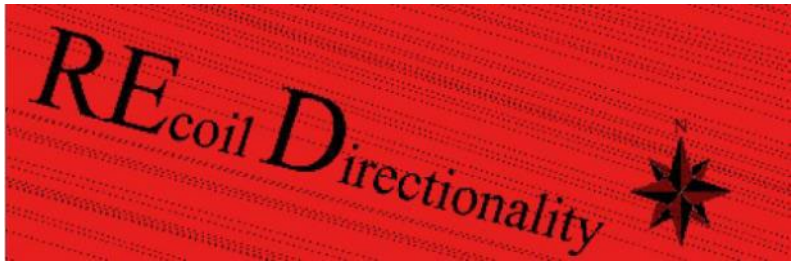


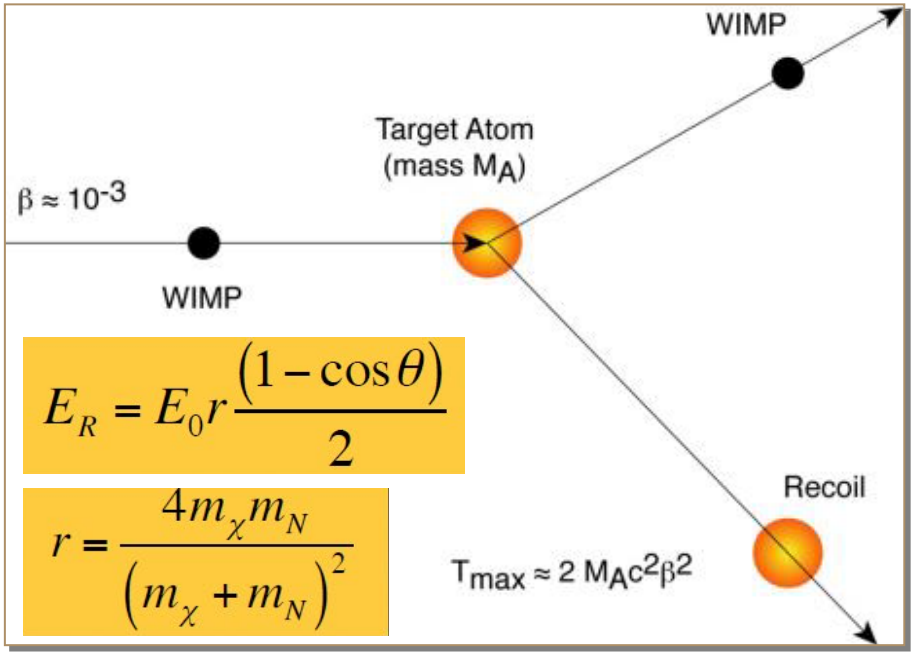
L. Pandola (LNS)

on behalf of the DarkSide LNS Group

Gruppo 2 Local Meeting, June 30th 2025

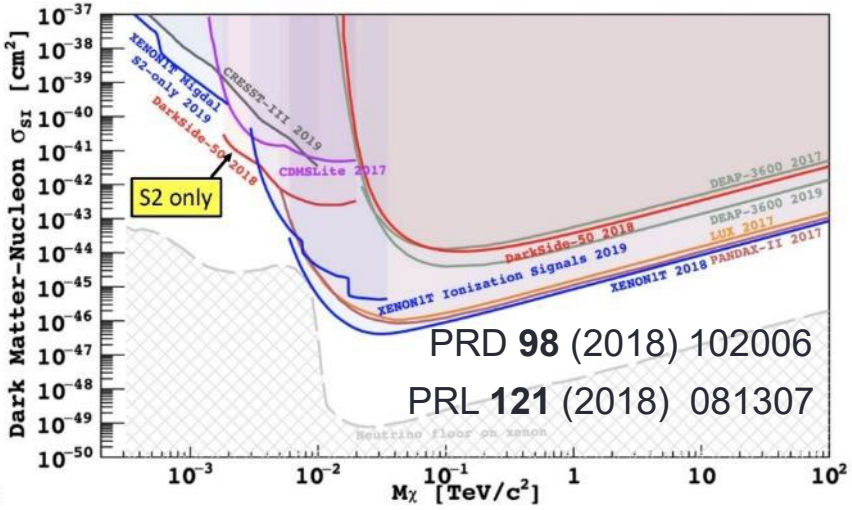
Physics background

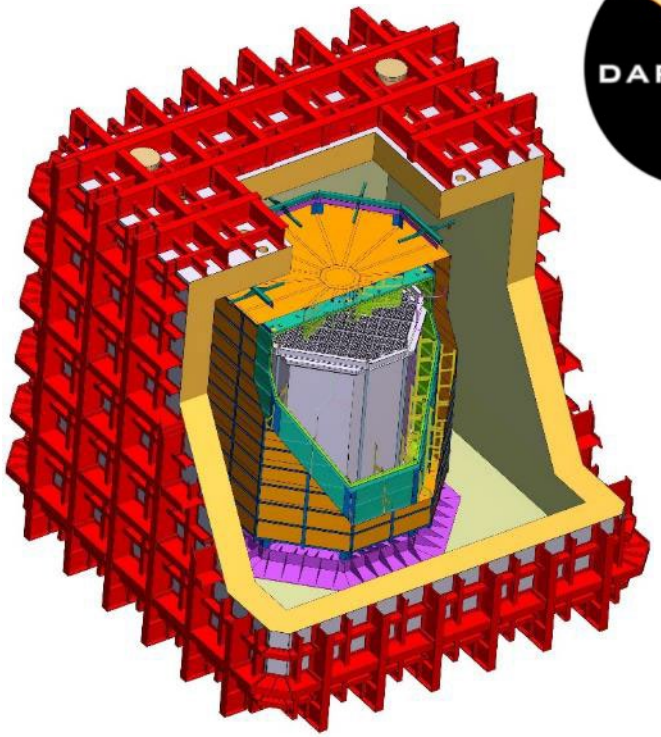
- Search for **dark matter** in the form of Weakly Interacting Massive Particles (WIMPs)
  - WIMP is a favourite candidate, but there are many others
- Signature: low energy (< 100 keV) nuclear recoil produced by WIMP elastic scattering
  - Backgrounds: e^- recoils, neutron-induced recoils
- Global effort worldwide:
  - Rates in the range from 10^{-1} to 10^{-6} events / (kg·day)
  - next generation experiments should eventually reach **exposures** in the range of **kton·day**
  - Need very low background level (and underground site)



