# Search for annual modulation of the event rate generated by dark matter in the DarkSide-50 ionization signal

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Theo Hugues (AstroCeNT/CAMK PAN/APC),
On behalf of the analysis team :
M.Kimura(AstroCeNT), M.Wada(AstroCeNT),
D.Franco(APC) & M.Kuźniak(AstroCeNT)

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Dark Wave
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# Annual Modulation

-Sensitivity to many kind of interactions between dark matter and argon.

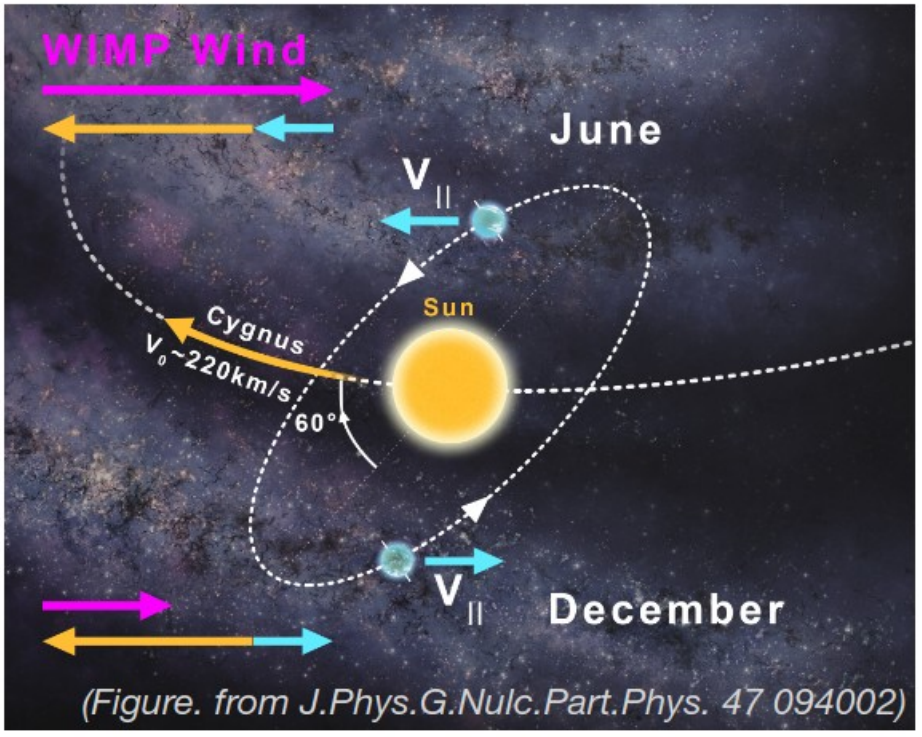
Results from other experiments

*NaI(Tl) detector*
- DAMA/LIBRA: modulation with proper features at 13.7σCL
- ANAIS112: reject DAMA with ≈ 3σ
- COSINE 100: consistent with both DAMA and the no-modulation case

*LXe detector*
- XENON100: reject DAMA's modulation in 2-6keV bin
- LUX: 9.2σ tension with the DAMA/LIBRA result
- XMASS: excludes the DAMA/LIBRA allowed region at ≈ 3σ

*LAr detector*
- This talk (arXiv:2307.07249)

**Search for dark matter annual modulation with DarkSide-50**



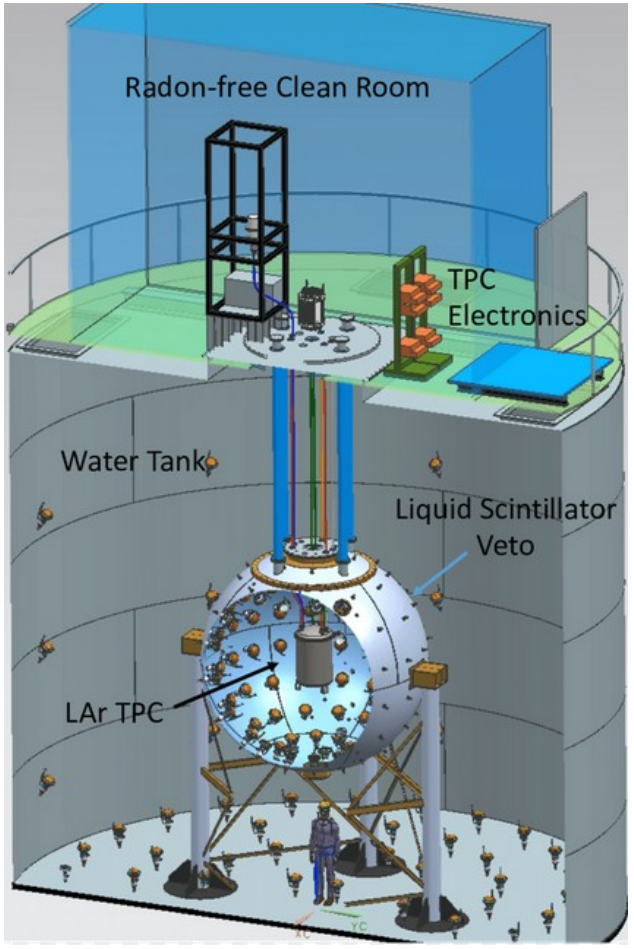

The rotation of the Earth around the Sun can induce an annual modulation of the event rate.
Such a modulation on the event rate would peak on June 2nd.

# DarkSide-50

*Where ?*
At LNGS, 3800 m.w.e under Gran Sasso

*When ?*
2013-2015 Atmospheric Argon
2015-2018 Underground Argon (~1400 depletion factor regarding $^{39}$Ar activity)

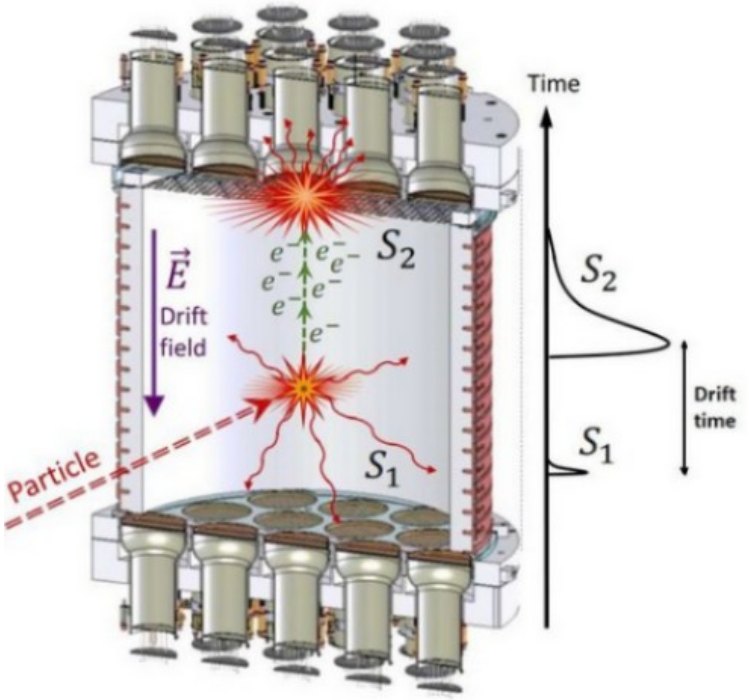
*What ?*
- Radon free clean room
- Water Cerenkov tank (1kt of ultra pure water)
- Liquid Scintillator veto (30t of 10B loaded scintillator)
- Liquid argon TPC

