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

29 August 2023

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on behalf of the DarkSide-50 Collaboration

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Dark Wave
Nicolaus Copernicus Astronomical Center of the Polish Academy of Sciences
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AstroCeNT

Annual Modulation

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

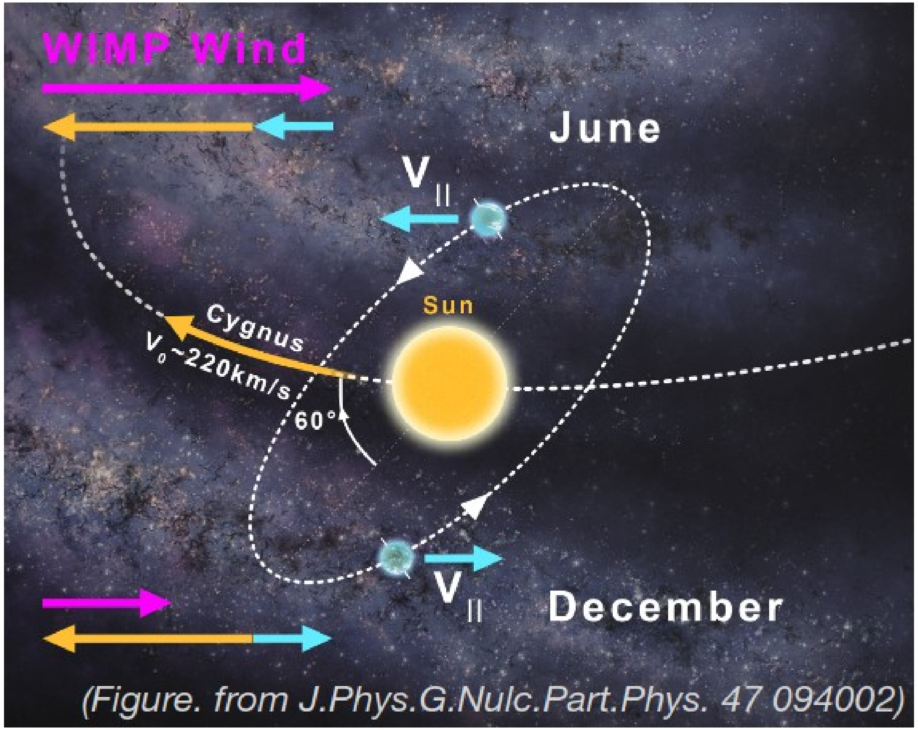
Results from other experiments

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



(Figure. from J.Phys.G.Nulc.Part.Phys. 47 094002)

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 ?

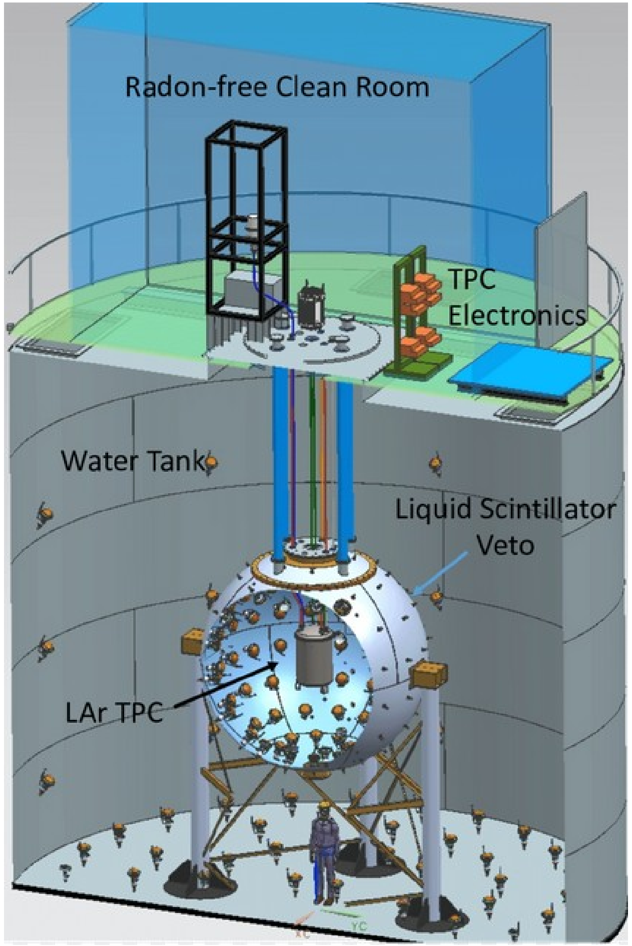
At LNGS, 3800 m.w.e under Gran Sasso

When ?

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

What ?

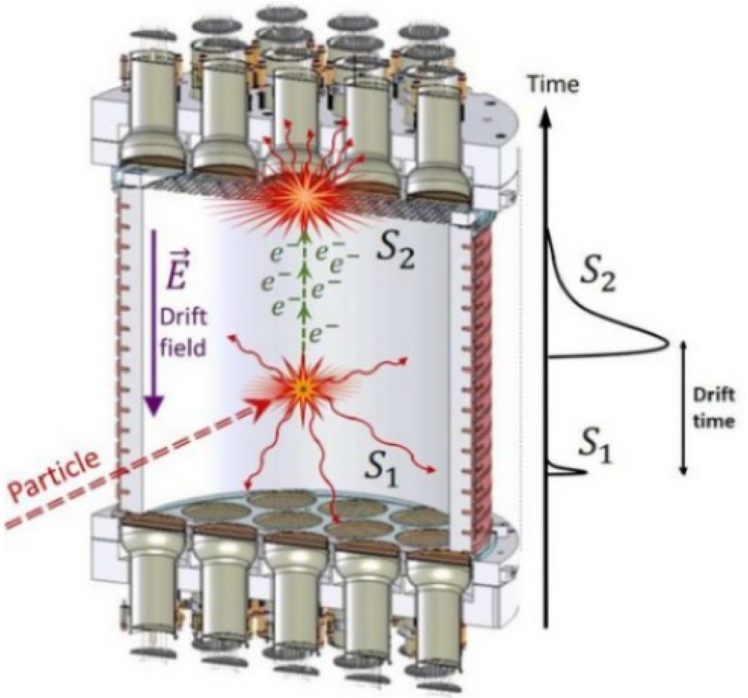
- Radon free clean room
- Water Cerenkov tank (1kt of ultra pure water)
- Liquid Scintillator veto (30t of 10B loaded scintillator)
- Liquid argon TPC