Physics background

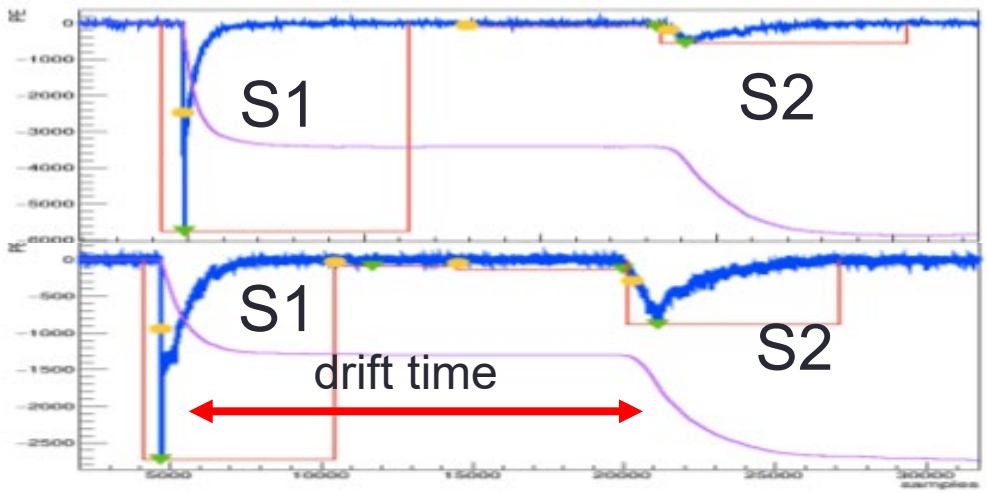
- **DarkSide** at Gran Sasso Laboratory, WIMPs search using a dual-phase TPC with low-radioactivity LAr
  - Operated a **50 kg TPC** (DarkSide-50)
  - Next step: 50 ton (20 ton fiducial) LAr **TPC** (DarkSide-20k)
    - Novel light readout with SiPM
    - Getting ready for data in **2027**, exposure O(100) ton yr
    - Expected sensitivity 10^{-47} cm^2 @ M_W =1 TeV/c^2
  - Next-next step: global worldwide effort (ARGO, 300 ton LAr)
- More sensitive to low-mass WIMP than Xe, due to the lighter target

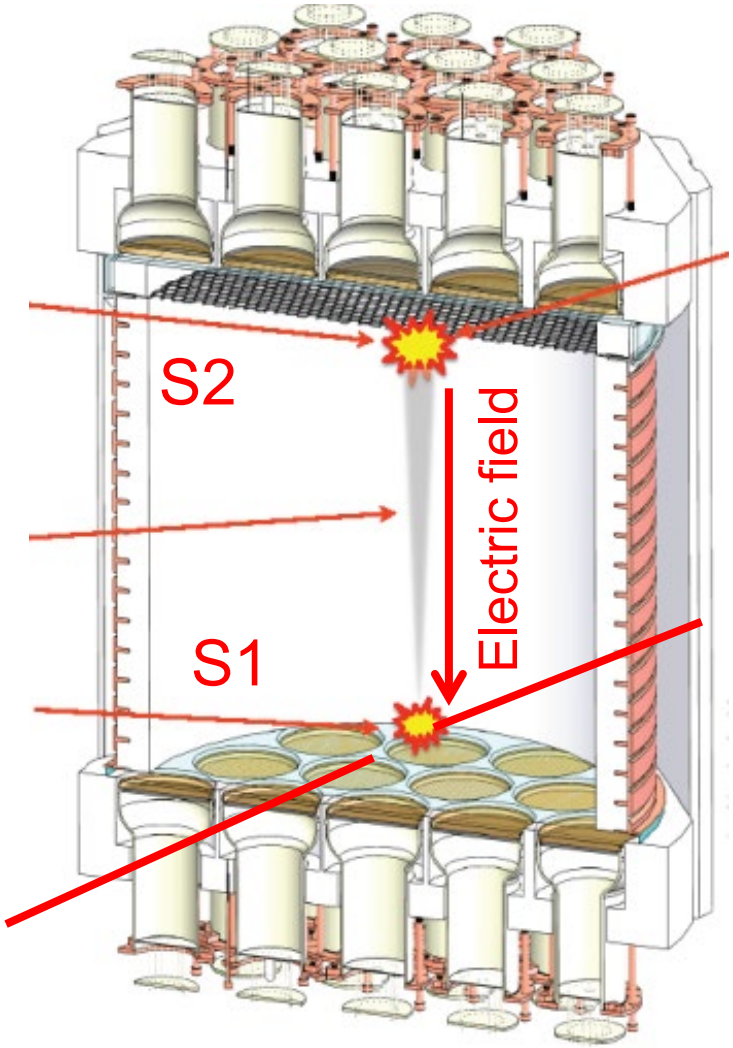




Dual-phase Ar TPC & low-mass WIMPs De

- The working principle…

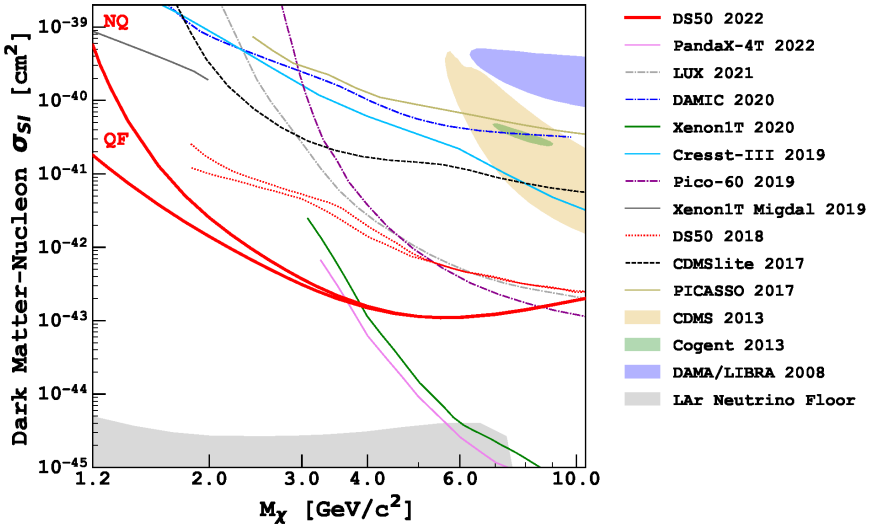




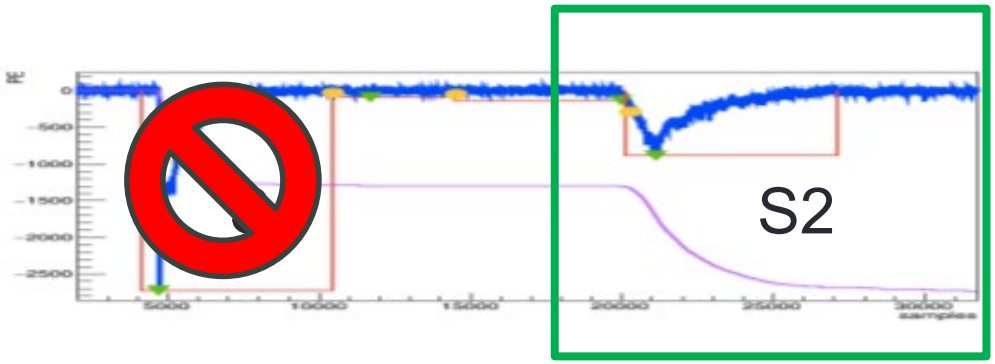
- Allows for full **3D reconstruction** (and hence fiducialization)
  - (X,Y) from the S2 light pattern in the top sensors
  - Z from the drift time between S1 and S2
    - Many 10's or 100's of μs
- Designed for optimal sensitivity to **"standard"** (100 GeV) WIMPs

