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+

L. Pandola (LNS)
on behalf of the ReD Working Group
(GADM Collaboration)

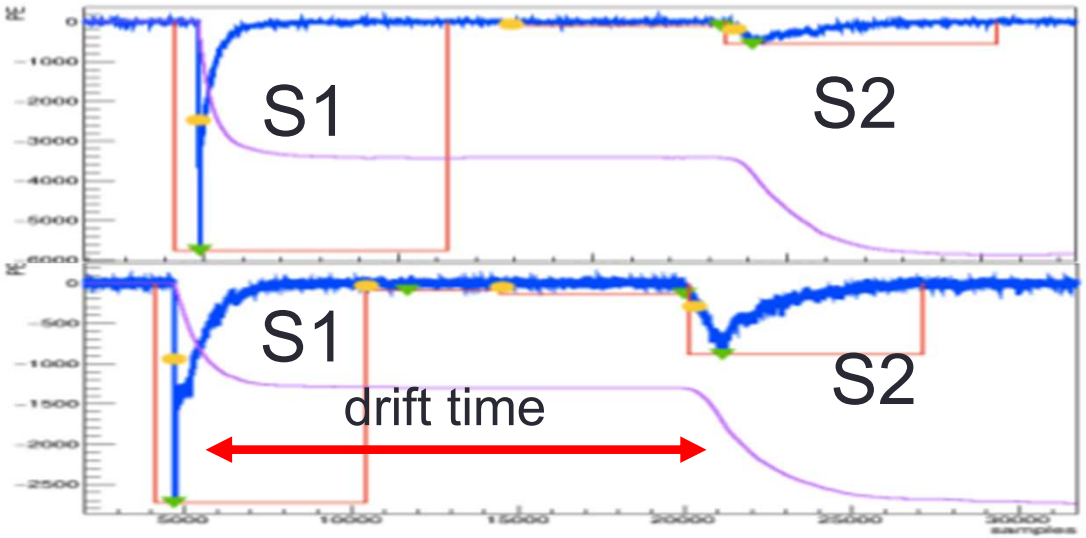
INFN LNS

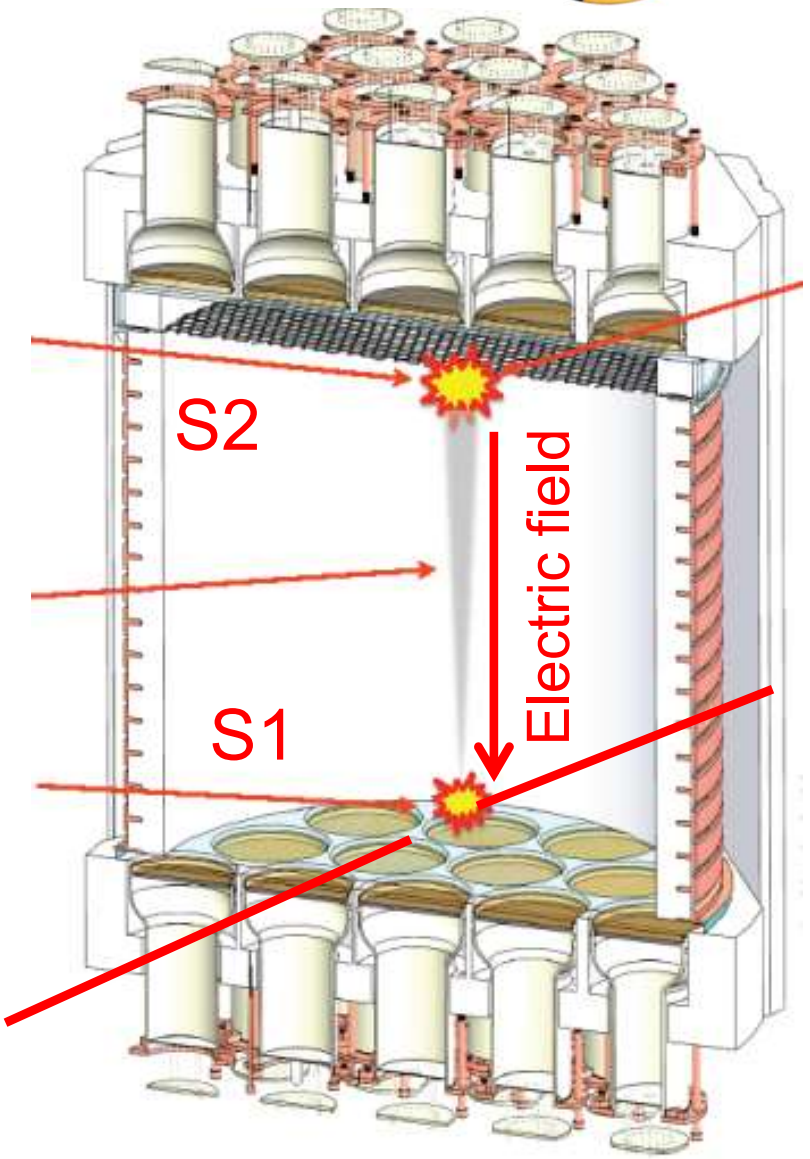
IDM 2024, L'Aquila
July 11th, 2024

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)