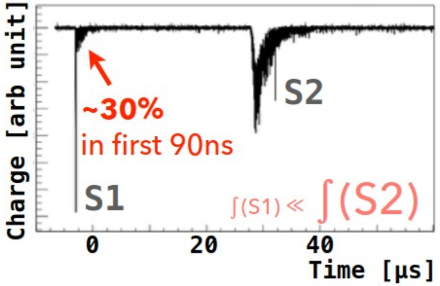
DarkSide-50

Light collected by top and bottom Photomultiplier Tubes (PMT)

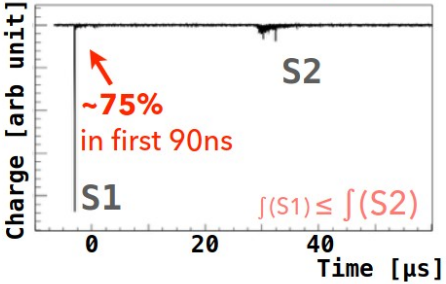
- S1 (primary scintillation), is produced in LAr due to excitation and recombination after ionization
- S2 (secondary scintillation) produced in the gas phase by drifted electrons
- Position in the XY plane is given by S2 hit pattern and the Z position from Drift time
- Efficient ER rejection from NR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



Electronic Recoil (ER)



Nuclear Recoil (NR)



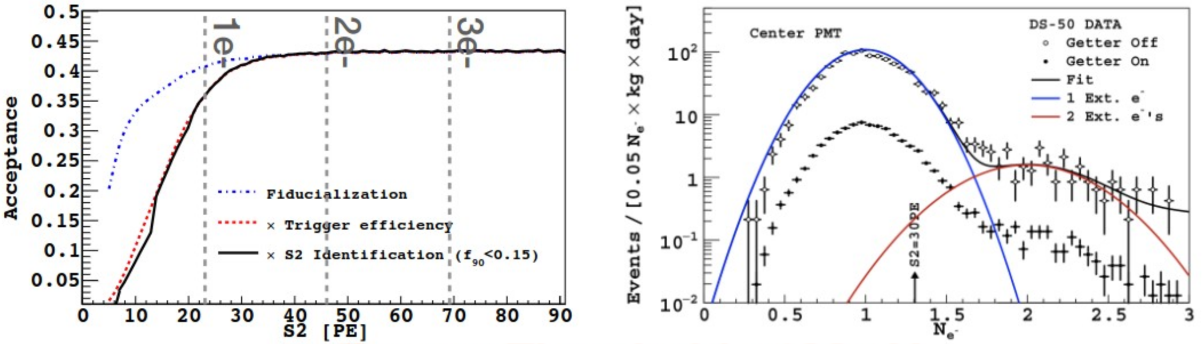
$>10^7$ ER rejection above ~10 keV

→ **ER-free search for $m_\chi > 10$ GeV/c^2**

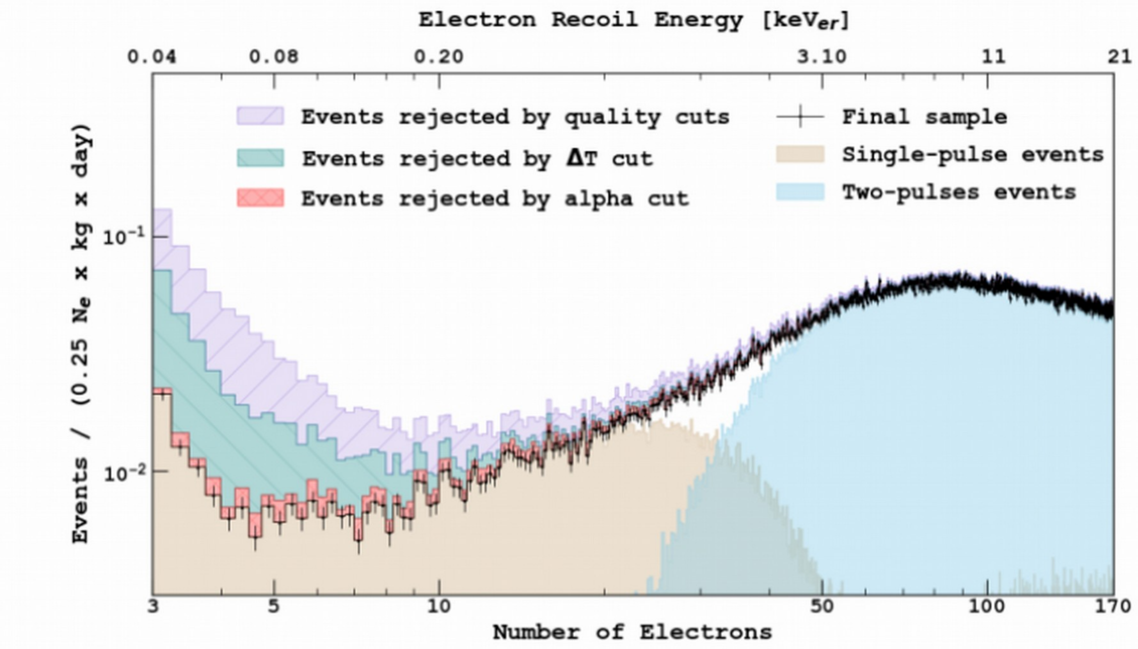
"Low-Mass" Dark Matter Search (Ionization Only)

