CHARACTERIZATION OF LOW-ENERGY ARGON RECOILS WITH THE RED EXPERIMENT

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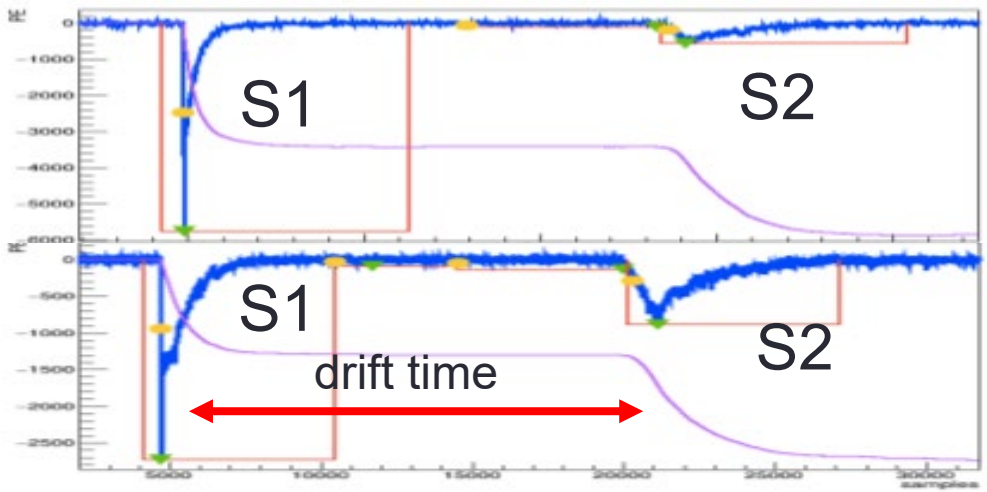
on behalf of the ReD Working Group
(GADM Collaboration)

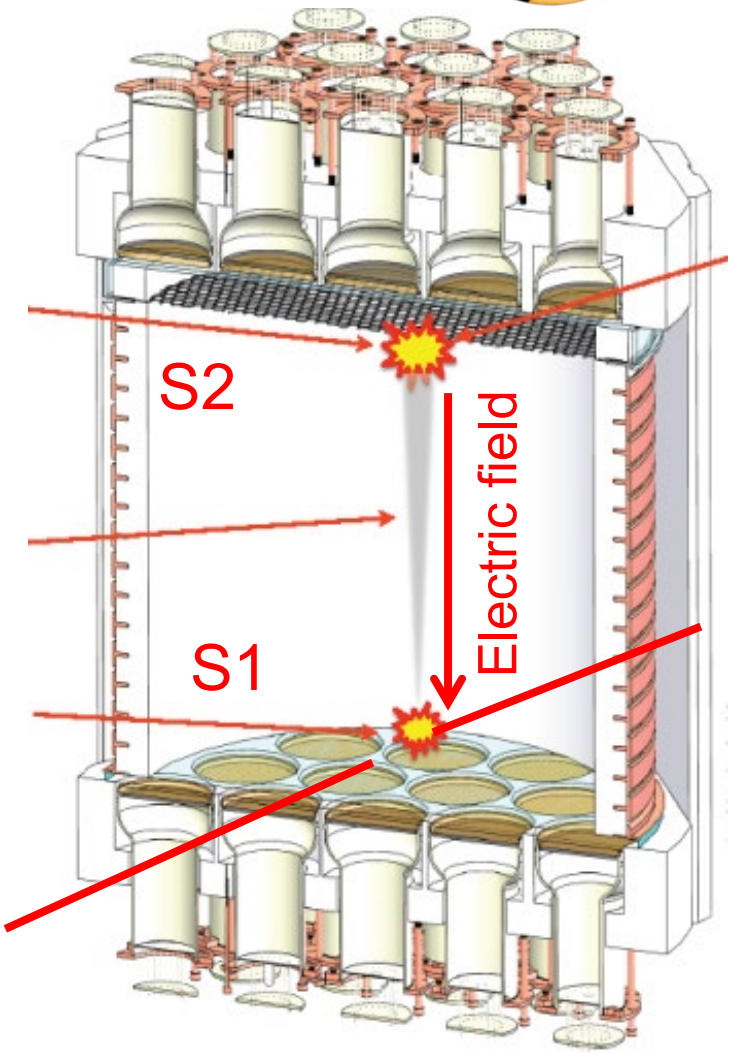
TAUP 2023, Wien
August 29th, 2023

Physics background

- **DarkSide program** at Gran Sasso Laboratory, WIMPs search using 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 SiPM
  - Pave way for next-generation (ARGO)