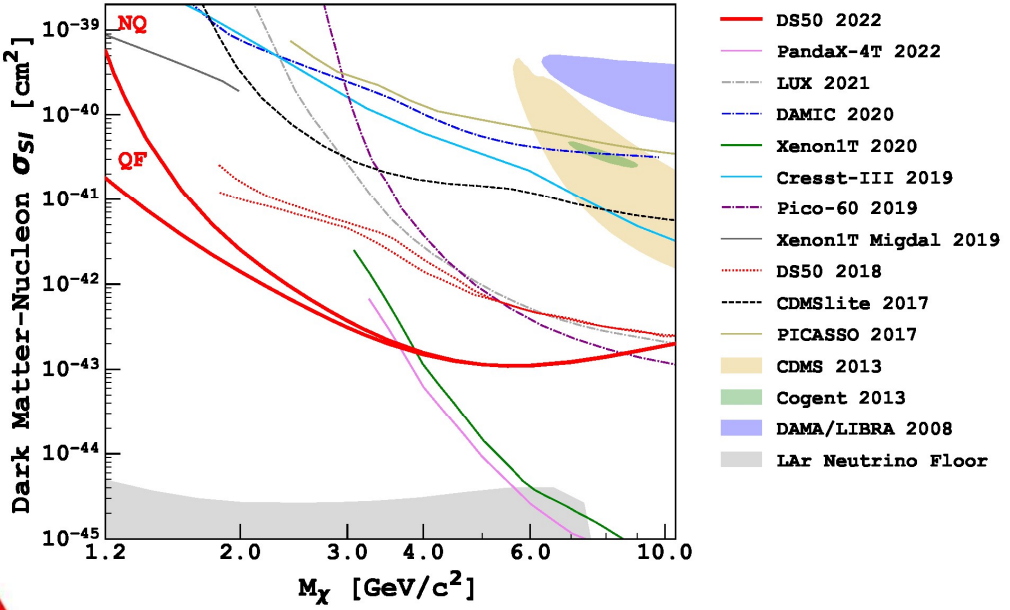
→ Talk by I. Ahmad





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 ➡ Talk by M. van Uffelen
- 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-)
- Analysis sensitive to **ionization yield** for keV NRs
  - **Poorly known** for Ar (data at ~6 keV)



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

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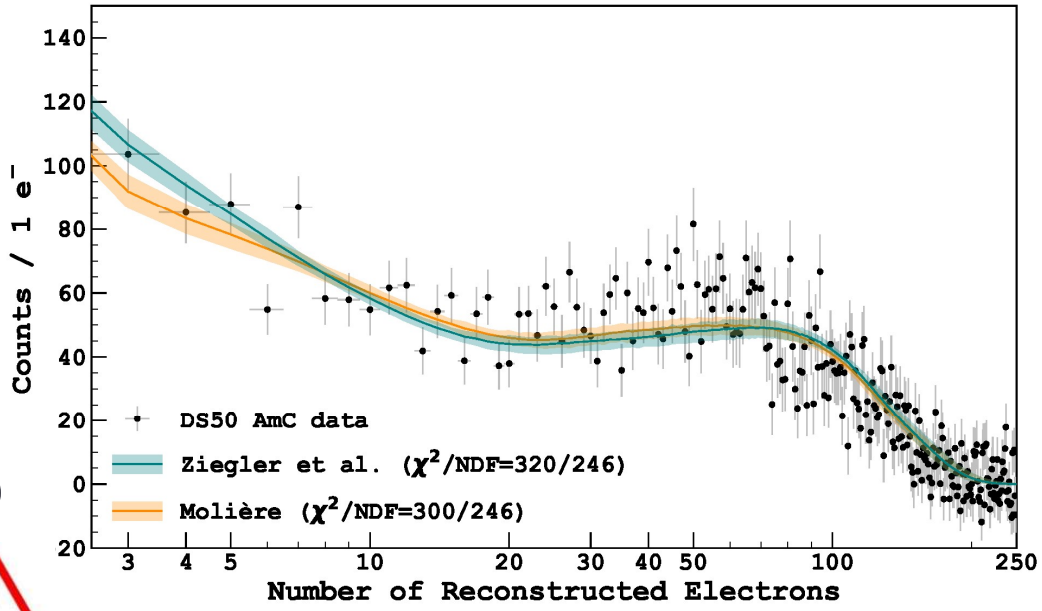
- Measurement within **DS-50**, with AmC and AmBe neutron sources
  - Custom 2-parameter model
  - Constrains from small low-energy sample from the AmC calibration