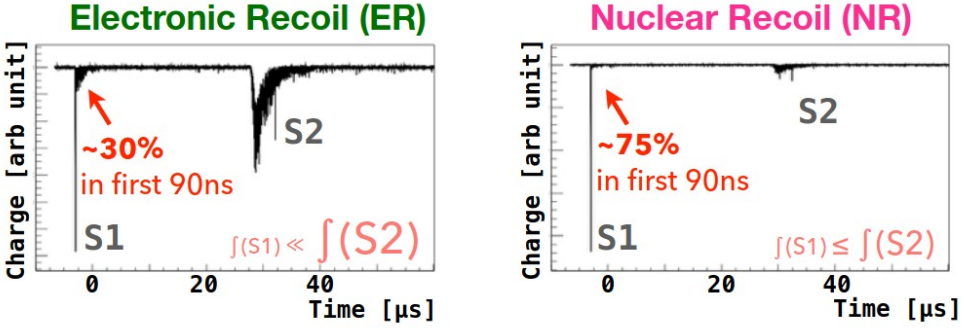


# DarkSide-50

Light collected by top and bottom Photomultiplier Tubes (PMT)

- S1 (primary scintillation), is produced in LAr due to excitation and recombination after ionization
- S2 (secondary scintillation) produced in the gas phase by drifted electrons
- Position in the XY plane is given by S2 hit pattern and the Z position from Drift time
- Efficient ER rejection from NR thanks to the Scintillation Pulse Shape Discrimination and S2/S1 Ratio




>$10^7$ ER rejection above ~10 keV

→ **ER-free search for $m_\chi$ >10 GeV/c²**

# Detector Stability

Some critical parameters are:

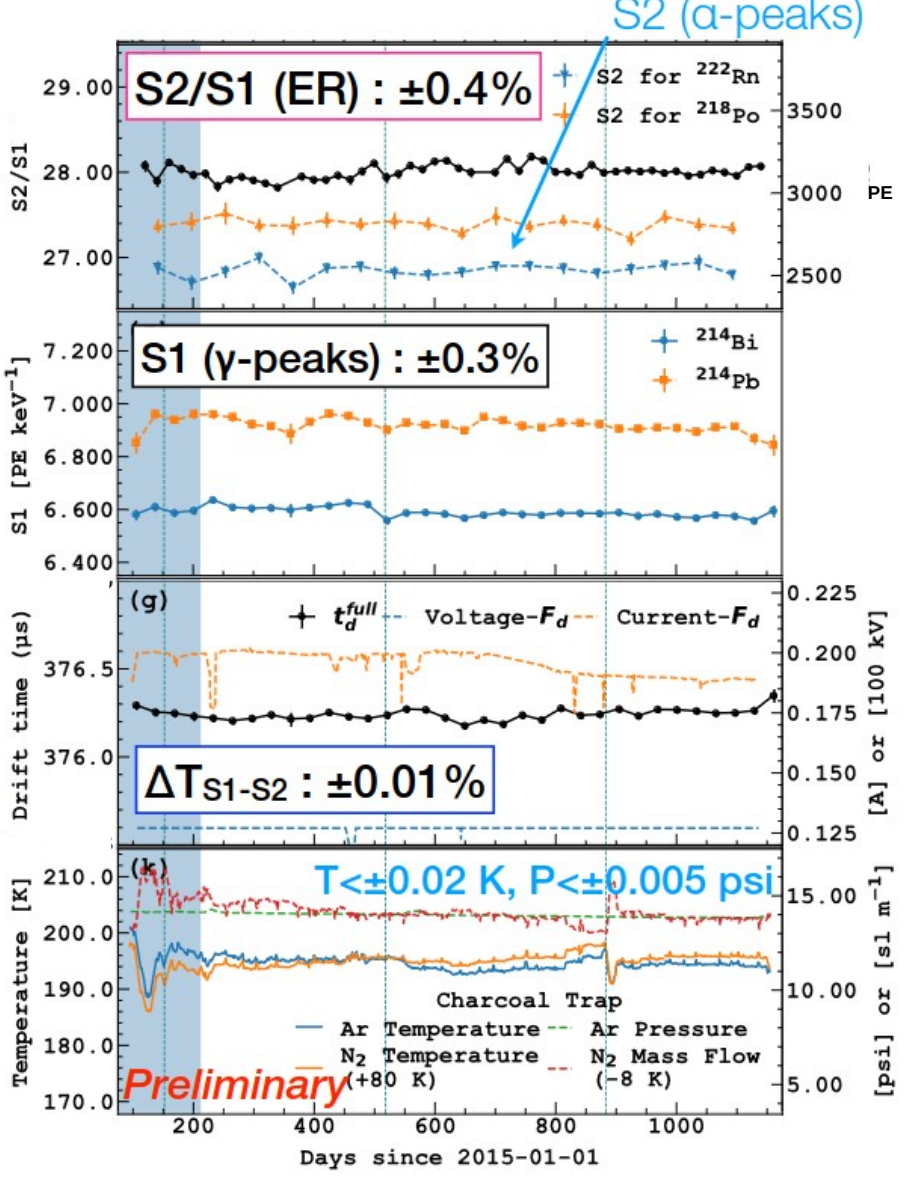
- the mean number of photoelectrons per ionization electron (g2 [PE/e-])
- the drift field ($F_d$ [V/cm])

g2 is stable within 0.5% traced by the S2/S1 ratio of continuous ER above the region of interest

- Consistent to the measurement from α-ray peaks
- Consistent to appropriate sensor readings inside the cryogenic system

Drift field is traced by the drift time, ΔTS1-S2: 0.01% variation

paper on detector stability is in progress



# Detector Stability

Stability of all 72 slow control parameters was checked:

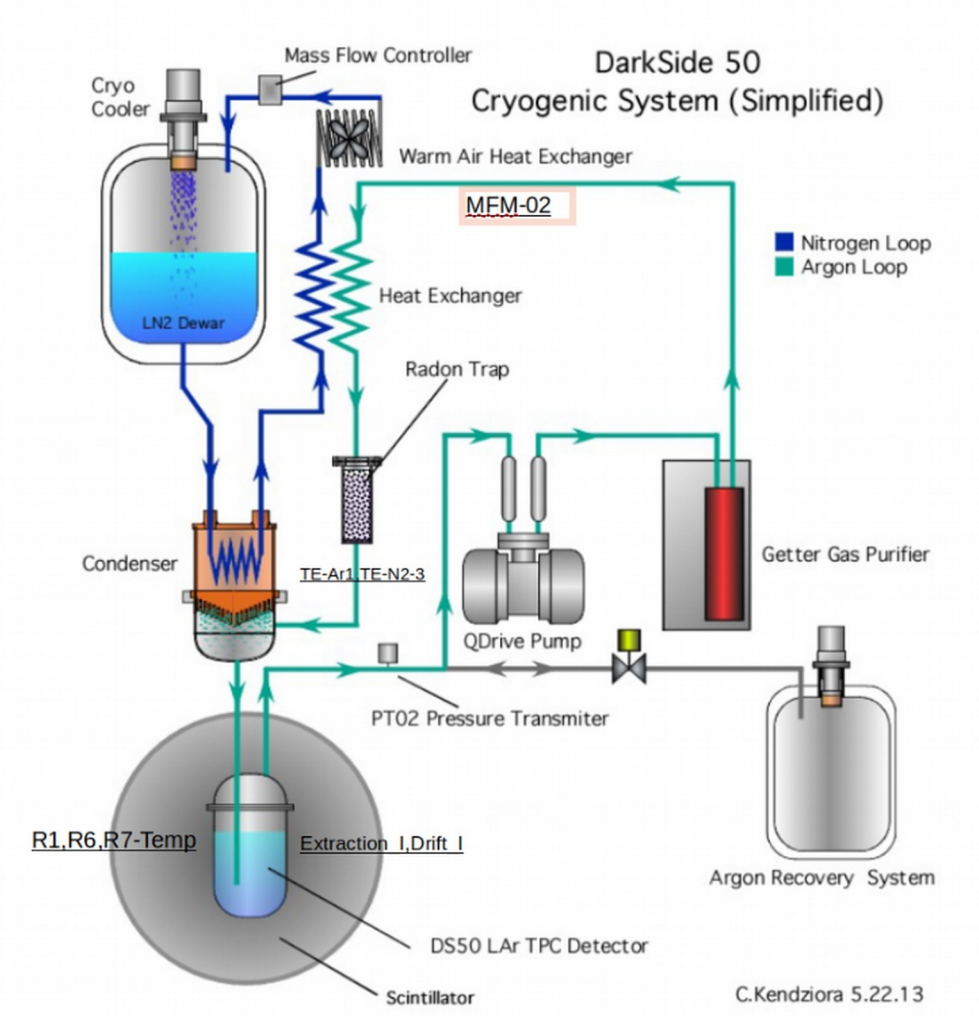
- Quantitatively
- Lomb-Scargle periodogram
- Correlation with Data

Correlation coefficients (r) are calculated on the residuals with:

- Pearson's correlation
- Spearman's rank correlation
- Kendall's rank correlation,

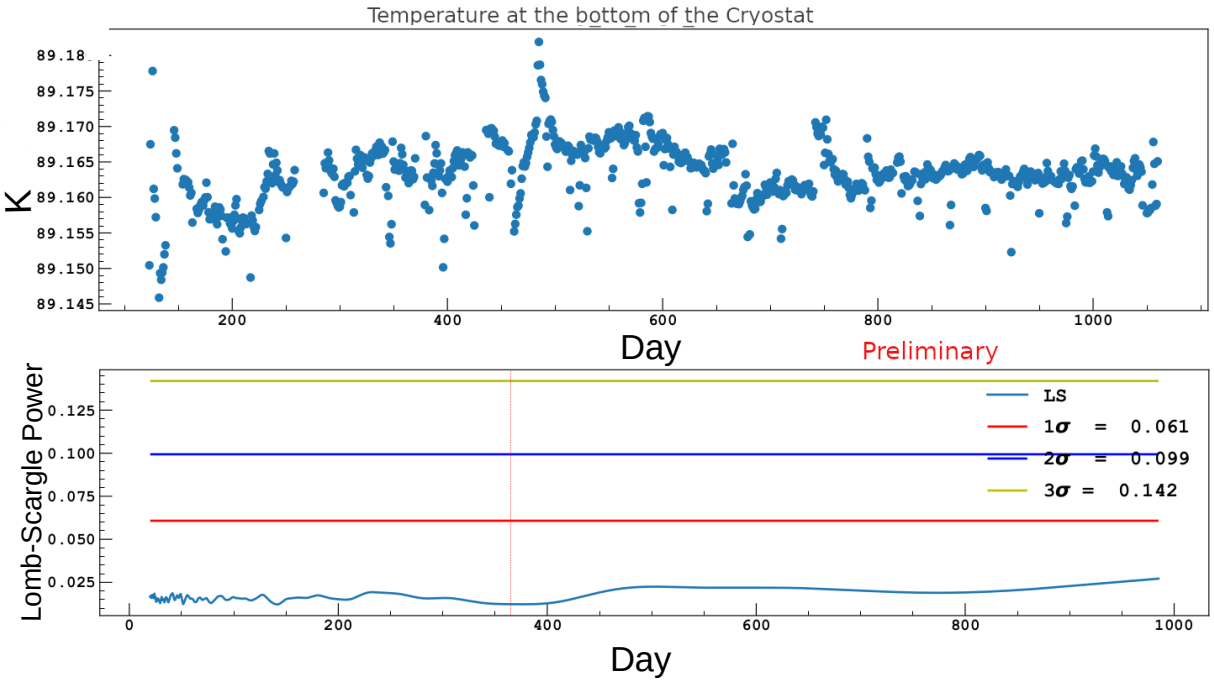
There is no significantly high coefficient found for each of Ne ranges, the highest are :
Drift/Extraction field and Mass flow circulation line

| | Extraction potential | Extraction current | Drift potential |
|---|---|---|---|
| r | 0.132 | 0.133 | 0.132 |



# Detector Stability

- Lomb–Scargle periodogram is **a method to estimate a frequency spectrum**
- uses a least squares fit of sinusoids to data to find, and **test the significance of weak periodic signals with uneven temporal sampling**.
- to quantify the significance of a peak we use **False Alarm Probability**, which measures the probability that a **data set with no signal would lead to a peak of a similar magnitude** (calculated with bootstrap simulations here).
- Few variable have a periodicity close to one year, but not the most relevant



# Likelihood Fit

- Four radioactive isotopes decaying in 3 years are taken into account

| Isotope ($l$) | $t_{1/2}$ | Place | Constrained by |
|---|---|---|---|
| $^{37}$Ar | 35 d | LAr | Initial dataset |
| $^{85}$Kr | 10.8 y | LAr | Same dataset above RoI |
| $^{54}$Mn | 312 d | PMT | Screening |
| $^{60}$Co | 5.3 y | PMT&Cryostat | Screening |

- Dark Matter Event rate as a function of time is modeled with a cosine signal:

$$f(t) = A_\chi \cos\left(\frac{t-\phi}{T/2\pi}\right) + \sum_l \frac{A_l}{\tau_l} e^{-t/\tau_l} + C,$$

Signal amplitude — Fixed to 1y — Including long-lived isotope (no constrain)

