Spurious Electron and S2-Only Backgrounds at DarkSide-50

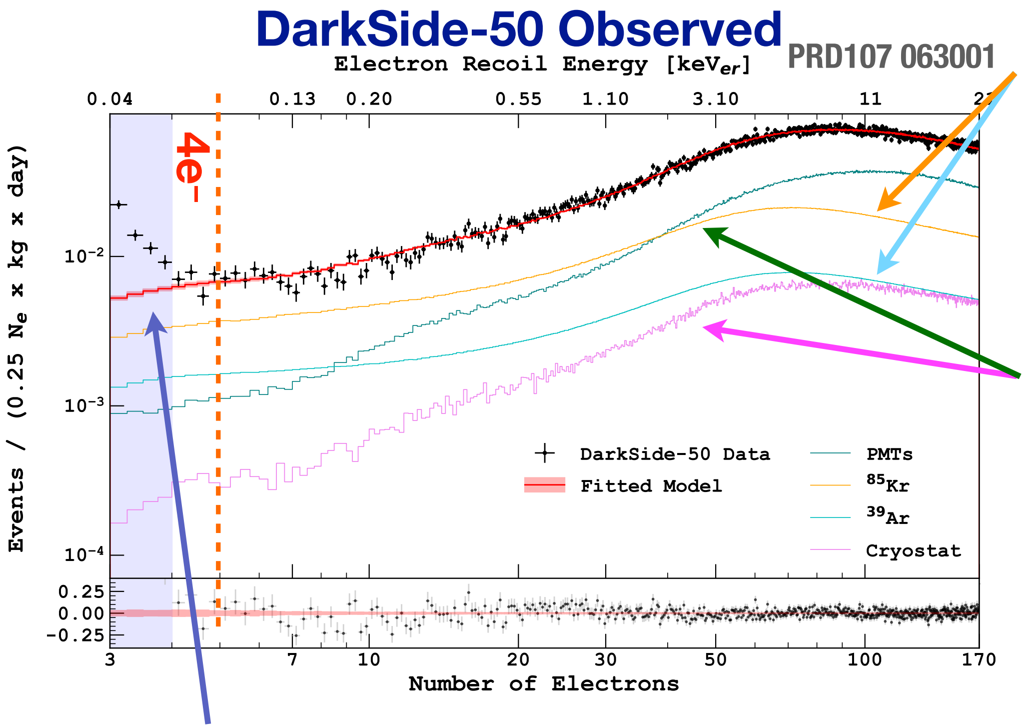
Masato Kimura (AstroCeNT/CAMK, Warszawa)
on behalf of the DarkSide-50 Collaboration

15th February 2024
Nagoya Workshop in Future Liquid Noble Gas Detectors | KMI, Nagoya U

European Funds Smart Growth
Republic of Poland
FNP Foundation for Polish Science
European Union European Regional Development Fund
This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 952480
Dark Wave
NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES
European Union
ASTROCENT

What Limit The Sensitivity?

in the DarkSide-50 S2-only analysis



① Spurious Electrons (SEs) below 4e-

→ **Focused on this talk**

② Diffused β-isotopes inside the bulk LAr (^{85}Kr and ^{39}Ar)

→ Underground argon & Isotope separation

(Federico's talk)

③ γs from photo-detectors and Cryostat

→ a) Radio-purification of instruments (such as replacing PMT with SiPM), **(Giacomo's talk)**

b) Isolating the fiducial volume

④ Limited exposure (1.2 ton-days)

→ Bigger detector

⑤ Limited understanding of LAr response

→ Low-energy calibration experiment

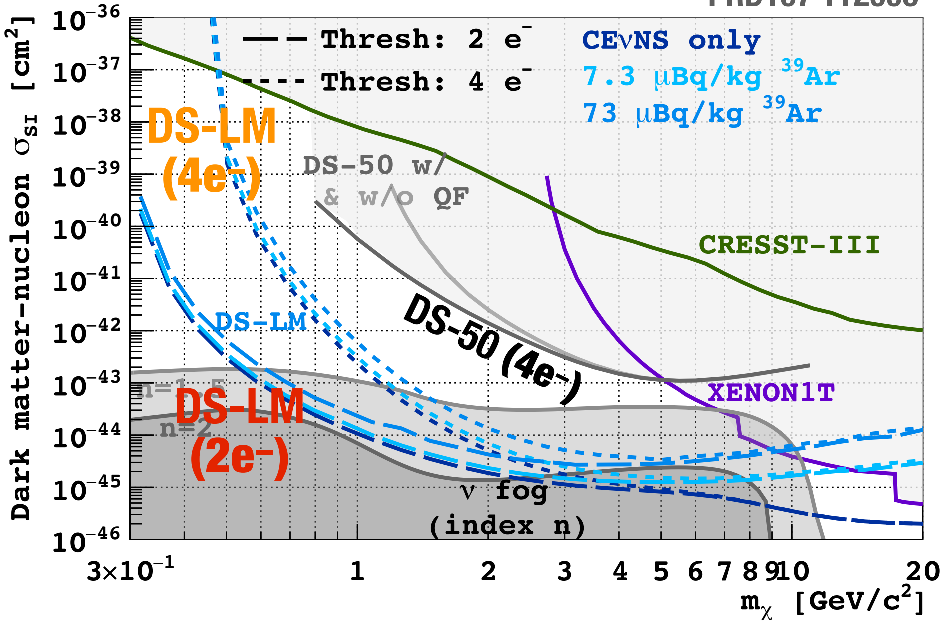
SE Determine the S2-Only Threshold

- **Energy threshold of the DarkSide-50 S2-only analysis was set at 4e⁻**
  - Clear divergence in "Sideband" samples from the background model in <4e⁻
    Such as events temporally closed to the previous one, and events during the system maintaining period
  - Resulted in the limited sensitivity to sub-GeV WIMPs

- In a future S2-only-optimized detector ("DarkSide-LM"), projected sensitivity to m_{wimp}<1 GeV/c² improves **orders of magnitude** by lowering the threshold **from 4e⁻ to 2e⁻**.

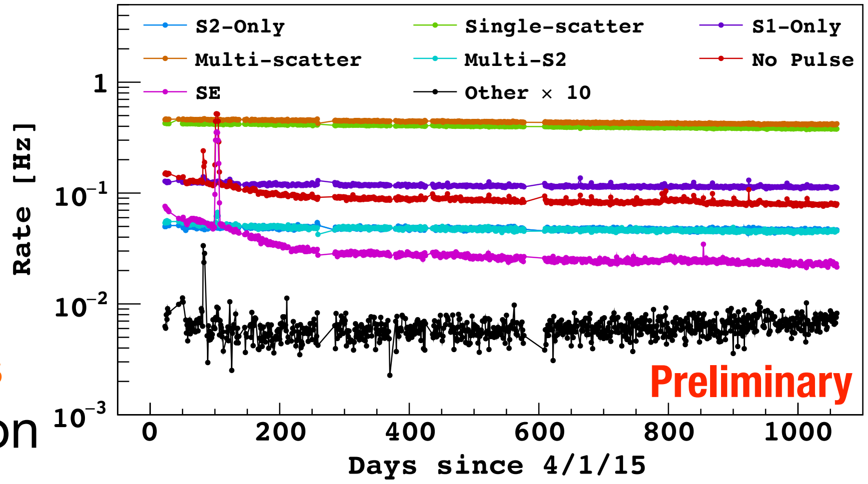
- The events from unclear source below 4e⁻ is called **spurious electrons (SEs)**
  - must be understood and mitigated