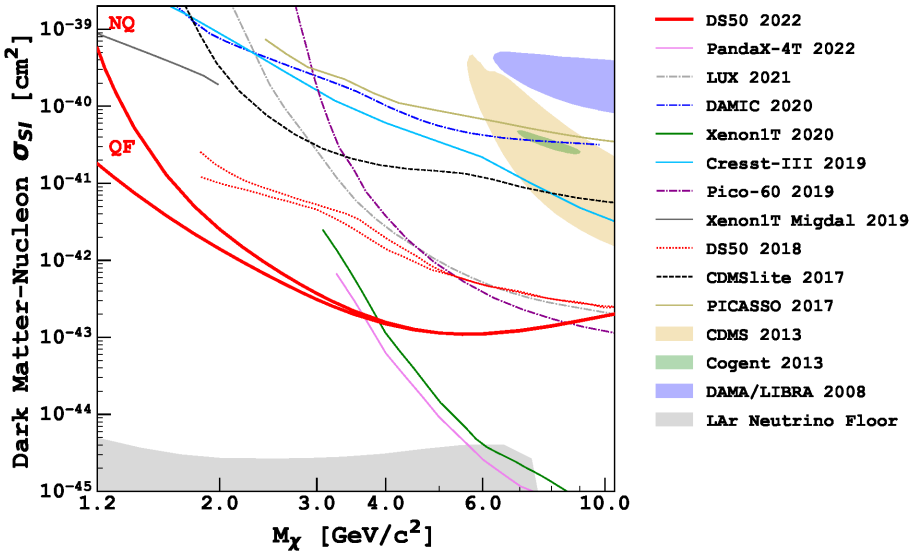
See talk by Y. Wang





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-)
  - DarkSide-LowMass



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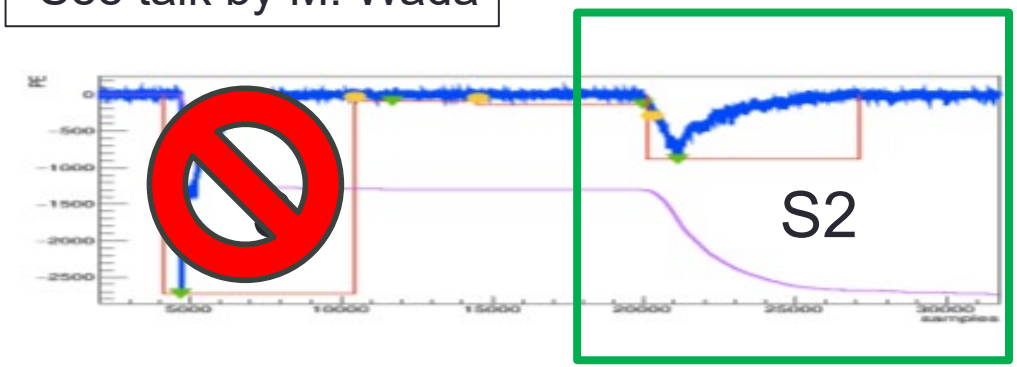
See talk by M. Wada



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

Ar NRs ionisation yield at low energy

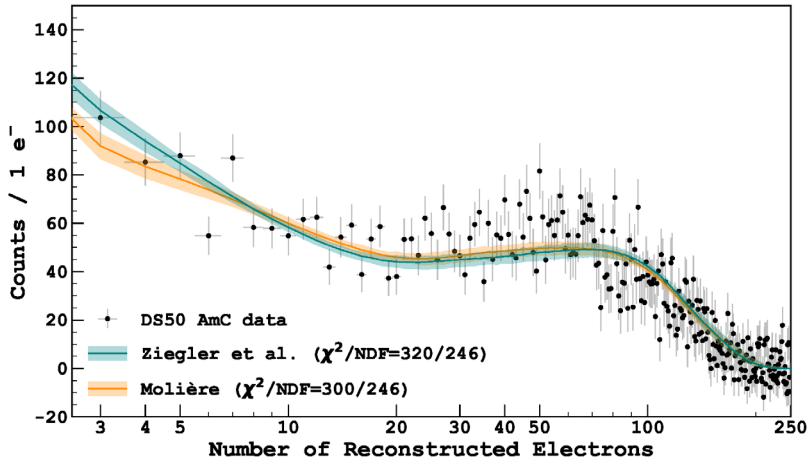
- Measurement within **DS-50**, with AmC and AmBe neutron sources
- Dedicated **2-parameter model**

Thomas-Imel

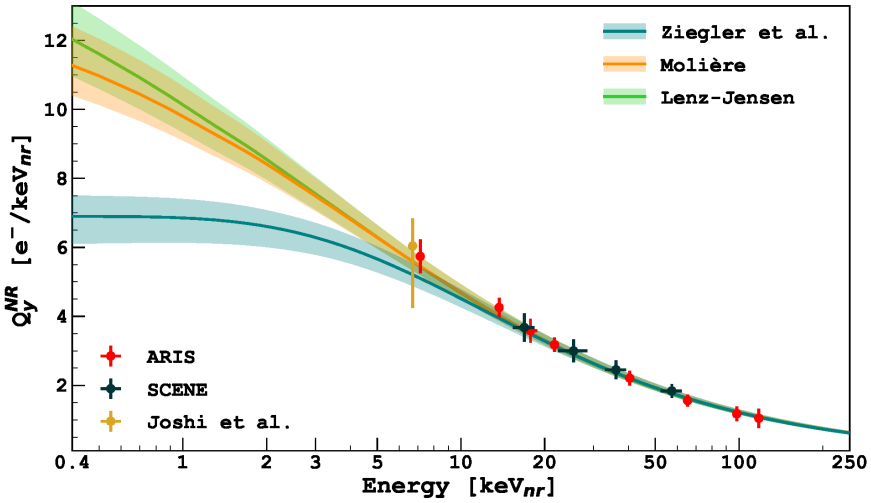
$$1 - r = \frac{1}{\gamma N_i} \ln(1 + \gamma N_i)$$