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-)
    - No sensitivity to Z coordinate



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



- Analysis sensitive to ionization yield for keV NRs
  - **Poorly known** for Ar
  - Literature down to 6 keV

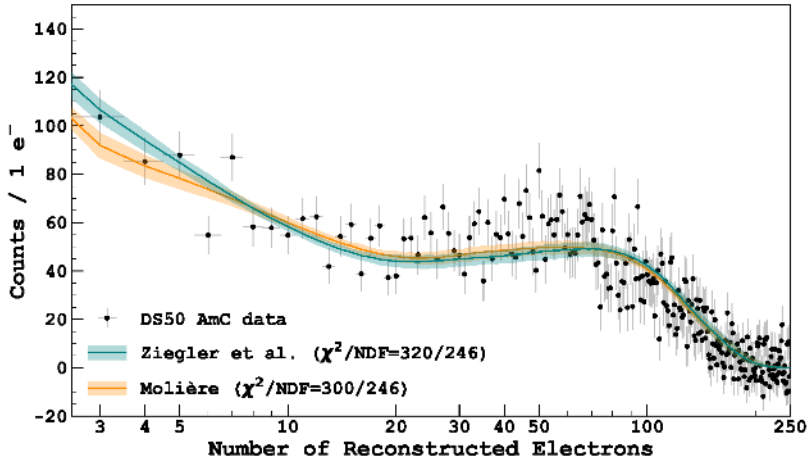
Ar NRs ionisation yield at low energy

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

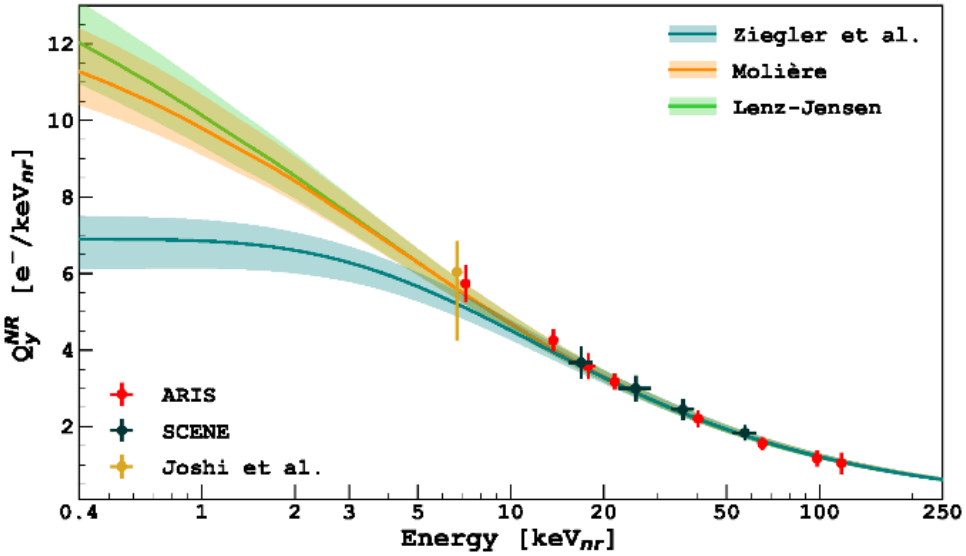
Thomas-Imel $1 - r = \frac{1}{\gamma N_i} \ln(1 + \gamma N_i)$

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

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



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 ReD project…since 2019

- **ReD project**, three-fold goal:
  - check if a dual phase LAr TPC has sensitivity to the direction of Ar recoil
  - characterize the response of the LAr TPC to very low-energy recoils (< few keV)
  - act as a test bench of the technical solutions for DarkSide-20k TPC
- Phase 1 (Naples) – **Characterization** of the TPC
  - Stability over time scale of months
  - Check that performance OK for phase 2
- Phase 2 (LNS) – **Directionality run**
  - TANDEM beam LNS (February 2020)
  - No indication for directionality
- Phase 3 (INFN Catania) – **Low-energy run** with ^{252}Cf
  - Data taking → Nov 2022 - Jun 2023
  - Preliminary results at TAUP2023
  - Getting ready for full release @TAUP2025

EPJ C 81 (2021) 1014

Eur. Phys. J. C (2021) 81:1014
https://doi.org/10.1140/epjc/s10052-021-09801-6
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

Performance of the ReD TPC, a novel double-phase LAr detector with silicon photomultiplier readout

P. Agnes[1], S. Albergo[2,3], I. Albuquerque[4], M. Arba[5], M. Ave[4], A. Boiano[6], W. M. Bonivento[5], B. Bottino[7,8], S. Bussino[9,10], M. Cadeddu[5], A. Caminata[7], N. Canci[11], G. Cappello[2,3], M. Caravati[5,12], M. Cariello[7],

EPJ C 84 (2024) 24

Eur. Phys. J. C (2024) 84:24
https://doi.org/10.1140/epjc/s10052-023-12312-1
THE EUROPEAN PHYSICAL JOURNAL C
Regular Article - Experimental Physics

Constraints on directionality effect of nuclear recoils in a liquid argon time projection chamber

DarkSide-20k Collaboration*

PROCEEDINGS OF SCIENCE

Characterization of low-energy argon recoils with the ReD experiment

INFN

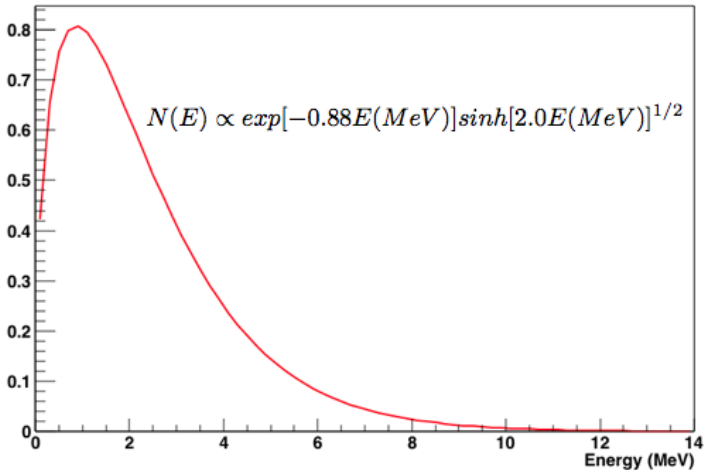
CHARACTERIZATION OF LOW-ENERGY ARGON RECOILS WITH THE RED EXPERIMENT