PRD107 112006



SEs Analysis in DS-50

- DS-50 was operated with underground argon continuously over almost 3 years
- We found that..
  - the observed "normal" event rates were stable over the whole data-taking period
  - the observed rate in <4e⁻ was O(10^{3-4}) times higher than the background model prediction



Analysis strategy

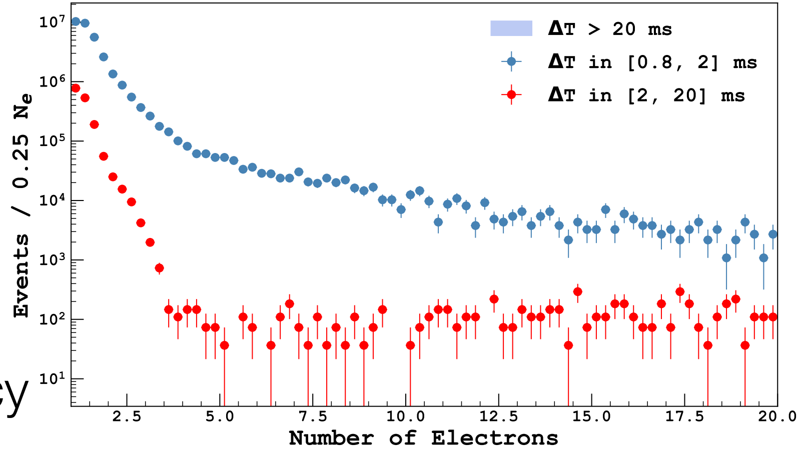
- Define **[0, 4] e⁻ events as a SE sample** and find out its property
  - Particularly focus on its correlations to the preceding events' topology
  - Divide the sample into 1e⁻ bins and investigate how multi-electrons event looks like
  - Discuss about the correlation to the cryogenic system condition
- Discuss possible origins of the SE events along with phenomenological literatures

Properties of
The SE Events

Coincidence between SE and Its "Parent"

- Several indications that SEs have its "parent", i.e. a preceding event correlated to each SE event
- Time difference from the previous triggered event (ΔT) is the most sensitive parameter
  - The DS-50 physics analysis simply requires $\Delta T > 20$ ms, corresponding to 97% signal efficiency

PRD107 063001



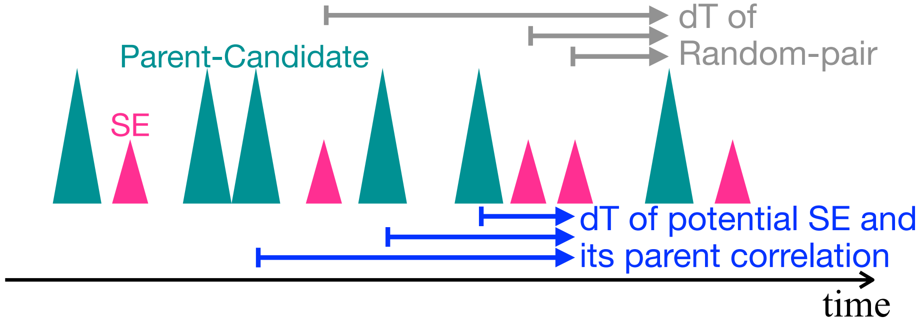
- **The SE analysis on DS-50, discussed here, always relies on the parameter ΔT**

Input behind the analysis (only to those who may be interested..)

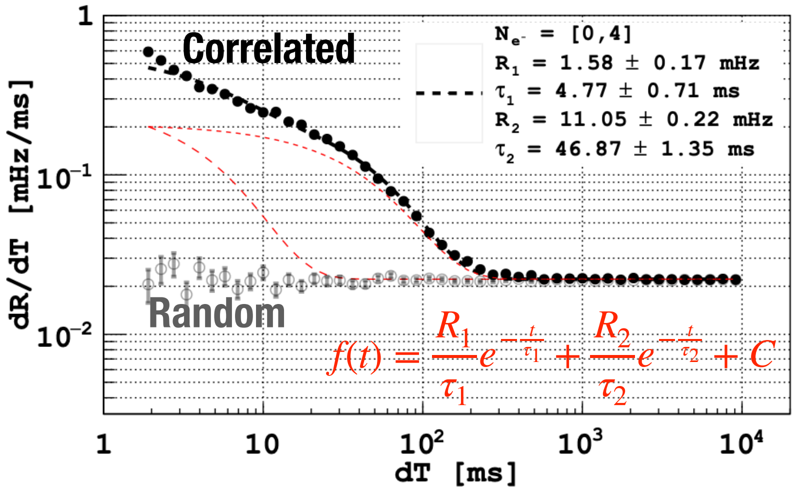
- Electroluminescence gain (g_2) is 23 PE/e^- at the center of the TPC, decreasing by ~30% at the edge of the fiducial volume for S2-only and SE analysis
- Trigger efficiency ⊗ pulse-finder efficiency reaches 100% at around 1.3e^-
- An "event" in DS-50 cannot be defined within ~2 ms after the previous trigger due to the DAQ system

Temporal Correlation Analysis

- Define "parent candidate" samples as S1>1000 PE (~150 keV_{ee}) events
- **Correlated dT sample**:
  For each SE event, time differences (dT) from all preceding parent-candidate
- **Random dT sample**:
  For each parent-candidate, dT from all preceding SE
  - Corresponding only to the accidental pairing

