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

CHARACTERIZATION OF ARGON RECOILS AT THE KEV SCALE WITH RED AND RED+

L. Pandola (LNS)

on behalf of the ReD Working Group

(GADM Collaboration)

INFN LNS

LIDINE2025, Hong Kong, SAR, China

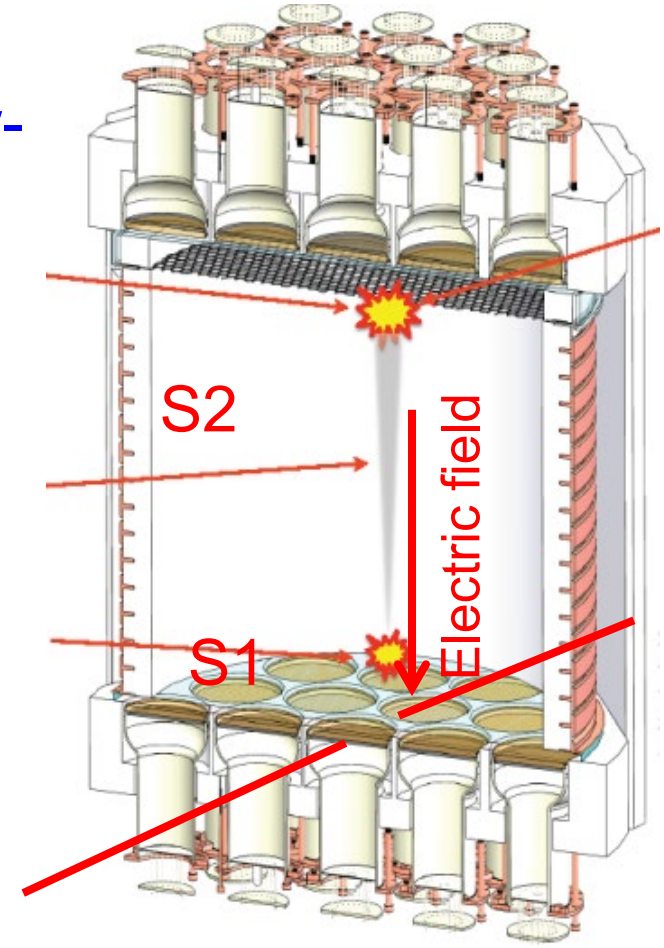
October 21st, 2025

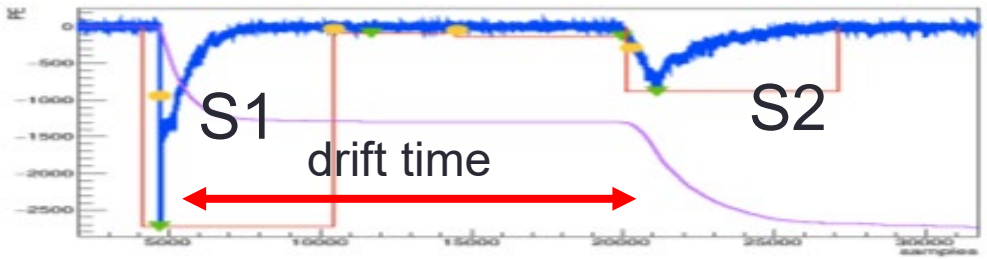
DARKSIDE

REcoil Directionality

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**)





Talks by A. Jamil, M. Walczak, P. Salomone, G. Matteucci, D. Rudik, S. Tullio, …

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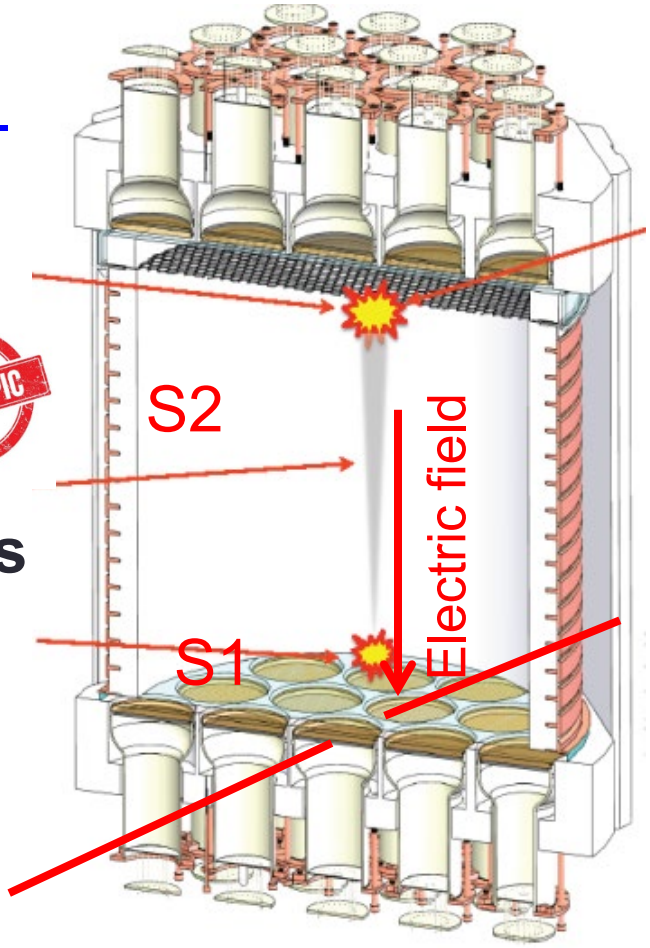
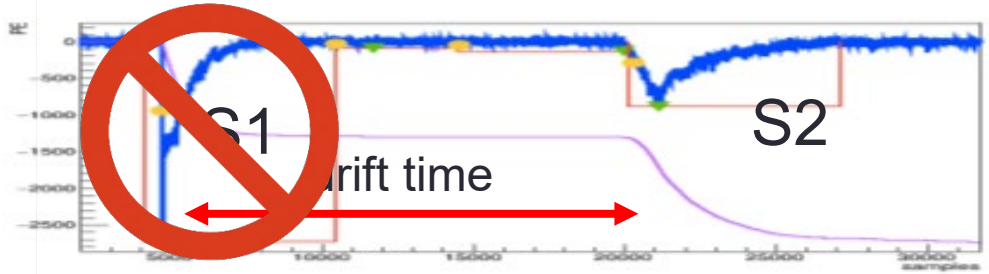
    - Novel light readout with SiPM
  - Pave way for next-generation (**ARGO**)
- Technology sensitive to **low-mass WIMPs**
  - A few GeV instead of the "standard" 100's GeV
  - Slower recoil, O(1 keV) instead of 20-100 keV
  - **Challenging!** S1 too small, S2-only