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

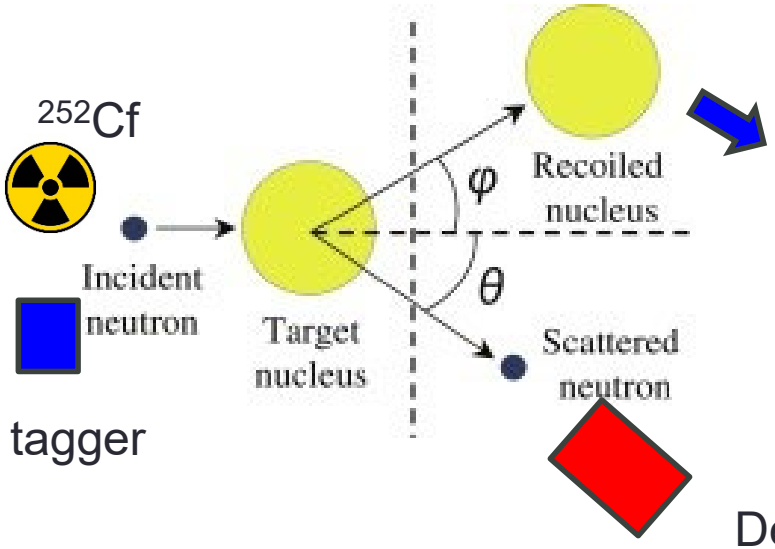
TAUP 2023, Wien
August 29th, 2023

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



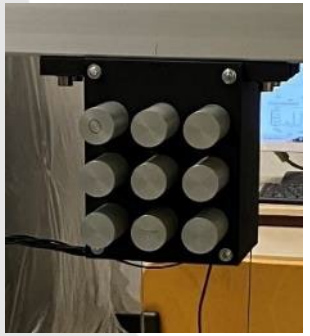
$$E_{NR} = 2KE_{neutron}\frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - cos\theta_{scatt})$$

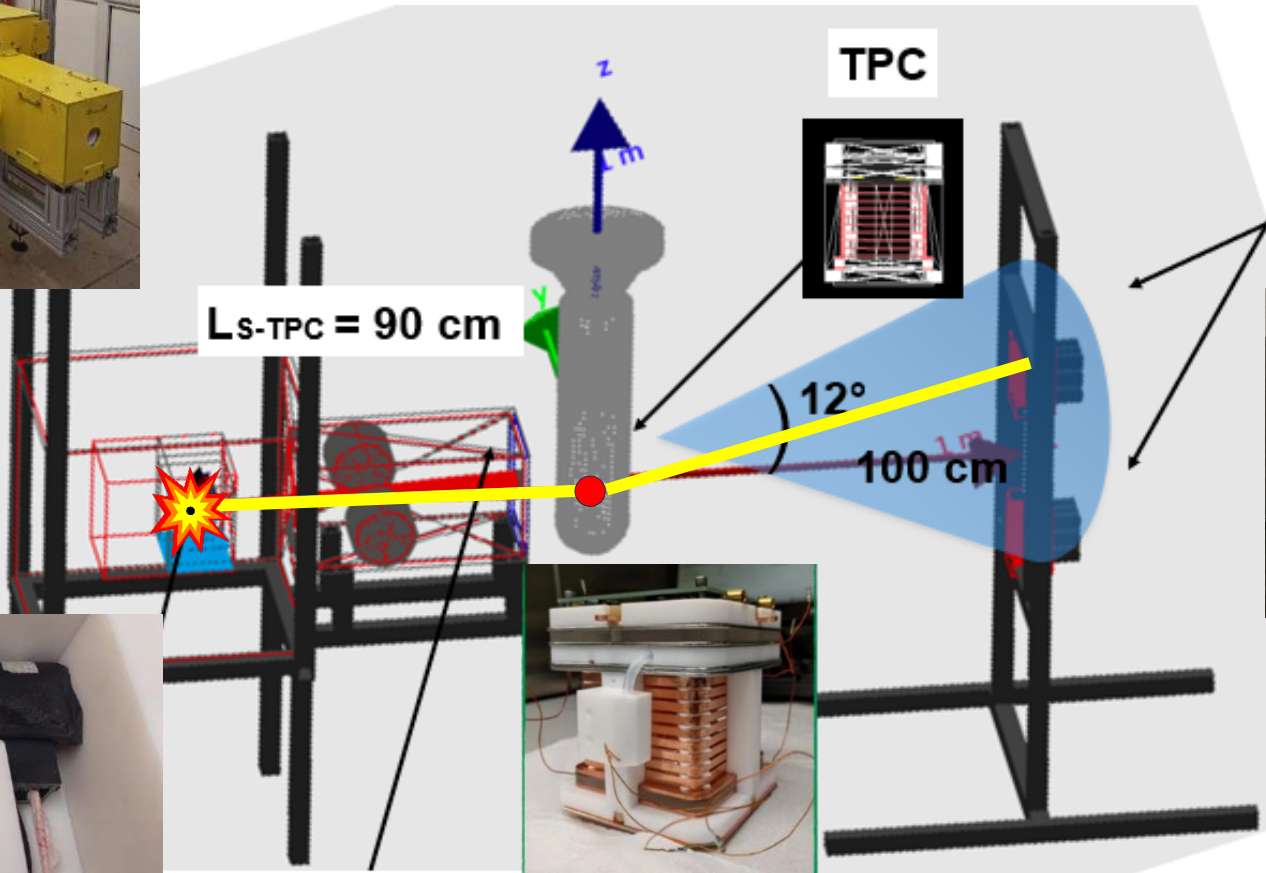
Time of flight

Fixed by geometry

Two-body kinematics!

