Finanziato dall'Unione europea NextGenerationEU | Ministero dell'Università e della Ricerca | Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA | INFN

CHARACTERIZATION OF LOW-ENERGY ARGON RECOILS WITH RED AND RED+

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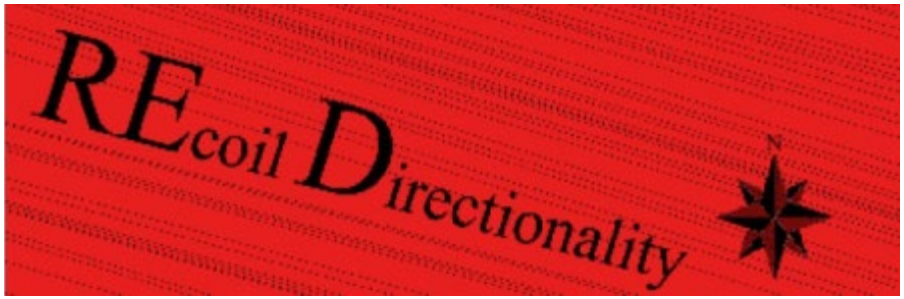
on behalf of the ReD Working Group

(GADM Collaboration)

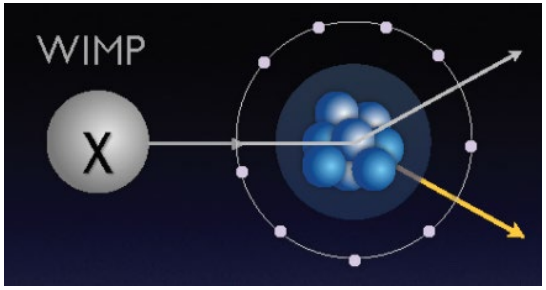
INFN LNS

MAYORANA2025, Modica

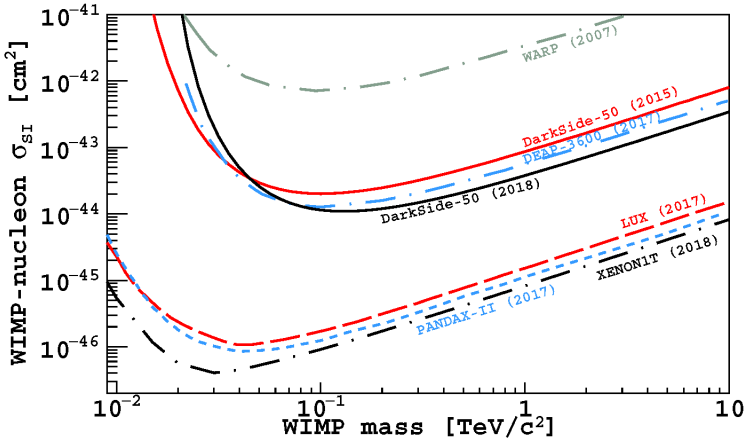
June 18th, 2025



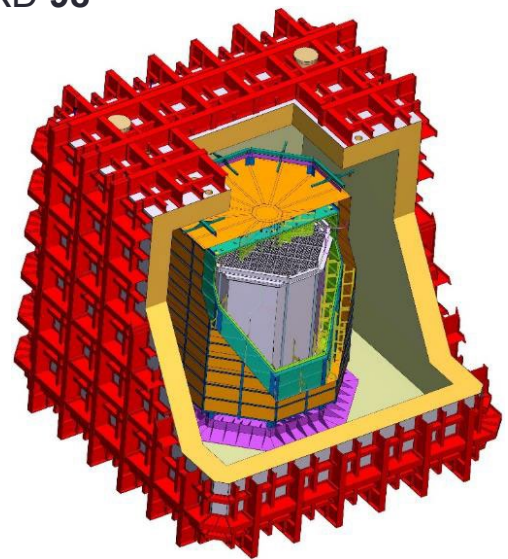
The DarkSide program



- **DarkSide program** at Gran Sasso Laboratory: direct search for **WIMP dark matter** → very rare **elastic scattering** interaction with ordinary **nuclei**
- Strategy: dual-phase Time Projection Chamber with low-radioactivity LAr
- Operated a **50 kg TPC** (DS-50)
- In preparation: **50 ton TPC** (DS-20k)
  - Novel light readout with cryogenic SiPM
  - Experiment being constructed now
- Pave way for **next-generation** (ARGO)