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

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



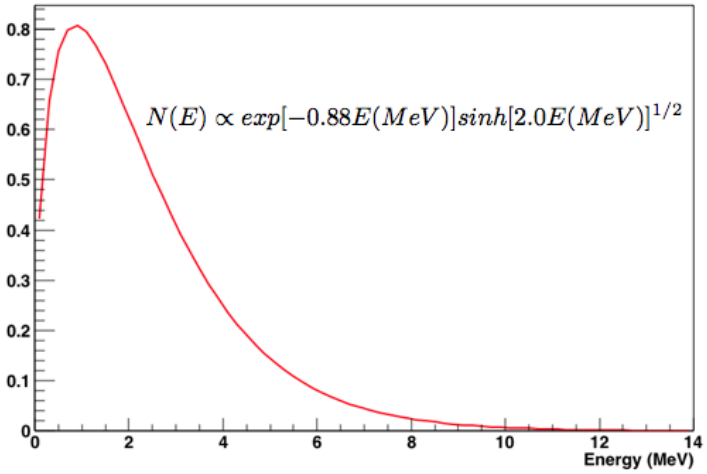
Agnes et al. PRD **104** (2021) 082005



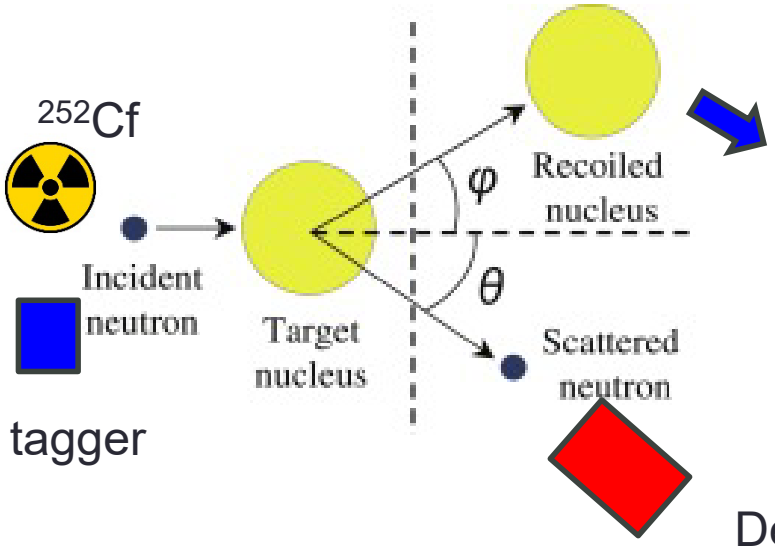
- Different screening models for s_n, possible low-E suppression for s_e
- Constrains only by small low-energy sample from the AmC calibration of DS-50
  - No closed 2-body kinematics
- **Strong case** for a LAr **direct measurement** at **1-5 keV$_{nr}$**

The working principle

- 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 NR of a few keV



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



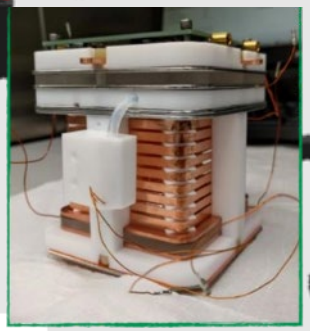
$$E_{NR} = 2KE_{neutron}\frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - cos\theta_{scatt})$$

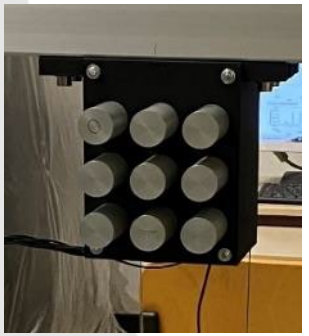
Time of flight

Fixed by geometry

Two-body kinematics!

The ReD conceptual layout

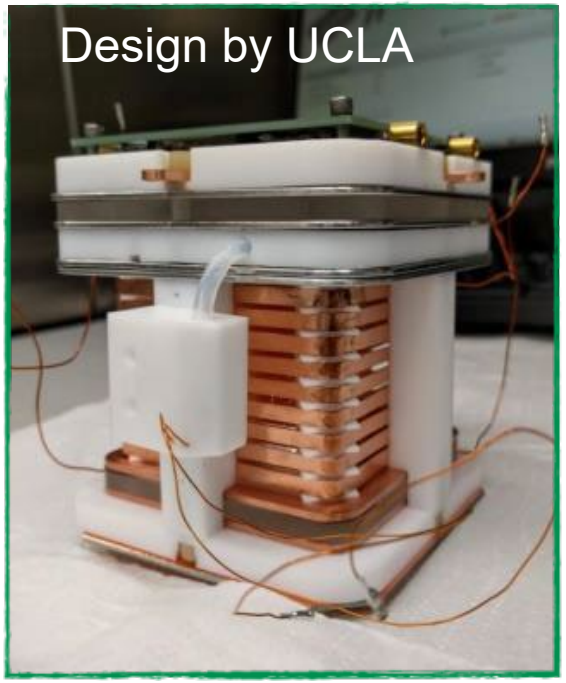




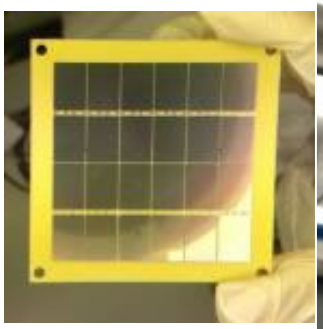
- Design sensitivity in the range **2-5 keV$_{nr}$**

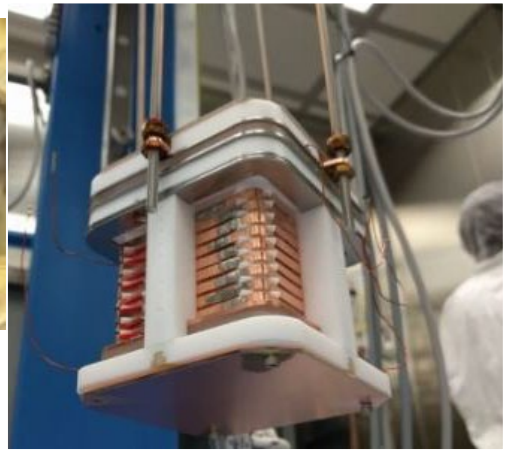
THE INGREDIENTS

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 = ~17 PE/e- (E_{drift} = 200 V/cm, E_{el}=5.79 kV/cm)
  - Electron lifetime > 1 ms