The ReD conceptual layout



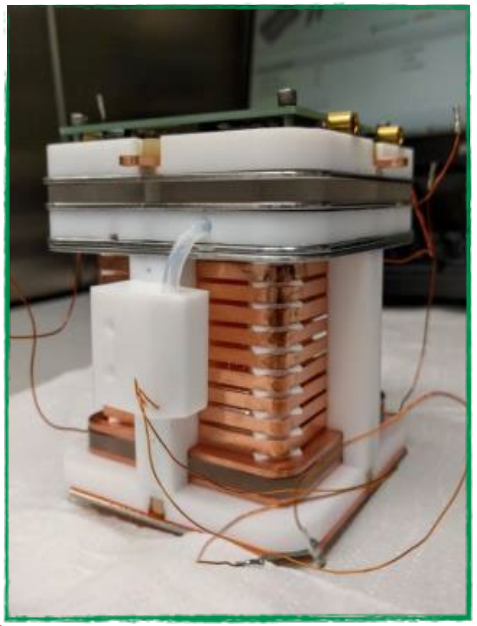


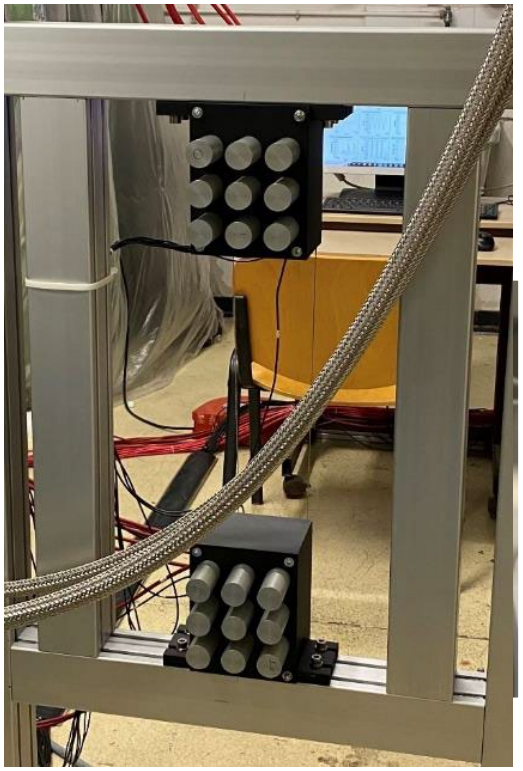
- Design sensitivity in the range **2-5 keV$_{nr}$**

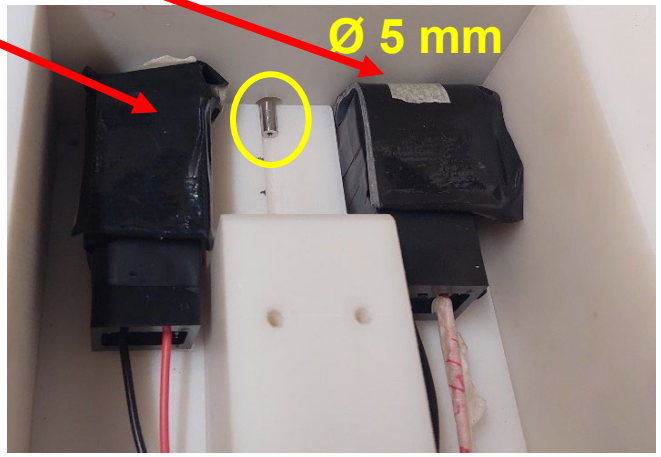
Conceptual design from University of Sao Paulo

The ingredients

- Our **ReD TPC**
  - Light readout: 5x5 cm^2 SiPM
- A neutron **spectrometer**
  - 18 1-in EJ-276 plastic scintillators
  - ToF STOP
  - Featuring n/γ discrimination
- Fission **tagger**
  - Two BaF_2 detectors
  - ToF START
- The ^{252}**Cf** source (0.86 MBq)
  - About 26 kBq SF
  - Collimator of opening angle ~2°
  - Shines the entire TPC at 1 m distance
- Tag Ar recoils down to **~1-2 keV$_{nr}$**