- Likelihood fit to the model with 7-d time bin:

$$\mathscr{L} = \prod_{i \in t_{\text{bins}}} \mathscr{P}\left(n_i \,|\, m_i(A_\chi, \phi, C, \Theta)\right) \times \prod_{\theta_k \in \Theta} \mathscr{G}(\theta_k \,|\, \theta_k^0, \Delta\theta_k)\,.$$

| Parameter | $\theta_k^0$ | $\Delta\theta_k$ |
|---|---|---|
| T | 1 yr | 0 |
| Fiducial volume | 19.4 kg | 1.5% |
| $\tau_{^{37}\text{Ar}}$ | 35.0 d | 0 |
| $\tau_{^{85}\text{Kr}}$ | 10.8 yr | 0 |
| $\tau_{^{54}\text{Mn}}$ | 312.1 d | 0 |
| $\tau_{^{60}\text{Co}}$ | 5.27 yr | 0 |
| $A_{^{37}\text{Ar}}$ | 2.1 counts/(d kg)$^\dagger$ | 14% |
| $A_{^{85}\text{Kr}}$ | 1.7 counts/(d kg)$^\dagger$ | 4.7% |
| $A_{^{54}\text{Mn}}$ | 0.02 counts/(d kg)$^\dagger$ | 40% |
| $A_{^{60}\text{Co}}$ | 0.58 counts/(d kg)$^\dagger$ | 12% |
| $^{85}$Kr $\beta$-decay spectrum | 1.7 counts/(d kg)$^\dagger$ | 0.7% |
| Ionization response | 4.4 counts/(d kg)$^\dagger$ | 0.4% |

# Final results

The 1D fit (uppers plots) are **consistent to the background-only model**

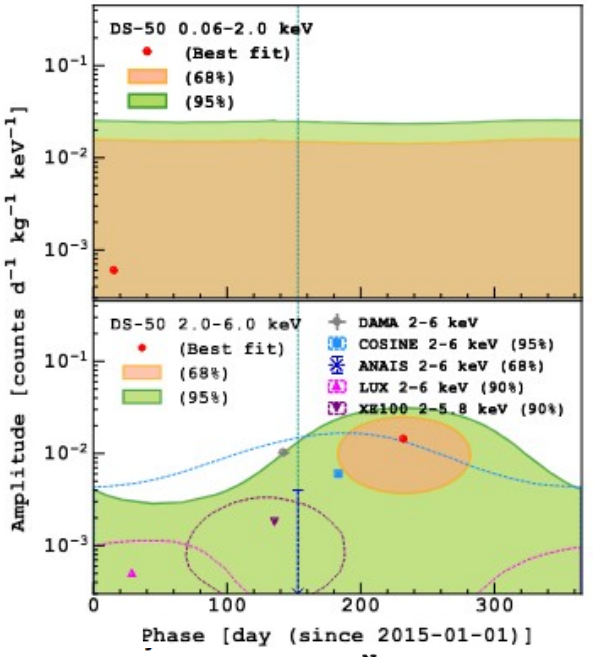
- Neither confirm nor reject the DAMA's observation

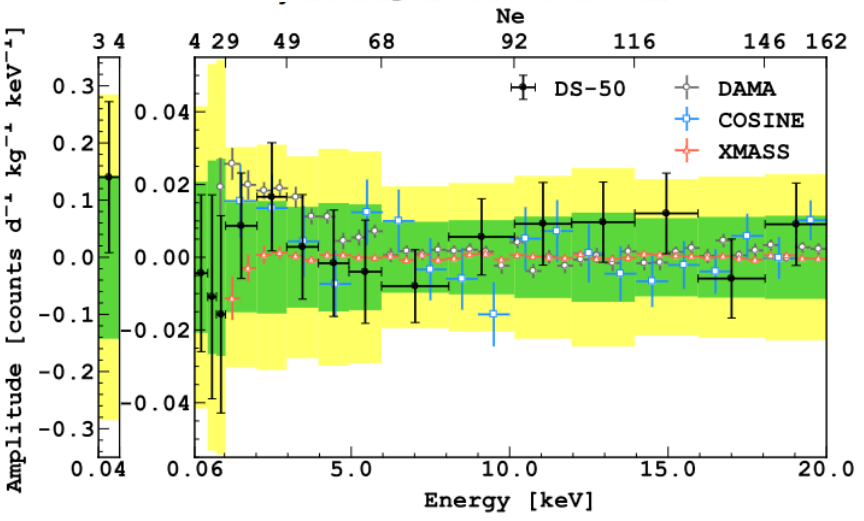
The 2D simultaneous fit (bottom plot) in both time and energy bins uses:

$$\mathscr{L} = \prod_{i \in t_{\text{bins}}} \prod_{j \in E_{\text{bins}}} \mathscr{P}\left(n_i^j \,|\, m_i^j(A_\chi^j, C^j, \tilde{\Theta})\right) \times \prod_{\tilde{\theta}_k \in \tilde{\Theta}} \mathscr{G}(\tilde{\theta}_k \,|\, \tilde{\theta}_k^0, \Delta\tilde{\theta}_k),$$

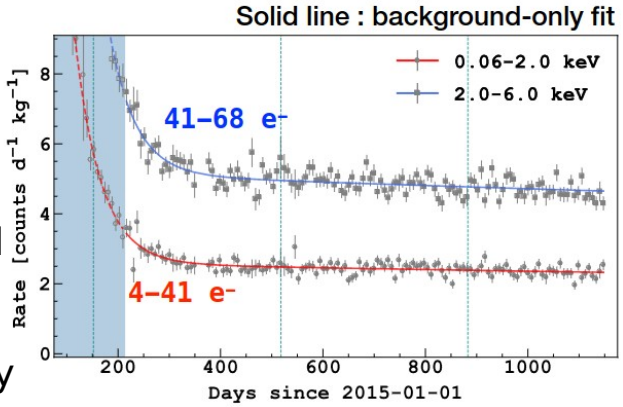
- Fixed the phase φ (June 2nd ) and period T (1-yr)

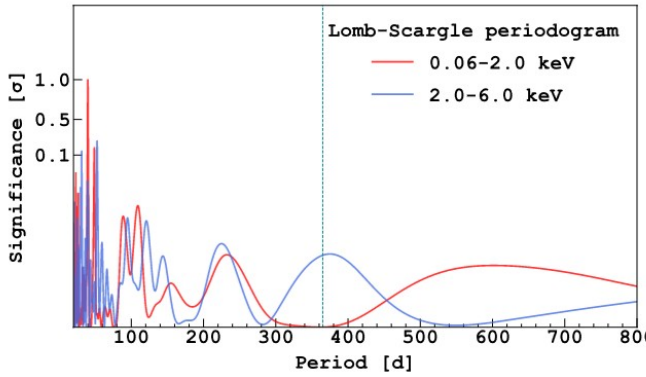
- Amplitudes of the short-decayed component for each energy bin are correlated