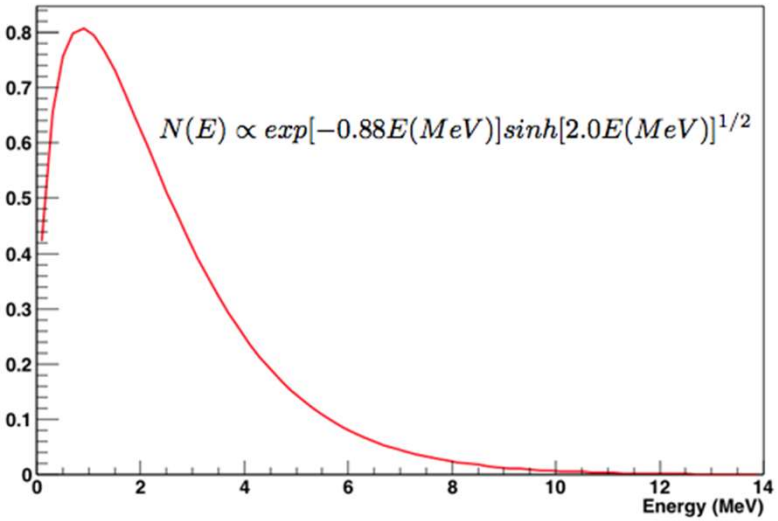


Agnes et al. PRD **104** (2021) 082005

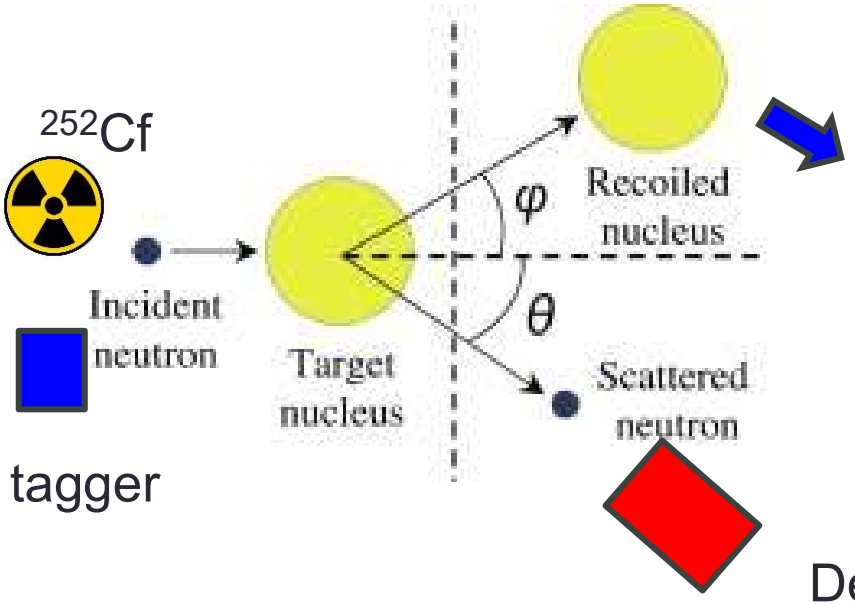
- No closed 2-body kinematics
- **Strong case** for a LAr **direct measurement** at **2-5 keV$_{nr}$**

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 recoils of a few keV



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



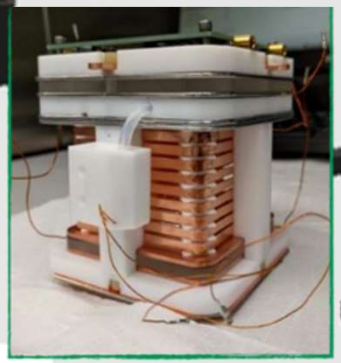
$$E_{NR} = 2KE_{neutron}\frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - cos\theta_{scatt})$$

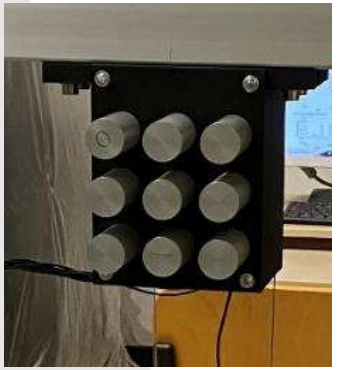
Time of flight

Fixed by geometry

Two-body kinematics!

The ReD conceptual layout

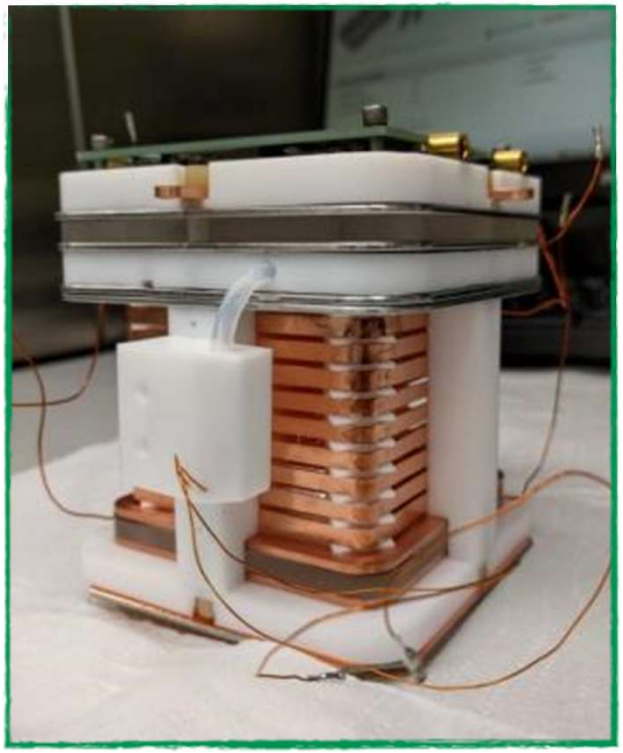




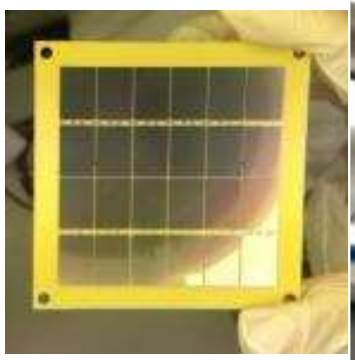
- Design sensitivity in the range **2-5 keV$_{nr}$**