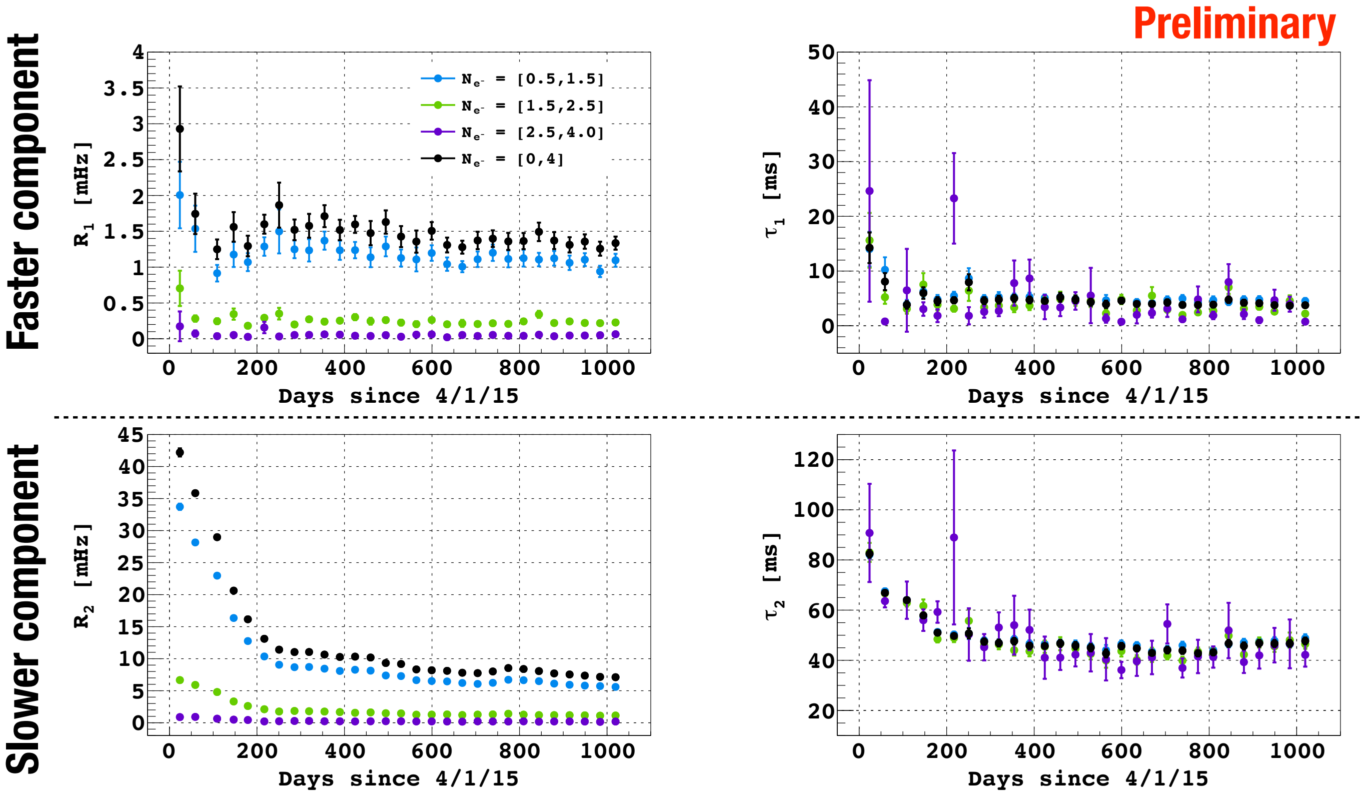


- **Clear population over the accidental estimation at dT<500 ms**
- Explained by **two exponentials** with the time-scales of **5 ms** and **50 ms**
  - This may indicate that the origin goes through Poisson process



Temporal Evolution

- The same analysis is repeated for each month in each Ne bin

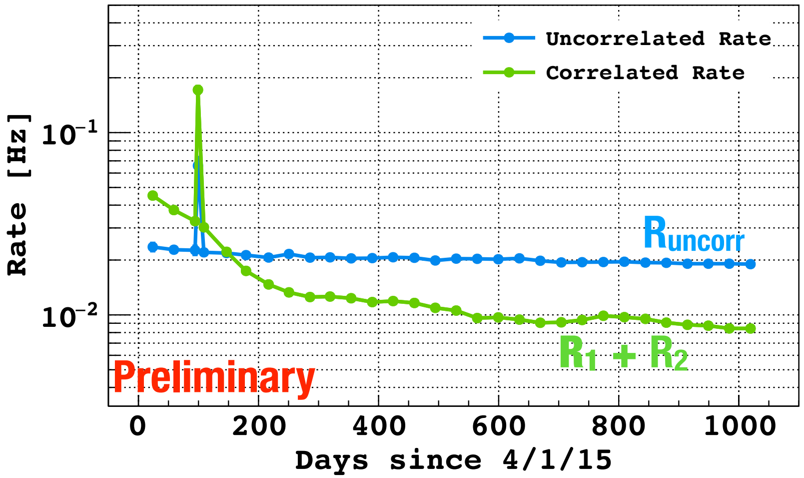


- The faster-correlated component seems to be stable in both rate and tau
- The slower-correlated one decreases rapidly within the first 200 days and moderately in the rest
- Consistent behavior in all Ne bins

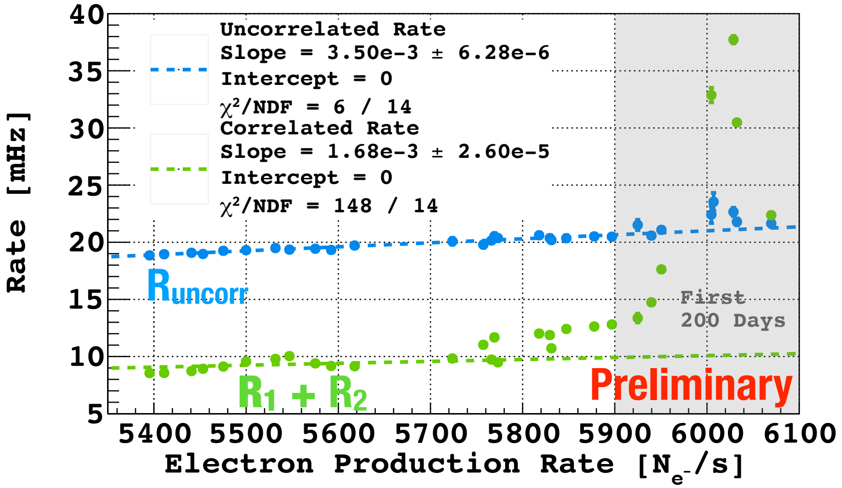
Temporally Uncorrected Events

- Definition : Total SE rate = $R_1 + R_2 + R_{uncorr}$, where R_1 and R_2 from the dT fit

As A Func. of Day



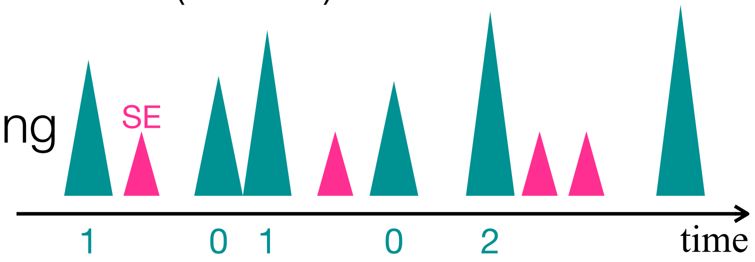
As A Func. of Normal Events' e⁻ Rate



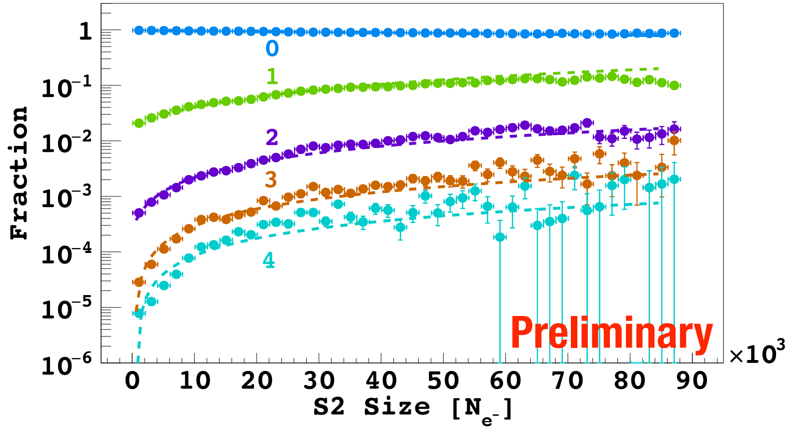
- Temporally-correlated component decreases over the period while the uncorrelated one is rather constant
- Both correlated and uncorrelated rates are roughly proportional to the total e⁻ production rate inside the TPC