# Lomb-Scargle periodogram



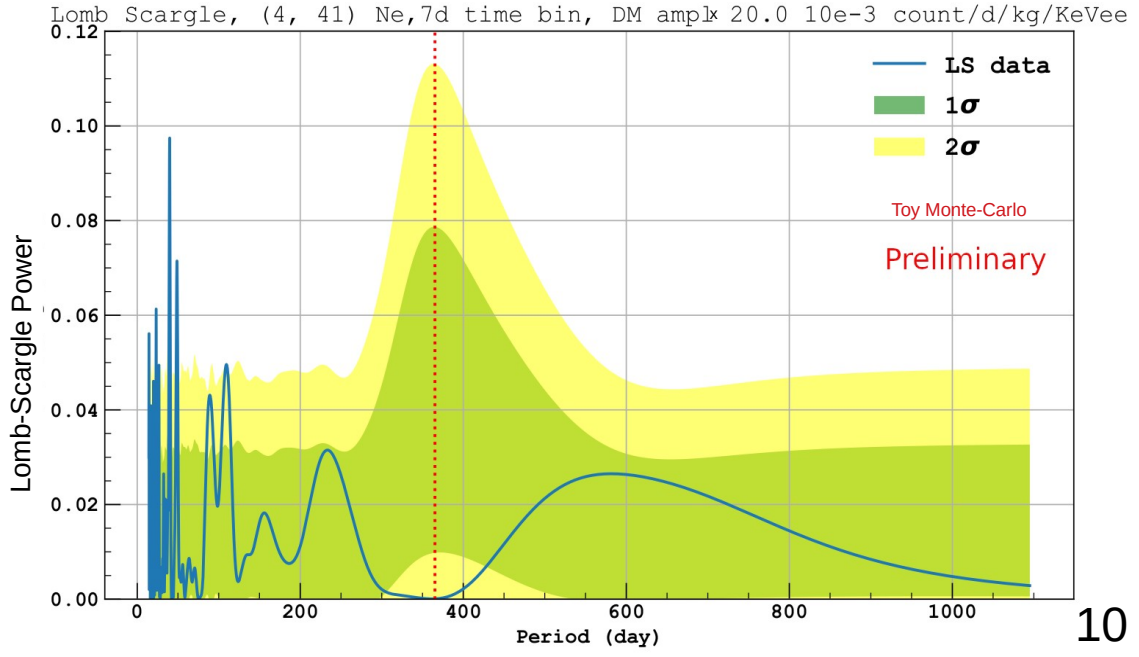




Lomb-Scargle algorithm is applied to look for any periodic signal

- Residuals of the background-only fit are converted into the frequency space

**No significant signal is observed**

- Bottom plot shows a Lomb-Scargle periodogram, with Brazilian band corresponding to toy-MC datasets, showing that a median of 1σ significance for the false alarm probability is obtained with the addition of 0.03 counts/(d kg keV)



# Summary

**No modulation signals are observed in the analyzed intervals**,

- Owing to the stable operation of the detector over years, and the matured S2-only analysis technique
- The lowest energy threshold of **0.04 keV** is achieved
- First annual modulation search using argon target
- Neither confirm nor reject the DAMA/LIBRA's positive observation

->**arXiv:2307.07249**

The next generation detectors, DarkSide-20k is under construction and DarkSide Lowmass is proposed

- x400 mass, 100t-y exposure, less instrumental background level (DS-20k)
- Data taking expected in 2026 (DS-20k)

# Thank You

20 December 2023 | Theo Hugues

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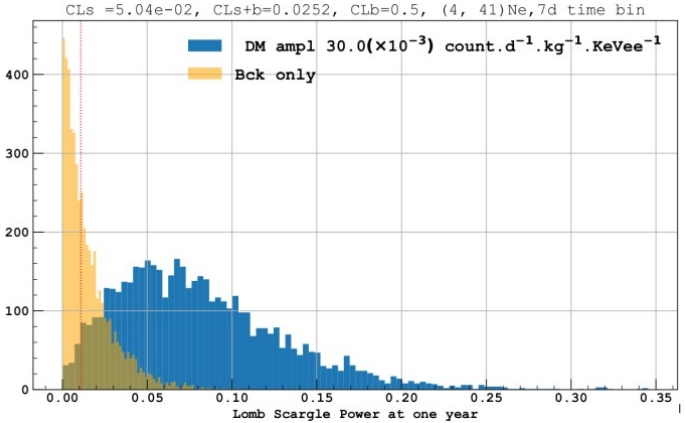
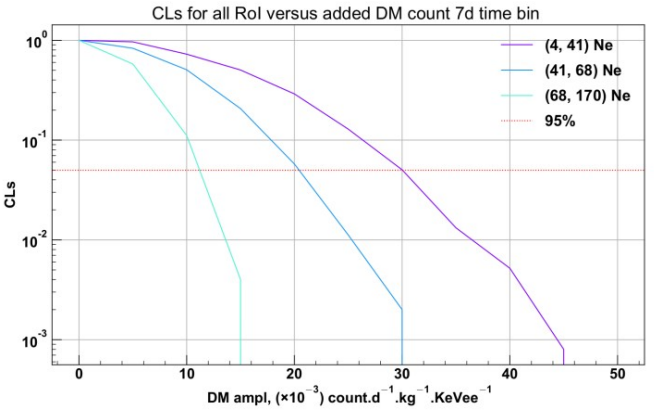
# Setting Upper limits



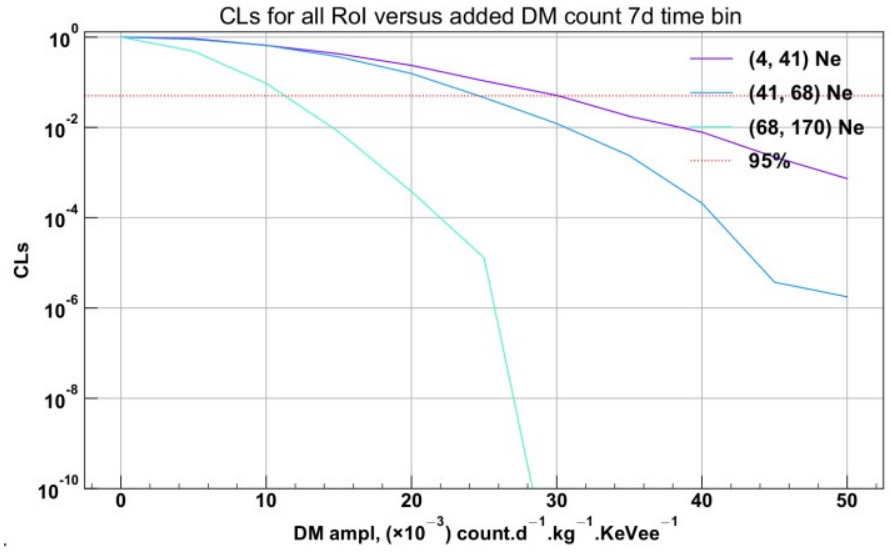

- 5000 simulated pseudo dataset

- Looking at the distribution of Lomb-Scargle Power at one year

- CLb is the integral between the median of the background only simulation and 0, for the expected CLs and between the observed LS Power at one year and 0 for the observed CLs.