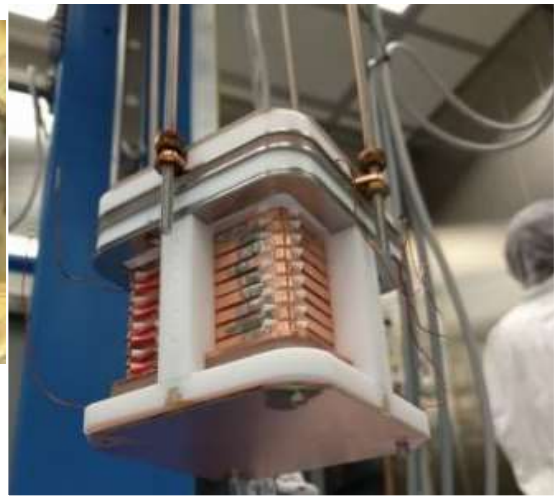
THE INGREDIENTS

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 cm^2 SiPM**, 24x1cm^2 SiPM
  - 24 ch readout (top), for increased (x,y) resolution
  - 24x1cm^2 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





Agnes et al. EPJ C **81** (2021) 1014

… 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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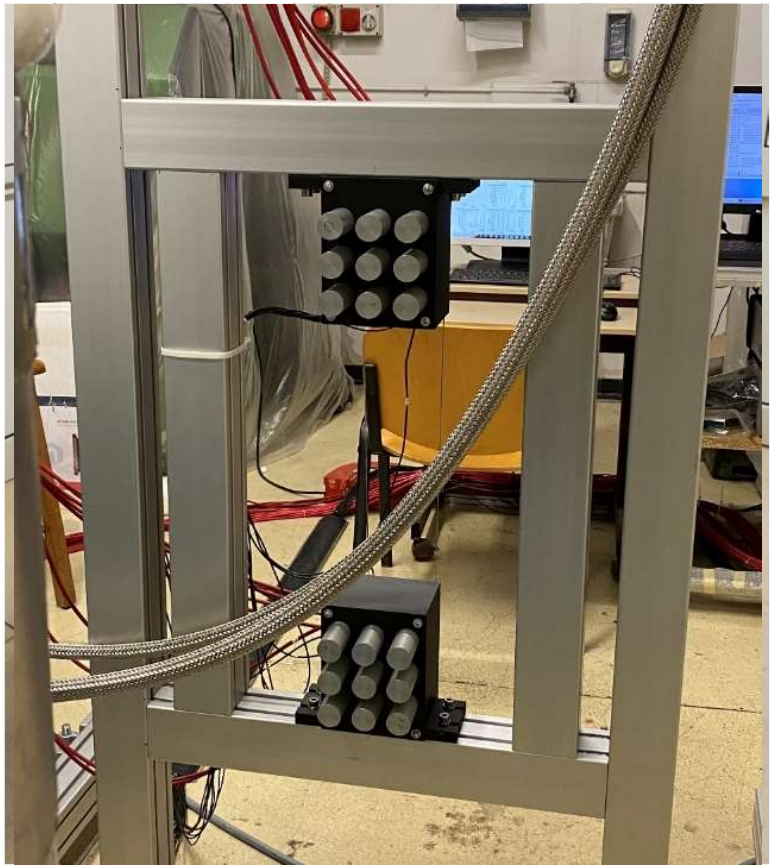
