for veto

DarkSide-20k: Data Acquisition System

Veto System: Channel & Digitiser Level

Current Readout Proposal: Work-in-progress
- Sample at 12.5 MS/s (factor of 10 in data reduction compared to TPC)
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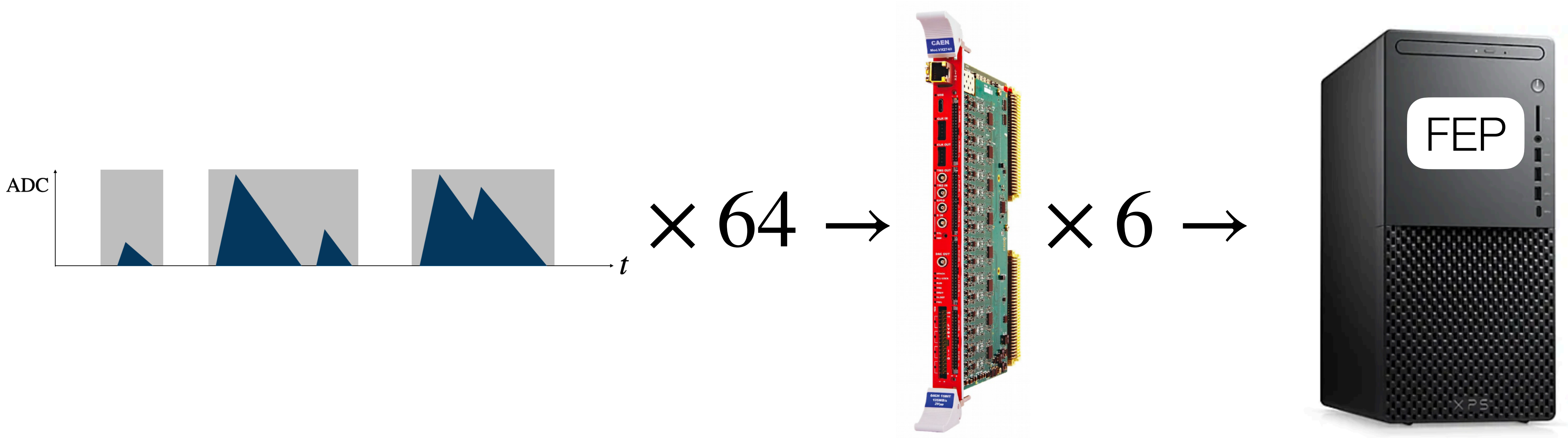
On channel-basis, use pulse-finding algorithm in FPGA to identify SiPM signals
- Dynamic Acquisition Window (DAW): only recording segments of digitised waveform around a pulse; removes recording only baseline
- In example waveform below, only waveform segments in grey boxes are recorded