- CLs+b is the same integral but for the signal + background distribution

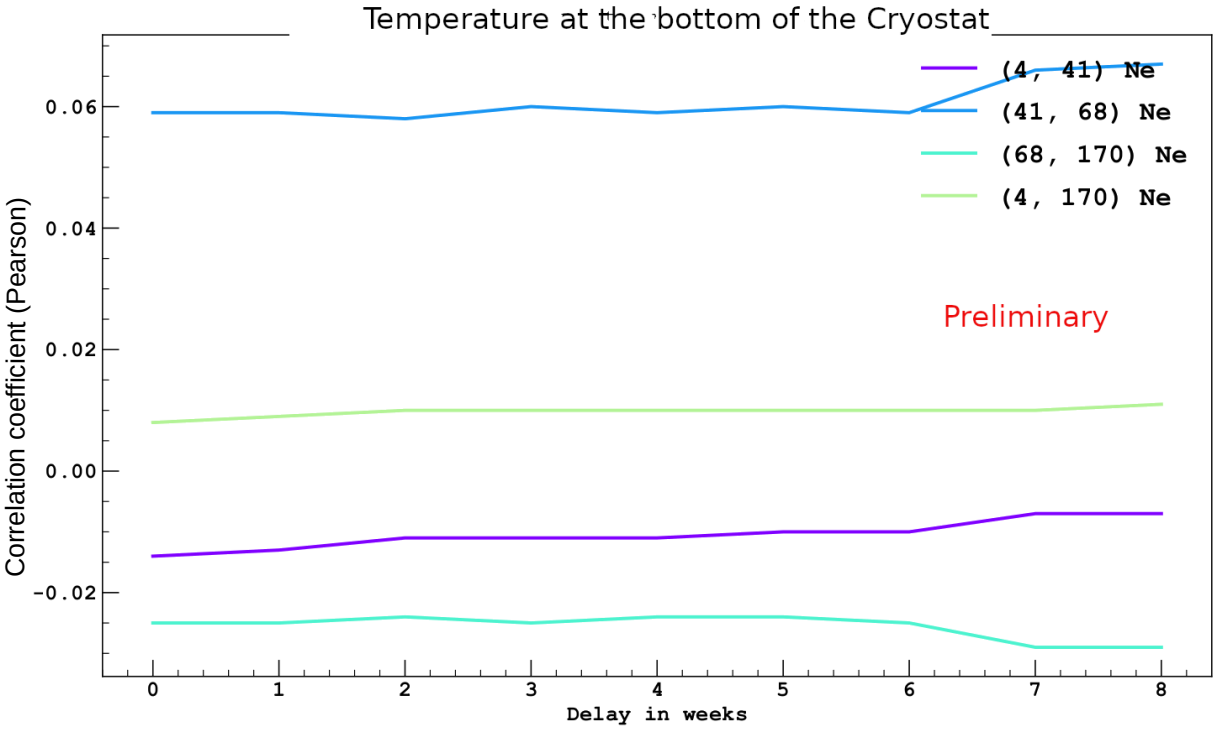
- CLs = $\frac{\mathbb{P}(n \leq n^* | s+b)}{\mathbb{P}(n \leq n^* | b)}$.



# Detector Stability

- Evolution of correlations coefficients found between data and sensor shows very low and stable coefficient (calculated for assumed 0 to 8 weeks delay between the sensor readings and the event rate).

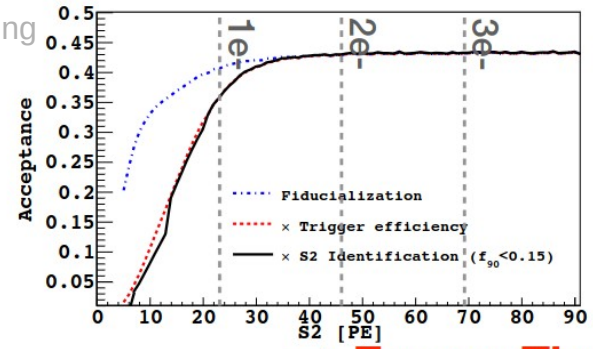
- **DarkSide 50 was very stable**, from non-trivial delayed correlations, Lomb-Scargle periodogram and g2/Fd stability.

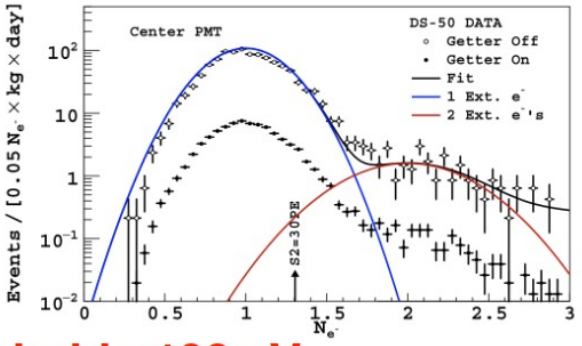


# "Low-Mass" Dark Matter Search (Ionization Only)

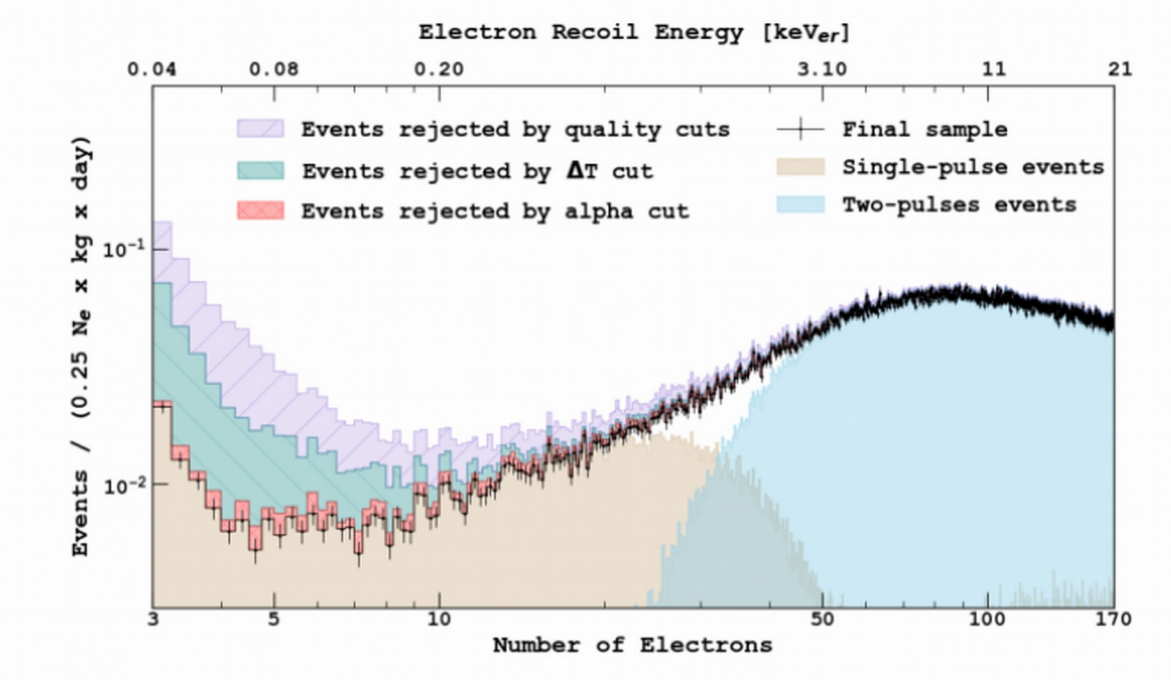
This work is based on the preceding analysis: PRD 107 (2023) 063001

- Efficient electron extraction (~100%) and electroluminescence amplification (g2, >20 PE/e-)
- No requirement on S1 (Detection efficiency g1 ~ 16%)
  ->No NR/ER discrimination
- Select single-scatter S2 pulse, ~100% detection efficiency for 3e- (0.04 keV)