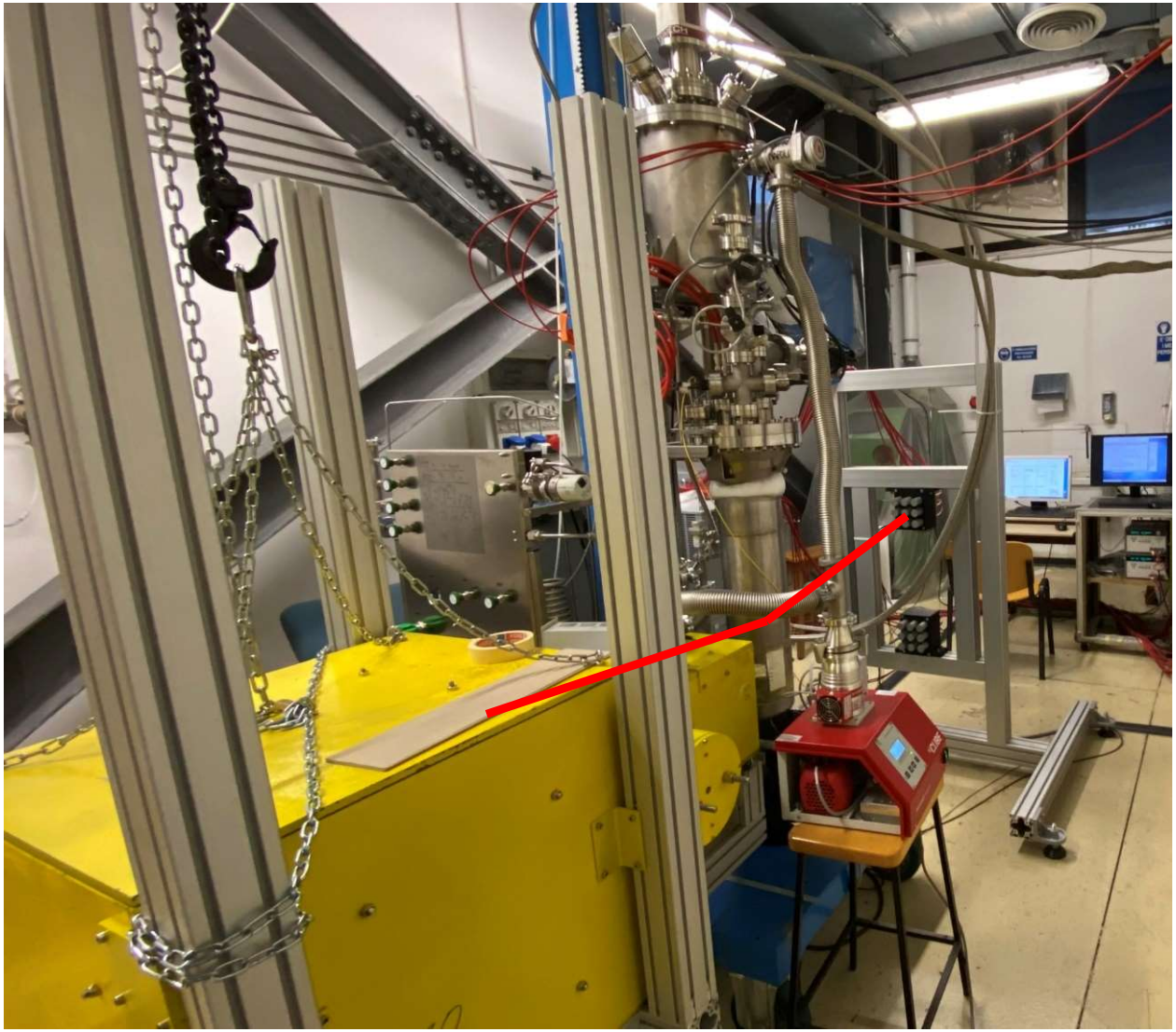
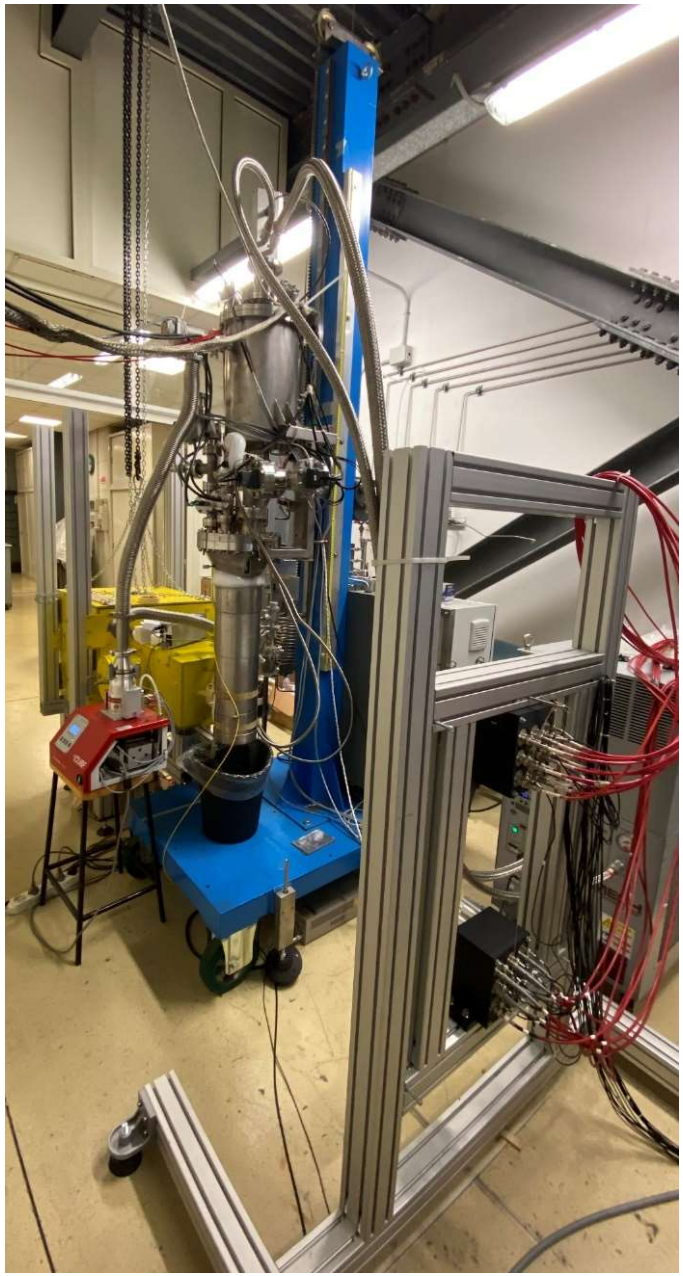
  - Fast (high source rate, pile-up)
  - START for time of flight
- **Neutron spectrometer**: two 3x3 arrays of EJ276 **plastic scintillators**
  - STOP for time of flight
  - Features n/γ discrimination
  - 1 m downstream the TPC
  - Symmetric deployment to control systematics due to alignment
  - **θ ~ 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