SE Following Probability

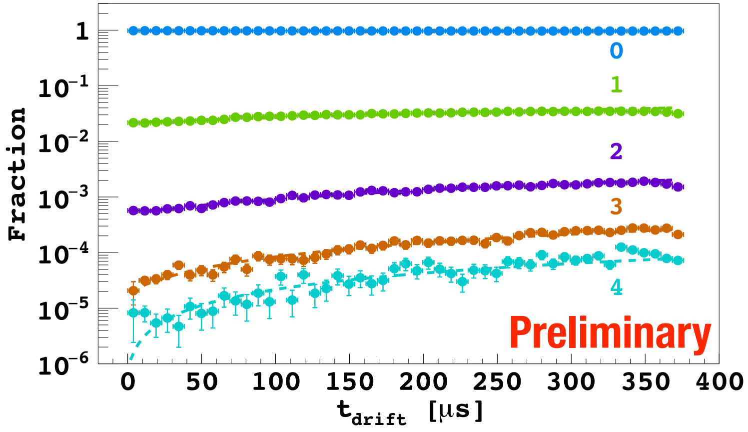
- Pair each SE with the most recent parent candidate to make the parent sample
  - Such pairing makes sense as the time-scale of the correlation (50 ms) is much shorter than the average event rate (~1.5 Hz)
- For each parent-candidate, count the number of following SE before the occurrence of next parent-candidate



As A Func. of S2 Size



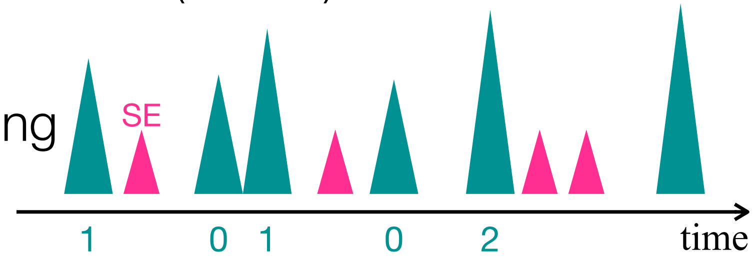
As A Func. of t_{drift}



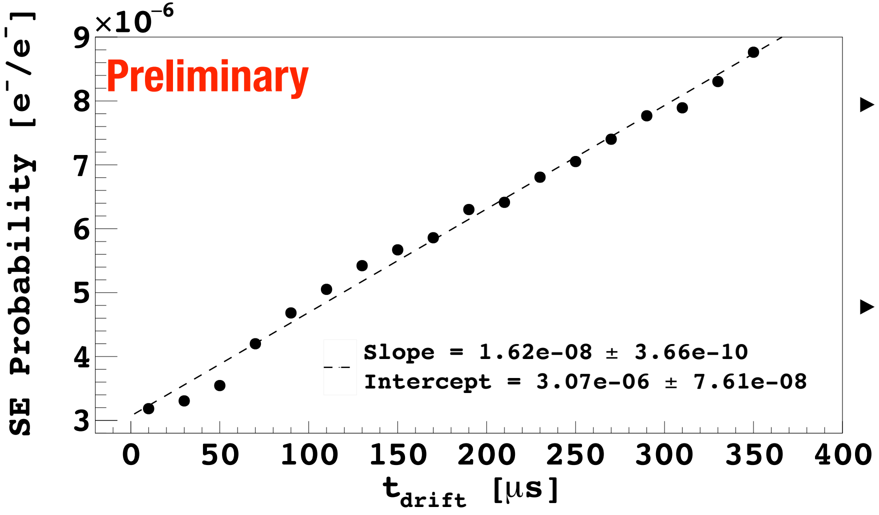
The number of following SEs increases linearly as functions of both S2 and t_{drift} of the parent-candidate

SE Following Probability

- Pair each SE with the most recent parent candidate to make the parent sample
  - Such pairing makes sense as the time-scale of the correlation (50 ms) is much shorter than the average event rate (~1.5 Hz)
- For each parent-candidate, count the number of following SE before the occurrence of next parent-candidate



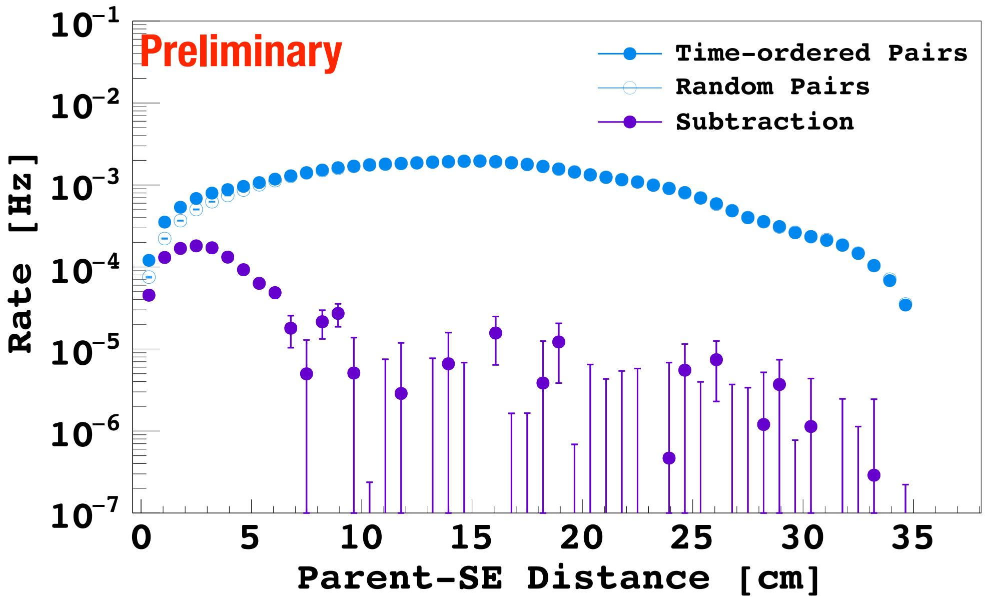
Total charge of all SEs following parent candidates normalized by that of the parent candidates



- Temporally-correlated SEs show linear relationship to t_{drift} of parent-candidate
- Nonzero intercept corresponds to temporally-uncorrelated SEs

Spacial Correlation

- Spacial correlation (in horizontal plane) between SEs and parent-candidate is investigated as with the same way
  - Scanned over events within a 10-sec window



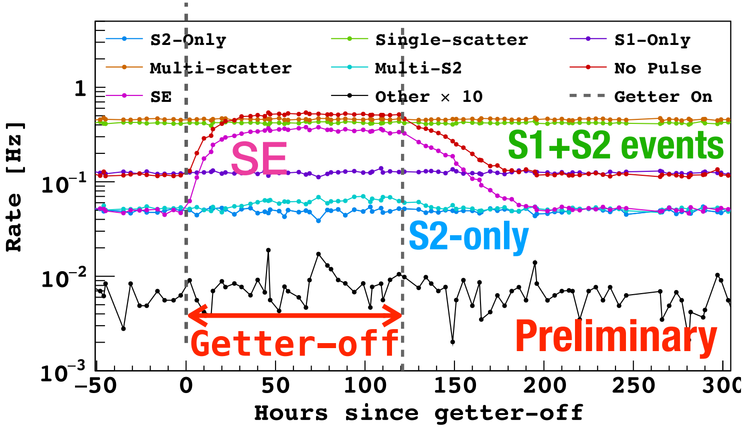
Note:
Uncertainty from the reconstruction algorithm for a few e^- signal is not included yet