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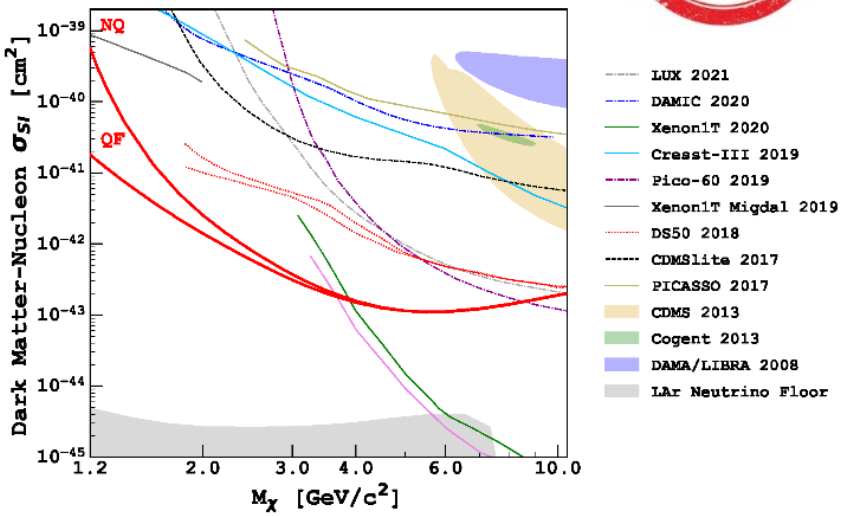
The search for low-energy WIMPs

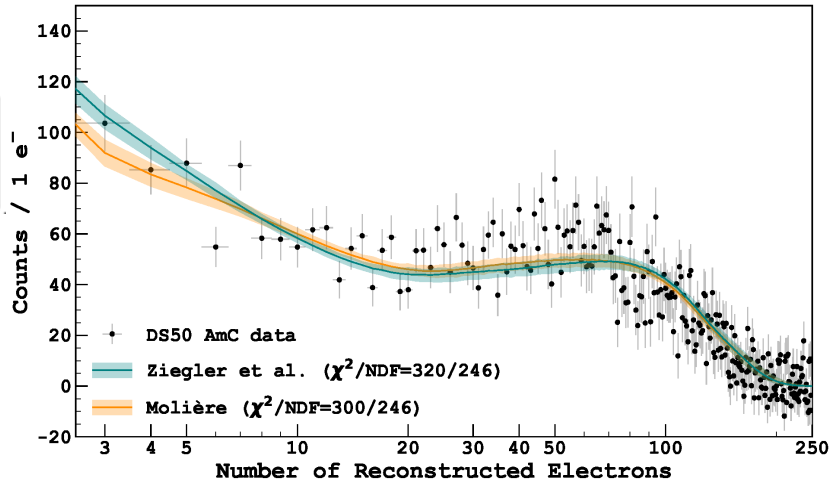
- Analysis sensitive to **ionization yield** for keV NRs
  - **Poorly known** for Ar (data at ~7 keV)
- Measurement within **DS-50**, with AmC and AmBe neutron sources
  - Combined fit with direct measurements (ARIS, SCENE)
  - Constraints from small low-energy sample from the AmC calibration
  - Custom 2-parameter model based on Thomas-Imel box

$$f_q(E_{nr}) = \frac{F}{E_{nr}\, C_{\text{box}}} \ln\left[1 + \frac{C_{\text{box}}}{F} \cdot \beta \cdot \frac{\epsilon(E_{nr})\, s_e(\epsilon)}{s_e(\epsilon) + s_n(\epsilon)}\right]$$



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

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



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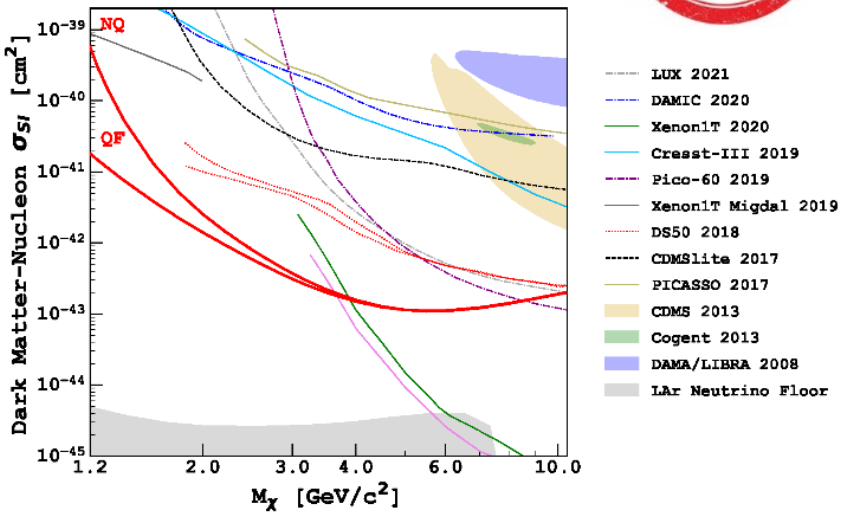
- Different screening models for s_n
- **Strong case** for a LAr **direct measurement** at **1-5 keV**



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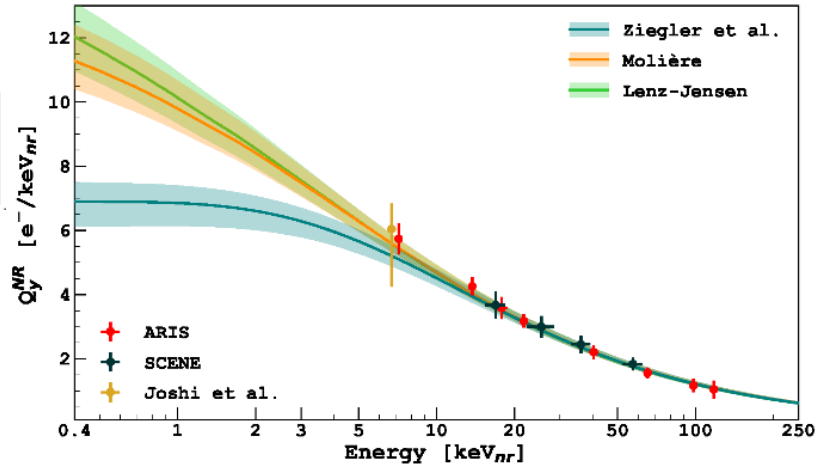
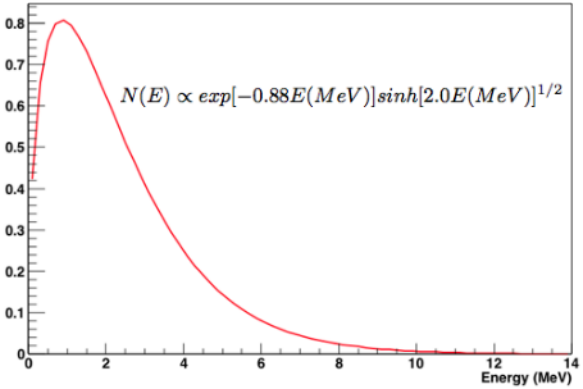


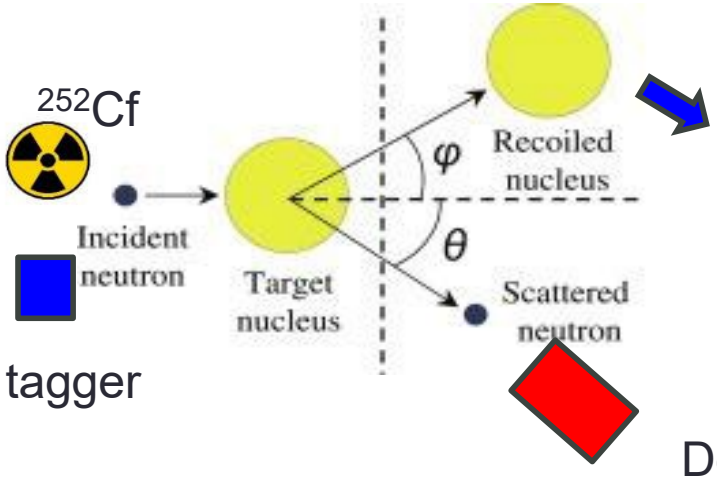
The ReD project

- Measurement **within the ReD project**
  - 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