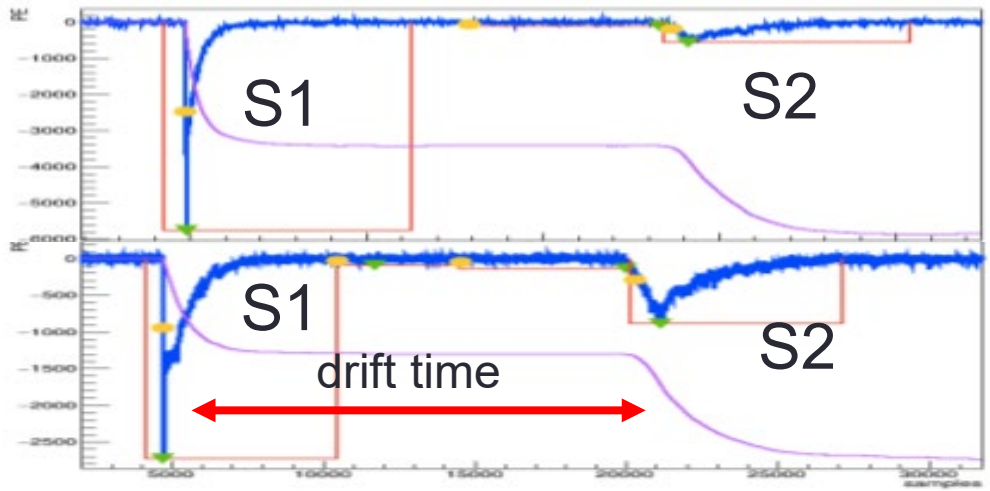


Agnes et al. PRD **98** (2018) 122006

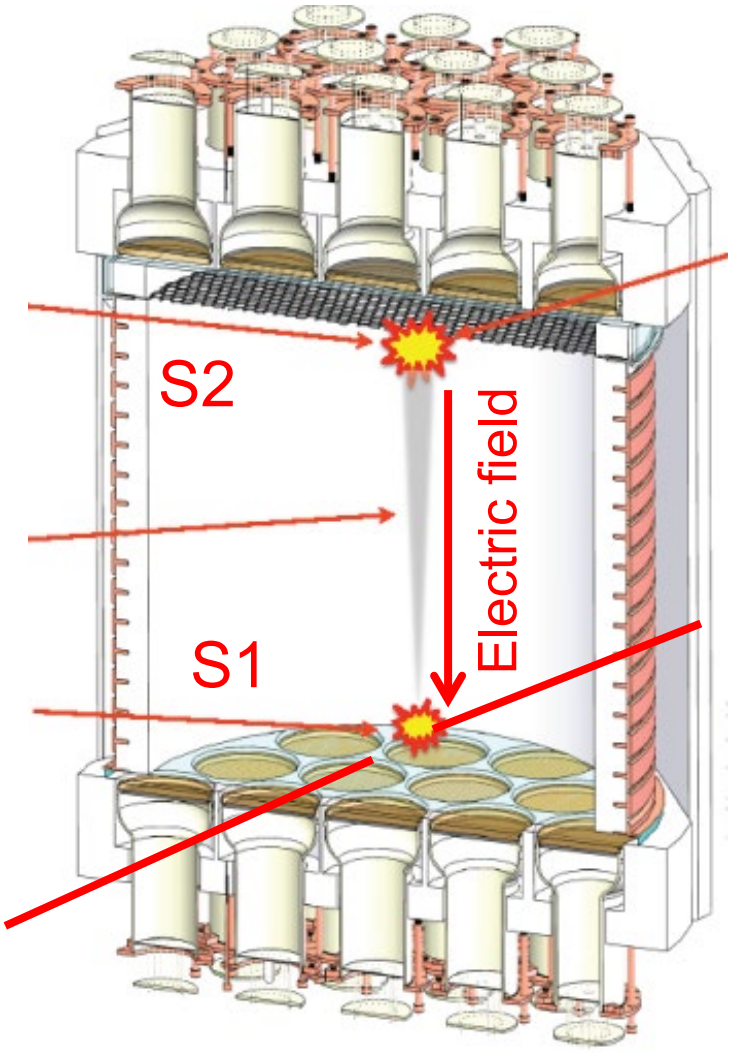


DARKSIDE

The dual-phase LAr TPC in one slide

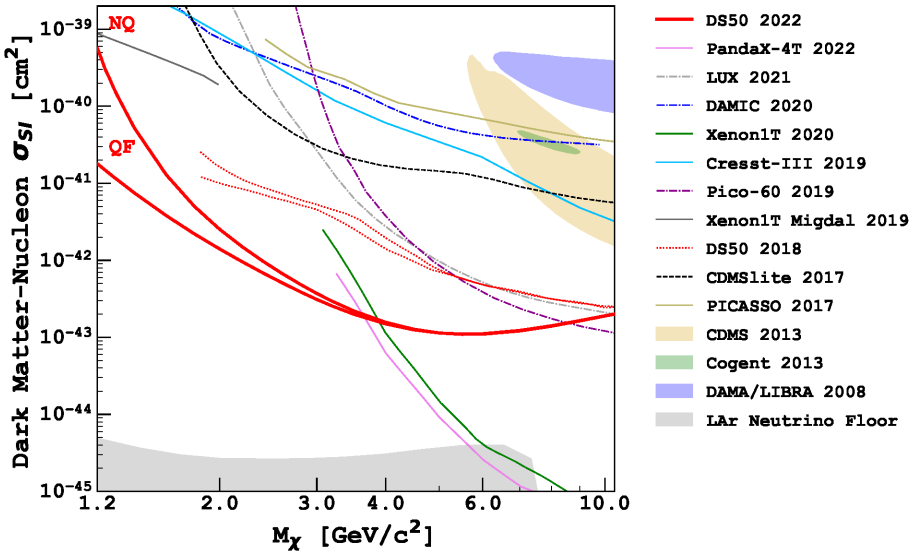


- Prompt **scintillation** signal: **S1**
- Delayed **electroluminescence** signal: **S2**
- **Time difference** between S1 and S2 → **z** position
- **Light pattern** of S2 → **(x,y)** position

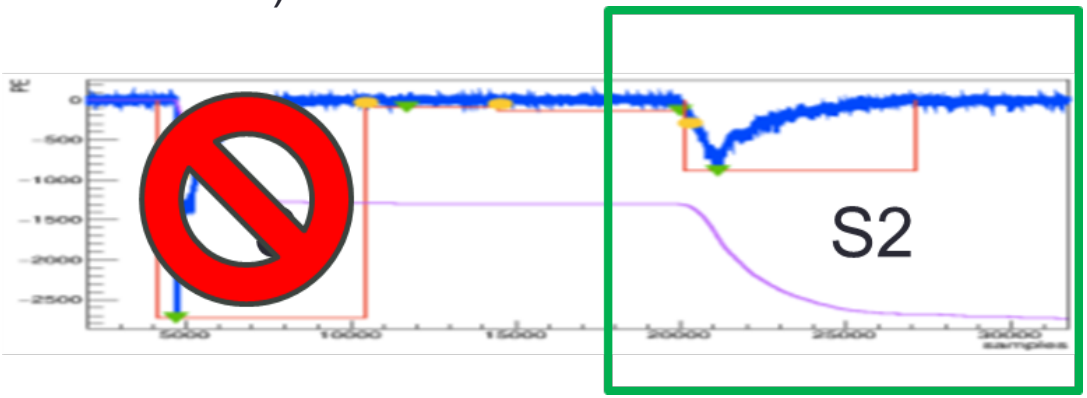


The search for low-energy WIMPs

- LAr TPC sensitive in the search of **low-mass WIMPs**
  - A few GeV instead of the "standard" 100's GeV
- Lighter WIMP = **slower recoil**
  - O(1 keV), instead of 20-100 keV
- **Challenging!**
  - S1 too small to be detected
  - **S2-only events**
    - Only ionization detected (~20 PE/e-)



Agnes et al. PRD **107** (2023) 063001



- Analysis sensitive to ionization yield for keV NRs
  - **Poorly known** for Ar

Ar NRs ionisation yield at low energy

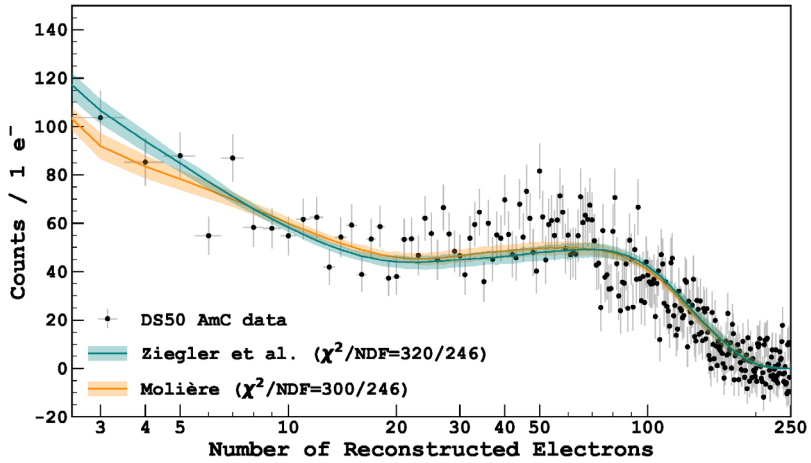
- Measurement within **DS-50**, with AmC and AmBe neutron sources
- Dedicated **2-parameter model**

Thomas-Imel

$$1 - r = \frac{1}{\gamma N_i} \ln(1 + \gamma N_i)$$

$$Q_y^{NR} = \frac{N_{i.e.}}{E_{nr}} = \frac{(1-r)N_i}{E_{nr}}$$

$$N_i = \beta\ \kappa(\epsilon) = \beta \frac{\epsilon\ s_e(\epsilon)}{s_n(\epsilon) + s_e(\epsilon)}$$



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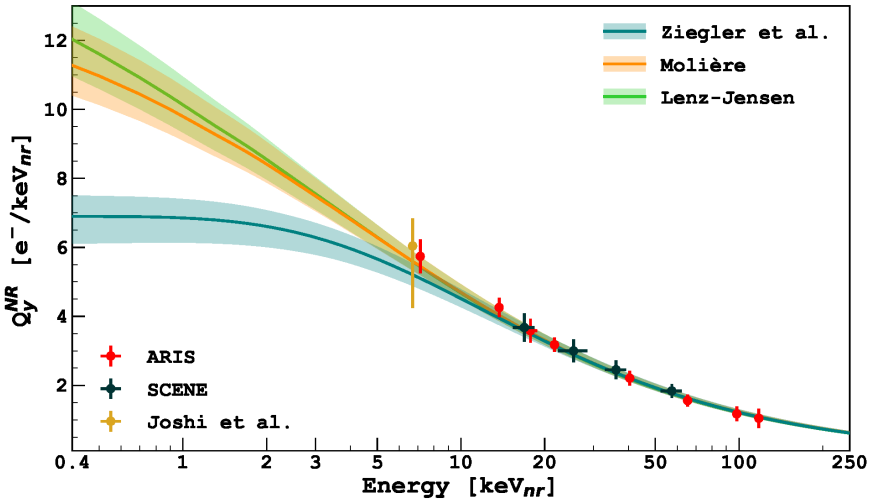
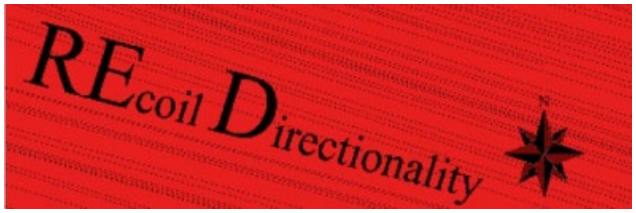
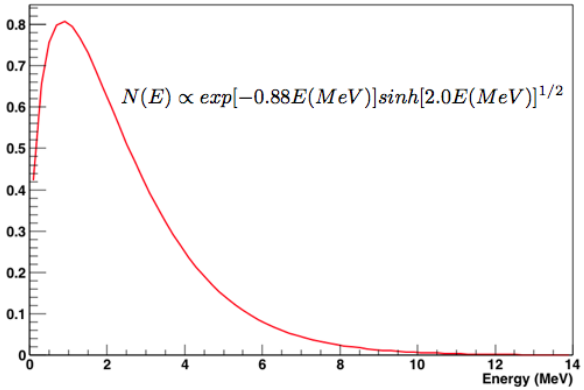


- Different screening models for s_n, possible low-E suppression for s_e
- Constrains only by small low-energy sample from the AmC calibration of DS-50
  - No closed 2-body kinematics
- **Strong case** for a LAr **direct measurement** at **1-5 keV$_{nr}$**