DarkSide-20k: Data Acquisition System

Veto System: FEP Level

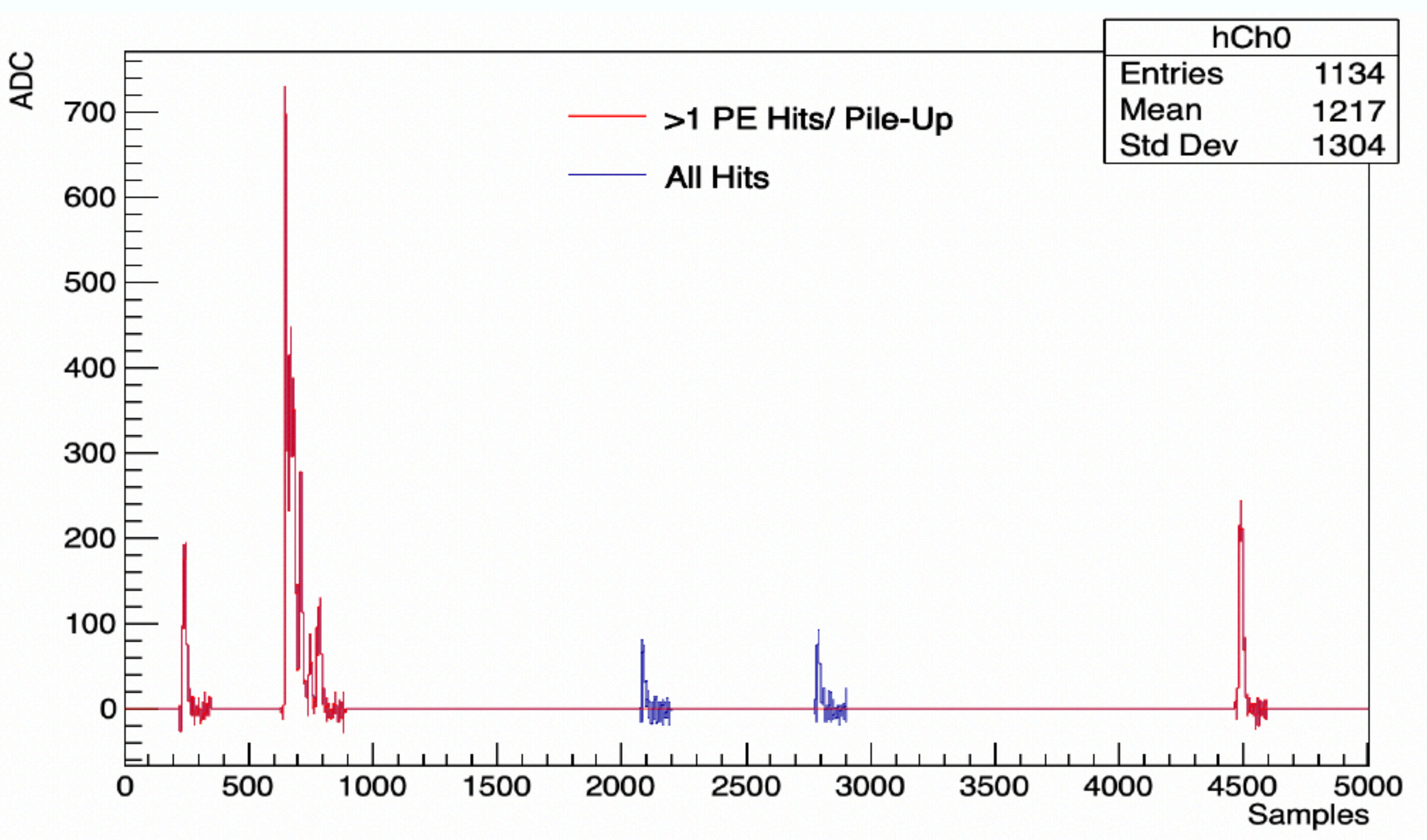
Work-in-progress



Each FEP reads input from 6, 64-channel digitisers: 8 FEPs in total yields 3000 channels in total

Max output rate per digitiser = 125 MB/s (uncompressed raw data equivalent)

- At FEP, can perform pulse analysis on individual channel waveforms
  - ➡ Single PE hits, i.e. from dark noise, can be compressed into charge and time information only (QT), ~ 10 B in size
  - ➡ Keep waveform segments for > 1 PE pulses/ pile-up events for approx 10 us, ~ 256 B of data/segment
  - ➡ Early simulations of ^{39}Ar, γ's and neutron captures in the veto indicate a 25% - 35% reduction in data throughput from compressing single PE hits into QT only
- At FEP, will also sum together waveforms over multiple channels before sending data to TSP to ensure output rate does not surpass 125 MB/s FEP output limit
  - ➡ Early simulations of ^{39}Ar, γ's and neutron captures in the veto indicate performing QT on single PE pulses and summing together groups of channels into single waveforms should fit into available bandwidth for FEP output
  - ➡ Number of channels summed together at this stage yet to be optimised; trade off between retaining good SNR without losing physics information