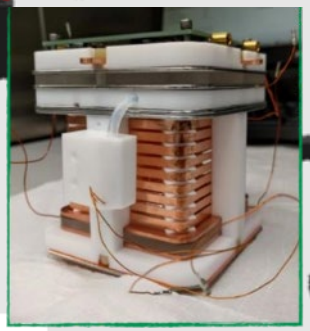
$$E_{NR} = 2KE_{neutron}\frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - cos\theta_{scatt})$$

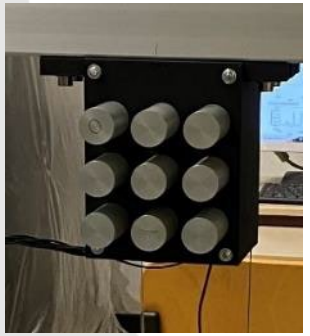
Time of flight

Fixed by geometry

Two-body kinematics!

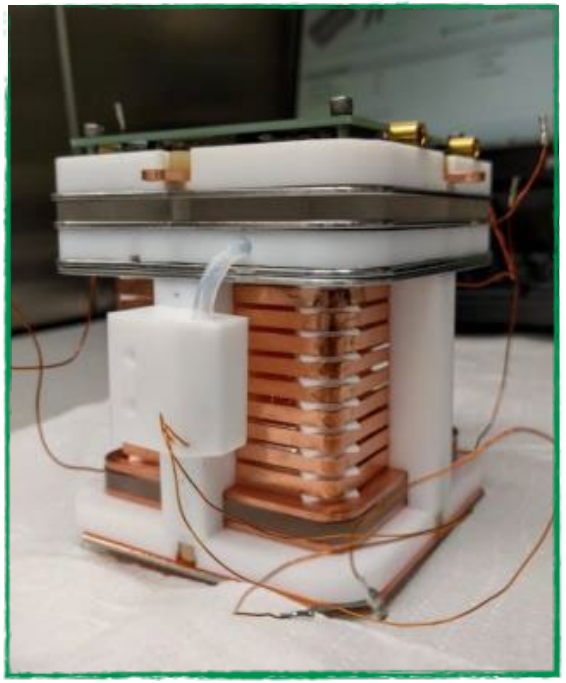
The ReD conceptual layout



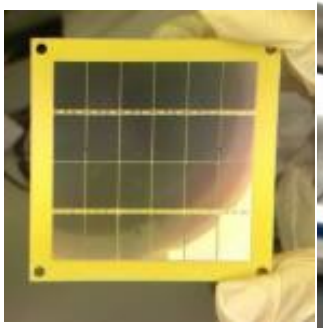


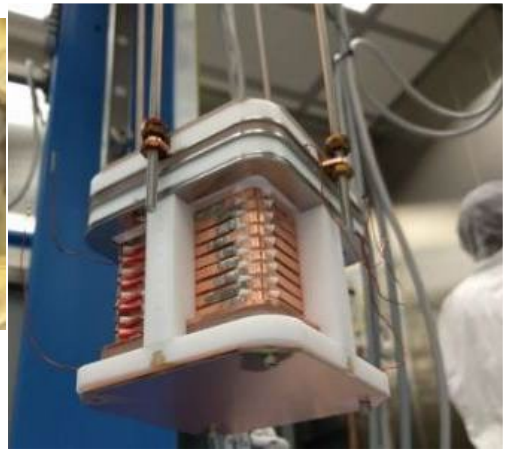
- Design sensitivity in the range **2-5 keV**

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 ~54 μs)
- In this campaign:
  - g_2 = ~19 PE/e- (E_{drift} = 200 V/cm, E_{el}=5.79 kV/cm)
  - Electron lifetime > 1 ms

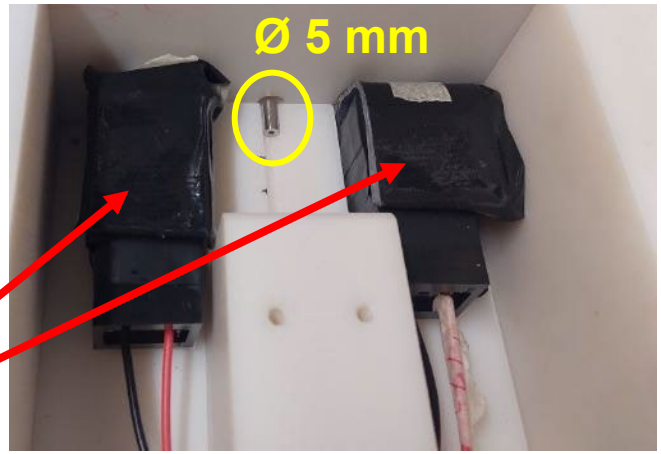




Agnes et al. EPJ C **81** (2021) 1014

… and all the rest

- **^{252}Cf source** (26 kBq fission)
  - Collimator of opening angle 2.6°
  - 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