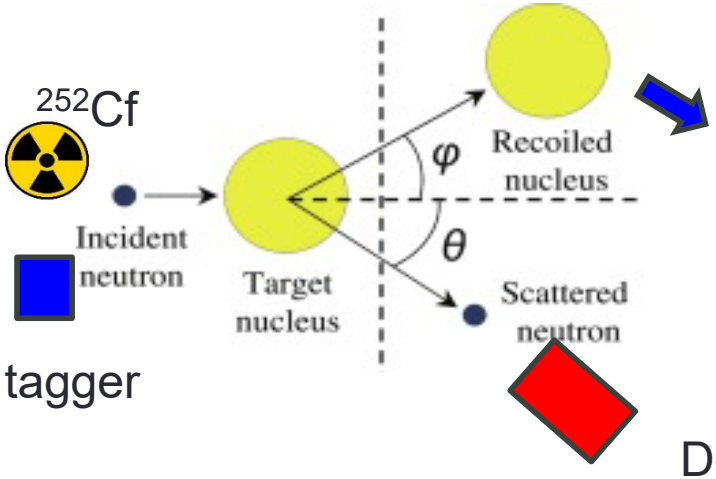
The ReD project



- Measurement **within the ReD project**
  - R&D activity within DarkSide
  - Operates a small dual-phase LAr TPC with SiPM readout
- Strategy: Produce **Ar recoils** of **known energy** in the TPC by **(n,n')**
- Neutrons from a **^{252}Cf fission source**
  - Neutrons O(2 MeV) and up to 10 MeV
  - Appropriate to produce recoils of a few keV



- **Close detectors** (BaF_2) to tag fission events
- **Neutron spectrometer** to detect neutrons scattered off-Ar



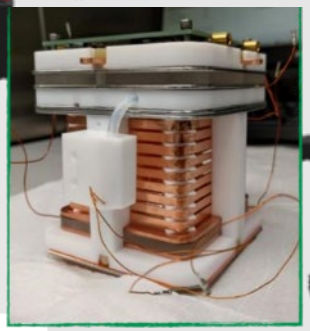
$$E_{NR} = 2KE_{neutron}\frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - cos\theta_{scatt})$$

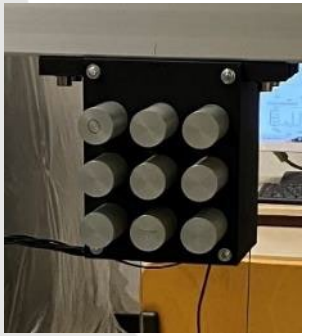
Time of flight

Fixed by geometry

Two-body kinematics!

The ReD conceptual layout

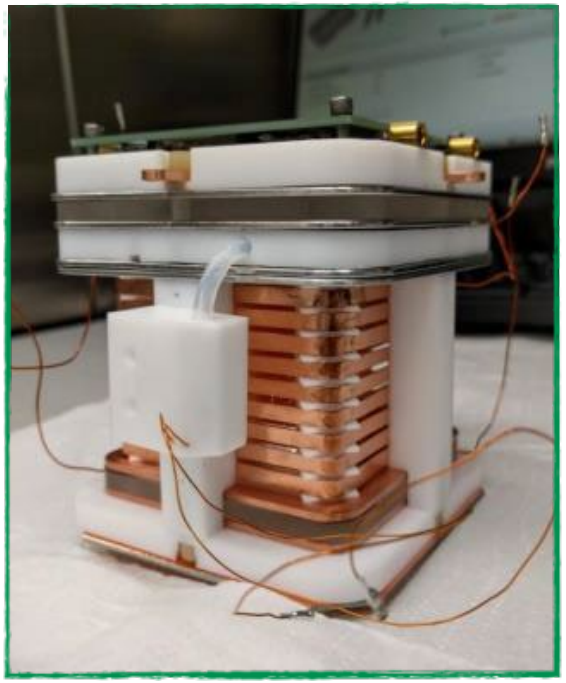




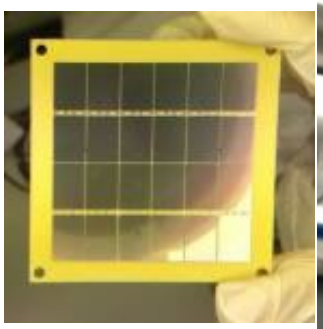
- Design sensitivity in the range **2-5 keV$_{nr}$**

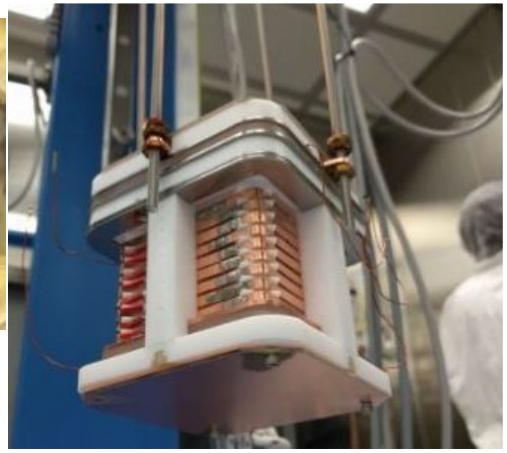
THE INGREDIENTS

The TPC …



- **Miniaturized version** of the DS-20k TPC
  - Active volume: 5(L) x 5 (W) x 6 (H) cm
  - Gas pocket: 7 mm thick
  - TPB coating for wavelength shifting
- DS-20k light readout: **5x5 cm² SiPM**, 24x1cm² SiPM
  - 24 ch readout (top), for increased (x,y) resolution
  - 24x1cm² SiPM, 4 ch readout (bottom)
- **Front End** from the DS-20k R&D
- **3D event reconstruction:**
  - (x,y) from S2 pattern on the top SiPMs
  - z from **drift time** (up to ~55 μs)
- In this campaign:
  - g_2 = ~18 PE/e- (E_{drift} = 200 V/cm, E_{el}=5.79 kV/cm)
  - Electron lifetime > 1 ms





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… and all the rest

- **^{252}Cf source** (26 kBq fission)
  - Collimator of opening angle ~2°
  - Shines the entire TPC at 1 m distance

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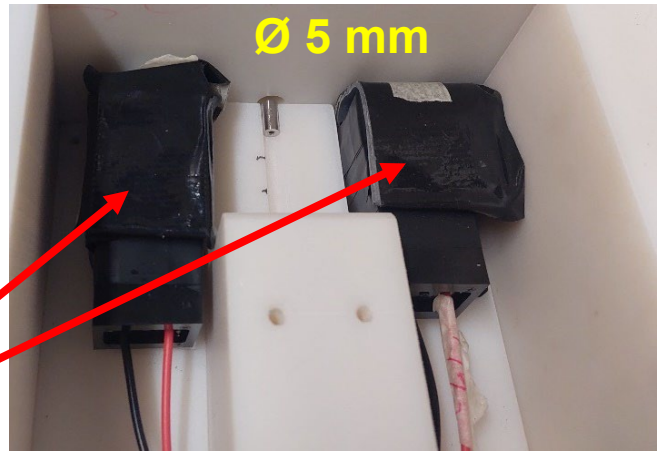
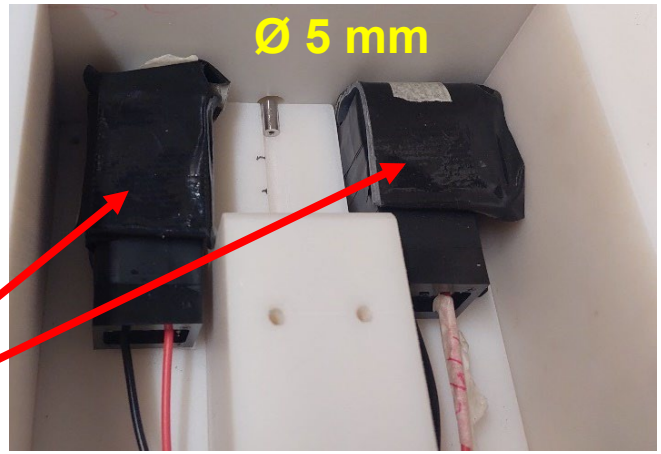
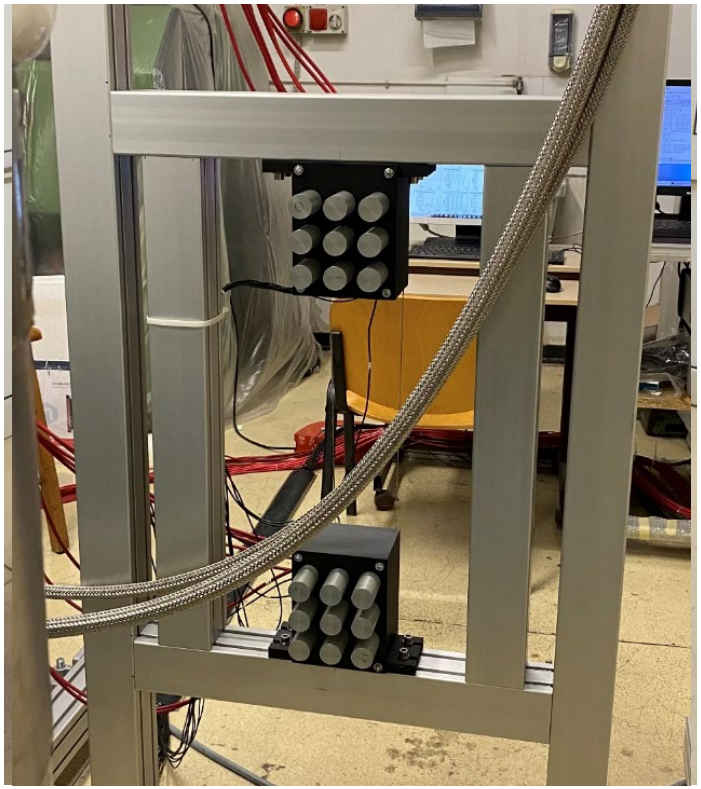
  - Collimator of opening angle ~2°
  - Shines the entire TPC at 1 m distance
- Two **BaF_2 detectors** to tag fission products
  - Fast (high source rate, pile-up)
  - START for time of flight