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

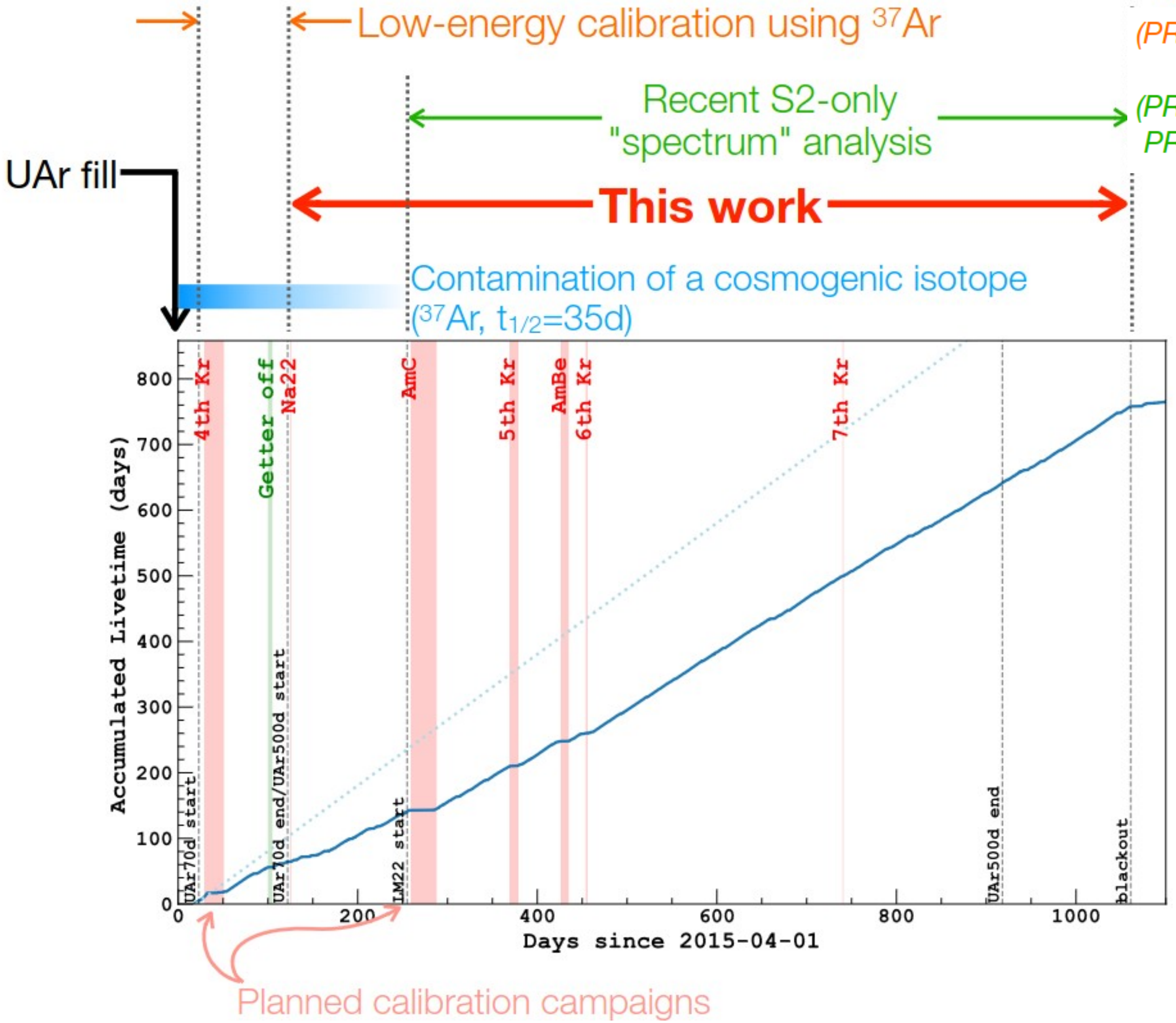
- Efficient electron extraction (~100%) and electroluminescence amplification (g2, >20 PE/e-)
- No requirement on S1 (Detection efficiency g1 ~ 16%)
  ->No NR/ER discrimination
- Select single-scatter S2 pulse, ~100% detection efficiency for 3e- (0.04 keV)



→ Energy Threshold <100 eV



DS-50 Underground Ar campaign



(PRD 104 082005)

(PRD 107 063001, PRL 130 101001, PRL 130 101002, EPJC 83 322)

-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

Detector Stability

Some critical parameters are:

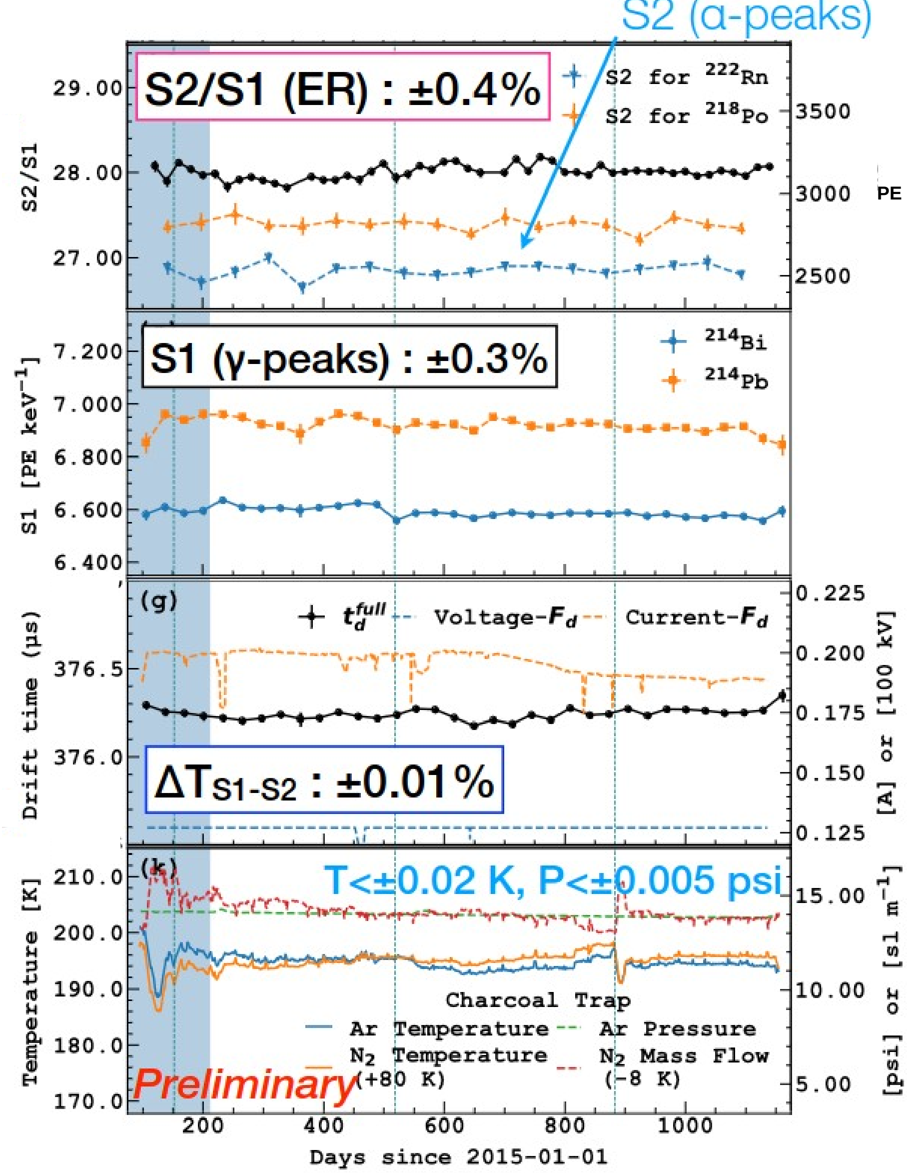
- the mean number of photoelectrons per ionization electron (g2 [PE/e-])
- the drift field (F_d [V/cm])