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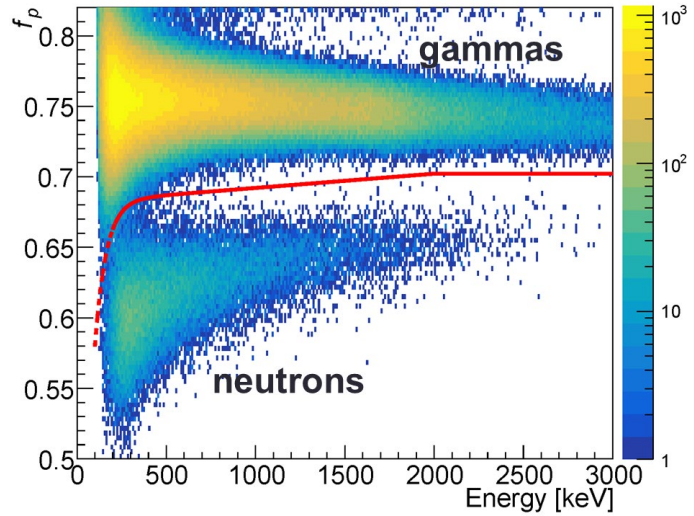
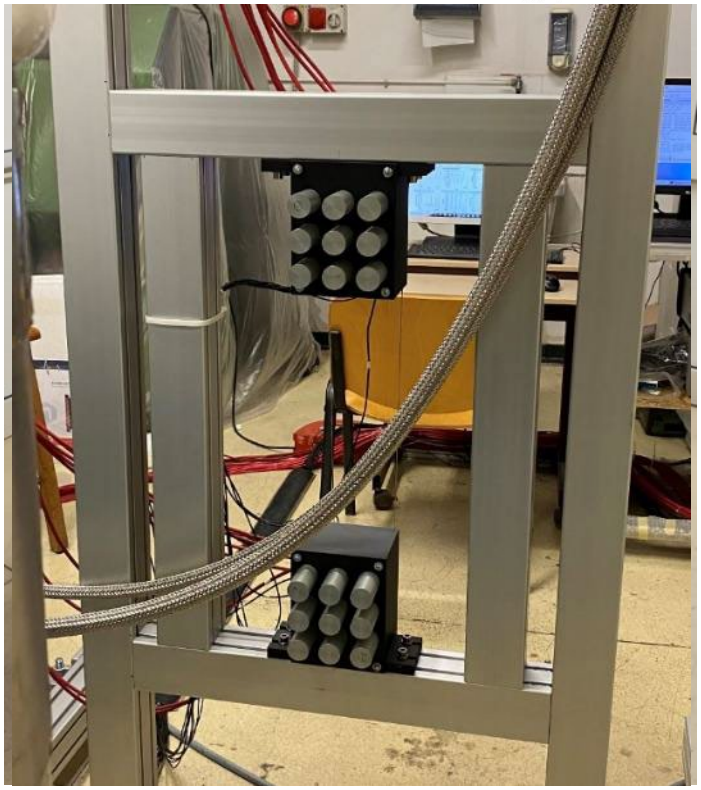
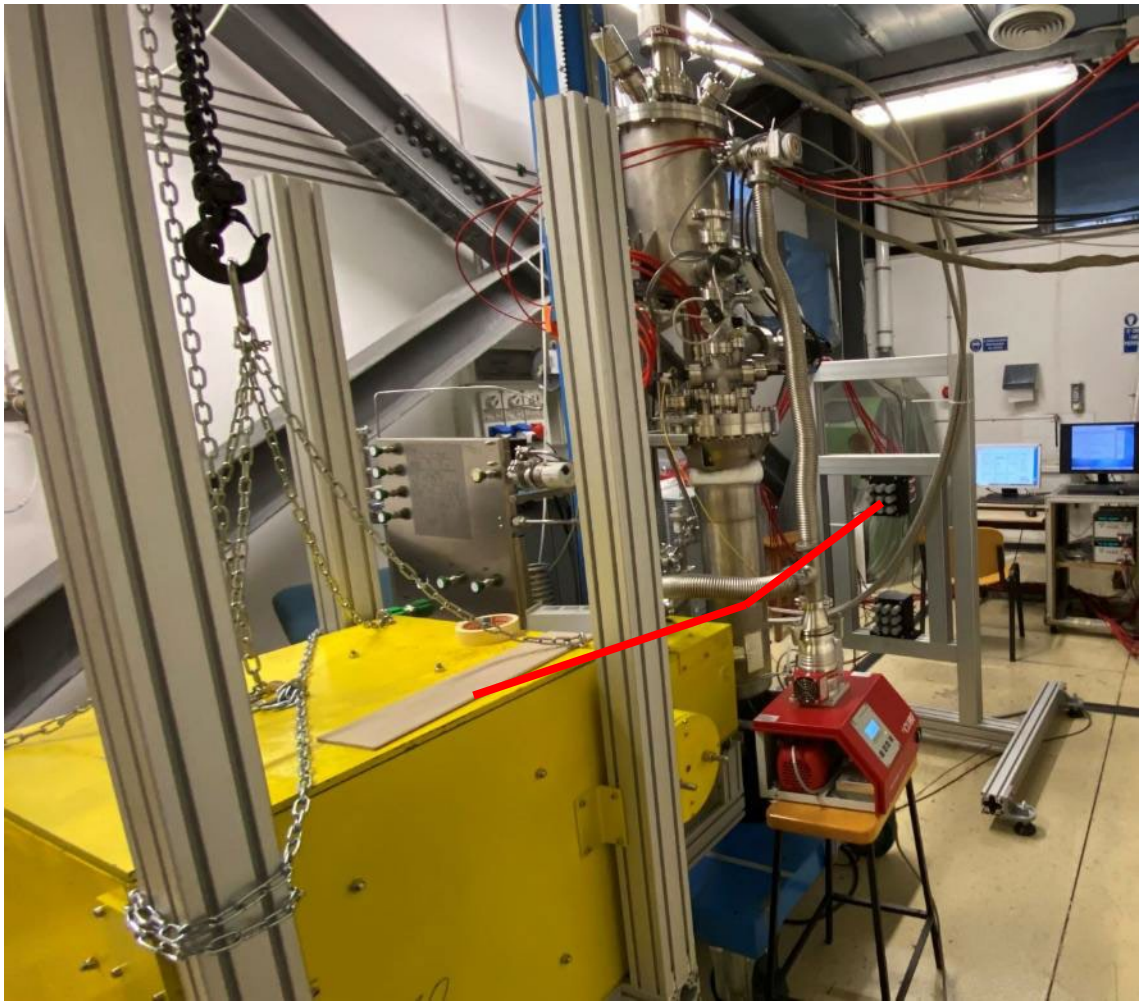
  - Collimator of opening angle 2.6°
  - Shines the entire TPC at 1 m distance
- Two **BaF_2 detectors** to tag fission products
  - Fast (high source rate, pile-up)
  - START for time of flight
- **Neutron spectrometer**: two 3x3 arrays of EJ276 **plastic scintillators** («PSci»)
  - STOP for time of flight
  - 1 m downstream the TPC
  - Symmetric deployment
  - Features n/γ discrimination
  - **θ ~ 12°-17°** in order to **avoid direct neutrons** from the source
- Tag Ar recoils down to **~1-2 keV**





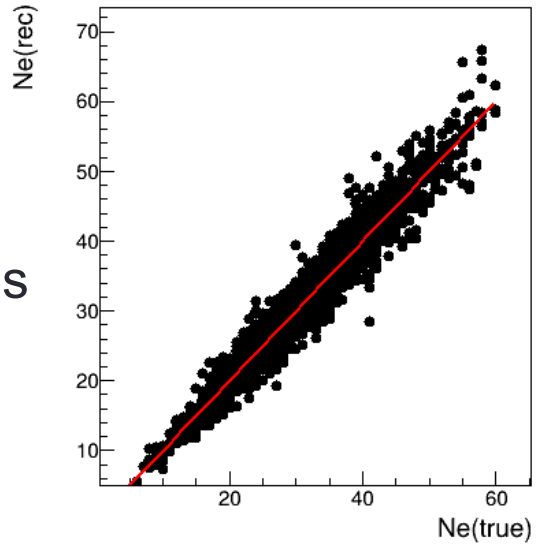
The real thing at

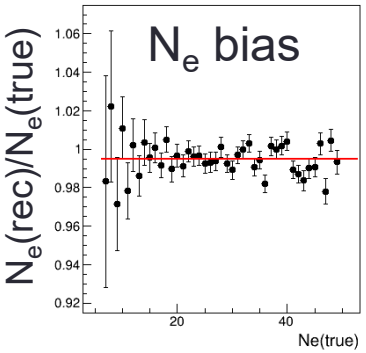
INFN Catania
Istituto Nazionale di Fisica Nucleare

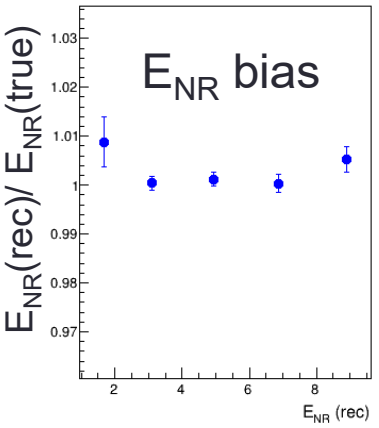


Data taking

- Data taking with ^{252}Cf for about **75 days** (Jan-Mar, 2023)
- Trigger logic: **"any BaF" ∧ "any PSci"**
  - Tagging ~60% of SF events (from MC)
  - 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-homogeneity 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**!
    - Reconstruction of N_e and E_{NR} unbiased (bias < 1%)