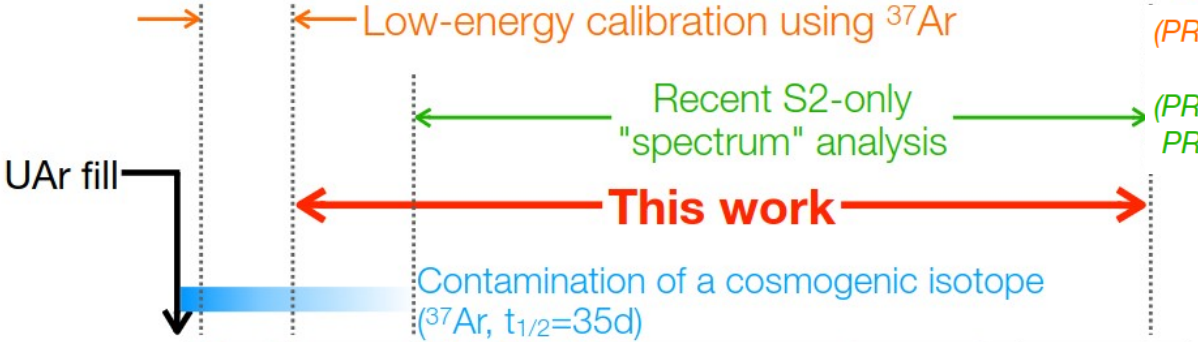


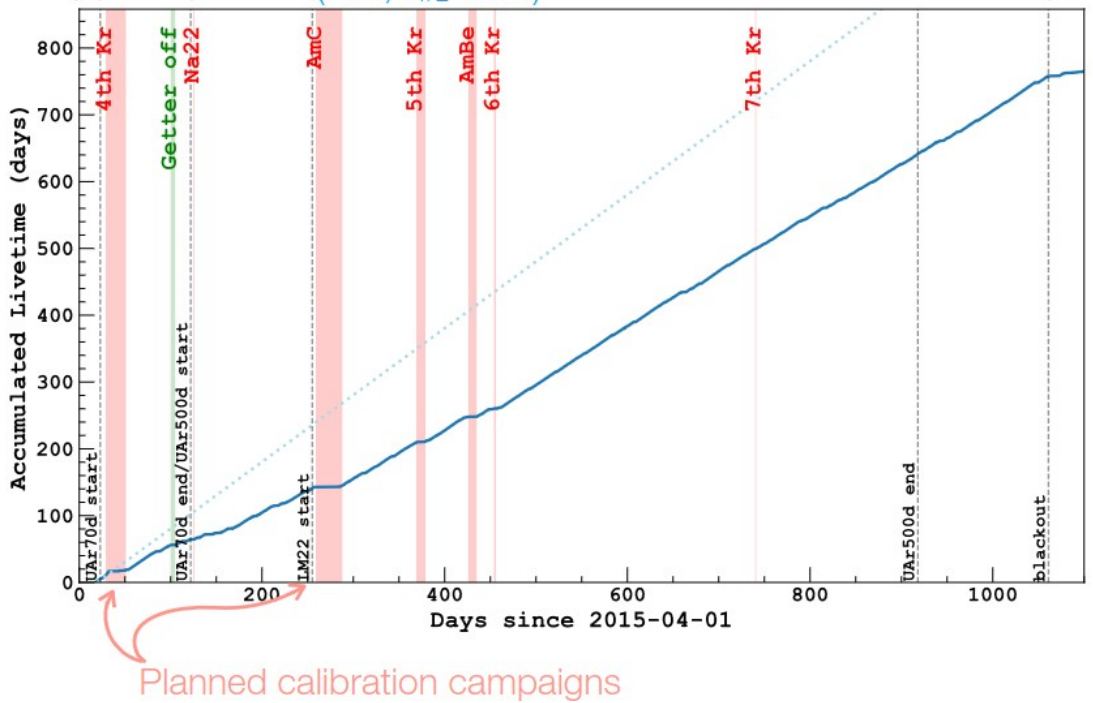




→ Energy Threshold <100 eV



# DS-50 Underground Ar campaign



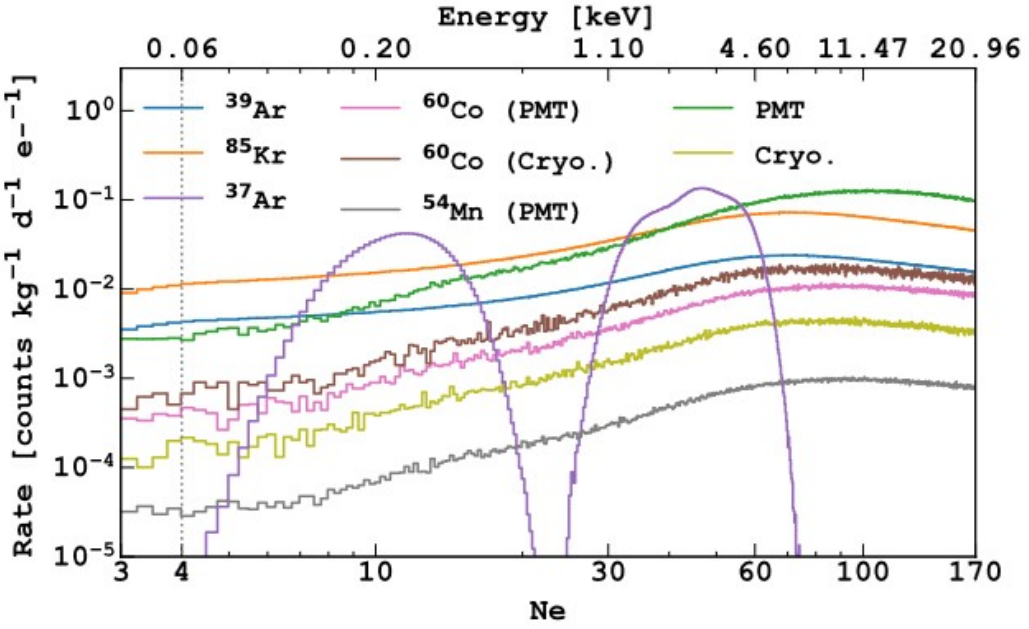



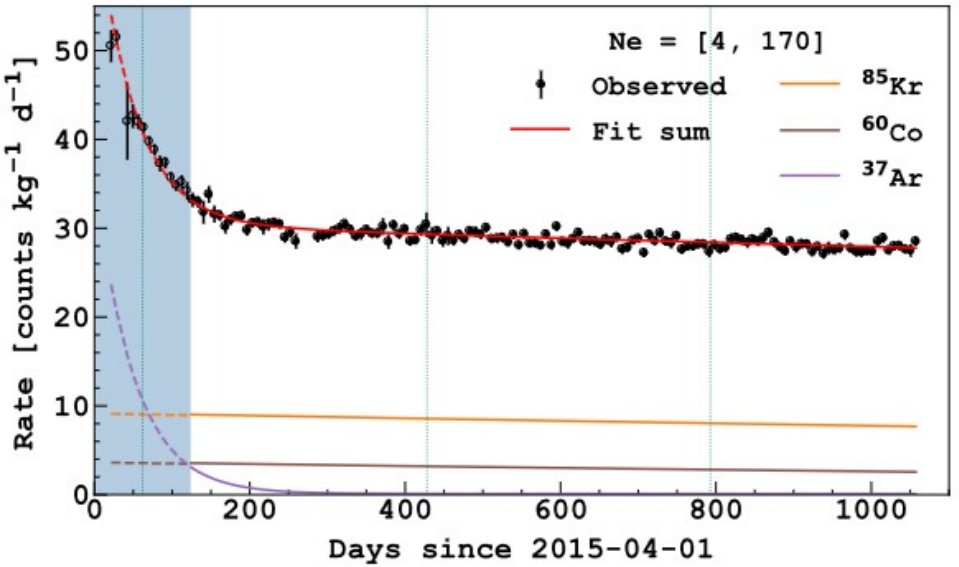

-Total livetime = 726.2 days

- Spanning 31months without any break longer than 30 Days

-This work uses the full dataset except the first 120 days used for the low-energy calibration