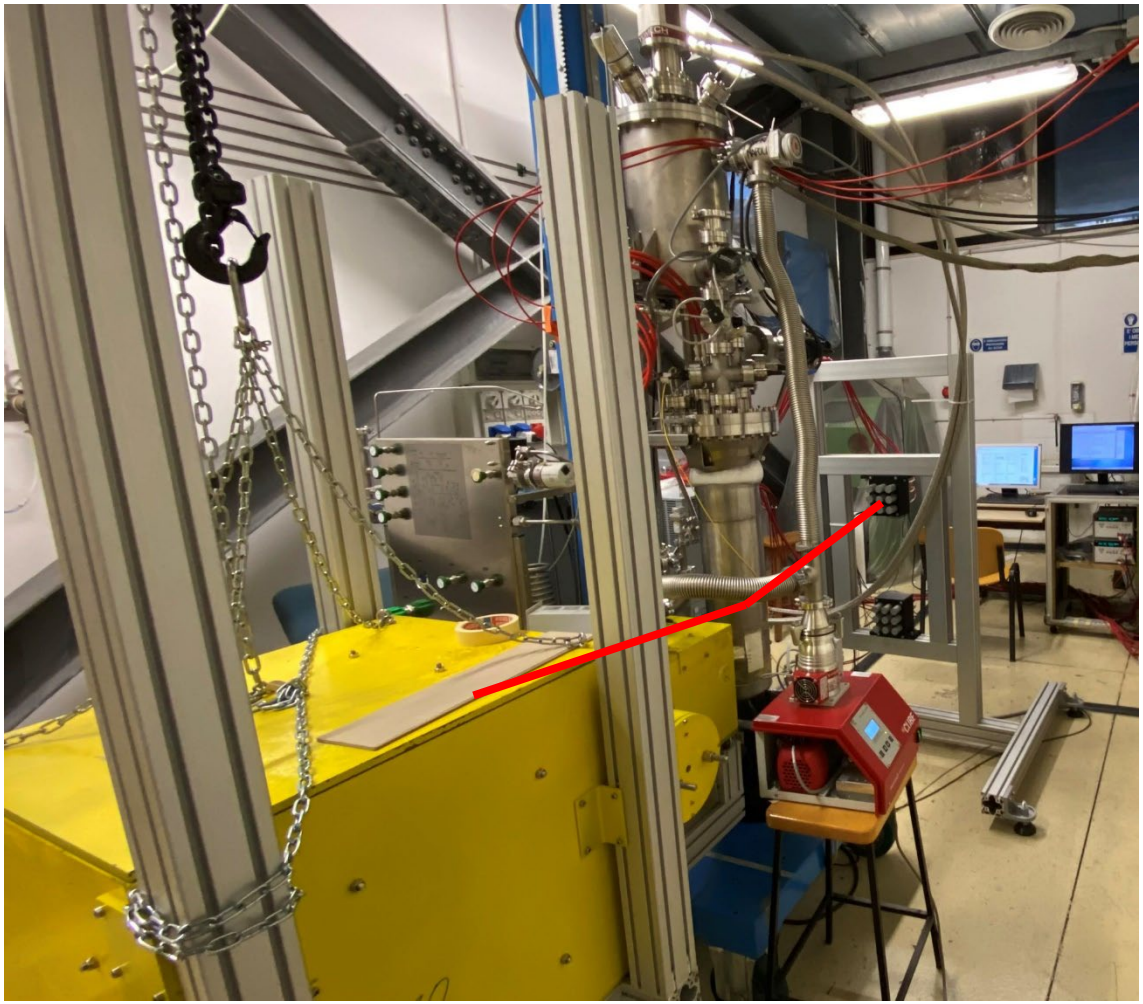


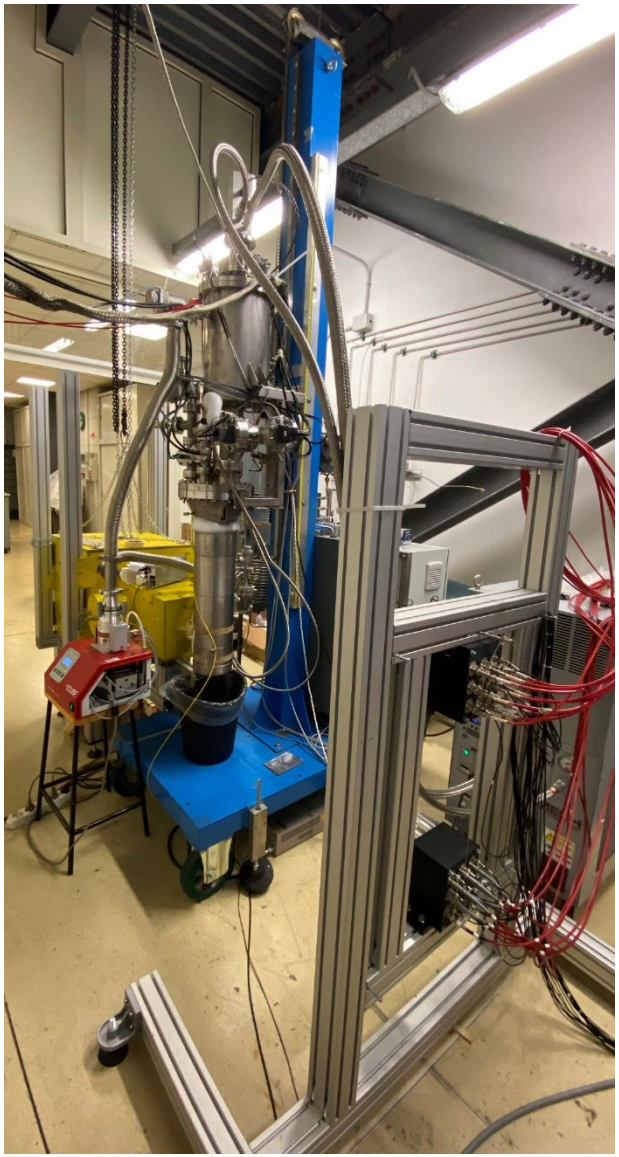




The real thing at

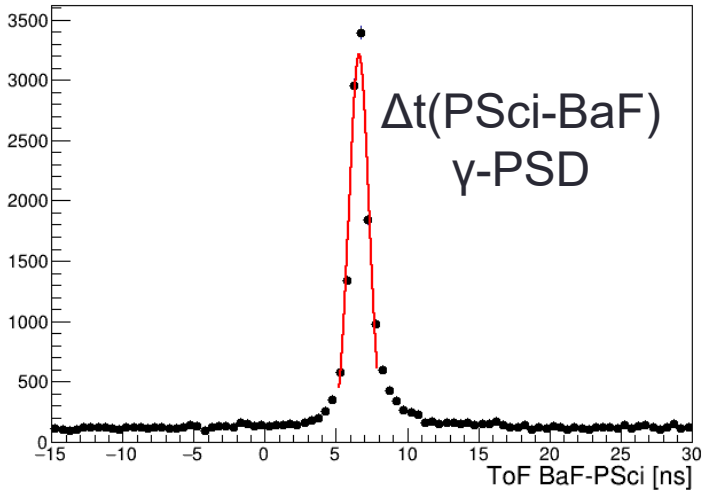
INFN Catania
Istituto Nazionale di Fisica Nucleare

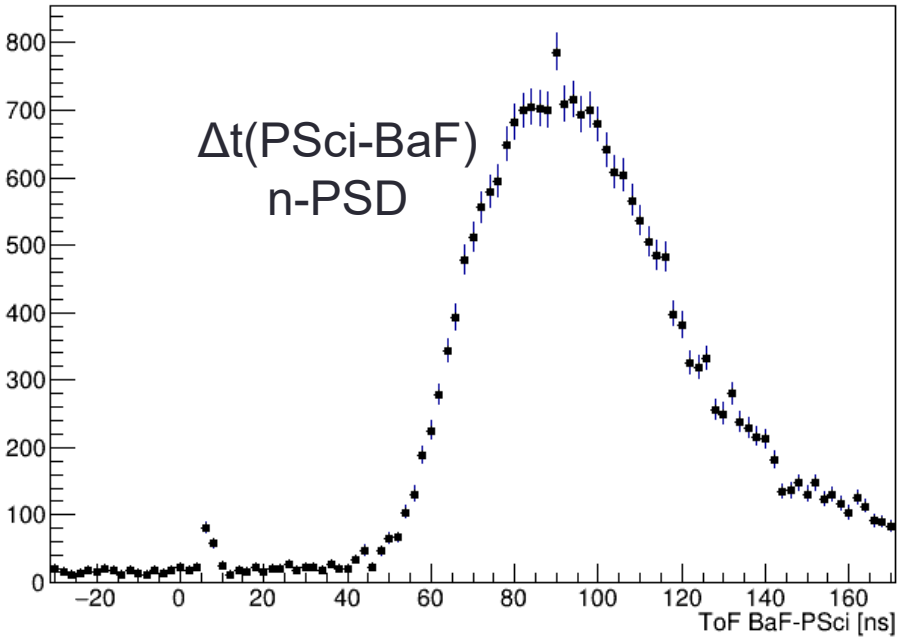




Data taking: finding neutrons…

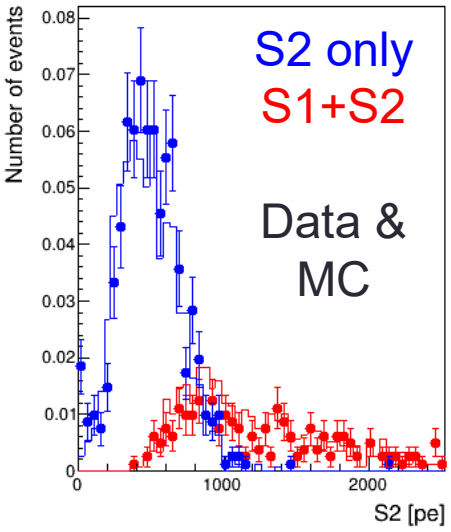
- Data taking with ^{252}Cf from **Jan to Mar, 2023**
- Trigger logic: **"any BaF" ∧ "any PSci"**
  - Tagging ~60% of SF events
  - TPC acquired in **follower** mode (may fail to trigger in S1)
  - Event rate dominated by γ-rays and accidentals
- Selection of candidate neutrons by **time of flight** and **PSD**
  - About 28 events/hour (0.3%)
- ToF resolution **~ 0.7 ns**
- Event-by-event E_n at <5%