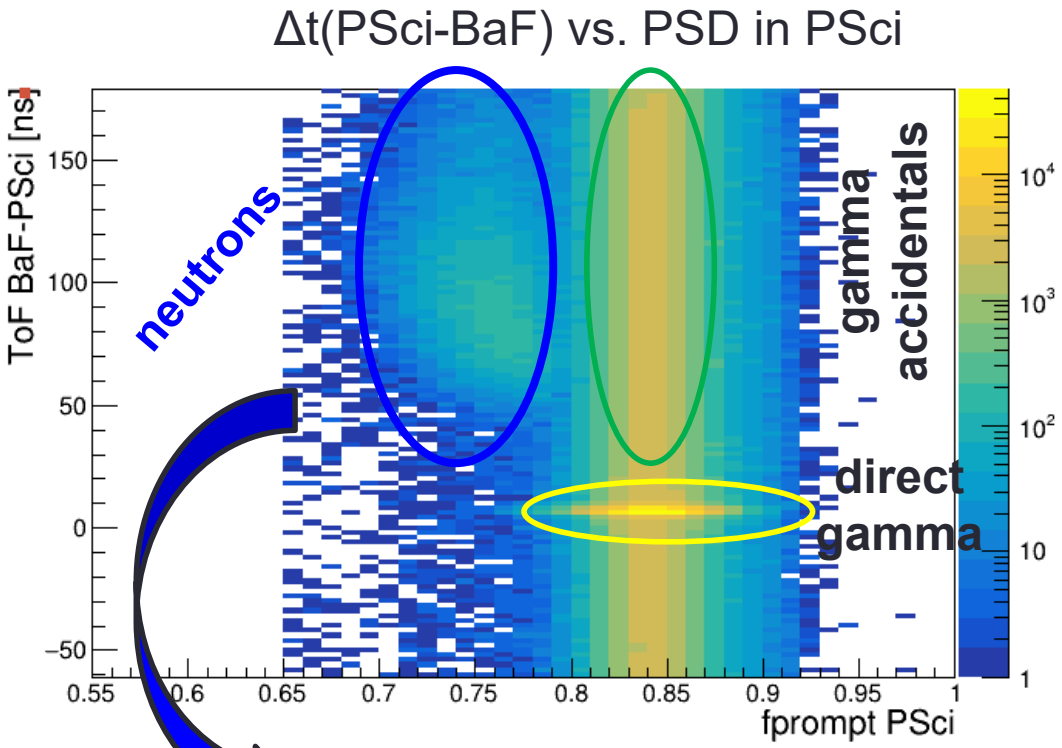


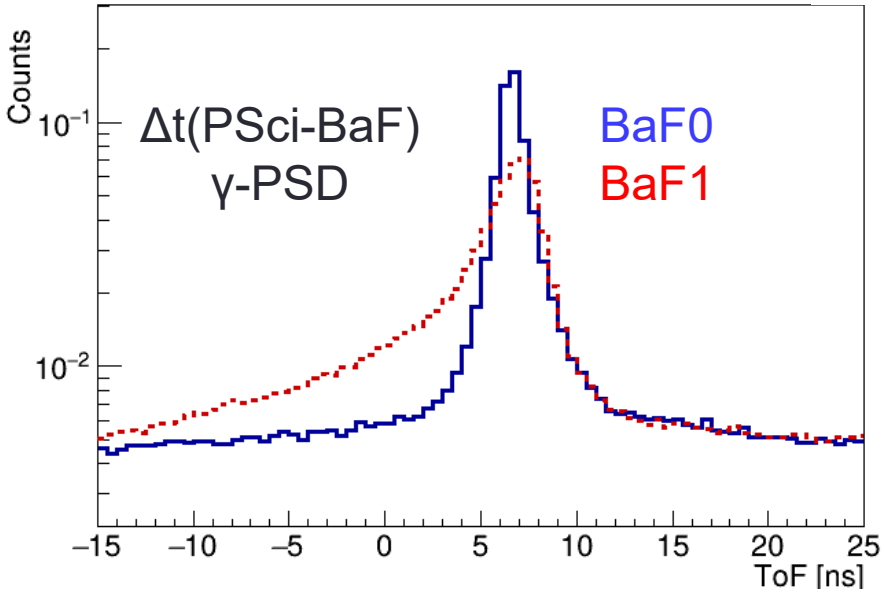


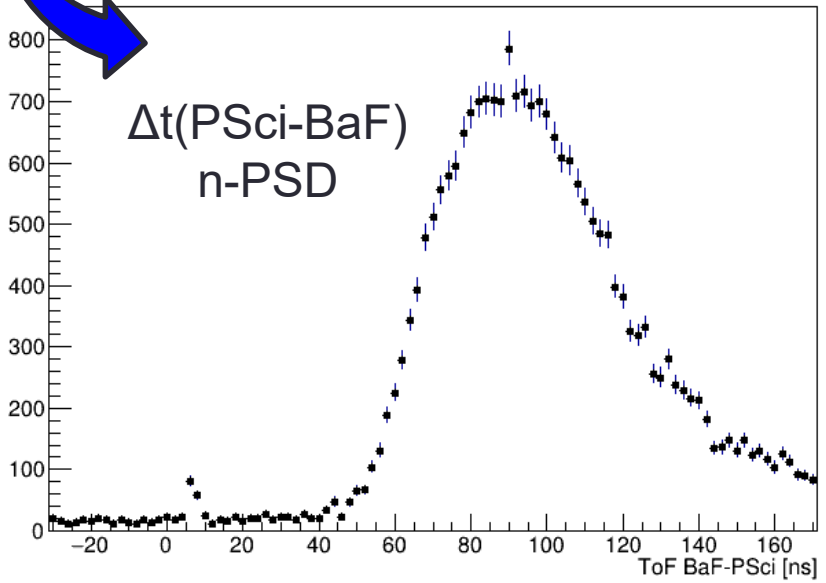


Finding neutrons…

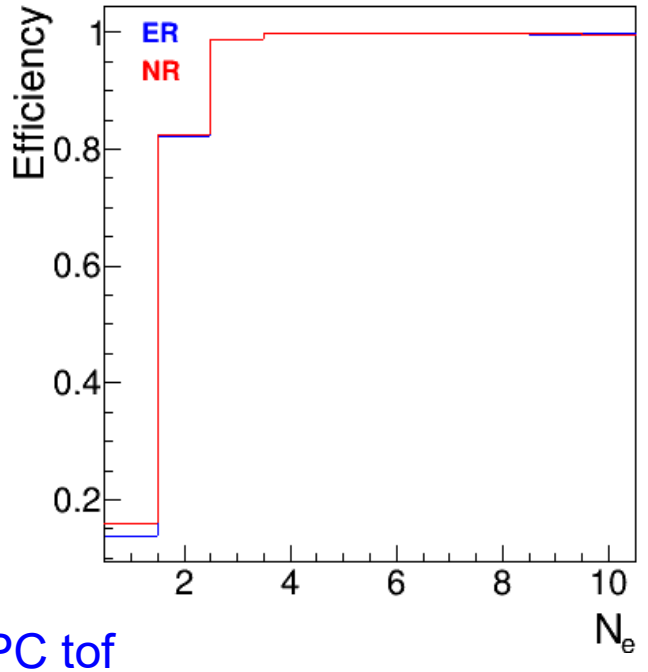
- Event rate dominated by **γ-rays** and **accidentals**
- Selection of candidate neutrons by **time of flight** and **PSD**
  - About 0.4% of total triggers
- ToF resolution **0.6-1.3 ns** rms
  - Event-by-event E_n at <5%