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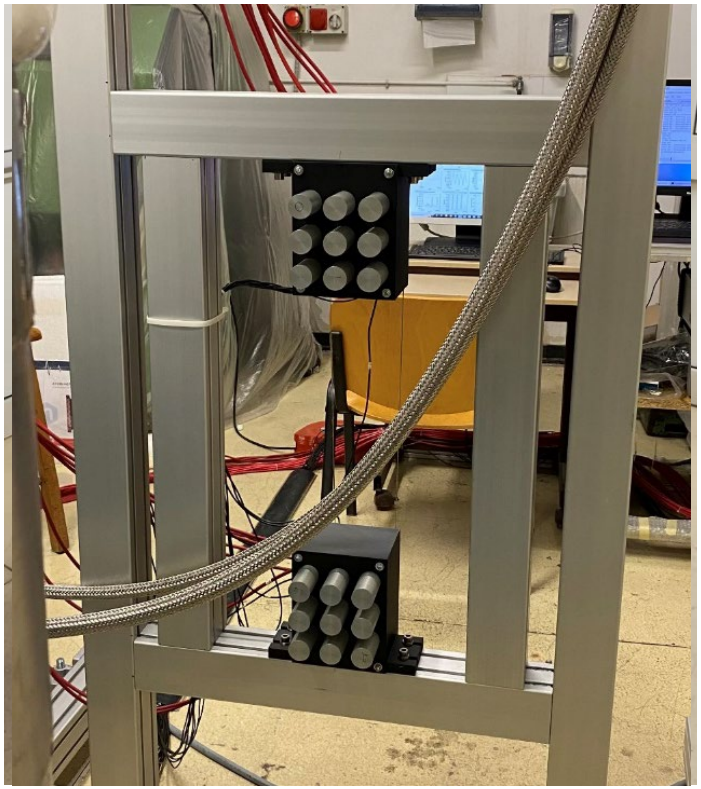
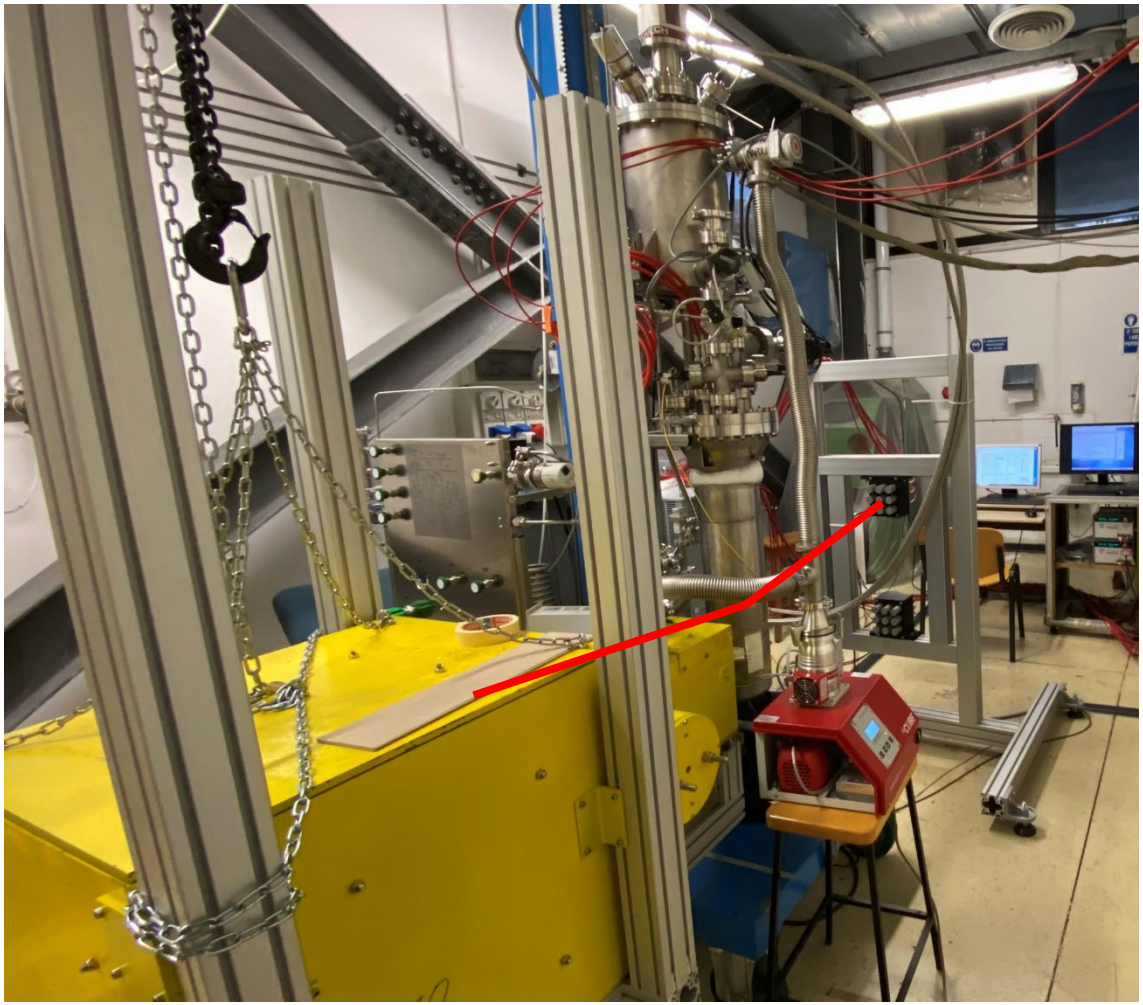
… and all the rest