… and all the rest

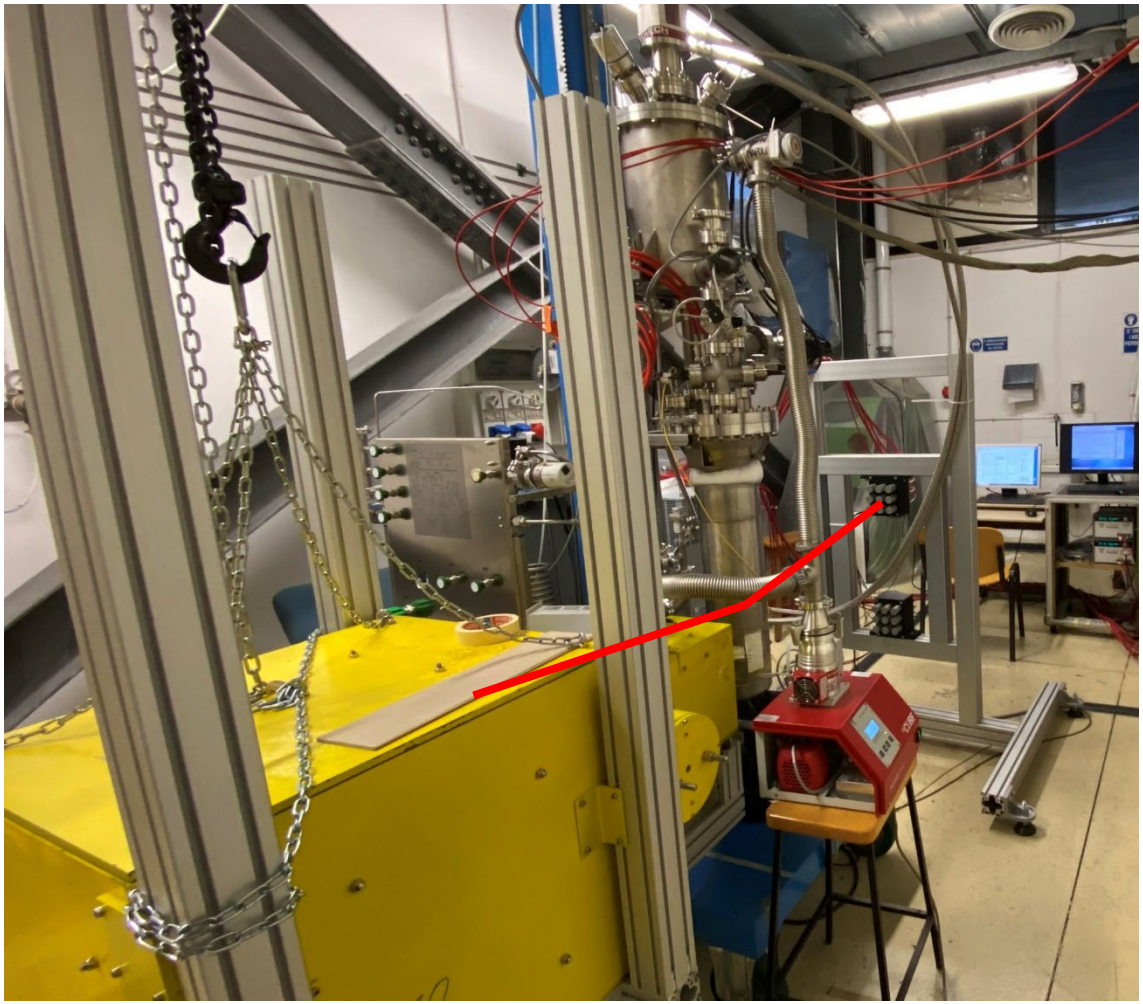


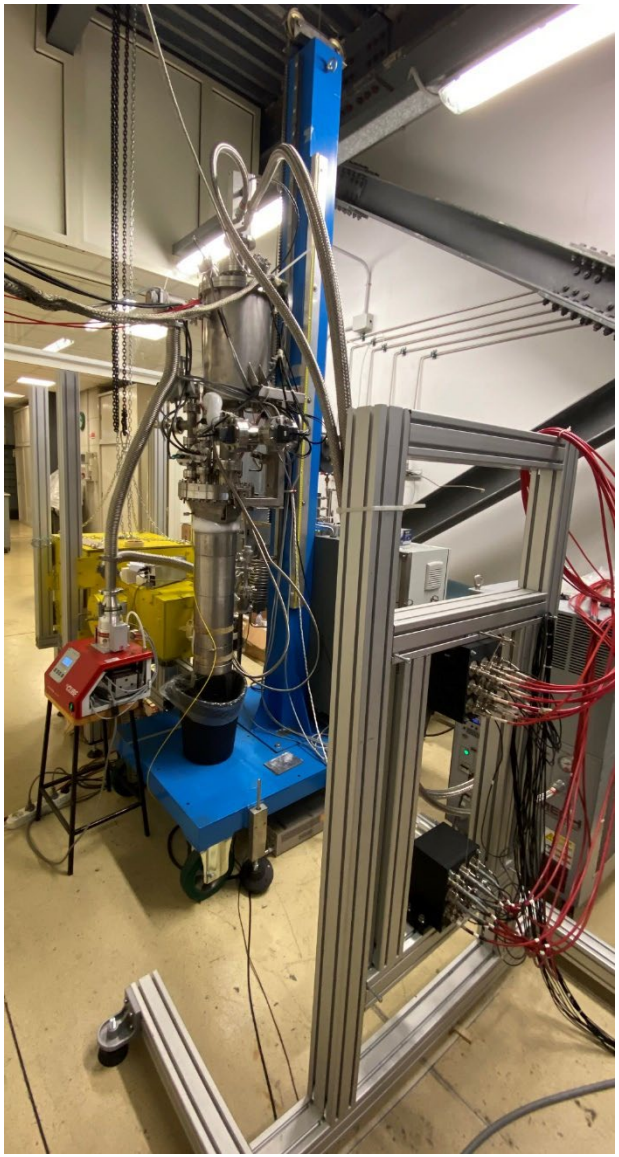
- **^{252}Cf source** (26 kBq fission)
  - Collimator of opening angle ~2°
  - Shines the entire TPC at 1 m distance
- Two **BaF_2 detectors** to tag fission products
  - Fast (high source rate, pile-up)
  - START for time of flight
- **Neutron spectrometer**: two 3x3 arrays of EJ276 **plastic scintillators**
  - STOP for time of flight
  - Features n/γ discrimination
  - 1 m downstream the TPC
  - Symmetric deployment to control systematics due to alignment
  - **θ ~ 12°-17°** in order to **avoid direct neutrons** from the source
- Tag Ar recoils down to **~1-2 keV$_{nr}$**



The real thing at

INFN Catania
Istituto Nazionale di Fisica Nucleare

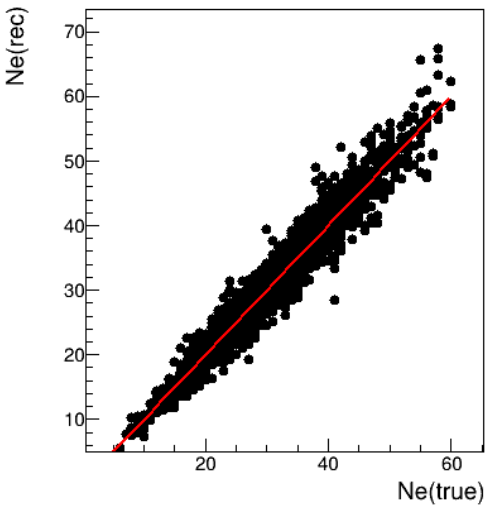


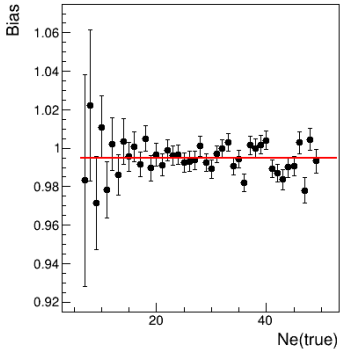


PUTTING EVERYTHING AT WORK

Data taking & Co.