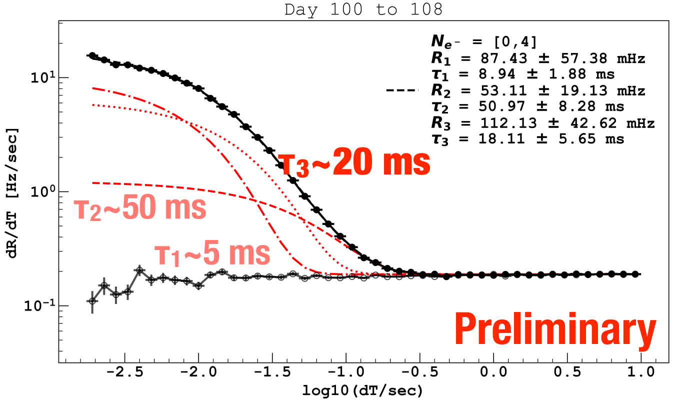
Temporally-correlated pairs predominantly reconstructed within 5 cm

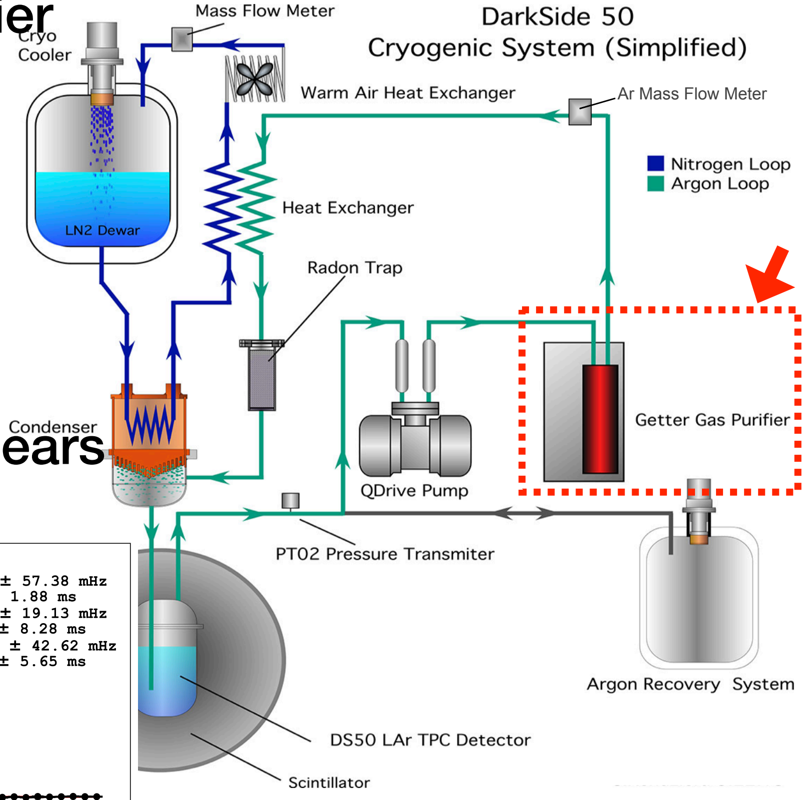
Correlation with The System Condition

-- A few indication the cryogenic system impacts on the SE rate

- **Sharp change of the SE rate when the gas purifier getter is bypassed**
  - x10 increase (plateau) 1-day after bypassing, getting back 3-day after reinstalling
  - No change on the "normal" event rate
  - No change on the electron lifetime
- **An intermediate temporally-correlated term appears**





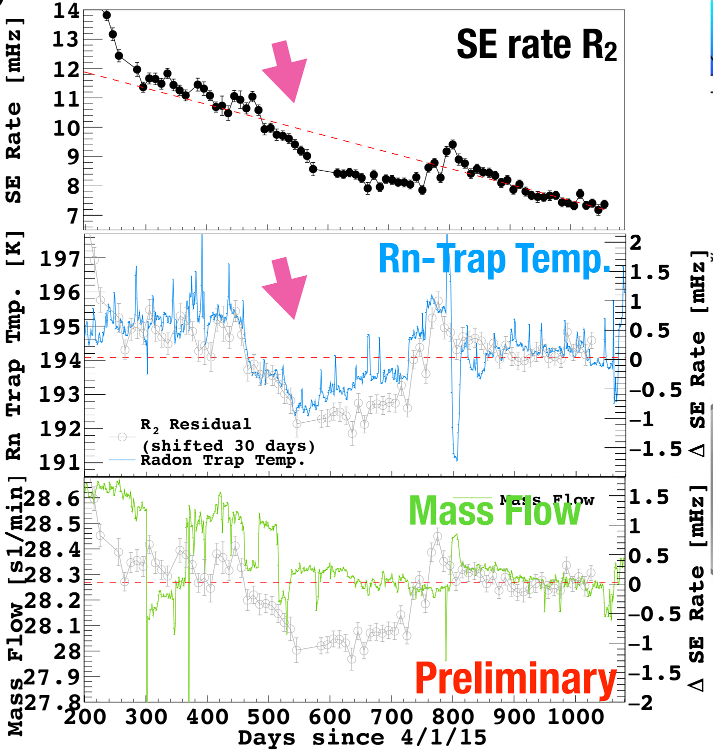


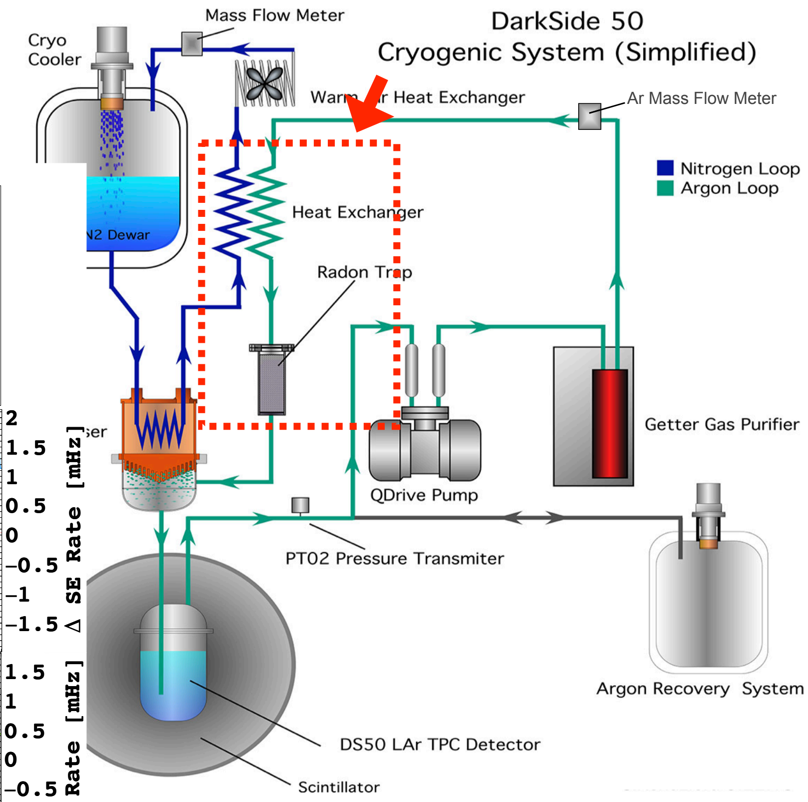
* Getter : Monotorr PS4-MT50-R-2

Correlation with The System Condition

-- A few indication the cryogenic system impacts on the SE rate

- **Delayed coincidence between the correlated rate and Rn-Trap temperature**
  - A ~1 year-duration dip in the temporally-correlated rate (R_2) on its gently decreasing trend
  - Similar dip in the Rn-trap temperature, with a time-delay of 30-days
  - No such structure in other monitoring parameters