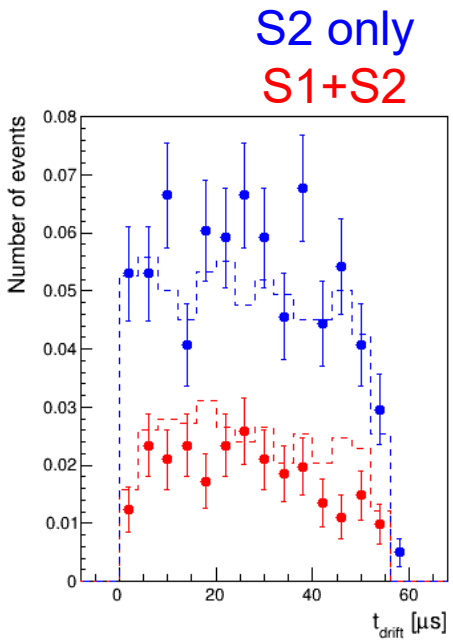




… interacting in the TPC

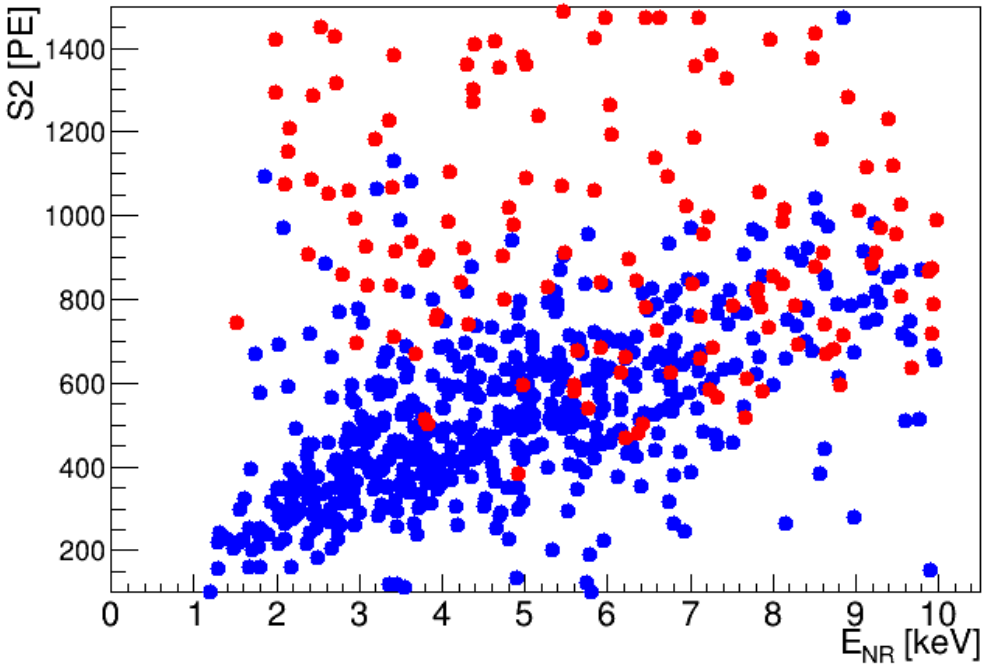
- Look for TPC events **offline**
  - Analysis flow: de-convolution of SiPM response function, TPC pulse finder
- From MC: pulse finder **fully efficient** for S1 > 25 PE, **S2 > 4 e-**
- Selection cuts:
  - One S2 within 65 μs from BaF_2 and optionally, an **S1** (< 100 PE)
  - If S1 available, consistent 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 2300 candidate neutron events w/ TPC signal
  - 70% 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)