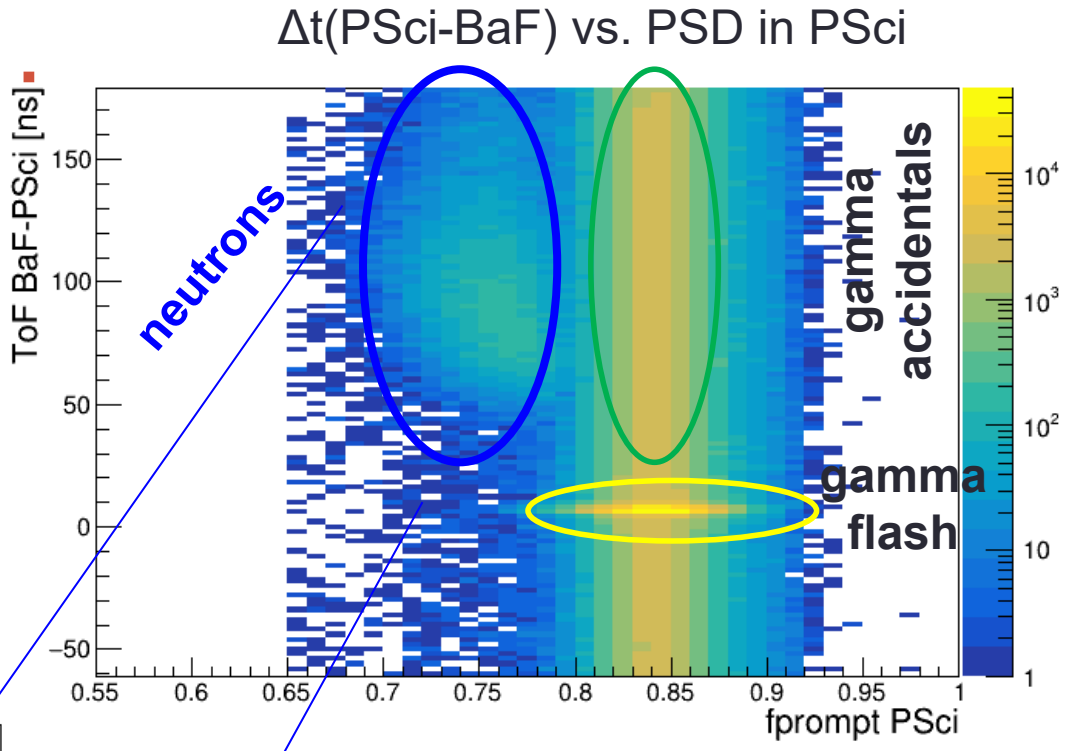
- Data taking with ^{252}Cf from **Jan 10th to Mar 16th, 2023**
  - Event rate **~2.5 Hz**, 80 µs waveforms
- Trigger logic: **"any BaF" ∧ "any PSci"**
  - Tagging ~60% of SF events
  - TPC acquired in **follower** mode (may fail to trigger in S1)
- **Weekly calibration** with laser and ^{137}Cs/^{241}Am
  - Calibrations and background runs used to determine and correct for non-homegeneity in the TPC response
- Detailed end-to-end **MC simulation** available
  - Produce synthetic data → same analysis flow than real data
  - Tuned and validated on calibrations
  - **Check reconstruction algorithms**!

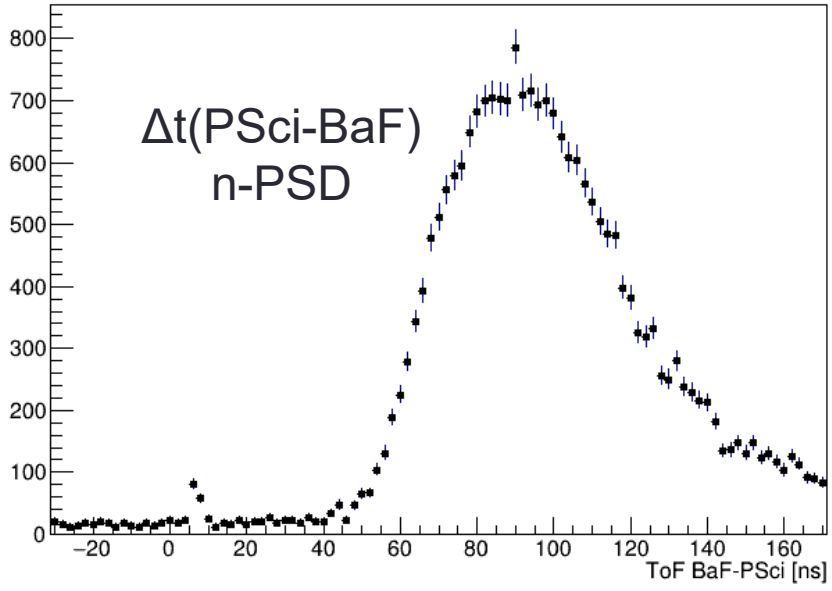


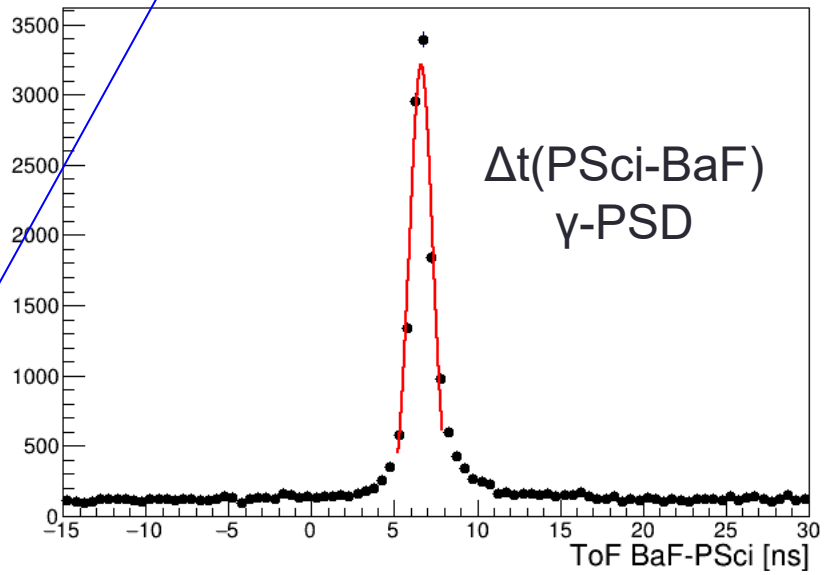


Finding neutrons…

- Event rate dominated by **γ-rays** and **accidentals**
- Selection of candidate neutrons by **time of flight** and **PSD**
  - About 40 events/hour (0.4%)
- ToF resolution **~ 0.7 ns**
- Event-by-event E_n at <5%