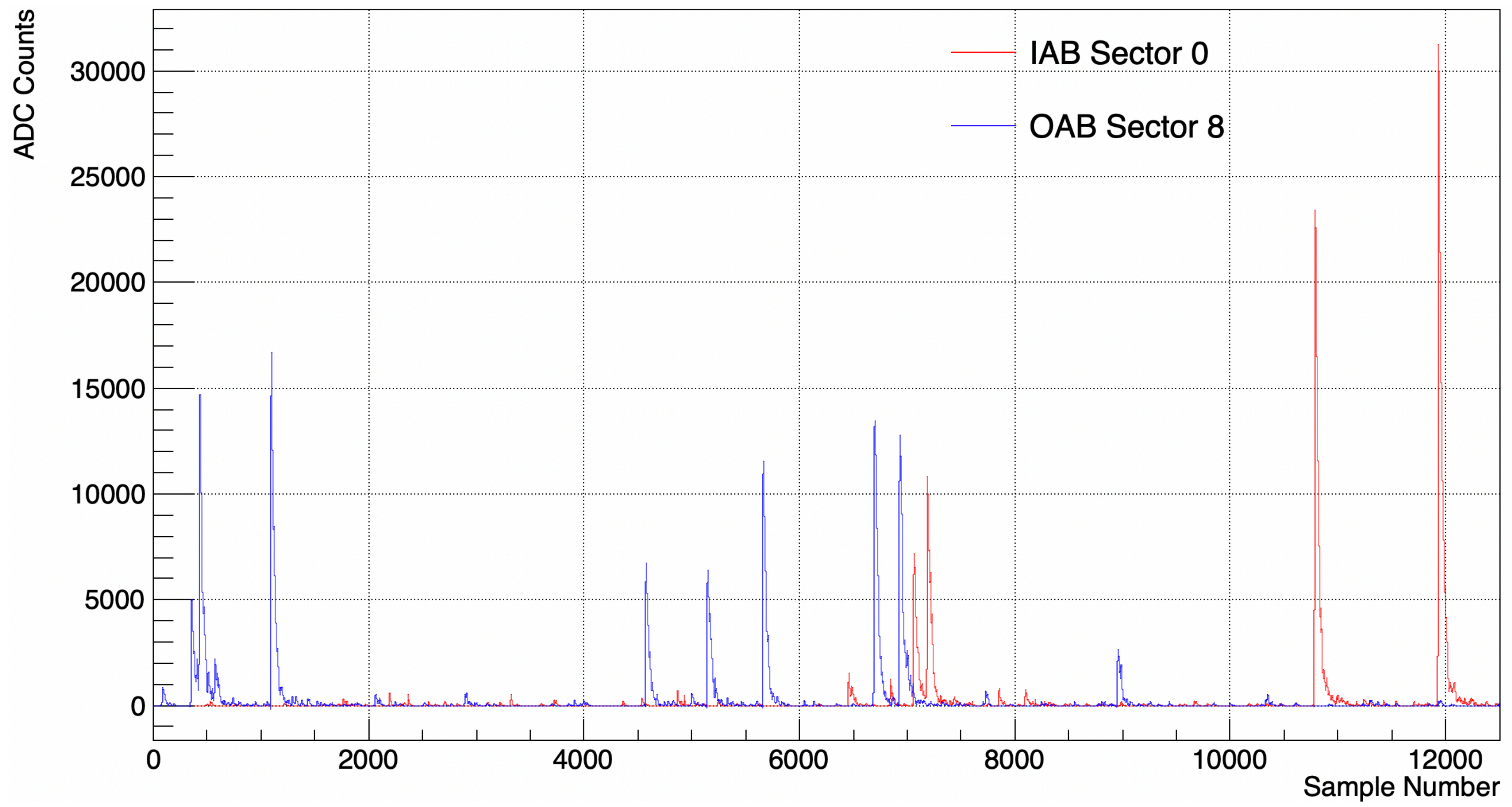
Simulated waveform of a single channel inside the inner AAr buffer (veto)