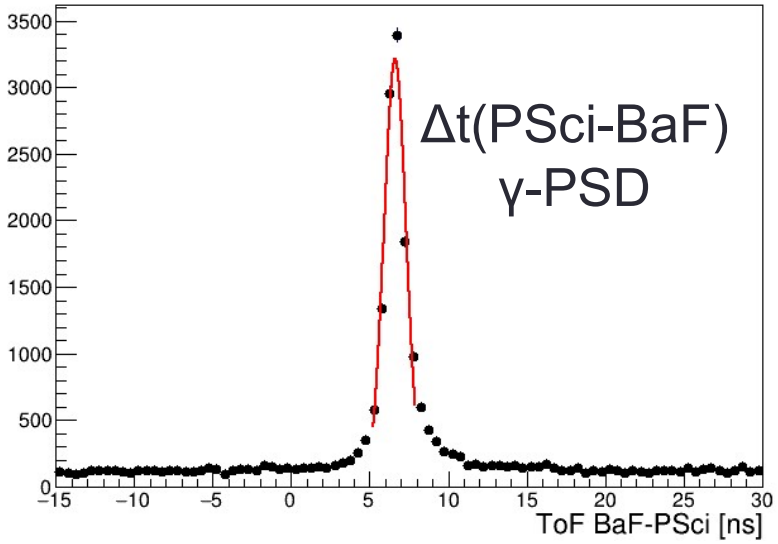


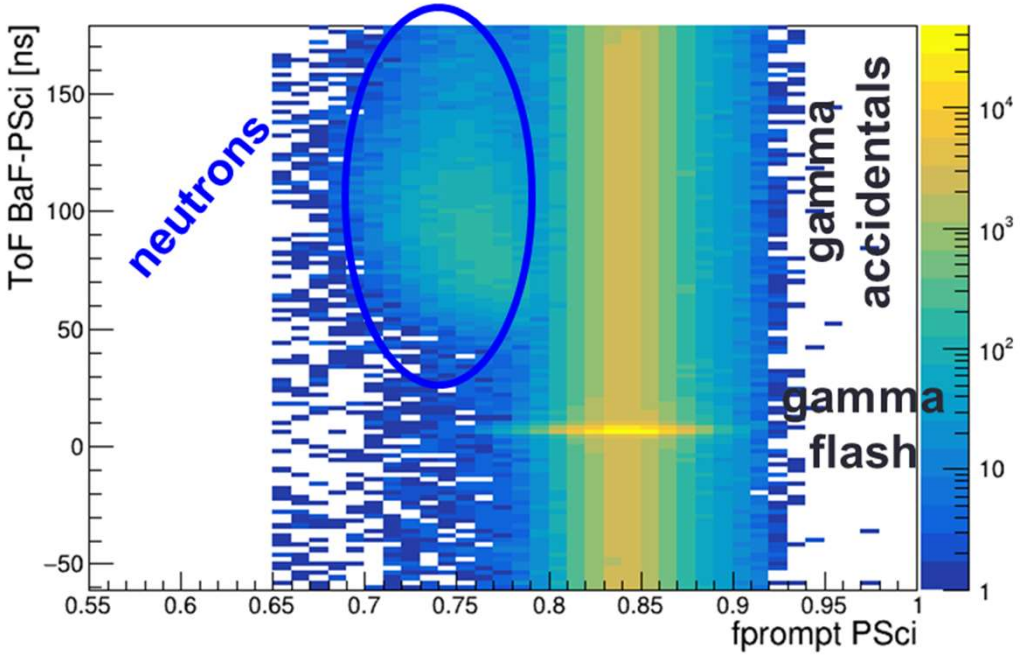


PUTTING EVERYTHING AT WORK

Data taking: finding neutrons…

- Data taking with ^{252}Cf from **Jan to Mar, 2023**
- Trigger logic: **"any BaF" ∧ "any PSci"**
  - Tagging ~60% of SF events
  - TPC acquired in **slave** mode (may fail to trigger in S1)
  - 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**