# Background


Energy [keV]
0.06
0.20
1.10
4.60
11.47
20.96
Rate [counts kg$^{-1}$ d$^{-1}$ e$^{-1}$]
$^{39}$Ar
$^{85}$Kr
$^{37}$Ar
$^{60}$Co (PMT)
$^{60}$Co (Cryo.)
$^{54}$Mn (PMT)
PMT
Cryo.
Ne


Ne = [4, 170]
Observed
Fit sum
$^{85}$Kr
$^{60}$Co
$^{37}$Ar
Rate [counts kg$^{-1}$ d$^{-1}$]
Days since 2015-04-01

# Event selection

## Fiducialization

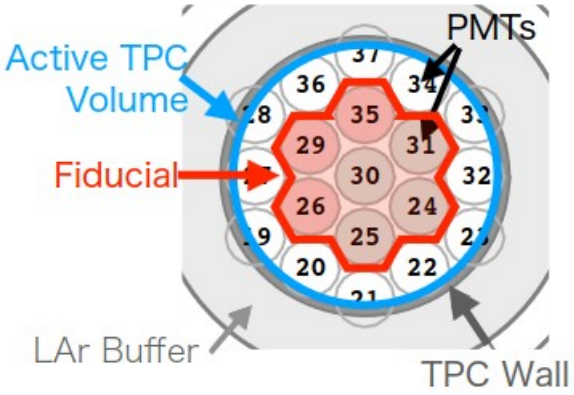
- Select event with max fraction of detected S2 photoelectron in one of the 7 central top PMTs
- Acceptance ~ 41%

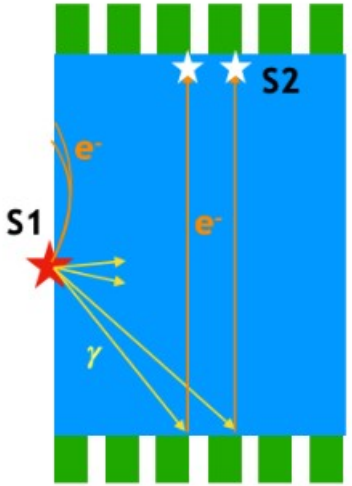
## Alpha-induced S2

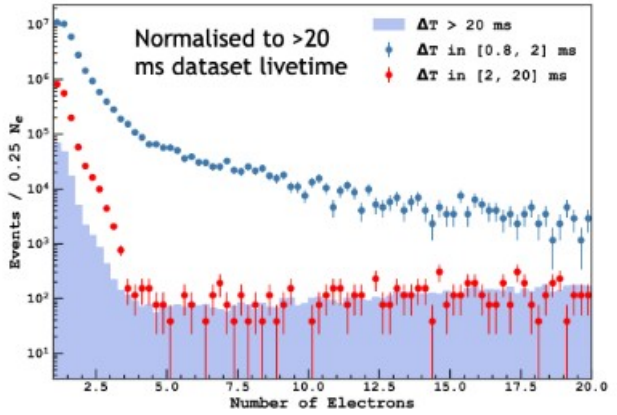
- Reject events with "anomalous" S2/S1 ratio, originated from α-decay on the detector surface
- Cut tuned on calibration data
- Acceptance ~ 99%

## Spurious electrons

- Reject time-correlated events if within 20 ms from the previous one
- Acceptance ~ 97%

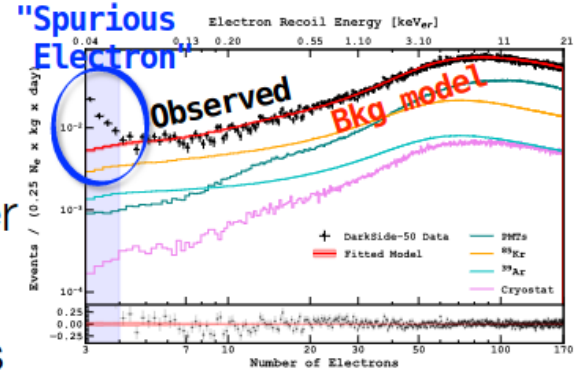


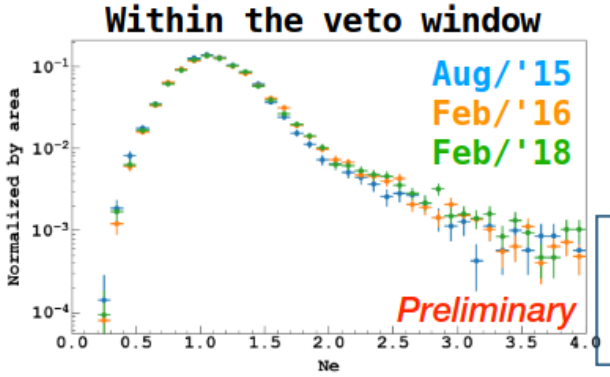



# Analysis in 3e- Bin

- More events than the expectation from the radioimpurities,
  - They have been suppressed by a 20-ms veto after each trigger
  - No a priori prediction on their properties
- For this analysis, they are characterized with sideband samples

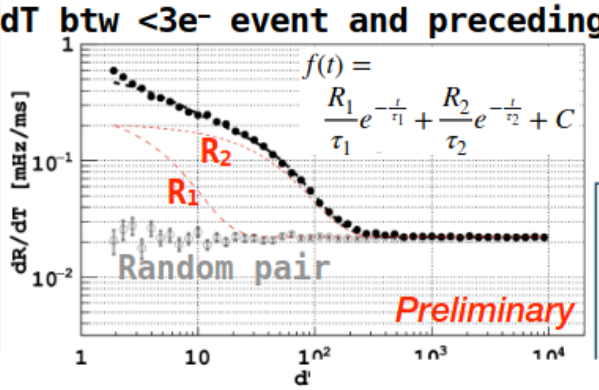



Spectrum




The spectral shape doesn't vary over time

Rate




Their time-correlation to the preceding events allows us to evaluate the SE's rate

- The relative change of the SE rate in $N_e$=3 is traceable from the time-correlated rate below 3e-:

$$R_{\mathrm{SE}}(t_i,\, N_e = 3) = \alpha \times \left( \sum R_i(t_i) \right)$$

  - Added to this term only in the first bin ($N_e$=3) of the model