DarkSide-20k: Data Acquisition System

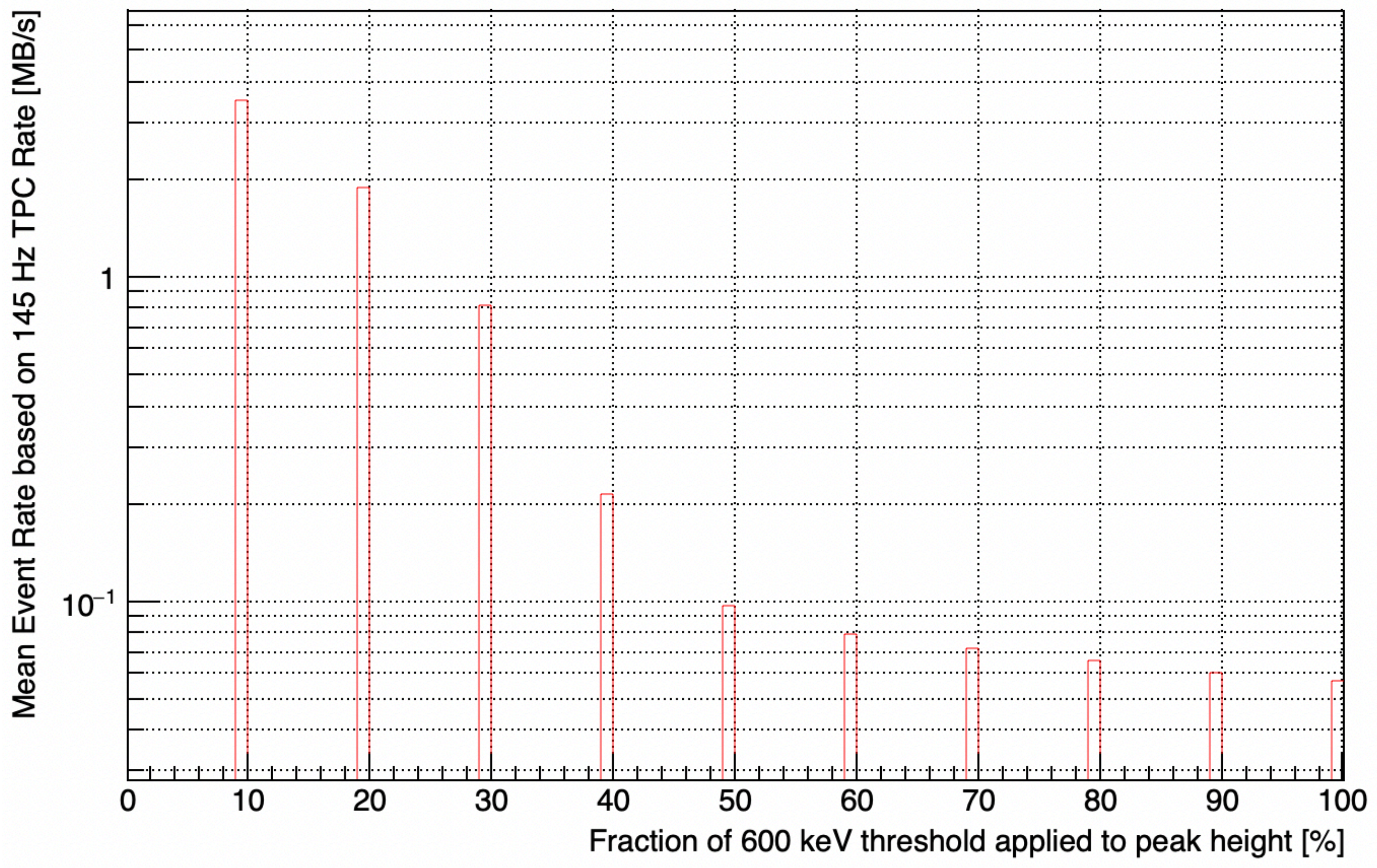
Veto System: TSP Level

Work-in-progress

- At TSP level, open a TPC-veto coincidence window (~ 1 ms in length) about the time an event is observed in TPC - only look at veto data within this window
  - ➡ Relies on correlating TPC-veto information in real time
  - ➡ Strategy refers to a “typical” high-mass analysis with perfect online reconstruction; other analysis use cases exist for which major adjustments may be necessary to allow some reprocessing & handle special cases
- Need to develop an algorithm to decide what parts of waveform to save to disk
- One potential idea:
  - ➡ Sum together waveforms for each sector
  - ➡ Only save WF segments of pulses which correspond to an energy deposition > 600 keV
  - ➡ ^{39}Ar endpoint = 565 ± 5 keV
  - ➡ 600 keV threshold would remove majority of ^{39}Ar background; energy deposition of neutron-captures γ >> 600 keV
- Threshold needs to be optimised to ensure neutron-capture detection efficiency > 95%, whilst minimising amount of background data written to disk
- Veto event size estimates based on saving waveform segments from each sector that cross threshold in TPC-veto coincidence window
  - ➡ Could consider saving waveform segments from finer grouping of channels instead of sector sums for further reconstruction information down the chain,
  - ➡ One example: save waveform segments from groups of channels clustered together for position reconstruction purposes



Two example summed sector WFs (one IAB, one OAB) constructed by adding together ZLE segments from individual channels of 1 ms TPC-veto coincidence window containing 1 neutron capture, ^{39}Ar and background γ 's normalised to their expected rates



Mean veto event rate (assuming a 145 Hz TPC rate) as a function of threshold applied estimated using simulations of 1 ms TPC-veto coincidence window containing 1 neutron-capture, ^{39}Ar and background γ 's normalised to their expected rates

DarkSide-20k: Conclusions and Outlook

Thank you - Questions?

- The DarkSide-20k experiment intends to stream data continuously during operation via a software-based trigger system
- Large number of channels and fast sampling rate of digitisers poses various logistical challenges to the data acquisition (DAQ) system if no data reduction is employed at the different layers of the DAQ chain
- The veto detector has different data requirements to the TPC; has to be able to record high energy neutron-capture γ events
- To deal with high expected background rates from ^{39}Ar, γ's from detector material, veto DAQ chain will employ a combination of data reduction schemes, such as dynamic acquisition windows (DAW), charge-time (QT) compression, waveform summation and threshold-based self-trigger decisions
- Other potential veto readout strategies are being explored, for example, saving veto data stream independently of TPC activity, and saving all veto information as QT summary information