* Radon trap is a charcoal filter

Summary of The SE Property

	How to analysis	Observation	
		Temporally-Correlated	Random
Components	Look at dR/dT - dT = time difference from paired parent-candidate - dR = observed rate	- **Two exponentially-temporally-correlated terms** (τ_1~5 ms and τ_2~50 ms) - Random (temporally-uncorrelated) term	
Absolute Rate	dR/dT	- 60% → 30% of the total SE - The longer one gets decreased over years	- 40% → 70% of the total SE - Rather constant over years
Corr. with the total activity in TPC	SE rate vs. S2 rate	- Roughly linear	- Roughly linear
Corr. with the parent's size	Look at the most recent parent-candidate	- Linear	N/A
Corr. with the parent's position		- Looks exist	N/A
Corr. with the system	getter-off period	- Clearly exist - Additional term (τ_3~20 ms) appears	- Clearly exist
	Look together with slow-monitoring parameters	- A hint with the correlation to the Rn-trap temperature	- Not observed

Summary of The SE Property

	How to analysis	Observation	
		Temporally-Correlated	Random
Components	Look at dR/dT - dT = time difference from paired parent-candidate - dR = observed rate	- **Two exponentially-temporally-correlated terms** (τ_1~5 ms and τ_2~50 ms) - Random (temporally-uncorrelated) term	
Absolute Rate	dR/dT	- 60% → 30% of the total SE - The longer one gets decreased over years	- 40% → 70% of the total SE - Rather constant over years
Corr. with the total activity in TPC	SE rate vs. S2 rate	- Roughly linear	- Roughly linear
Corr. with the parent's size	Look at the most recent parent-candidate	- Linear	N/A
Corr. with the parent's position	Look at the most recent parent-candidate	- Looks exist	N/A
Corr. with the system	getter-off period	- Clearly exist - Additional term (τ_3~20 ms) appears	- Clearly exist
Corr. with the system	Look together with slow-monitoring parameters	- A hint with the correlation to the Rn-trap temperature	- Not observed

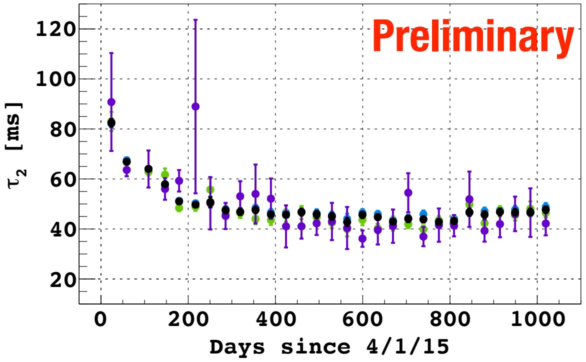
- Drifting-e⁻ is rarely captured by something during its path and released afterwards?
- Small electron signal is produced inside the TPC by some mechanism related to the TPC activity?

Discussion on Source(s) of The SEs

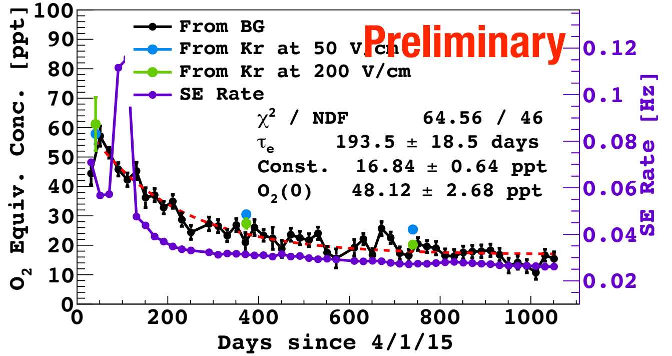
Source of SE : e^- release from impurity

- A possible source of the correlated SE:
  "e^- captured by an impurity and re-emitted with delay"
  - There should be <u>at least</u> two kinds of impurity corresponding to τ_1 and τ_2;
    Observed change of τ_2 over time may imply that it consists of several impurities having similar lifetime (e.g. 40 and 80 ms)

τ_2



O_2 Contamination



- O_2 is unlikely the source, since drifting-electron lifetime measurement shows different temporal evolution
- N_2 of ≥ppm level is also unlikely, as the S1 triplet lifetime is found to be stable over the period
- Trace moisture may be, as OH^- is known to have long resonance time to release e^-
  (J.Am.Chem.Soc.106, 3402 & J.Chem.Phys.39,3209)
- TPB dissolved in LAr may be, as such benzenoid molecules have long-lived anionic states

Source of SE : Biexcitonic ionization

- Another possible source of the correlated SE:
  "e⁻ emitted from long-lived metastable state excited by δ-ray"
  - Argon is known to have two metastable states having lifetime of ~1 min, and TPB may have such long-lived states as well (PRA17,1117 & IEEE Trans.Dielectr.Electr.Instr.11,649)
  - These states (M*) may produce electron via Penning or Associative ionization:

$$\text{Penning ionization:} \quad M^* + M^* \rightarrow M + M^+ + e^-$$
$$\text{Associative ionization:} \quad M^* + M^* \rightarrow M_2{}^+ + e^- .$$

- There should be parent-SE correlation in time and space, and the SE rate should be proportional to the parent energy, while the rate should be independent from parent's t_{drift}
  - This cannot be an only source of the SE
- If the relevant lifetime of metastable states is too long, we may find it as "uncorrelated" SE

Source of SE : Other possibilities

- **Delayed e– extraction**

(J.Phys.C19, 4329 & Phys.Rev.158, 305)

  - Extracted e⁻ backscatter in GAr may reflect back into LAr;
    it may be trapped at the surface for a while and re-enter the gas phase
  - Both extrapolation from measurement in literature and theoretical calculation predict the timescale of μsec for these process under the DS-50's field (2.8 kV/cm);
    Therefore, it is unlikely the source in our case

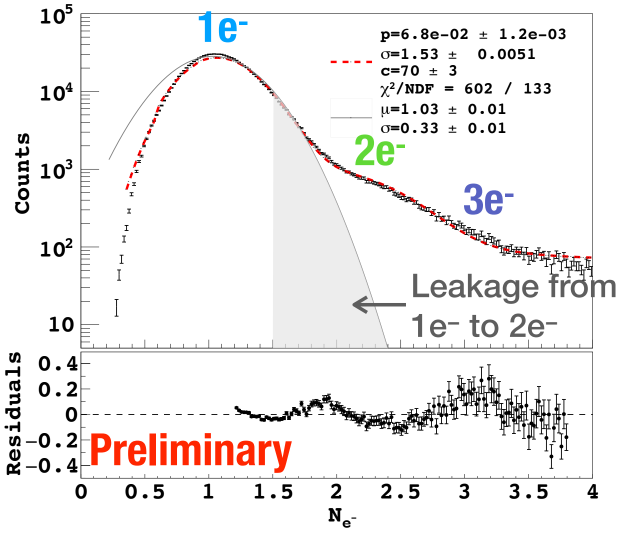
- **Radical impurity cluster interactions**