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:

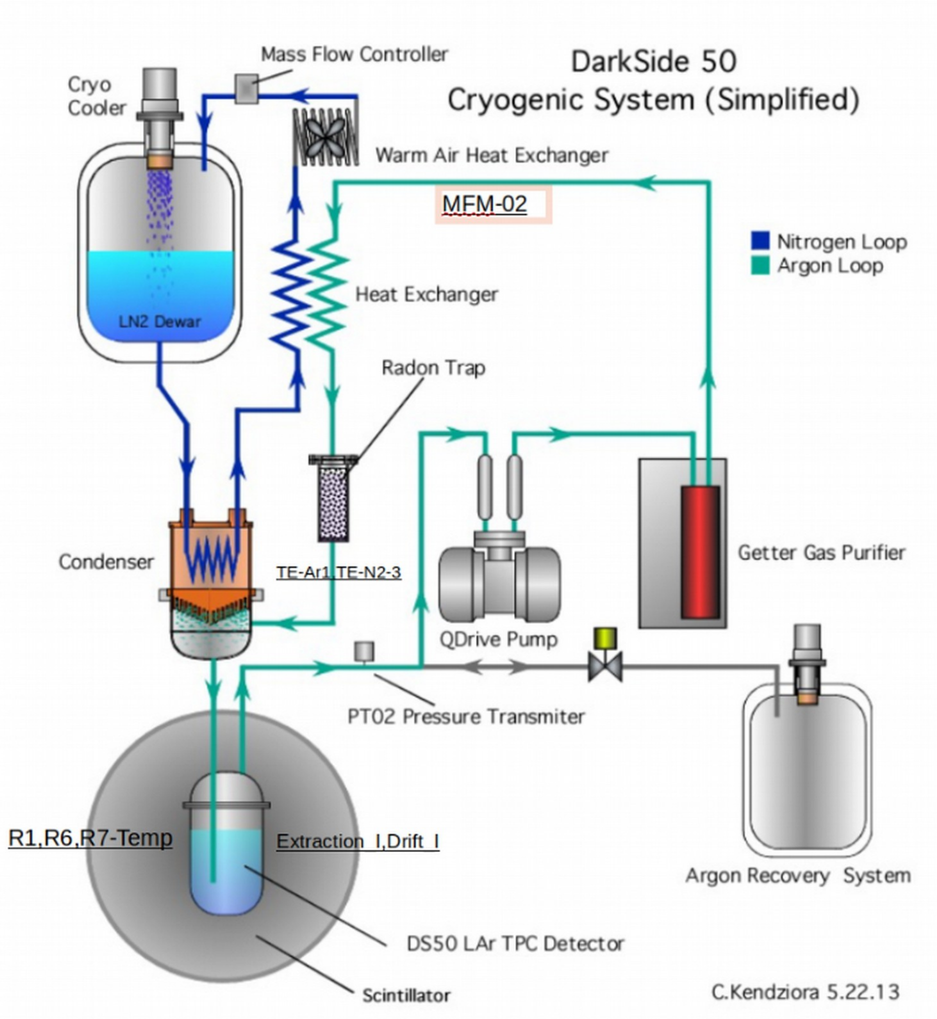
- Quantitatively
- Lomb-Scargle periodogram
- Correlation with Data

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

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

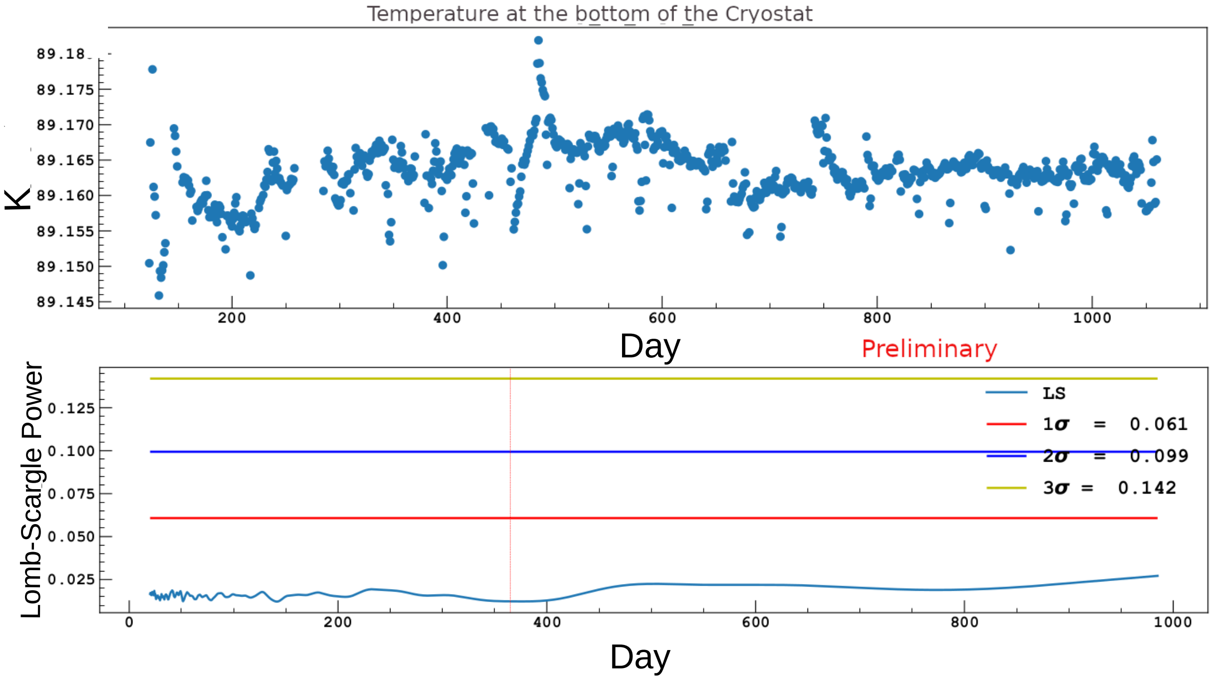
There is no significantly high coefficient found for each of Ne ranges, the highest are :
Drift/Extraction field and Mass flow circulation line