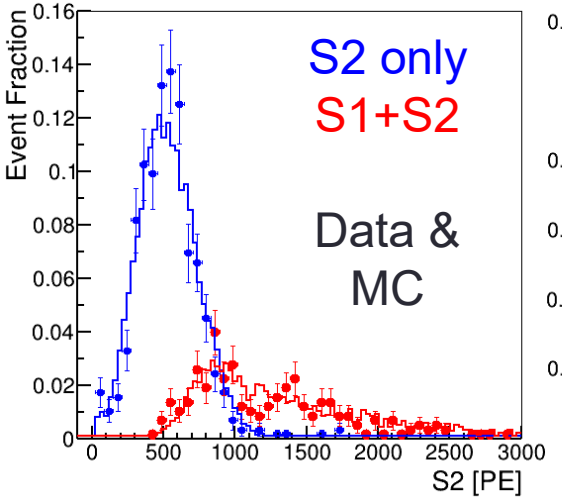




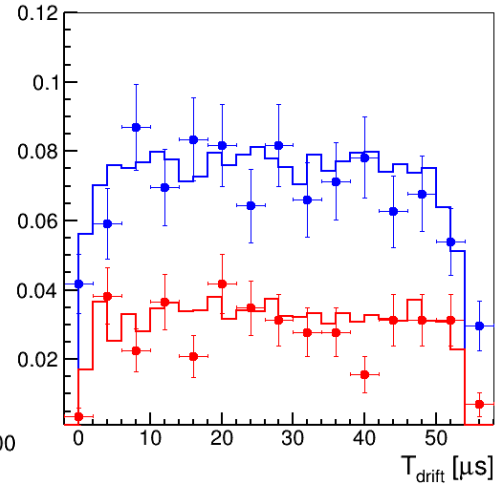
… interacting in the TPC



- 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** based on topology:
  - One S2 within 65 μs from BaF_2
  - Optionally, an **S1** (< 100 PE) w/ consistent BaF-TPC tof
  - (x,y) in the central 4x4 cm region, no tails of previous S2's
- Final sample: **806** passing all cuts, out of 2258 candidate neutron events w/ TPC signal
  - 71% are S2-only (~ as in MC)
  - 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 $\mathbf{E_{NR}}$ from time of flight (and geometry) down to **1-2 keV**
  - Select 1-10 keV due to kinematics
  - ^{241}Am calibration to constrain TPC vertical alignment $\Delta z = (0.23 \pm 0.95)$ cm
  - Uncertainty 9% @ 2 keV (6% @8 keV), driven by PSci solid angle

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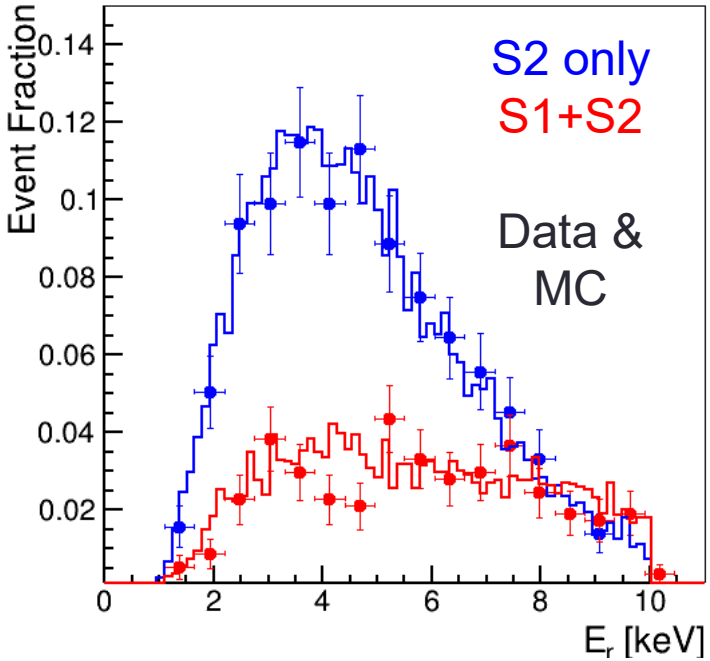

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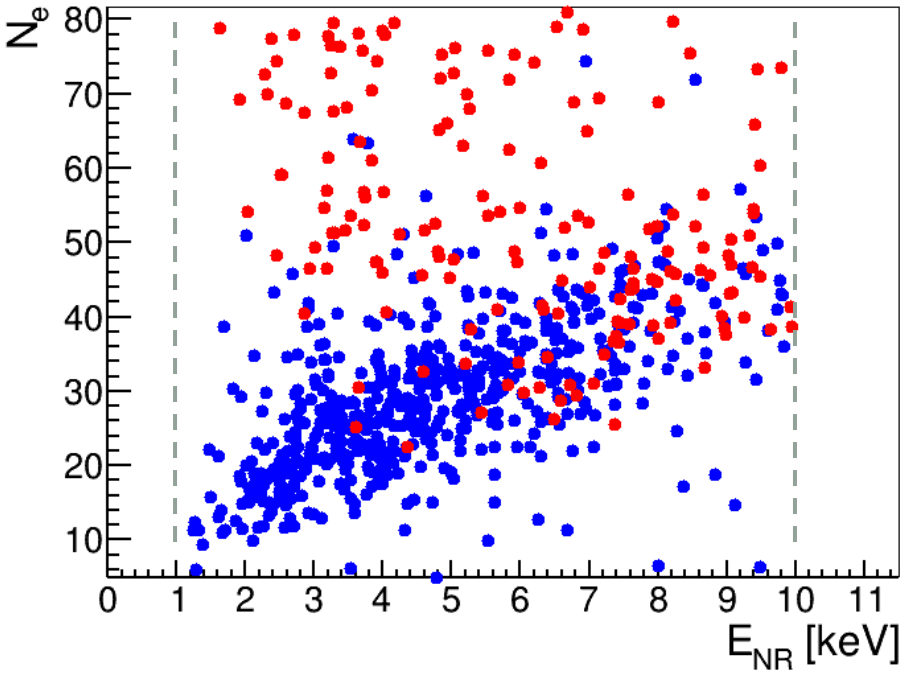
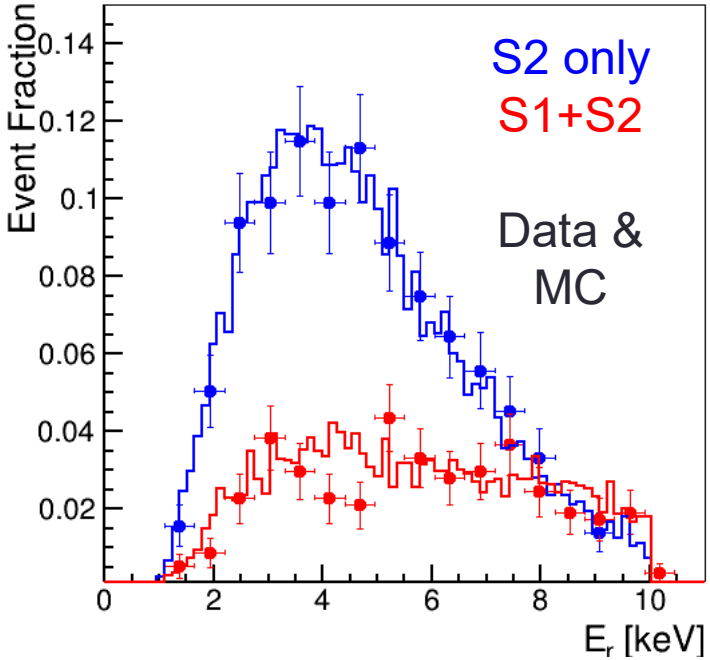
  - Uncertainty 9% @ 2 keV (6% @8 keV), driven by PSci solid angle
- S2 converted into **N_e** via ionization gain **g_2 = (18.6 ± 0.7) PE/e-**
  - From ^{241}Am calibration, checked with «echo» events
  - N_e resolution 12% at N_e=10 (7% for N_e >40)