(PRD105, 063002 & PRA38, 364)

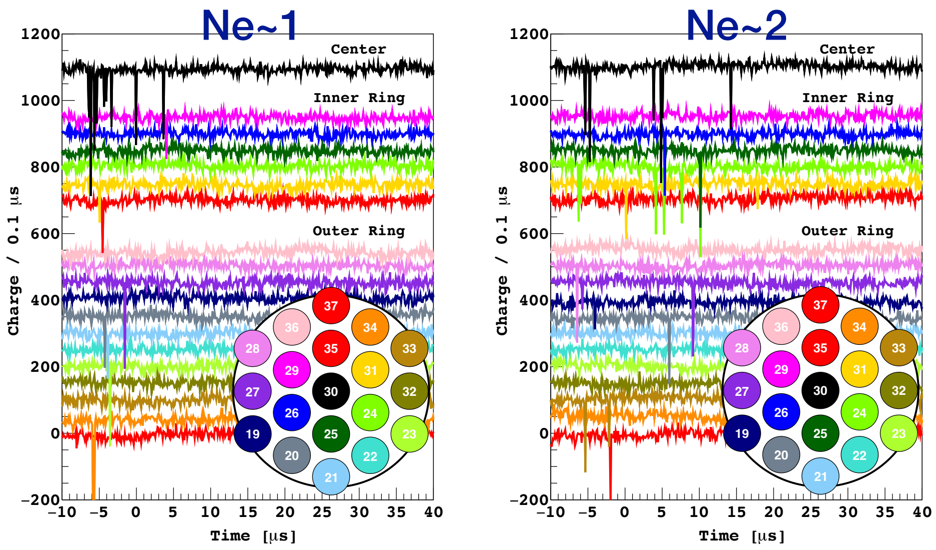
  - Radial impurities may exist in LAr and be induced defects from ionization events, which may then cluster together and release a burst of electrons
  - Such electrons are expected to follow a parent by a power-law (diffusion driven), but none of our observation is consistent to power-law

Source of Multi-Electrons Signal

- **We clearly observed 2e⁻ and 3e⁻ events**
- Accidental coincidence of independent 1e⁻ events **cannot** be their origin
  - Temporally-correlated SE has the rate of O(10 mHz)
  - Two S2 pulses separated in >2 μs are reconstructed as individual pulses
  - Probability for two pulses falling within 2 μs is obviously much smaller than the observed multi-electron signal rate



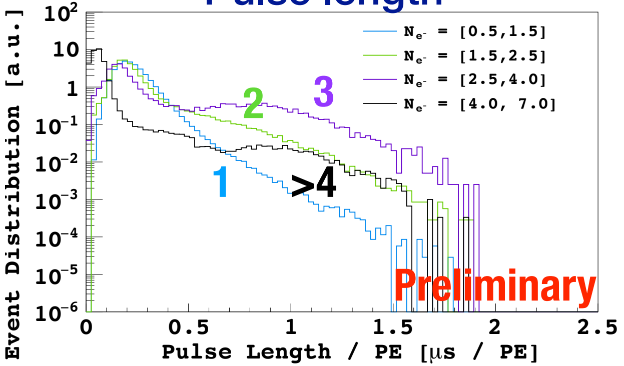
Typical Event Waveforms



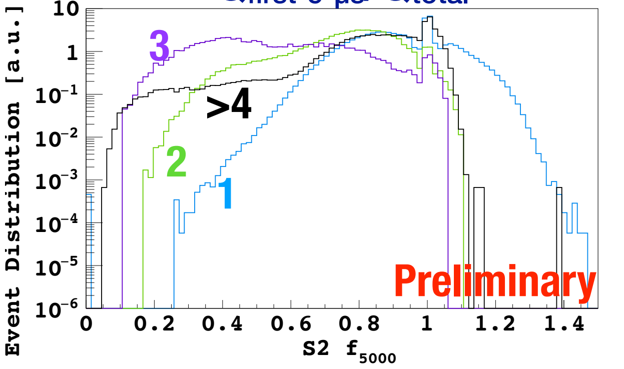
Source of Multi-Electrons Signal

- Several sources could contribute in a comparable level
  - Their pulse-shape parameters are not perfectly consistent to the 1e– nor >4e– ones
  - The fraction of >1e⁻ to 1e⁻ may slightly increase as time passes
- Yet to be concluded about the source of such signals
  - Main challenge from significant leakage into 2-4e⁻ from 1e⁻ event
  - A detector with better resolution and enhanced SE rate may be needed

Pulse length



Q_{first-5-μs}/Q_{total}



Summary

- Spurious electrons (SEs) prevents us from digging into the low-mass region
- Dedicated analysis with DS-50 physics run data shows that
  - Significant fraction of SEs follows its "**parent**" **within <100 ms**,
  - **Higher energy parent** produces **more daughter SEs**,
  - There is also SEs that seem to be **randomly** produced, and
  - Some of **getter-gas-purifiers** somehow affect SE rate
- Promising hypotheses about the sources are
  - 1) **electronegative impurities** (but the species are unknown) capturing and reemitting drift electrons, and
  - 2) Delayed emission of electron from **biexcitonic molecules**
- There is also **2-4e$^-$ SE events**, but its origin **may differ from 1e$^-$ SE**

A dedicated paper will be posted on arXiv soon!

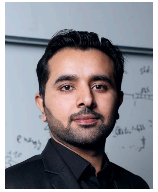
MEMBERS OF MY GROUP

One postdoc position is open!!

If you are interested, contact me at
masayuki@camk.edu.pl

- **Azam Zabihi**
  - **PostDoc** working on Medical applications

- **Andre Cortez**
  - **PostDoc** expert on gas and liquid noble detectors



- **Iftikhar Ahmad**
  - 4th year **PhD student** working on SiPM development

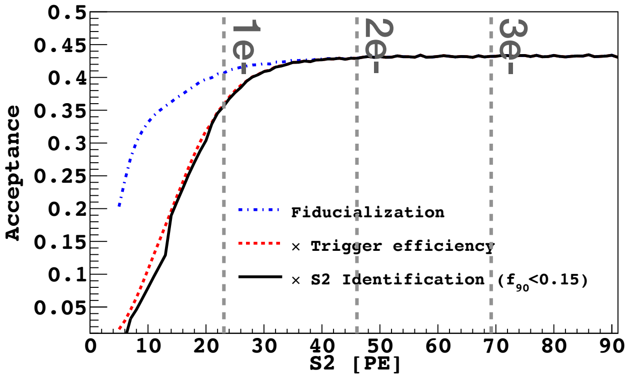
- **Paul Zakhary**
  - 4th year **PhD student** working on low energy calibration

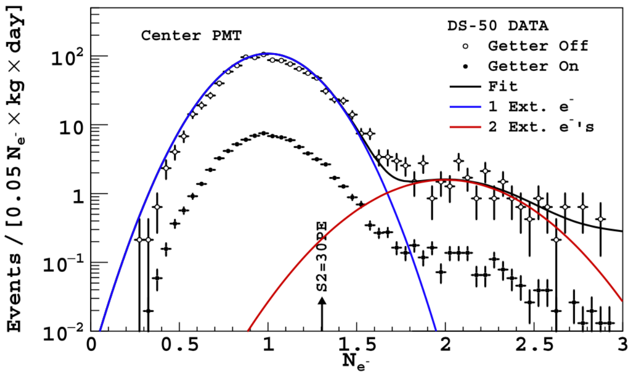
- **Clea Sunny**
  - 2nd year **PhD student** working on low energy calibration