	Extraction potential	Extraction current	Drift potential
r	0.132	0.133	0.132



Detector Stability

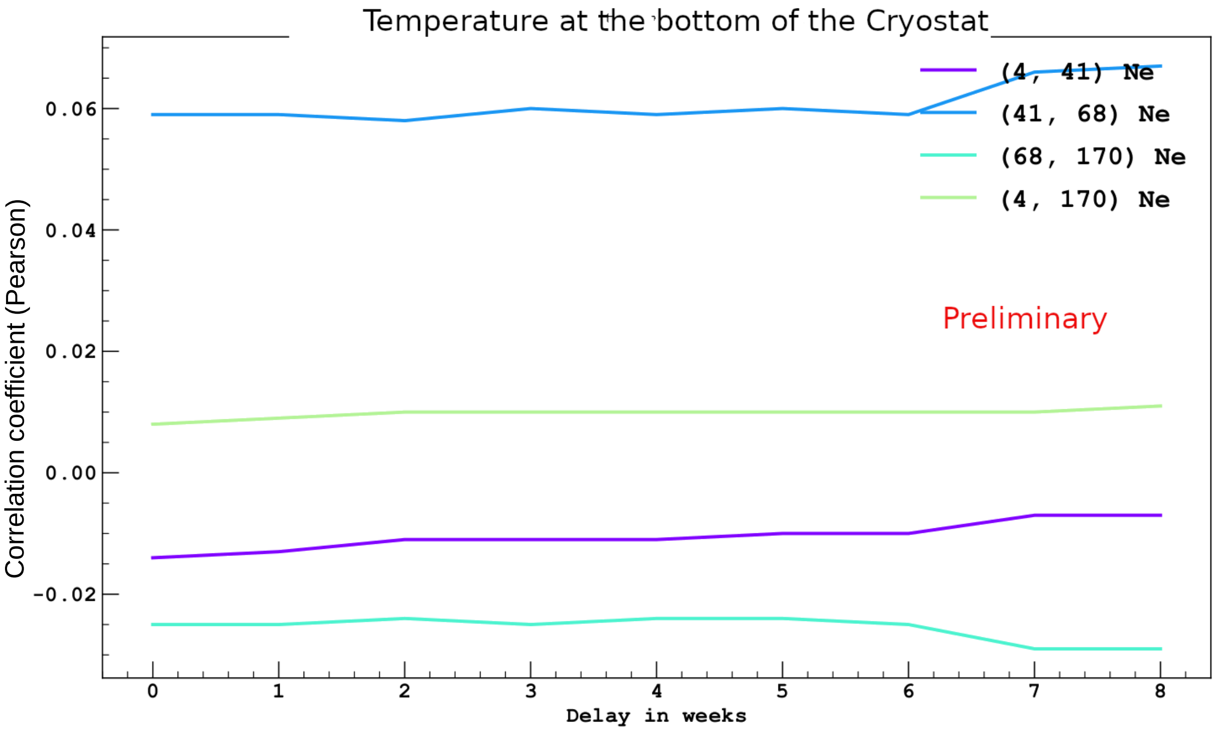
- Lomb–Scargle periodogram is **a method to estimate a frequency spectrum**
- uses a least squares fit of sinusoids to data to find, and **test the significance of weak periodic signals with uneven temporal sampling**.
- to quantify the significance of a peak we use **False Alarm Probability**, which 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



Detector Stability

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

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



Likelihood Fit

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

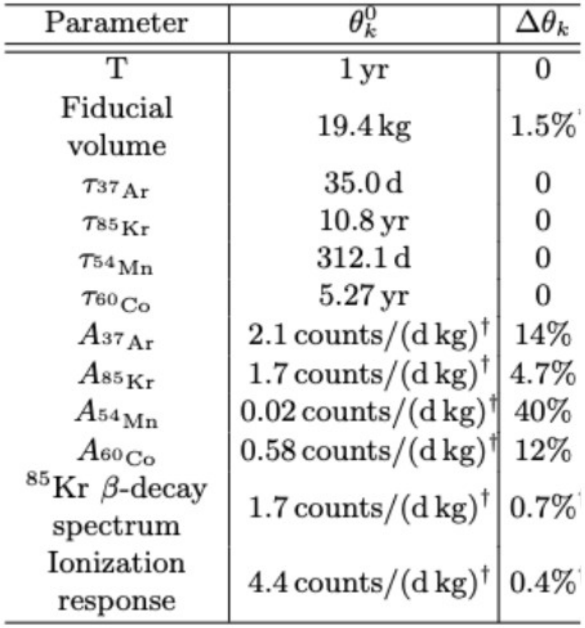
- Dark Matter Event rate as a function of time is modeled with a cosine signal:

$$f(t) = \underbrace{A_\chi}_{\text{Signal amplitude}} \cos\left(\frac{t-\phi}{\underbrace{T}_{\text{Fixed to 1y}}/2\pi}\right) + \sum_l \frac{A_l}{\tau_l} e^{-t/\tau_l} + \underbrace{C}_{\text{Including long-lived isotope (no constrain)}},$$