DarkSide-20k: Backup

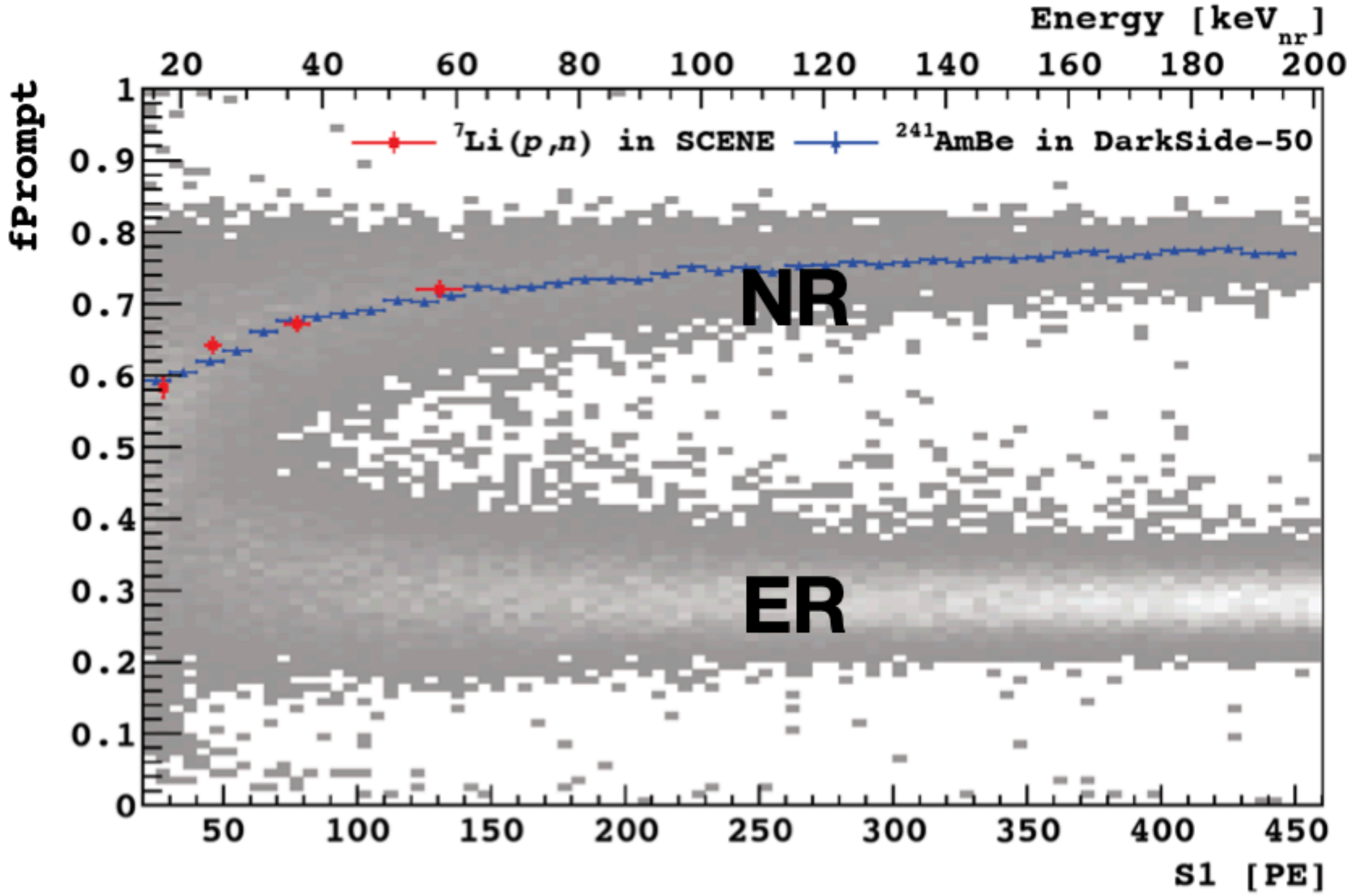
S1 Signal

$$F_{\text{prompt}} = \frac{\text{Prompt Light}}{\text{Total Light}}$$

- Property of LAr scintillation: electronic recoils ERs (β, γ) generate much more late light in comparison to nuclear recoils NRs (i.e. WIMP-induced)
- Pulse-shape discrimination (PSD) is a technique to discriminate NRs from ERs based on their time profiles
- Introduce discriminator parameter F_{prompt}: ratio of prompt light to total light generated in an event

  ➡ ERs, which generate higher fraction of late light, typically have lower F_{prompt} values than NRs