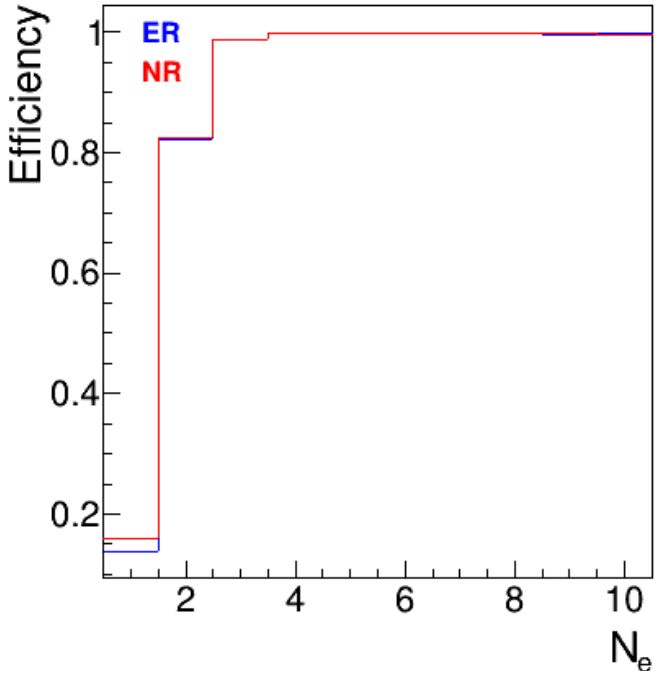


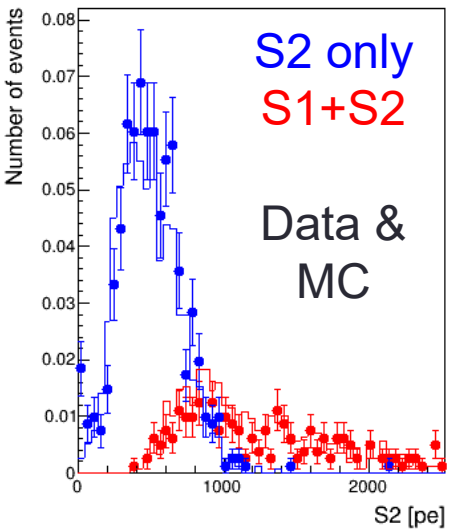


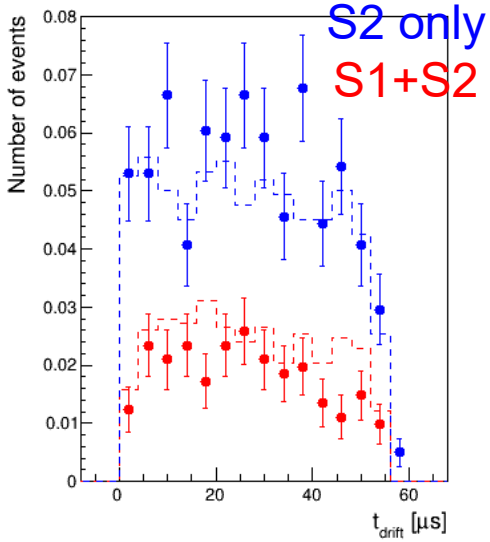


… interacting in the TPC

- Look for TPC events **offline**
  - Analysis flow: de-convolution of SiPM response function, TPC pulse finder
- From MC: pulse finder **fully efficient** for S1 > 25 PE, **S2 > 4 e-**
- Selection cuts:
  - One S2 within 65 μs from BaF_2 and optionally, an **S1** (< 100 PE)
  - If S1 available, consistent BaF-TPC tof
  - No tails of previous S2 pulses
  - (x,y) in the central 4x4 cm region (**fiducialization**)
- Final sample: **~800** passing all cuts, out of 2200 candidate neutron events w/ TPC signal
  - 72% are S2-only (~ as in MC)
  - Expected: S1~8 PE for 5 keV_{nr}

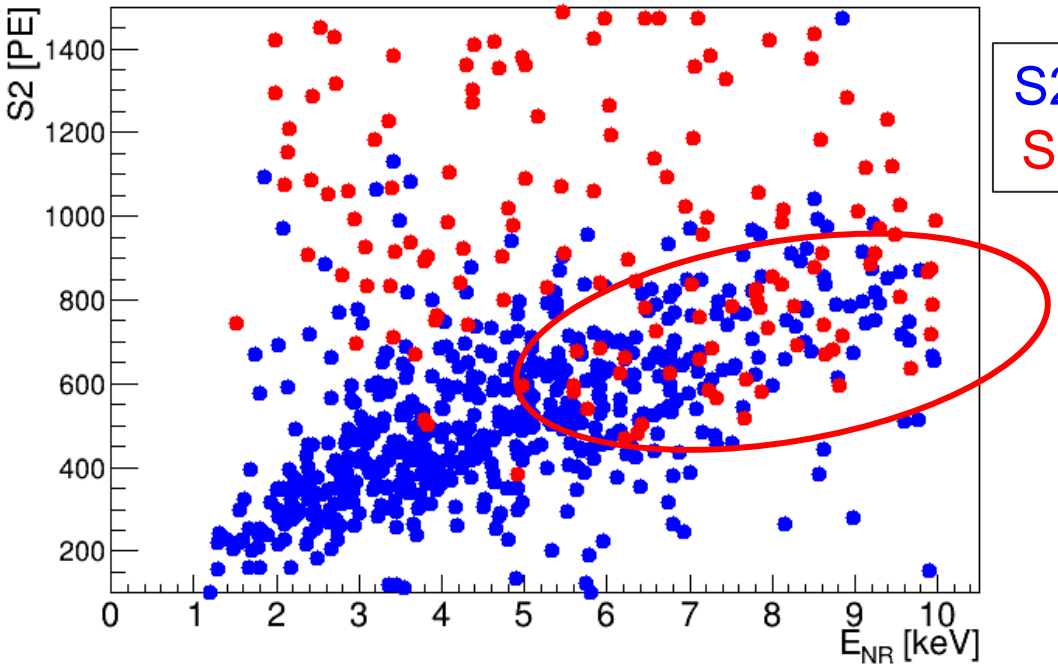




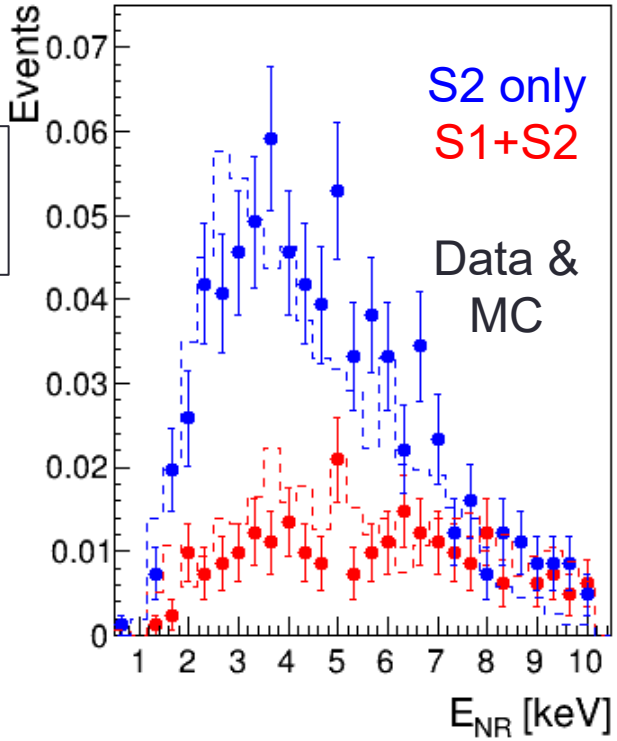


The sample of low-energy recoils

- Get **E_{NR}** from time of flight (and geometry), uncert. **±7%**
- **E_{NR}** down to **1-2 keV**
- Most S1+S2 outliers: multiple neutron scattering
  - Confirmed by MC
  - For genuine NRs below 5 keV, S1 always too small for the pulse finder
  - For higher NRs, some S1 reconstructed by the pulse finder → S1+S2 events populate the signal band