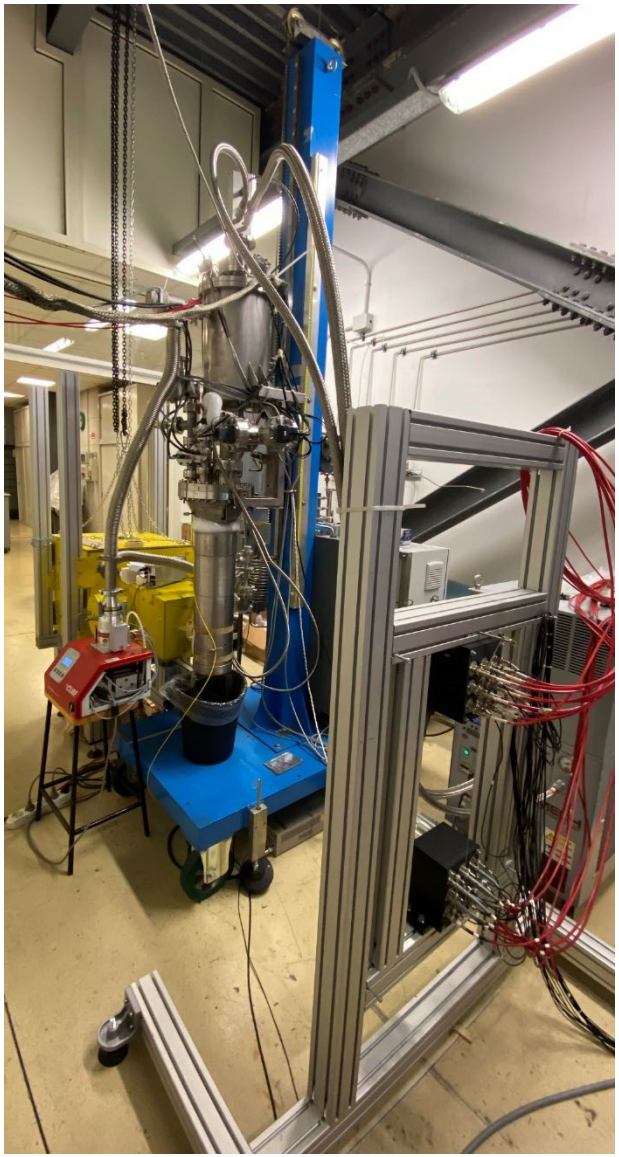
- **^{252}Cf source** (26 kBq fission)
  - Collimator of opening angle ~2°
  - Shines the entire TPC at 1 m distance
- Two **BaF_2 detectors** to tag fission products
  - Fast (high source rate, pile-up)
  - START for time of flight
- **Neutron spectrometer**: two 3x3 arrays of EJ276 **plastic scintillators**
  - 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

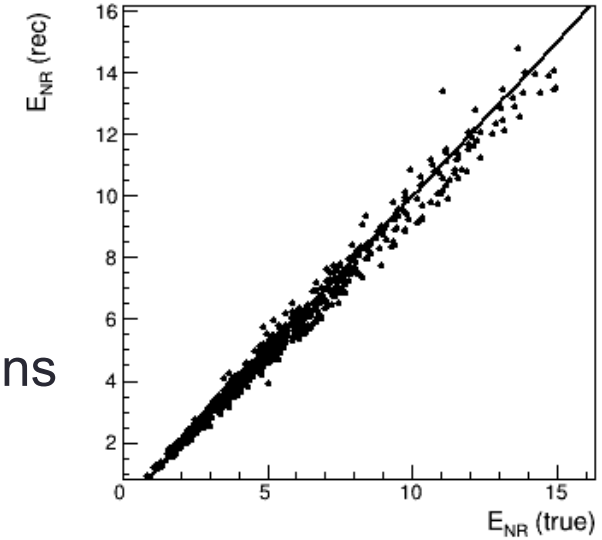


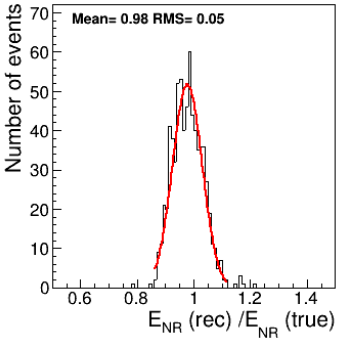


PUTTING EVERYTHING AT WORK

Data taking & Co.

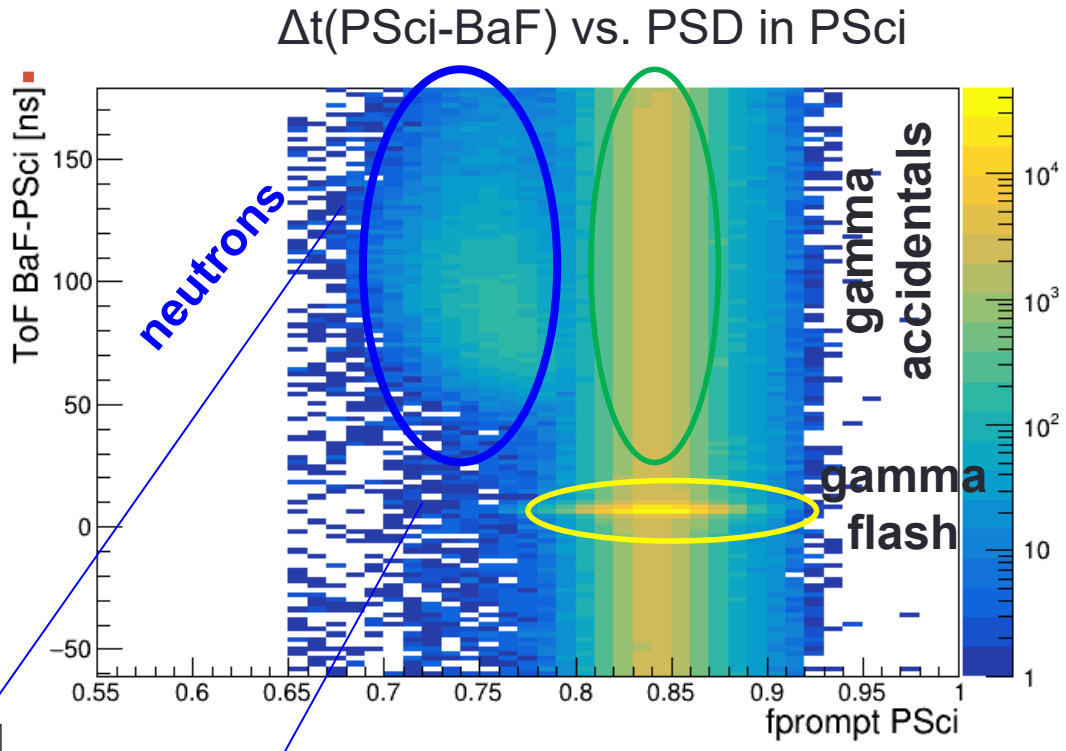
- Data taking with ^{252}Cf from **Jan 10th to Mar 16th, 2023**
  - Event rate **~2.5 Hz**, 80 µs waveforms (600 GB/day)
- Trigger logic: **"any BaF" ∧ "any PSci"**
  - Tagging ~60% of SF events
  - TPC acquired in **slave** mode (may fail to trigger in S1)
- **Weekly calibration** with laser and ^{137}Cs/^{241}Am
  - 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**!