ER background suppression of ~ 10^8 from PSD in LAr

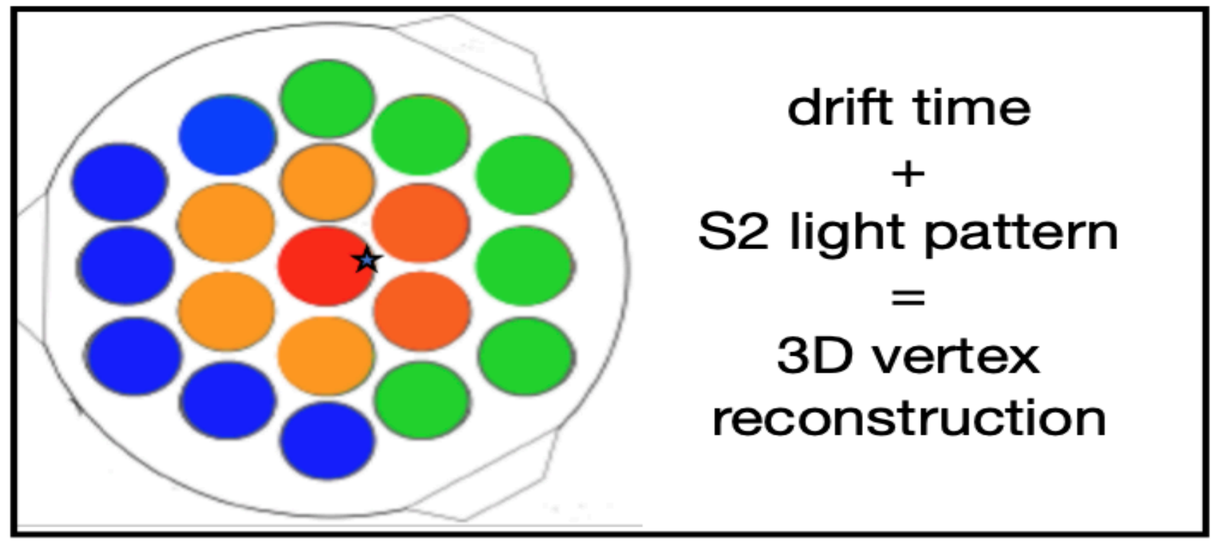


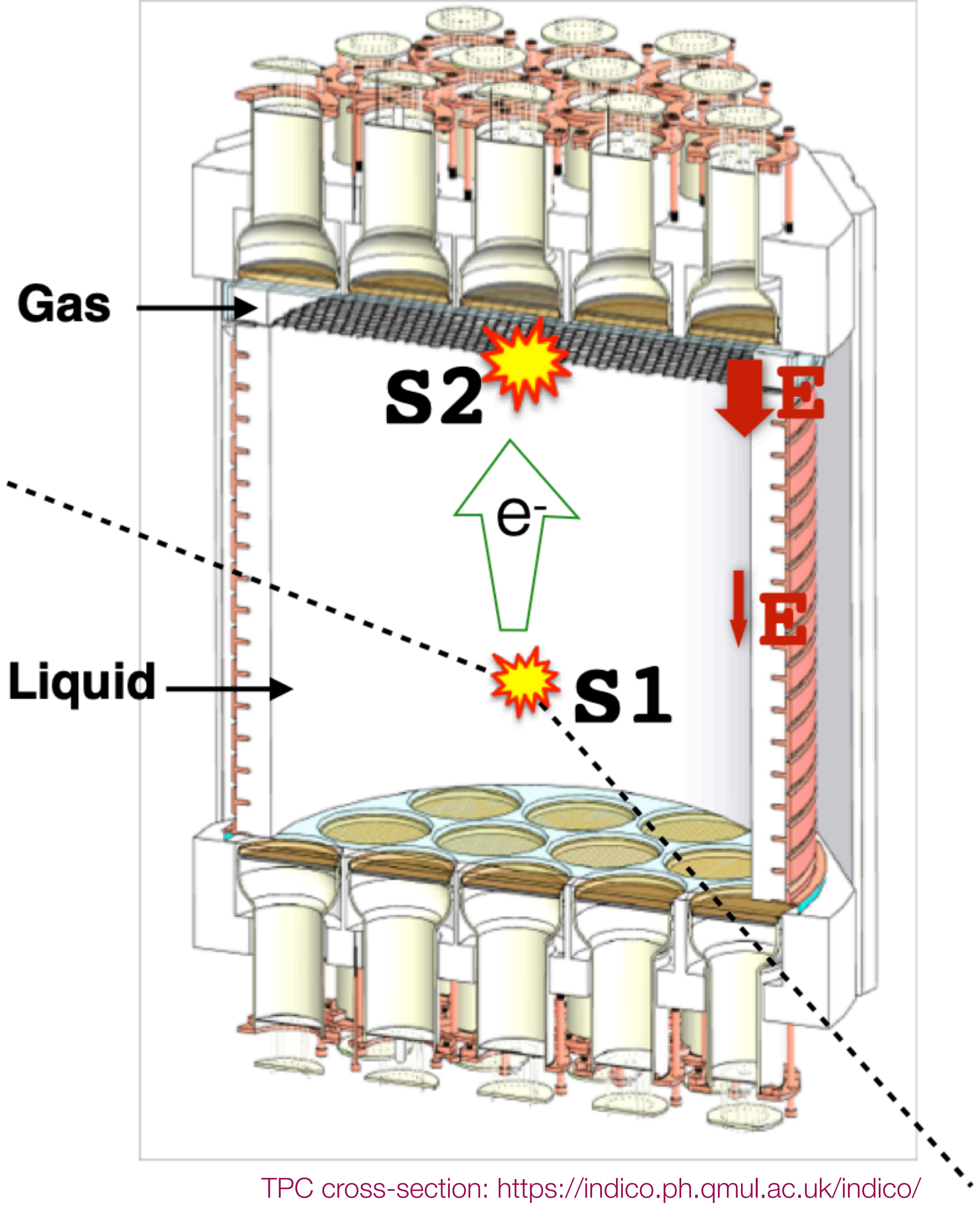
Fprompt vs S1: https://indico.ph.qmul.ac.uk/indico/getFile.py/access?resId=0&materialId=slides&confId=428