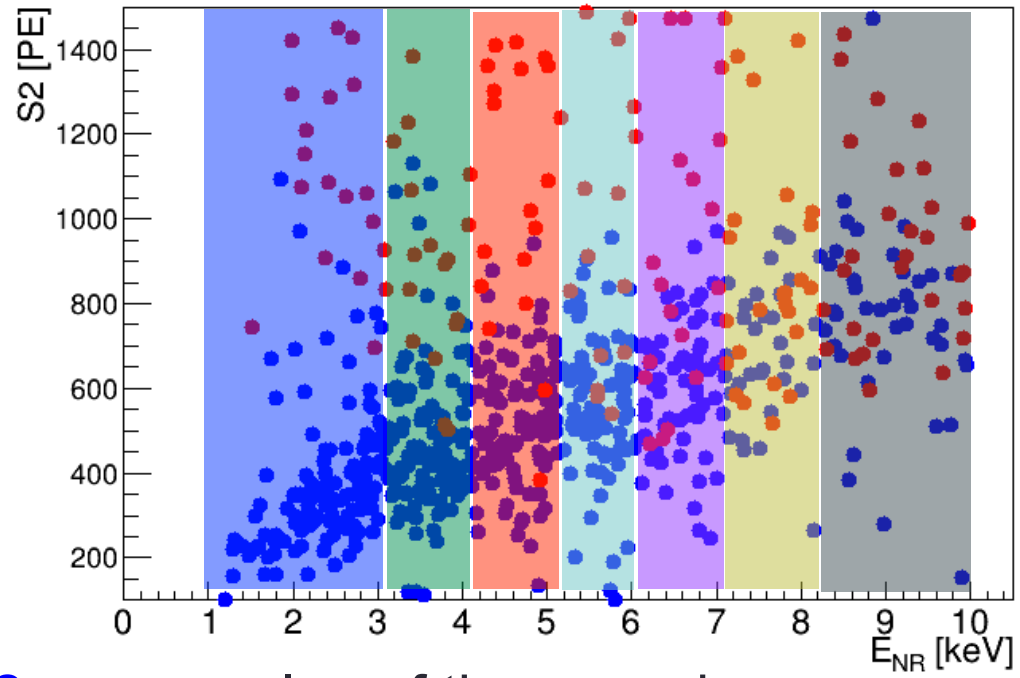
S2 only
S1+S2

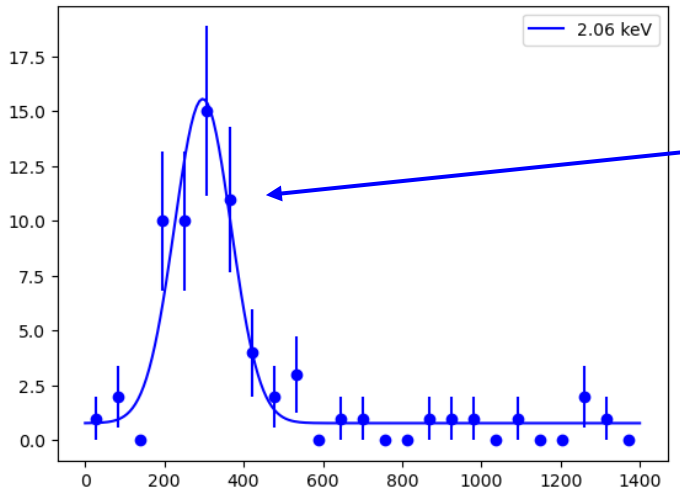


S2 vs. E_{NR}

- **Slice** (E_{NR},S2) data in **7 intervals** in E_{NR} (~ equally populated)
  - Take range 1-10 keV only

- For each slice, **unbinned maximum likelihood fit** of the S2 distribution
  - gaussian + **constant**
  - Constant term accounts for multi-scattering background

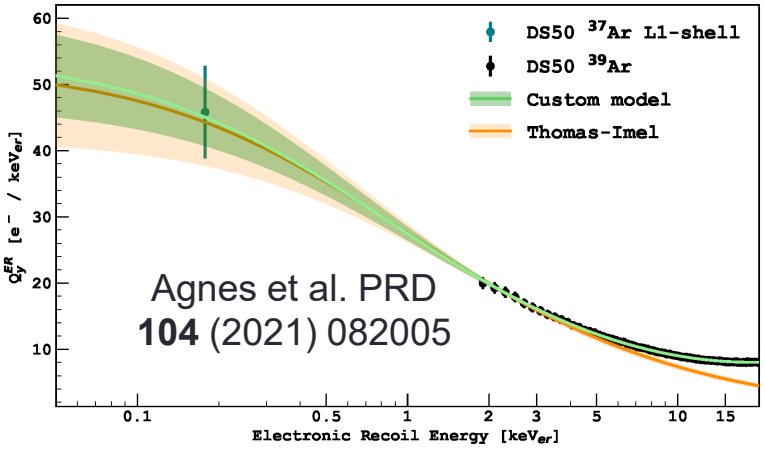




- S2: mean value of the gaussian
- < E_{NR} >: mean energy of the events
- Procedure validated with the MC-generated data sets
  - Unbiased, provided S1+S2 events are kept

From S2 to Ne: g_2

- Ionization gain $\mathbf{g_2}$ (PE/e-)
  - Detector property: must be measured by the ReD data
- Two different approaches
- Calibration with ^{241}Am (60 keV γ-ray)
  - S2 value from ^{241}Am data
  - Expected Ne calculated by MC, using the Qy(ER) model from DS50



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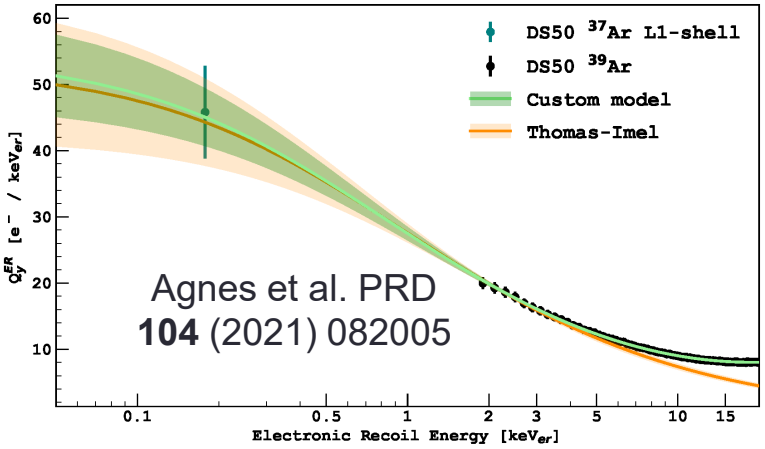
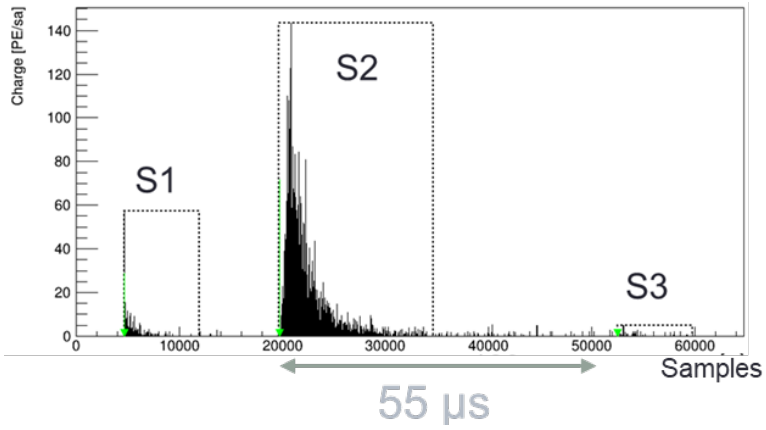
- «Echo» events (S3): photoionization of the cathode from the S2 pulse
  - Delay of 55 μs with respect to S2
  - A-few electron signal





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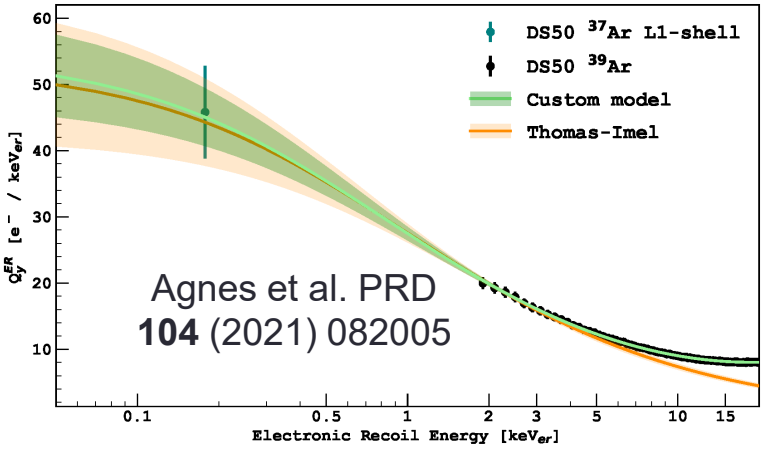
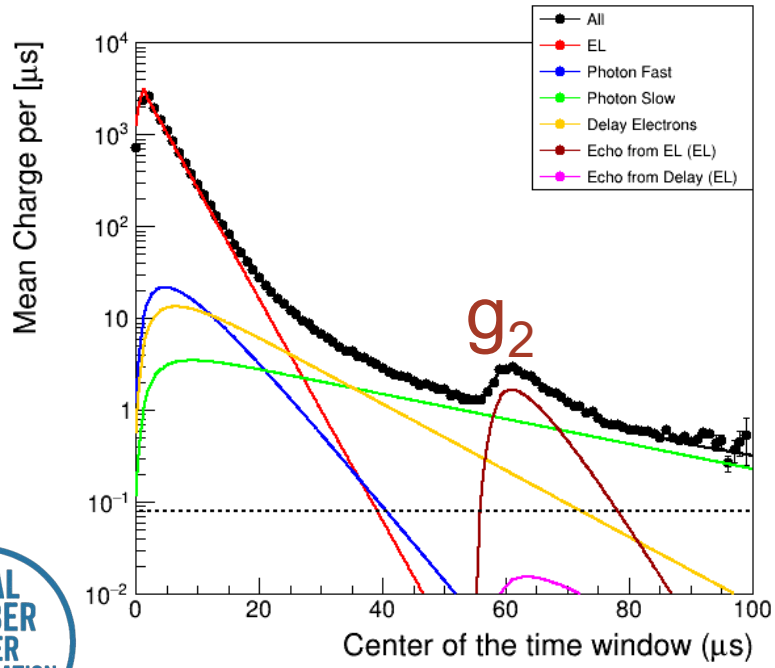
  - S2 value from ^{241}Am data
  - Expected Ne calculated by MC, using the Qy(ER) model from DS50
- «Echo» events (S3): photoionization of the cathode from the S2 pulse
  - Delay of 55 μs with respect to S2
  - A-few electron signal
  - Required the development of a full integrated shape model
- **Consistent** results: ~18.0 PE/e-