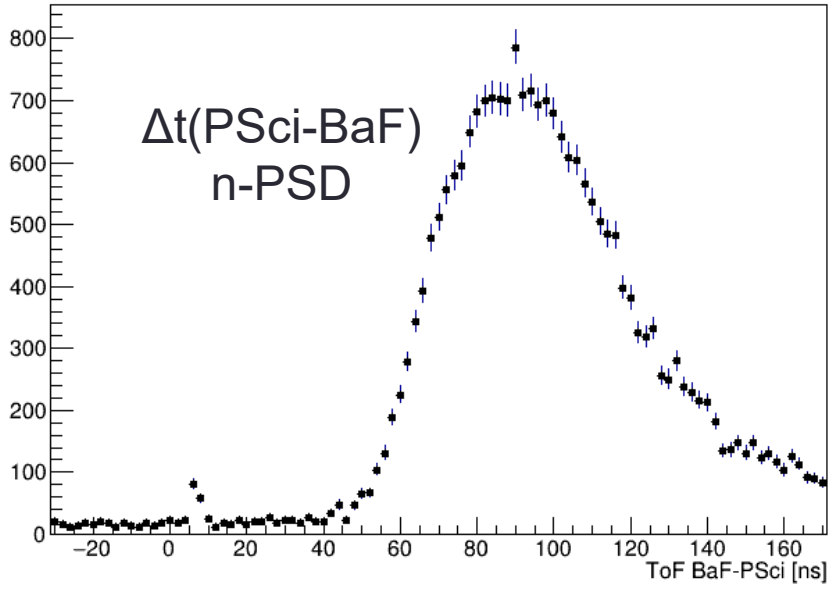


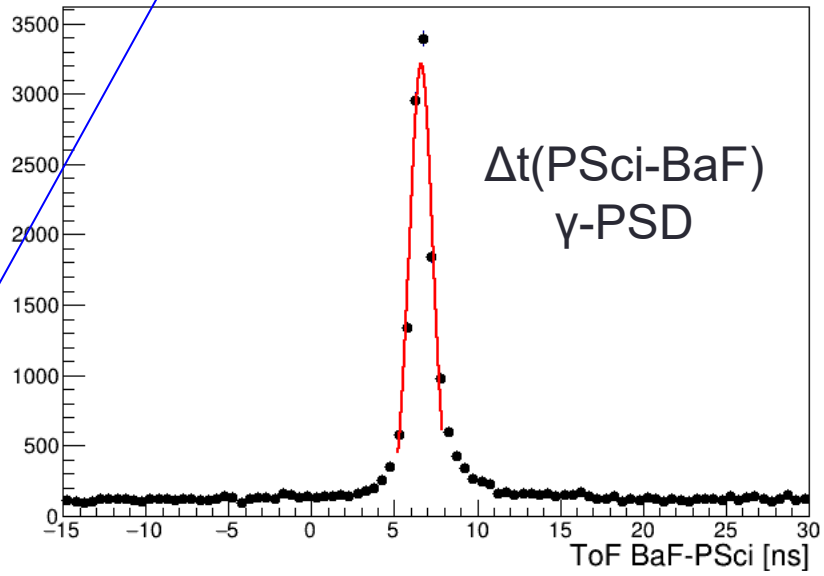


Finding neutrons…

- Event rate dominated by **γ-rays** and **accidentals**
- Selection of candidate neutrons by **time of flight** and **PSD**
  - About 28 events/hour (0.3%)
- ToF resolution **~ 0.7 ns**
- Event-by-event E_n at <5%