DarkSide-20k: Backup

S2 Signal

- S2/S1 ratio can also be used discriminate between ERs and NRs
  - ➡ ERs produce more free, ionised electrons compared to NRs, thus have a larger S2 signal compared to NRs; can be used to distinguish between interactions with equal S1 signals
- TPC technology allows for powerful position reconstruction
  - ➡ Free electrons all drift at the same velocity; the time difference between S1 and S2 can be used to determine *z*-position
  - ➡ Drift speed of electron in 200 V/cm applied field is ~1 mm/μs
  - ➡ Pattern of the S2 signal on the top PMT array used for *xy* reconstruction
  - ➡ Full 3D position reconstruction can discriminate surface backgrounds from the edge of the detector





TPC cross-section: https://indico.ph.qmul.ac.uk/indico/getFile.py/access?resId=0&materialId=slides&confId=428

DarkSide-20k: Backup

Detailed DAQ Chain Overview

1. Analog signals fed into VX2740 digitiser modules designed and produced by CAEN. The 64-channel VX2740 digitises the signal with a sampling rate of 125 MS/s.

2. Data are analysed online in the digitisers in order to identify the pulses from SiPM signals. This is referred to as pulse finding and is performed within the VX2740 field-programmable gate array (FPGA).

3. Data (typically waveform fragments) are transferred from the digitisers to the front-end processors (FEP) using ethernet Gbit/s links. Each FEP is a PC collecting data from 8/9 digitisers through a commercial network.

4. Pulses identified by the pulse finder in FPGA are analysed to extract their time and charge information (QT). This is called pulse analysis and can performed either in the digitiser or the FEPs.

5. FEPs arrange the information into time-slices that contain all the data within a time window of ~ 1s.

6. FEPs send the time slices to a network switch to distribute data; all the data corresponding to a particular time slice are sent to the same Time Slice Processor (TSP).

7. TSPs reconstruct event-level information from the time slices, associating the S1 and S2 signals and identifying the event types.

8. TSPs send data to be written to disk.