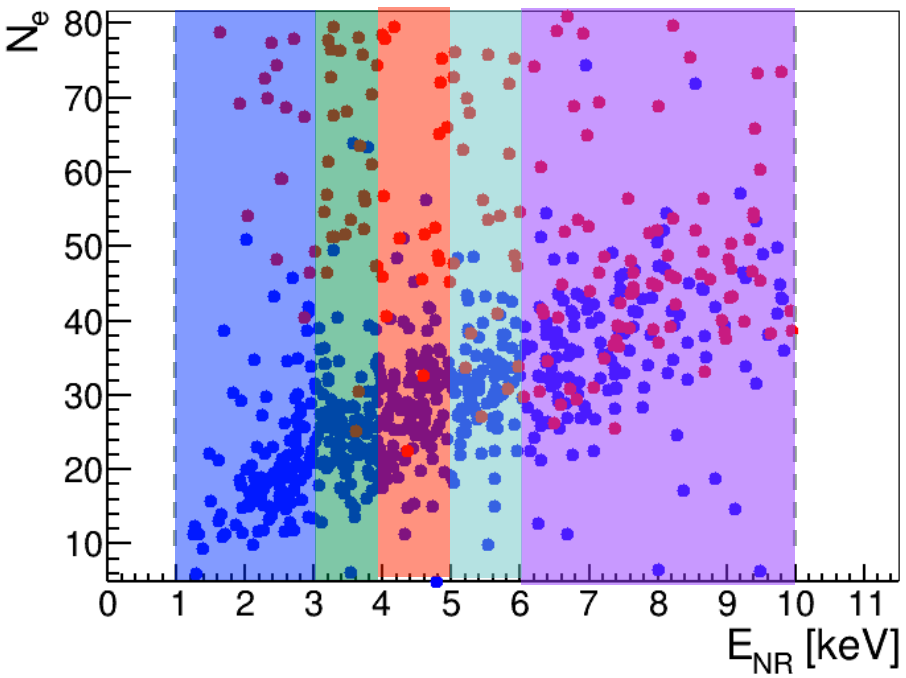


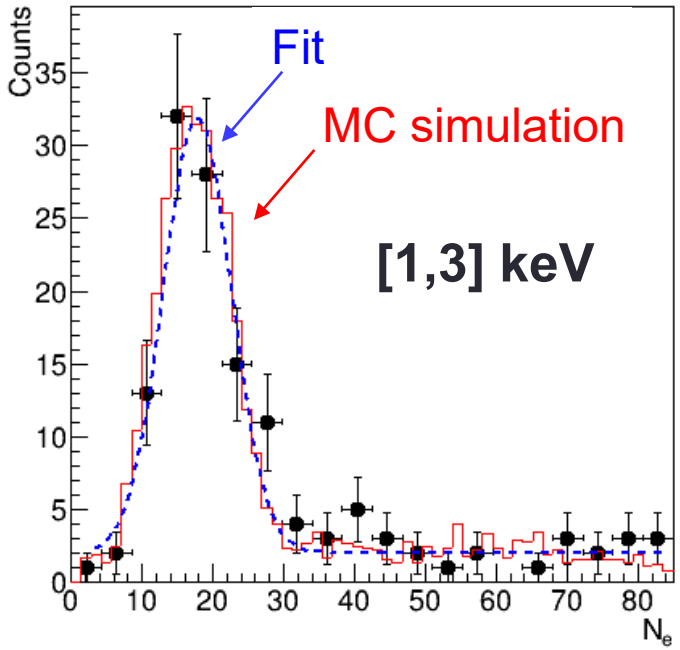
S2 only
S1+S2



Statistical analysis

- **Slice** data in **5 E_{NR} intervals**
- For each slice, **unbinned maximum likelihood fit**
  - gaussian + constant
  - Constant term accounts for multi-scattering background
  - N_e: mean value of the gaussian