Backup

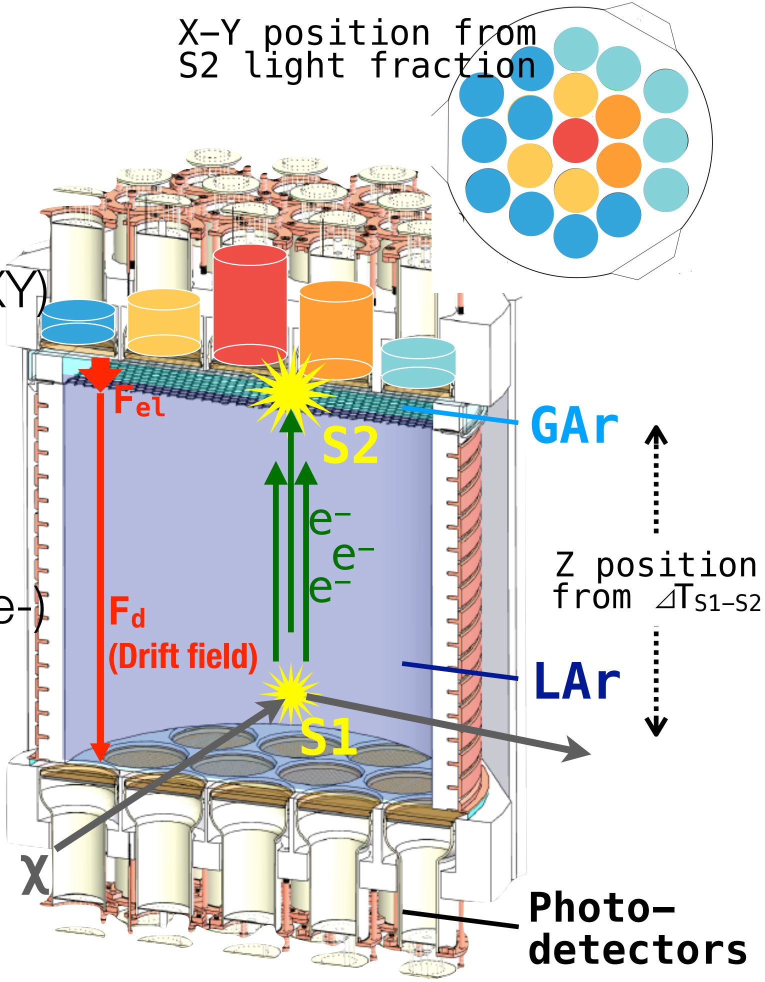
Dual-Phase Argon TPC

- Two time-separated light signals;
  primary **scintillation** (**S1**) and
  secondary **electroluminescence** from ionization e⁻ (**S2**)
- **3D position reconstruction** by $\Delta T_{S1\text{-}S2}$ (Z) and S2-map (XY)
- Efficient ER rejection from NR thanks to the Scintillation Pulse Shape Discrimination and S2/S1 Ratio
- **Efficient electron extraction** (~100%) and **large electroluminescence amplification** (g_2, >20 PE/e-)





→ **Energy Threshold <100 eV**

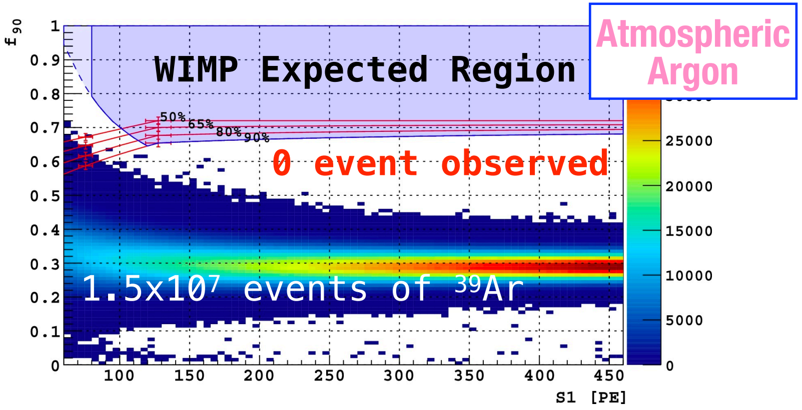


The DS-50 Results

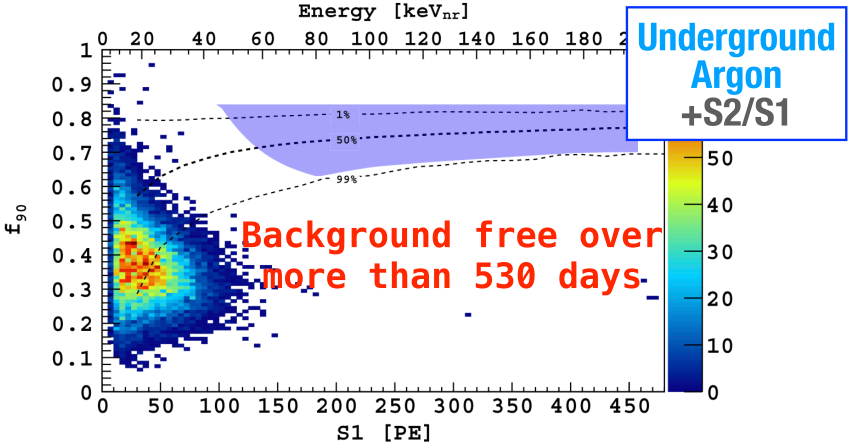
"Heavy" WIMP Search

Pulse Shape Discrimination

PLB 743 (2015) 456-466



PRD 98 (2018) 102006

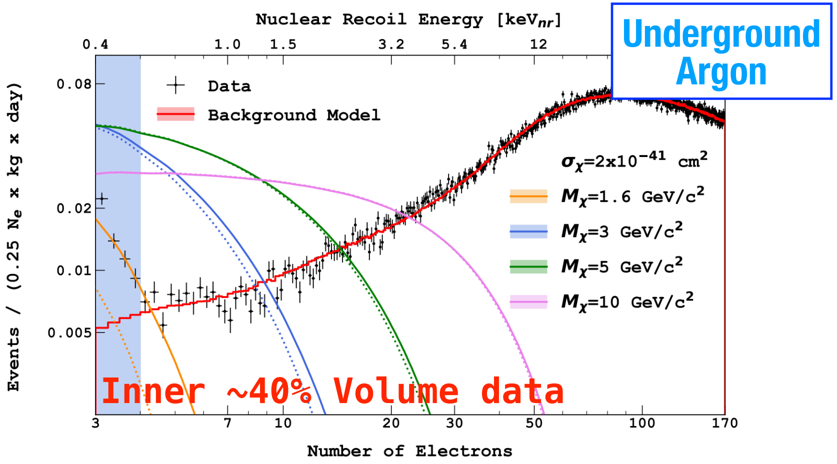


"Light" Dark Matter Search

Ionization Only

PRD 107 (2023) 063001

- No requirement on S1 (- Detection efficiency g1 ~ 16%)
- No NR/ER discrimination
- ~100% detection efficiency for 3e- (0.04 keV)
- Select single-scatter S2 pulse



Main topic of this talk