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

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

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



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

Final results

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

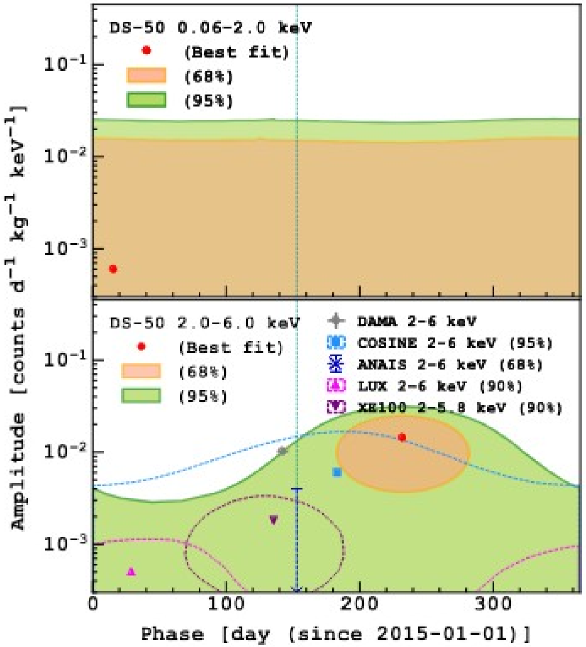
- Neither confirm nor reject the DAMA's observation

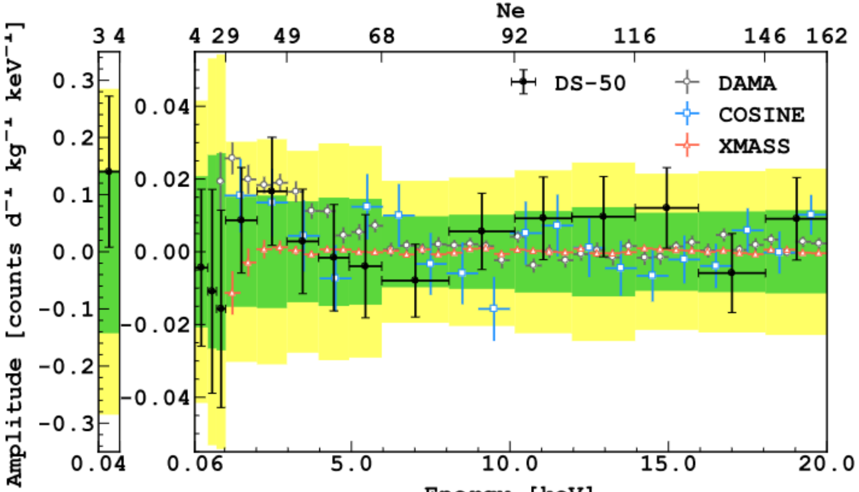
The 2D simultaneous fit (bottom plot) in both time and energy bins uses:

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

- 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

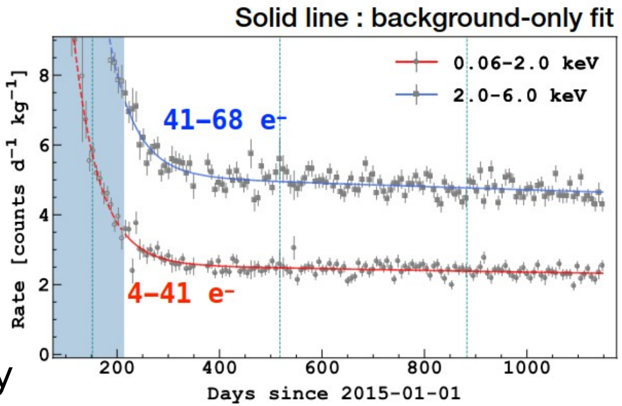
Lomb-Scargle algorithm is applied to look for any periodic signal

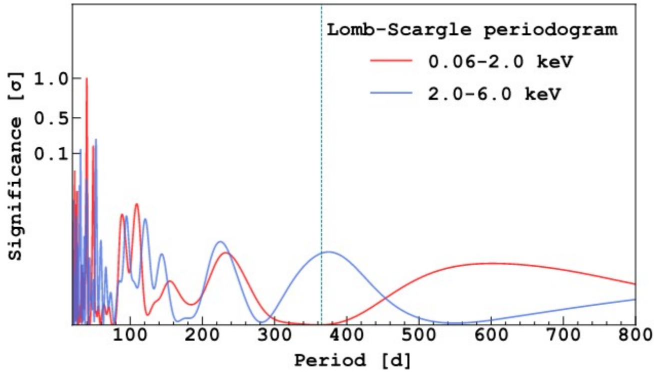
- Residuals of the background-only fit are converted into the frequency space