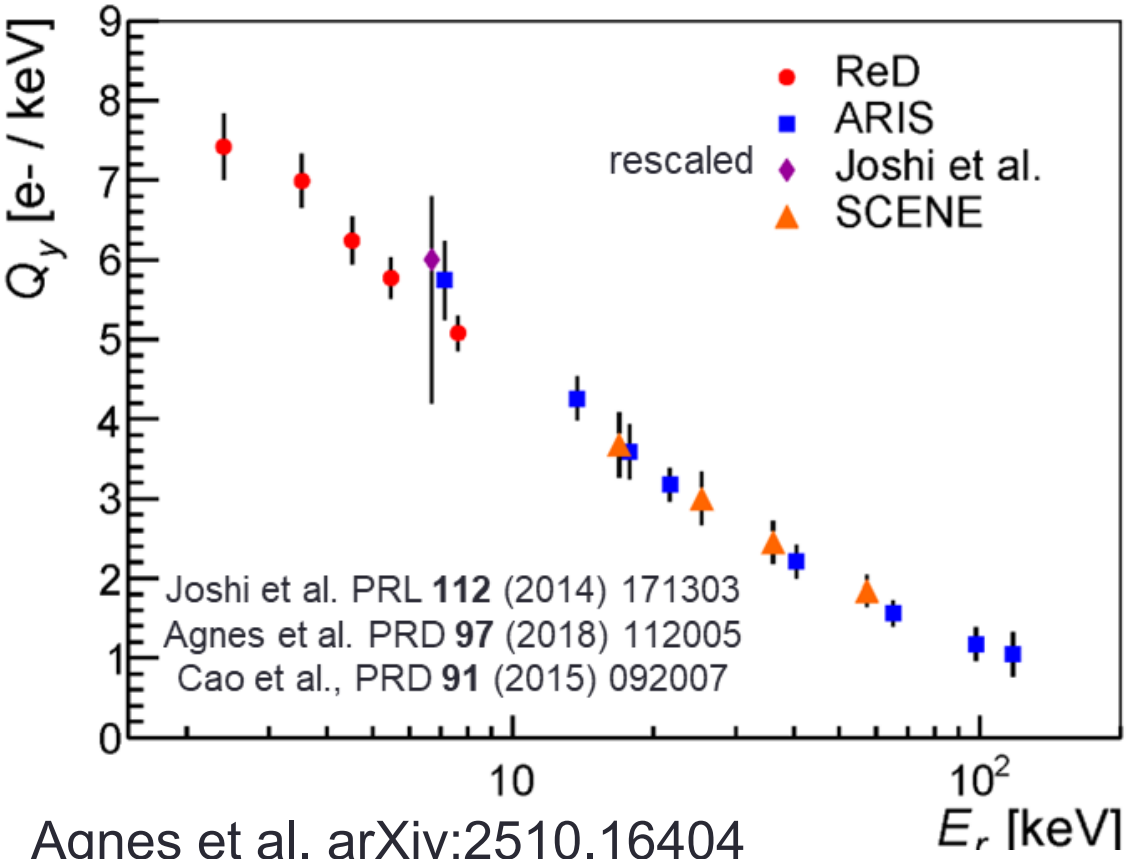




- $Q_y = N_e / \langle E_{NR} \rangle$
- Procedure **validated** with the **MC-generated** data sets
  - Unbiased, provided S1+S2 events kept
  - MC nicely describes N_e distribution → potential sensitivity to fluctuations

Qy results

- ReD in **agreement** with **existing data** above 7 keV
- Trend of **increasing Qy** at lower energy
- Total Q_y **uncertainty 4.5% - 6%**
  - Mostly systematic, driven by Δg_2 (3.8%)
    - Smaller effect from Δz
  - Statistical uncertainty 1.9%-3.6%
    - Comparable to syst only in the [1,3] keV interval



Agnes et al. arXiv:2510.16404

- Next step: use ReD data points in a **global fit** with DS-50, ARIS and SCENE to **constrain** models

See **next talk** by **D. Franco**

ReD+

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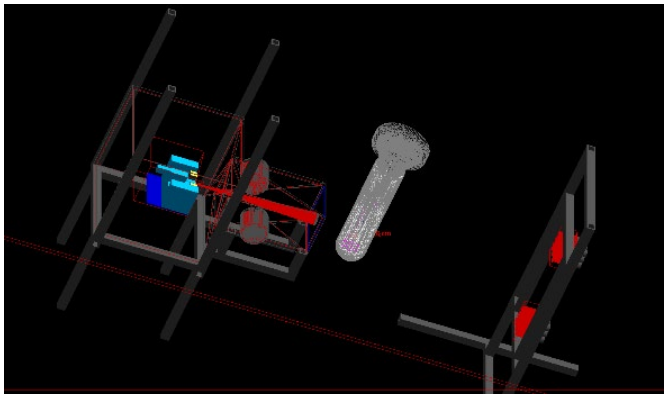
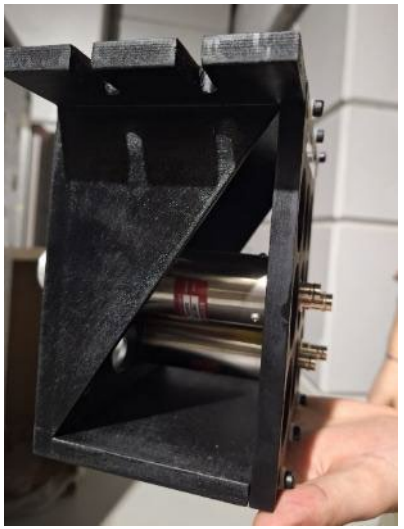
INFN

- Future project **ReD+**, funded as a PRIN project at INFN, Laboratori Nazionali del Sud
- Goal: **improve down to 0.5 keV** (and study **fluctuations**) with the **same approach** and optimized components
  - Redesigned TPC, larger spectrometer
  - Use the lesson learnt from ReD
  - Pilot run in winter 2025





ReD+

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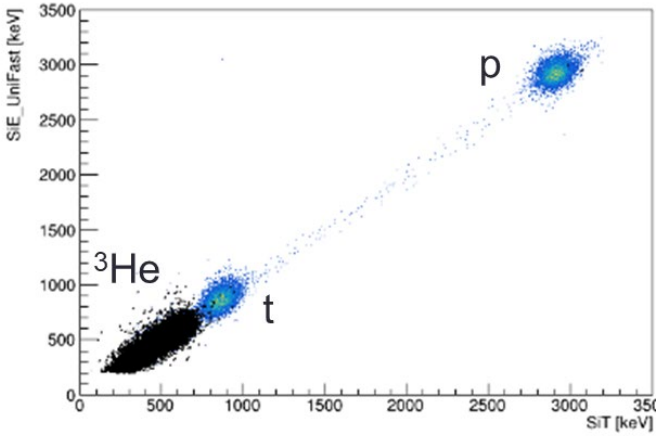
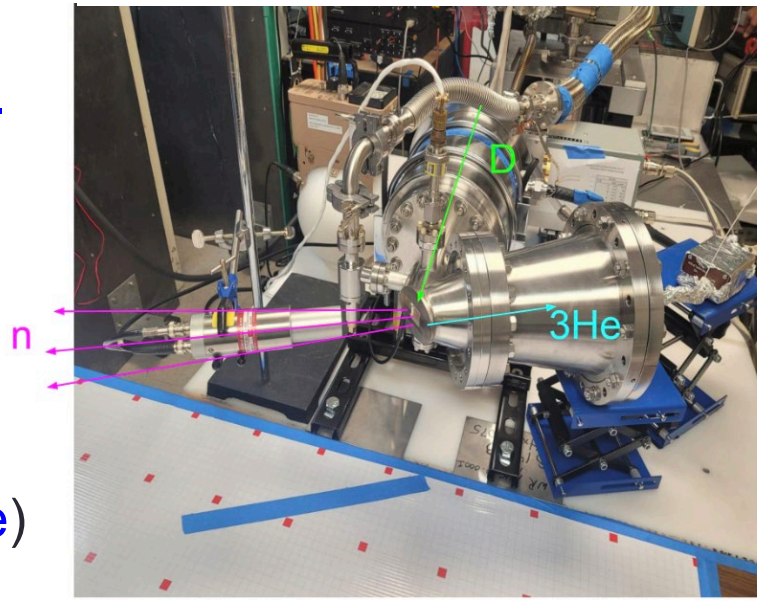
  - Redesigned TPC, larger spectrometer
  - Use the lesson learnt from ReD
  - Pilot run in winter 2025
- After that, aim at **0.2 keV** by using 2.4-MeV mono-energetic neutrons from a commercial **DD generator** (10^7 n/s)
  - Joint project with University of Sao Paulo (FAPESP grant)
  - Being commissioned now at USP
  - Neutron tagging capability (by detecting ^{3}He)





Conclusions & perspectives

- ReD **measured** the **ionization yield** of Ar down to **1-2 keV** using a miniaturized **LAr** dual-phase **TPC** @INFN Catania
  - Two-body kinematics approach: tagged ^{252}Cf fission source + neutron spectrometer to detect neutrons scattered off the TPC
- **First direct** measurement below 6.7 keV arXiv:2510.16404
  - Data being used to constrain fluctuation models

- Follow-up: **global fit** to constrain **screening functions**

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- Future: **ReD+ @ LNS**, to cover down to **0.2 keV** with ^{252}Cf (Italian PRIN funding) and DD neutron generator (Brazilian FAPESP grant)
  - Staged approach, first pilot run in winter 2025
- Information crucial for **"low-mass WIMP" analysis**