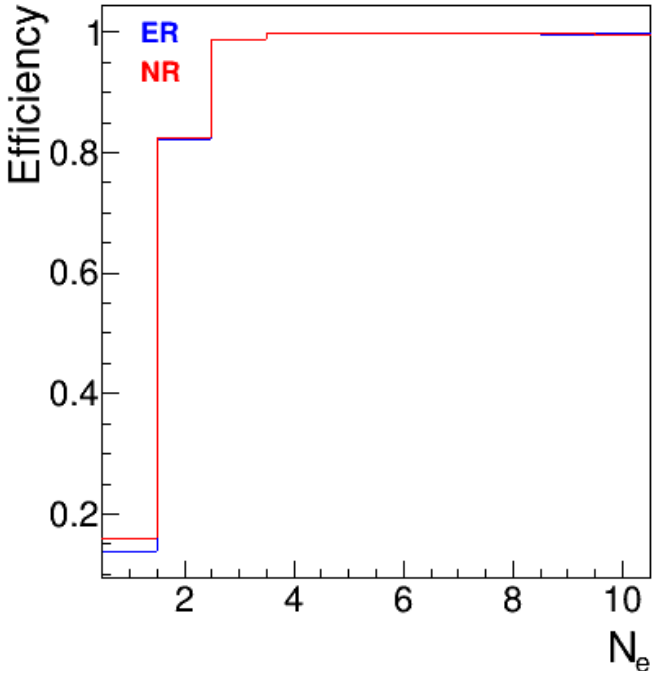


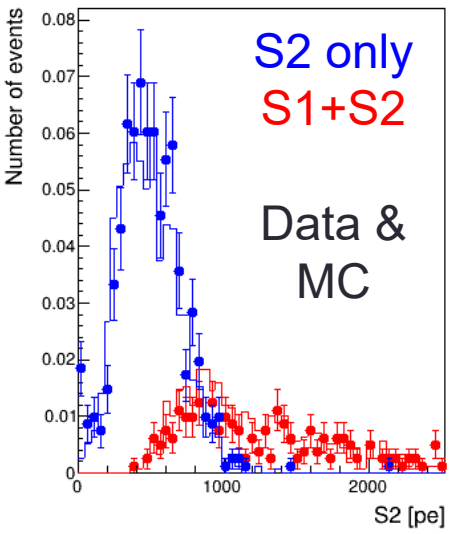


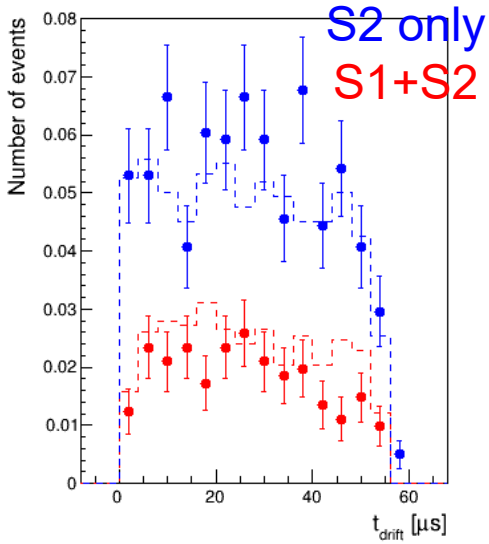


… interacting in the TPC

- 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: **~820** passing all cuts, out of 2300 candidate neutron events w/ TPC signal
  - 75% are S2-only (~ as in MC)
  - Expected: S1~8 PE for 5 keV_{nr}