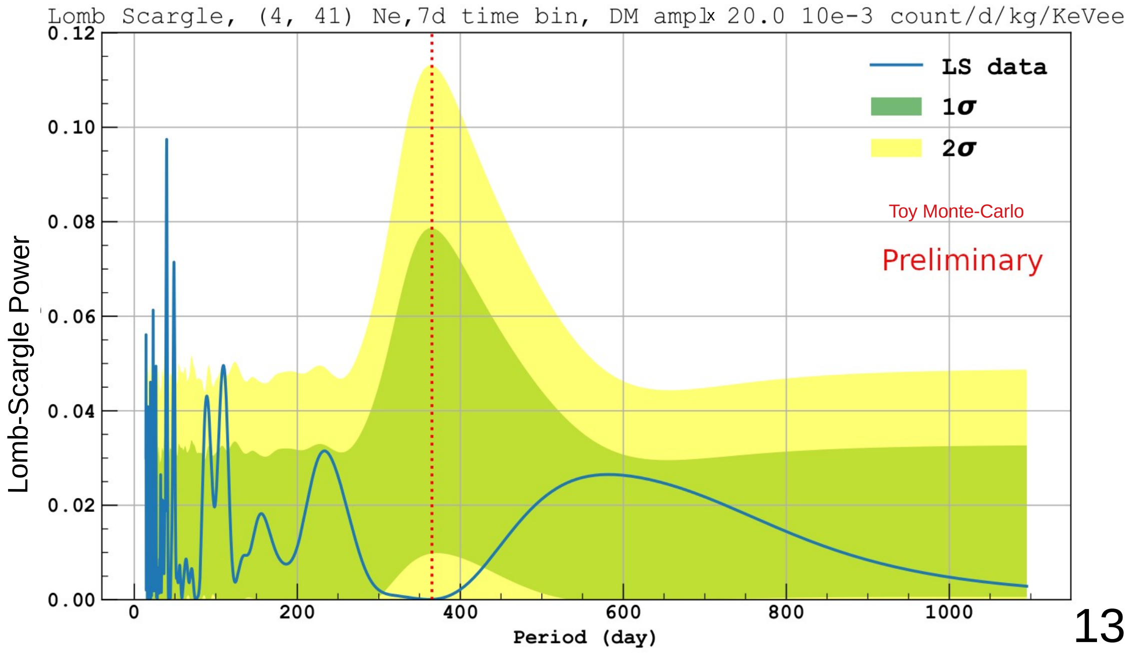
No significant signal is observed

- 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)

Solid line : background-only fit







Toy Monte-Carlo

Preliminary

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)
- Further detailed presentation here at TAUP

DS-20k, Y. Wang
Low energy run with Cf-252 @Red, L. Pandola
vPDU production and testing, D. Santone and P. Franchini
UAr production (ARIA + URANIA), W. Bonivento
DArT, L. Luzzi
DS Low-mass, M. Wada

Thank You

29 August 2023 | Theo Hugues

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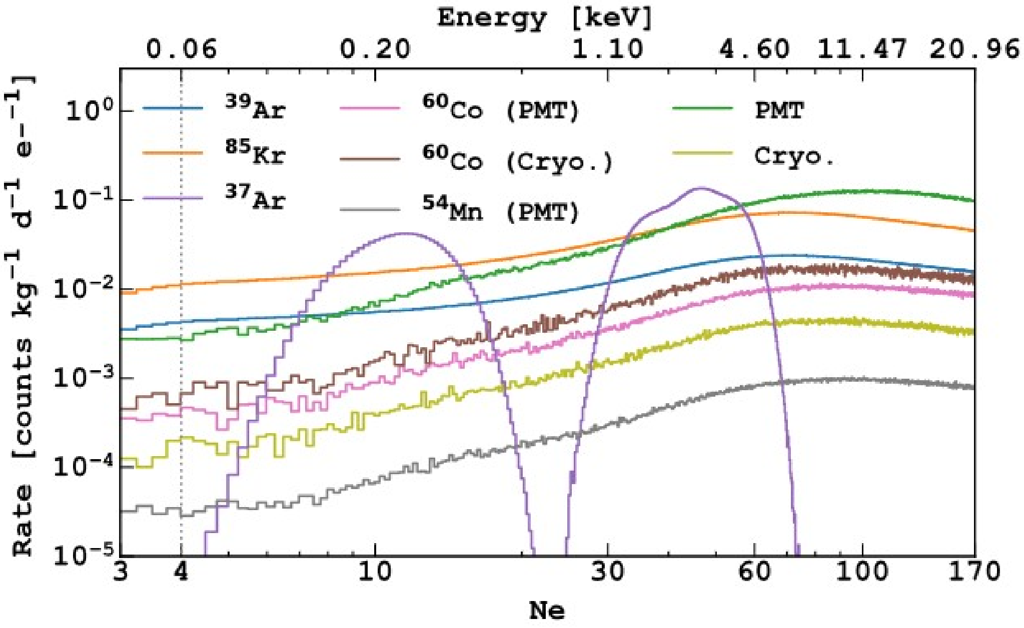
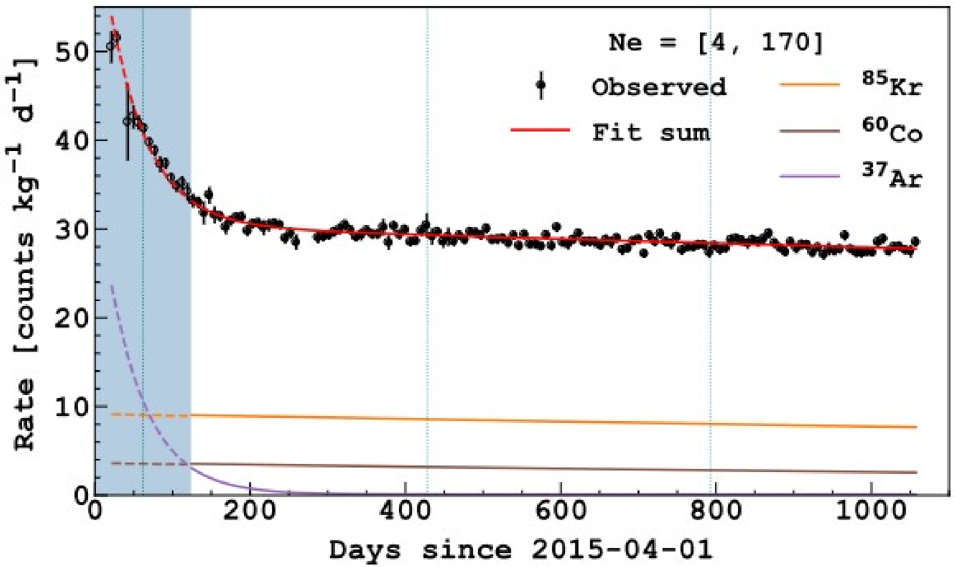
Dark Wave
NICOLAUS COPERNICUS ASTRONOMICAL CENTER OF THE POLISH ACADEMY OF SCIENCES
European Union
ASTROCENT