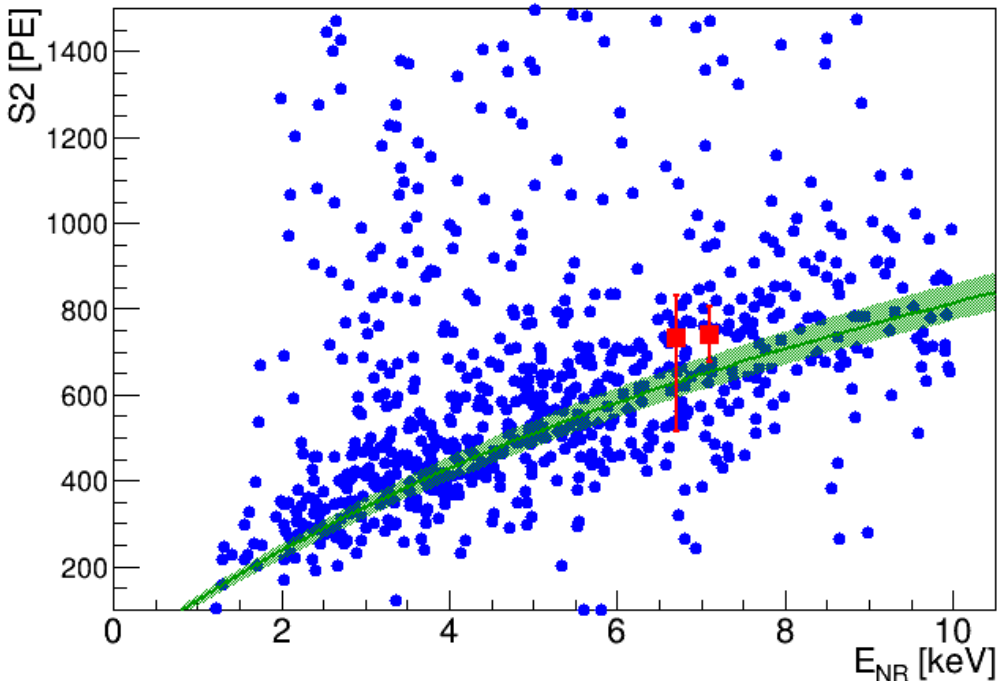




FINAL NUMBER UNDER COLLABORATION REVIEW

The sample of low-energy recoils

- Compare vs. **prediction of the DS-50 model** & literature data
  - Assuming a preliminary ionization gain g_2 = 18 PE/e- for ReD
- Use ReD data as **input to the model fit** to update parameters
  - Will allow for scrutiny of screening models s_n
- Machinery **ready** and tested, **analysis completed**
  - Final Qy vs. E_{NR} measurements down to 2 keV



DS-50 model

Joshi et al. PRL **112** (2014) 171303
Agnes et al. PRD **97** (2018) 112005

Under Collaboration Review, to be released shortly

ReD+

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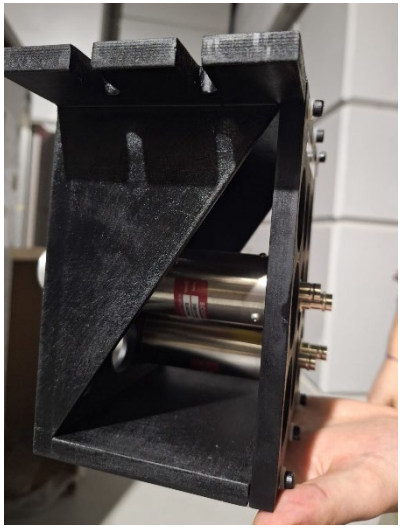
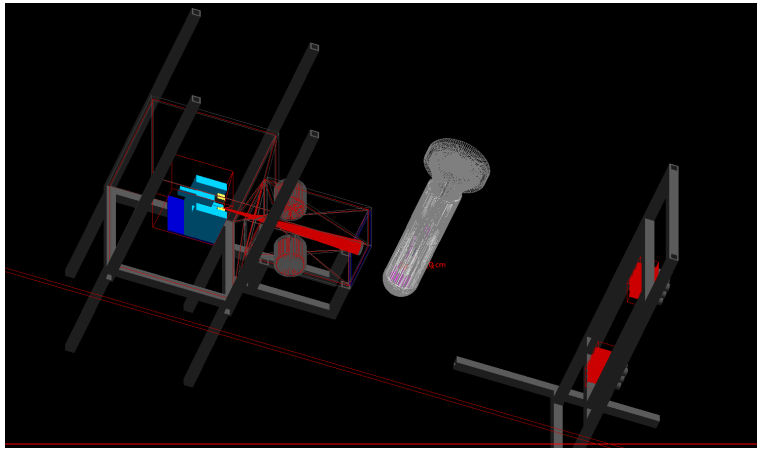
- Future project **ReD+**, funded as a 2-year PRIN project at INFN, Laboratori Nazionali del Sud
- Goal: **improve** and extend coverage of ReD **down to 0.5 keV** using the **same approach** (^{252}Cf source) but optimized components
  - TPC redesigned and being built, SiPM readout
  - Larger neutron spectrometer
- Use the **lessons learnt** from ReD
  - Reduce accidental background
  - Minimize passive volumes
  - MC-driven design
  - Constrain fluctuations of charge yield
- First run in Winter 2025





ReD+

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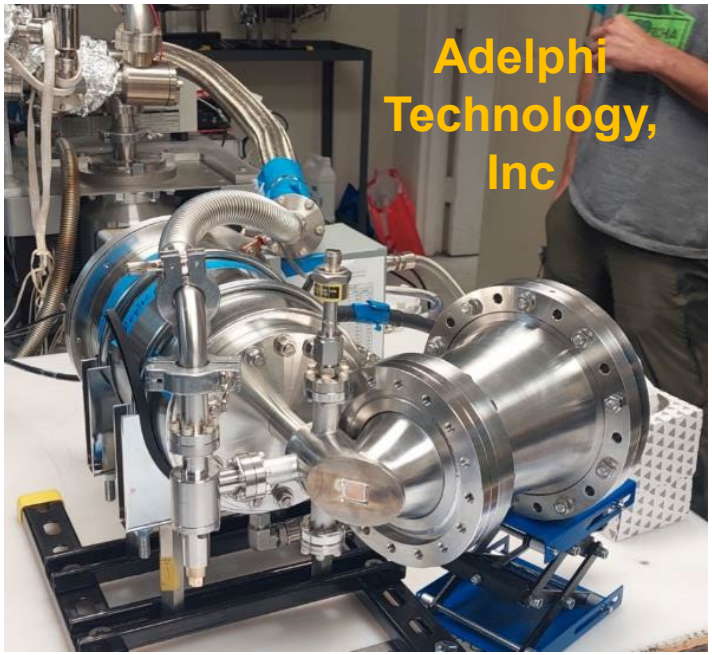
- Irradiate the **same TPC** with neutrons from a **DD generator**
  - Joint project with University of Sao Paulo (FAPESP grant)
- Goal: **improve** down to **0.2 keV**
- **DD-gun**: up to 10^7 n/s of quasi-monochromatic neutrons (2.4 MeV)
  - Commercial (tabletop) device by Adelphi Inc.,
  - Very small x-ray background
  - Delivered to USP in 2024: **being commissioned** now
  - **Neutron tagging** by detecting the accompanying ^{3}He with a Si detector (demonstrated @Adelphi and @USP)
  - Will be shipped to LNS within 2025



Conclusions & perspectives

- ReD measured the **response** of a miniaturized **LAr** dual-phase **TPC** to **O(keV) nuclear recoils** @INFN Catania (2023)
  - Neutrons produced by a ^{252}Cf fission source
  - BaF_2 taggers and neutron spectrometer to detect neutrons scattered off the TPC → two-body kinematics
- **Design sensitivity met**: E_{NR} down to **1-2 keV$_{nr}$**
  - Use the ReD experimental data to evaluate charge yield and constrain screening function models
  - Analysis completed, to be released shortly
- Future: **ReD+ @ LNS**, to cover down to **0.4 keV$_{nr}$** with ^{252}Cf (Italian PRIN funding) and DD neutron gun (Brasilian FAPESP grant)
  - Data talking in late 2025
- Information crucial for **"low-mass WIMP" analysis** of current DM experiments and for the **design** of next-generation

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