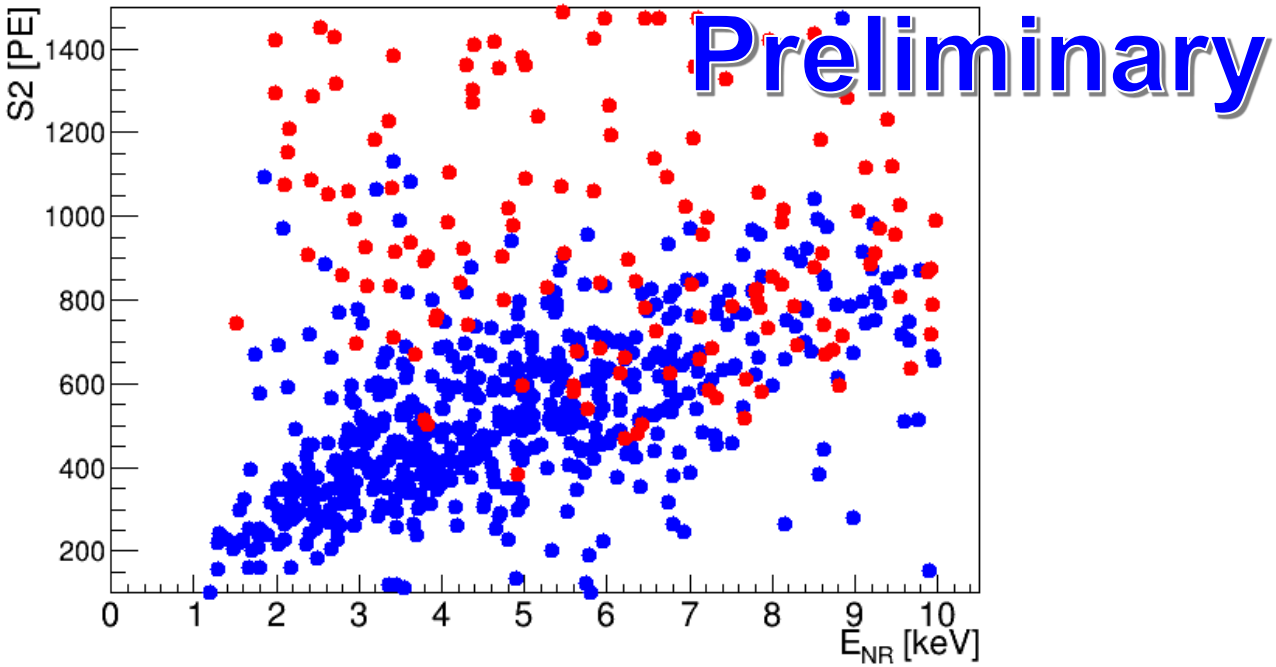


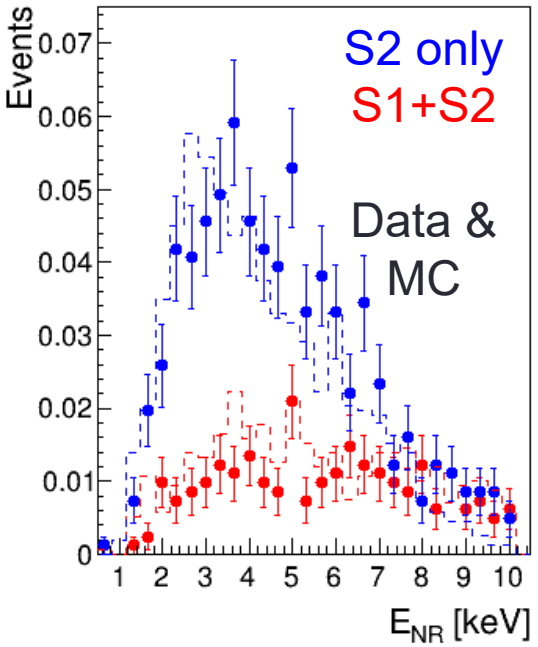




The sample of low-energy recoils

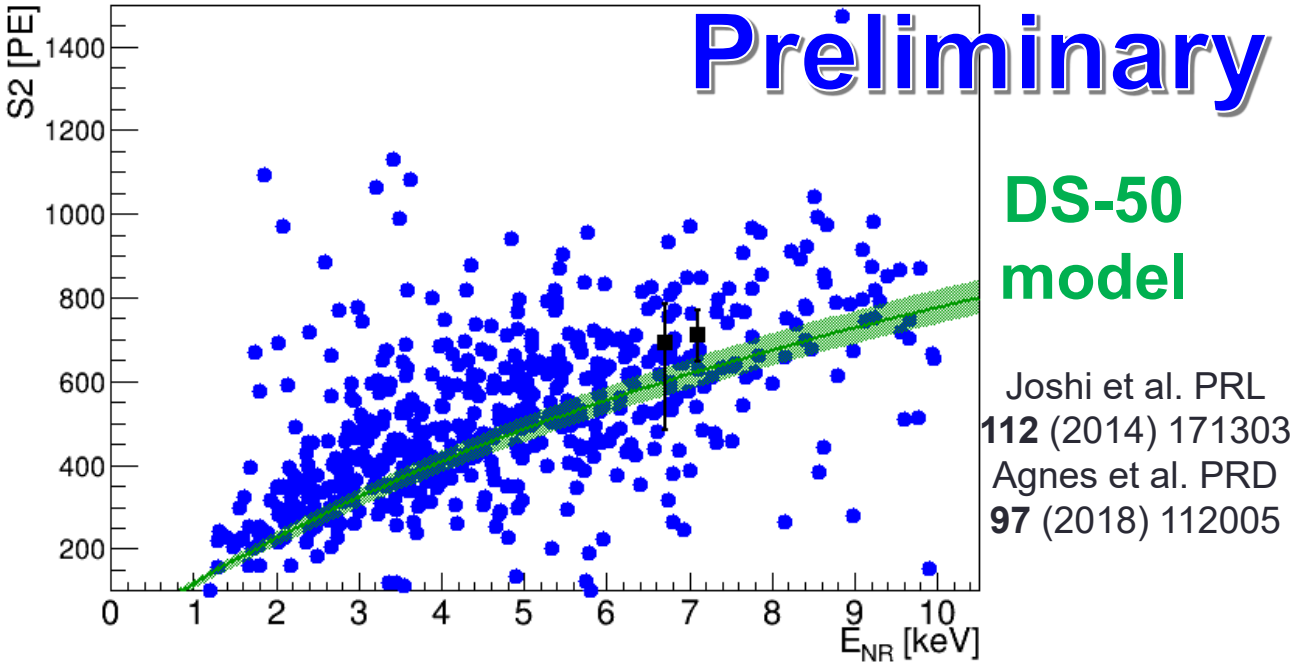
- Get **E_{NR}** from time of flight (and geometry), uncert. **±5%**
- Most S1+S2 outliers: multiple neutron scattering (→ confirmed by MC)

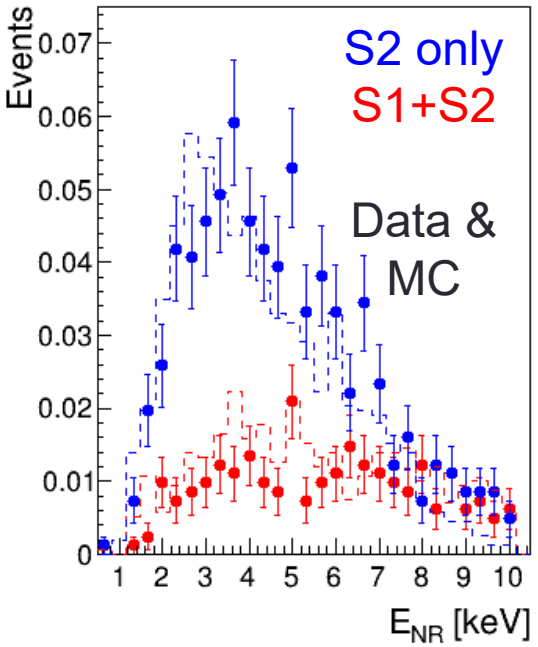




The sample of low-energy recoils

- Get **E_{NR}** from time of flight (and geometry), uncert. **±5%**
- Most S1+S2 outliers: multiple neutron scattering (→ confirmed by MC)
- Using **S2-only**: **E_{NR}** down to **1-2 keV$_{nr}$**
- Compare against **the prediction of the DS-50 model** and literature data, using a **preliminary** value of g_2
  - g_2 = 17.2 PE/e-, based on cross-calibration with DS-50
  - Work in progress to infer g_2 directly from ReD data





Conclusions and outlook

- ReD measured the **response** of a miniaturized **LAr** dual-phase **TPC** to **O(keV) nuclear recoils** @INFN Catania (Jan-Mar 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
  - Complemented by a full Monte Carlo simulation
- **Design sensitivity met**: E_{NR} down to **1-2 keV$_{nr}$**
  - Next step: use the ReD experimental data to **constrain** the parameters in the DS-50 ionization model (fit of data against MC distributions)
- Future: **ReD+**, to cover down to **0.4 keV$_{nr}$** with ^{252}Cf (Italian PRIN funding) and DD neutron gun (Brasilian FAPESP grant)
- Information crucial for **"low-mass WIMP" analysis** of current DM experiments and for the **design** of next-generation