Background

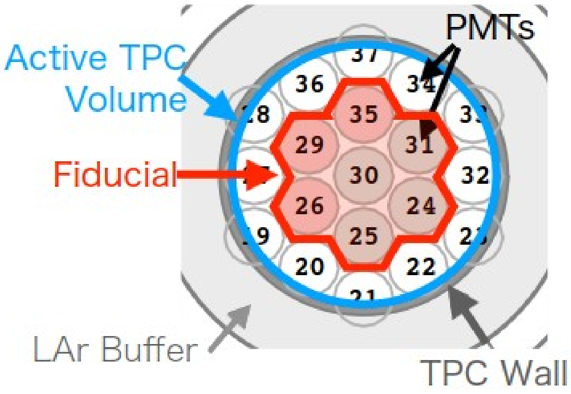

Energy [keV]
0.06
0.20
1.10
4.60
11.47
20.96
^{39}Ar
^{85}Kr
^{37}Ar
^{60}Co (PMT)
^{60}Co (Cryo.)
^{54}Mn (PMT)
PMT
Cryo.
Rate [counts kg^{-1} d^{-1} e$-^{-1}$]
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
3
4
10
30
60
100
170
Ne


Ne = [4, 170]
Observed
Fit sum
^{85}Kr
^{60}Co
^{37}Ar
Rate [counts kg^{-1} d^{-1}]
50
40
30
20
10
0
0
200
400
600
800
1000
Days since 2015-04-01

Event selection

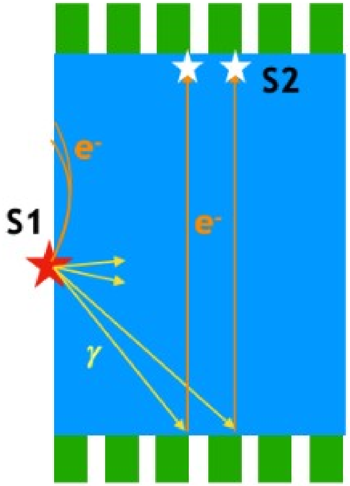
Fiducialization

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



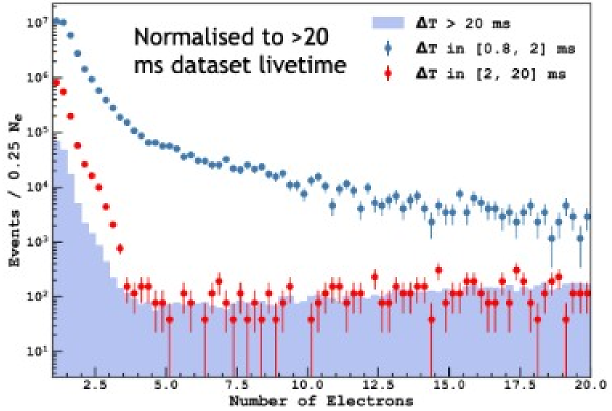
Alpha-induced S2

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



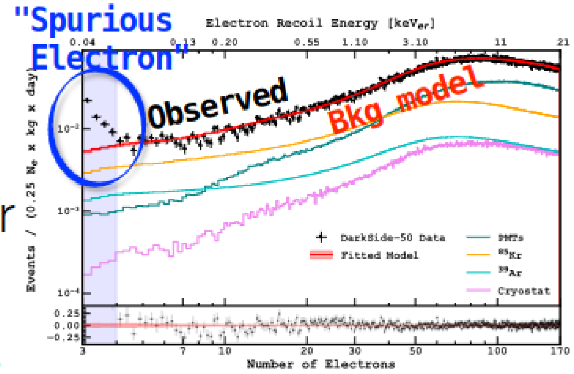
Spurious electrons

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



Analysis in 3e- Bin

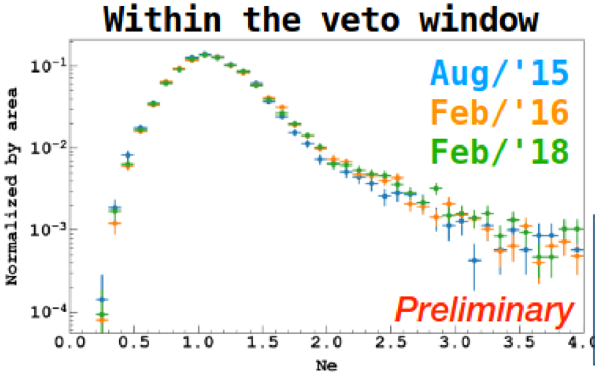
- More events than the expectation from the radioimpurities,
  - They have been suppressed by a 20-ms veto after each trigger
  - No a priori prediction on their properties
- For this analysis, they are characterized with sideband samples


"Spurious Electron"

Observed

Bkg model

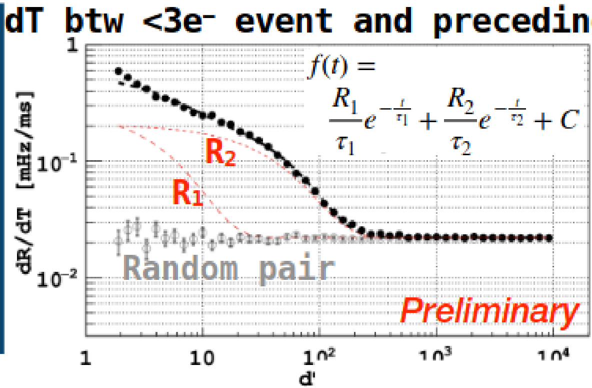
Spectrum


Within the veto window

Preliminary

The spectral shape doesn't vary over time

Rate


dT btw <3e⁻ event and preceding one

Random pair

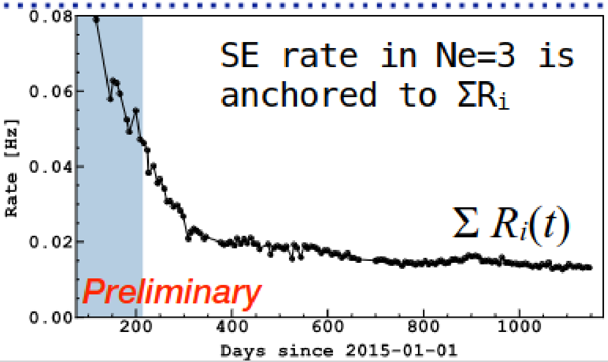
Preliminary

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-:

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

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


SE rate in Ne=3 is anchored to ΣR_i

Preliminary