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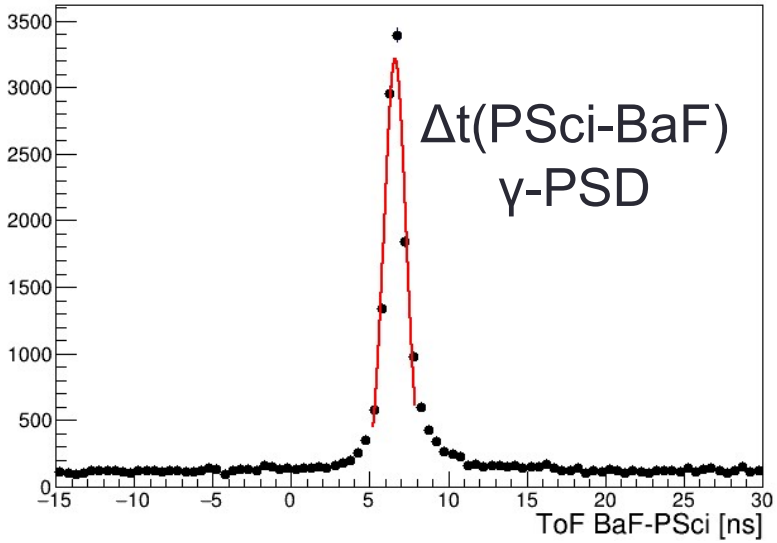
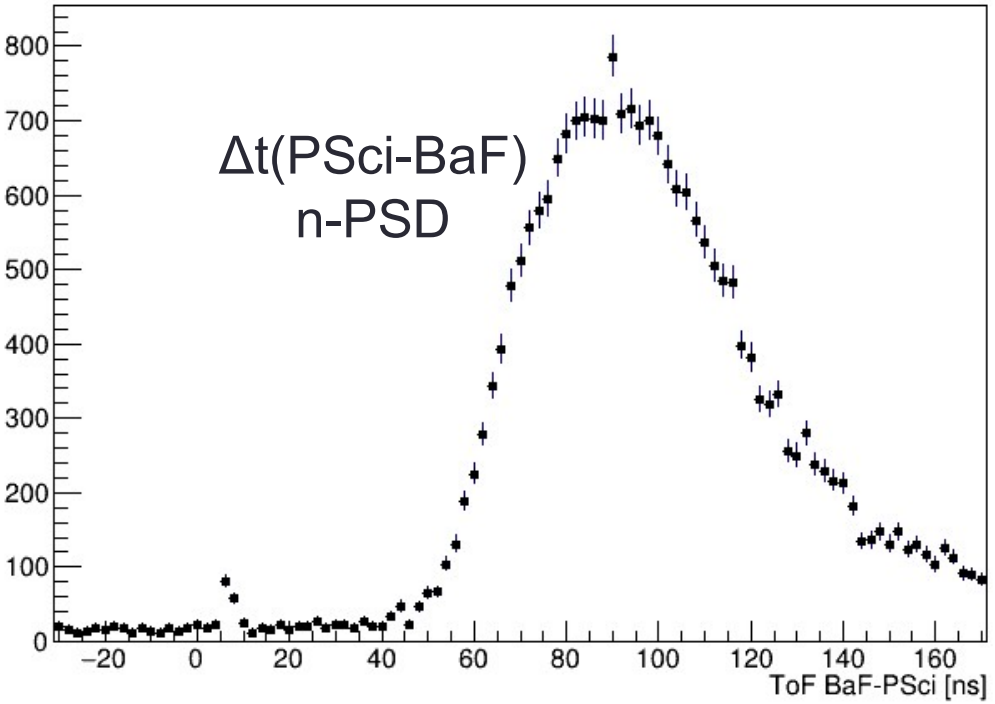
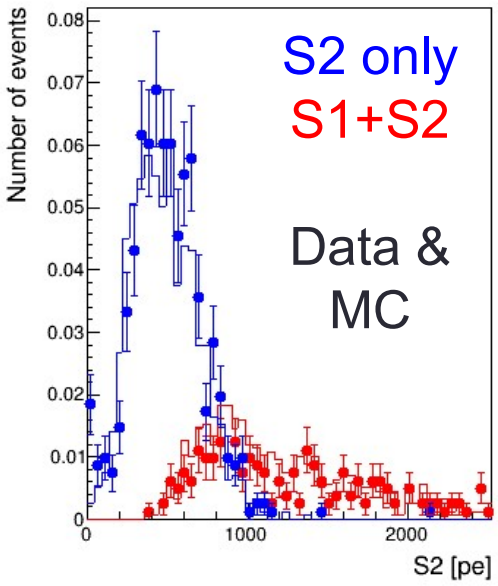
- Event-by-event E_n at <5%



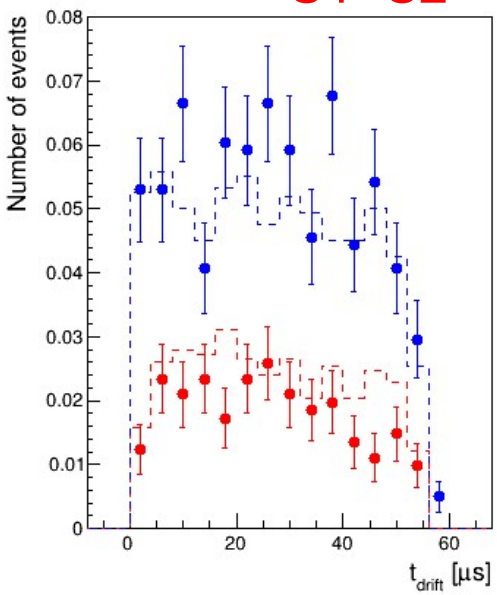


… interacting in the TPC

- 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}
  - From MC, most S1+S2 are expected to be multiple neutron scattering (→ no kinematic correlation)

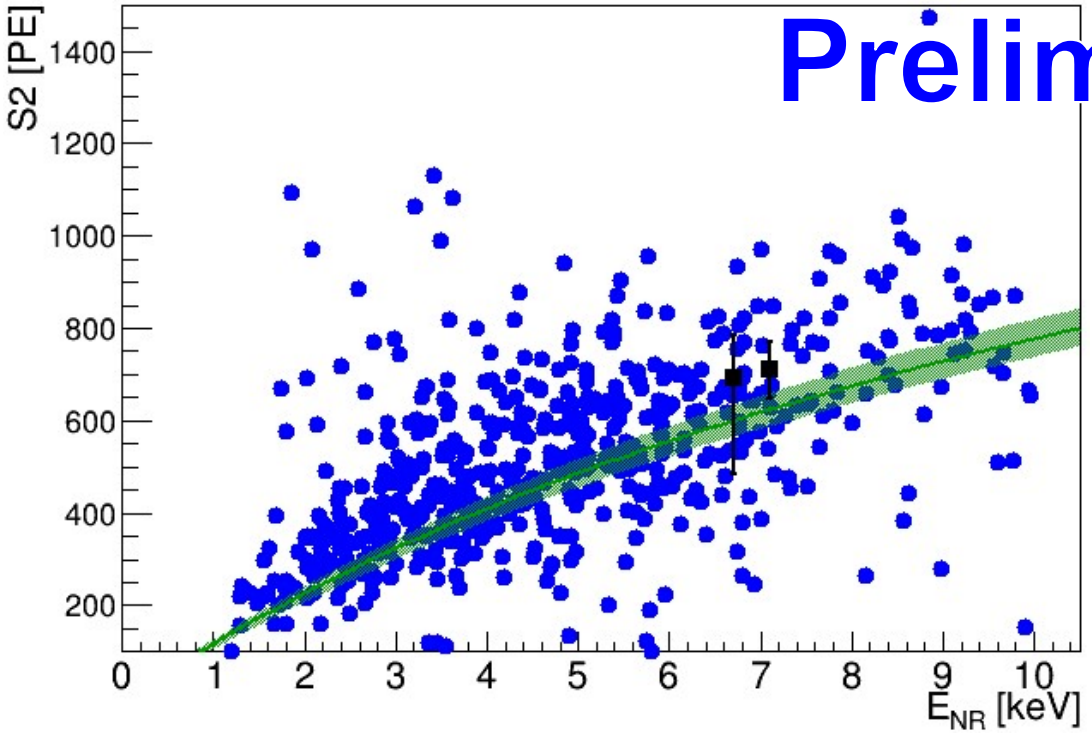


S2 only
S1+S2



The sample of low-energy recoils

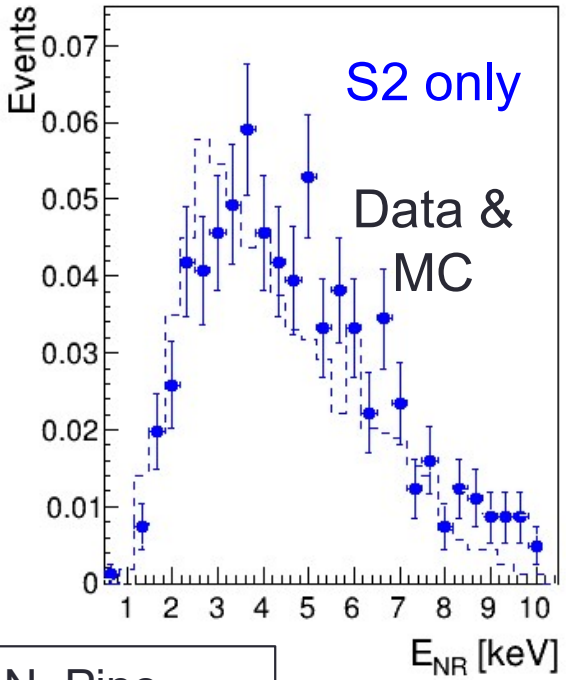
- Get **E_{NR}** from time of flight (and geometry), uncert. **±5%**
- Using **S2-only**: E_{NR} down to **1-2 keV$_{nr}$**
- Compare against **the prediction of the DS-50 model** and literature data, using a **preliminary** value of g_2
  - g_2 = 17.2 PE/e-, based on cross-calibration with DS-50
  - Work in progress to infer g_2 directly from ReD data
- Next: evaluate absolute **charge yield** and **constrain model**



Preliminary

DS-50 model

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



Poster by N. Pino

ReD+

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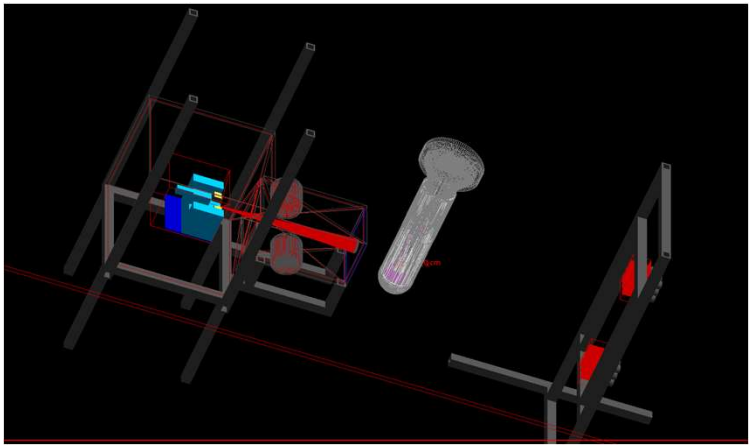
- Future project **ReD+**, funded as a 2-year PRIN project at INFN, Laboratori Nazionali del Sud
- Goal: **improve** and extend coverage of ReD **down to 0.4 keV** using the same approach (^{252}Cf source) but optimized components
  - TPC being redesigned and built, SiPM readout
  - Larger neutron spectrometer
  - Use the lessons learnt from ReD
    - Reduce accidental background
    - MC campaign in progress
  - Constrain fluctuations of charge yield
- Timeline: **Oct 2023-Oct 2025**
  - Will follow up into the activity 3.2.G1 of DRD2



ReD+

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- In addition, irradiate the same TPC with 2.4-MeV mono-energetic neutrons from a **DD generator**
  - Joint project with University of Sao Paulo (FAPESP grant)
  - Delivered to USP in June 2024: it will be commissioned and shipped to LNS
- Comparable **timelines** for the two projects

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$_{nr}$**
  - Next step: use the ReD experimental data to evaluate charge yield and constrain models
- Future: **ReD+ @ LNS**, to cover down to **0.4 keV$_{nr}$** with ^{252}Cf (Italian PRIN funding) and DD neutron gun (Brasilian FAPESP grant)
  - Optimized new TPC
  - Data talking in late 2025
- Information crucial for **"low-mass WIMP" analysis** of current DM experiments and for the **design** of next-generation