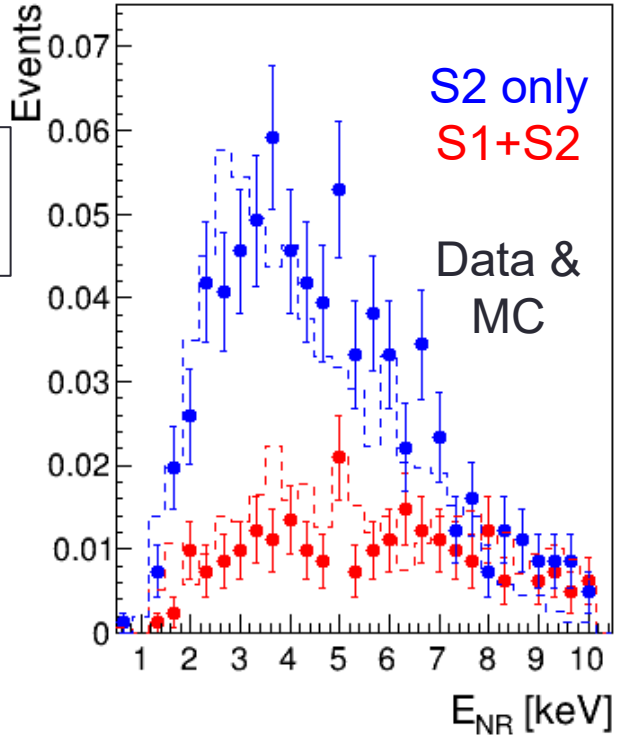


The sample of low-energy recoils

- 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



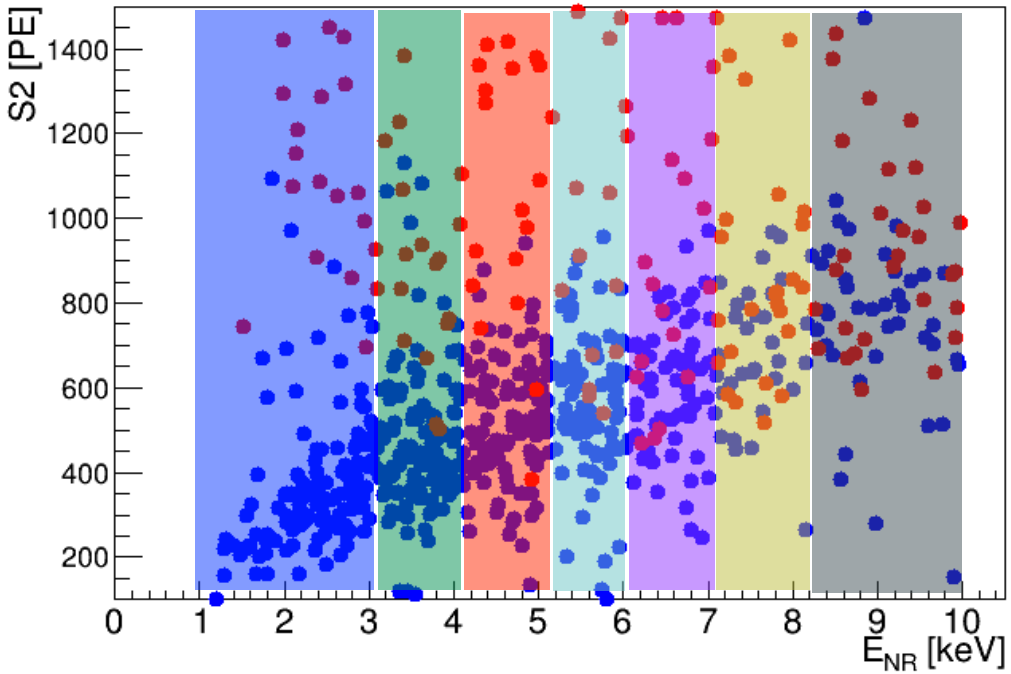
S2 only
S1+S2

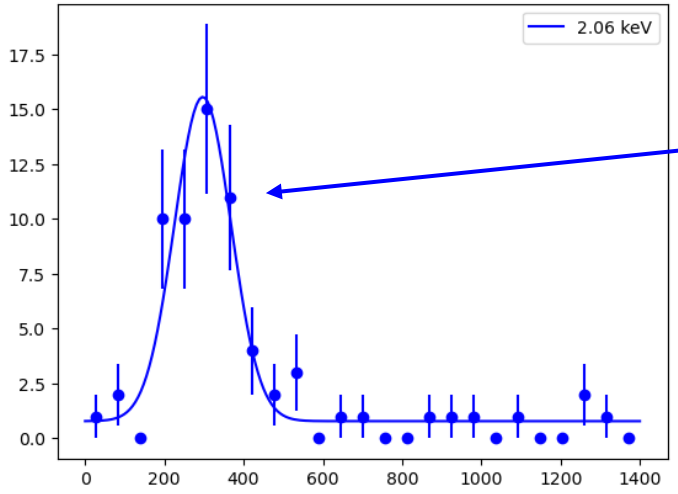


S2 vs. E_{NR}

- **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

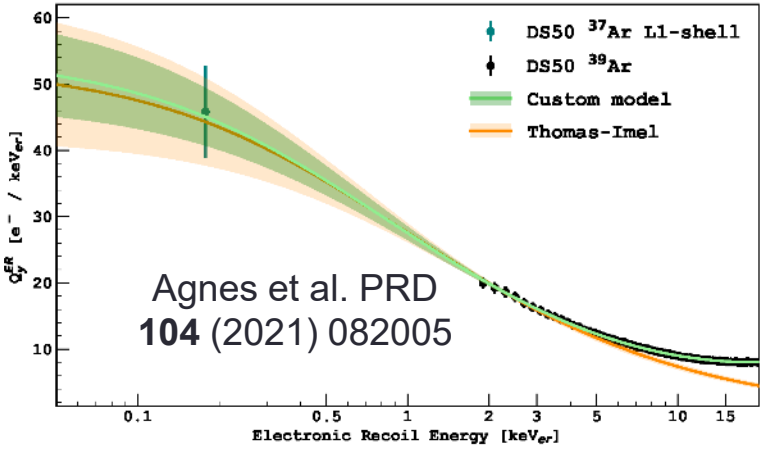


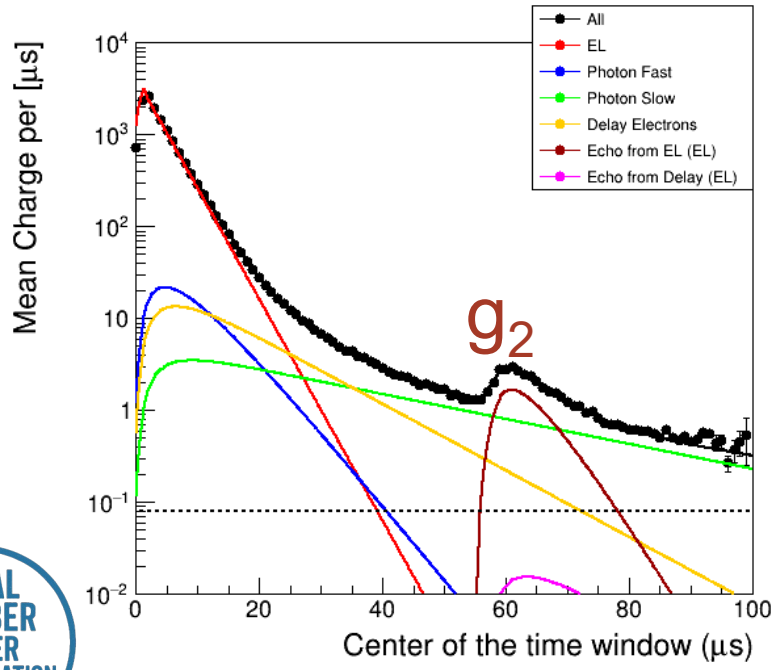


- S2: mean value of the gaussian
- < E_{NR} >: mean energy of the events
- Procedure validated with the MC-generated data sets
  - Unbiased, provided S1+S2 events are kept

From S2 to Ne: g_2

- Ionization gain **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
- «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 Qy vs. E_{NR} measurements down to 2 keV





FINAL NUMBER UNDER COLLABORATION REVIEW

Status and next steps

- ReD – as a part of the TDR of DarkSide – is **completed** ☑
  - Collaboration focused on the construction of the DarkSide-20k detector
- **Data analysis**: machinery ready and tested, analysis **completed**

  - Analysis under Collaboration Review
  - Final Qy vs. E_{NR} measurements down to 2 keV
  - Impact on DS20k sensitivity curves, discrimination of screening models
  - Two papers being drafted
- **ReD+: follow-ups** in Catania to further improve and push sensitivity down to **0.2 keV**:
  - New improved calibration with ^{252}Cf
    - Funded as a two-year PRIN project, INFN, UniCt, UniNa (183k€)
    - Started in September 2023 → **end March 2026**

  - Measurement using 2.4 MeV neutrons from a DD gun
    - Joint project with University of Sao Paulo (DDgun funded as a FAPESP grant)
    - Delivered to USP: being commissioned and then shipped to LNS in 2025

ReD+ activities

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

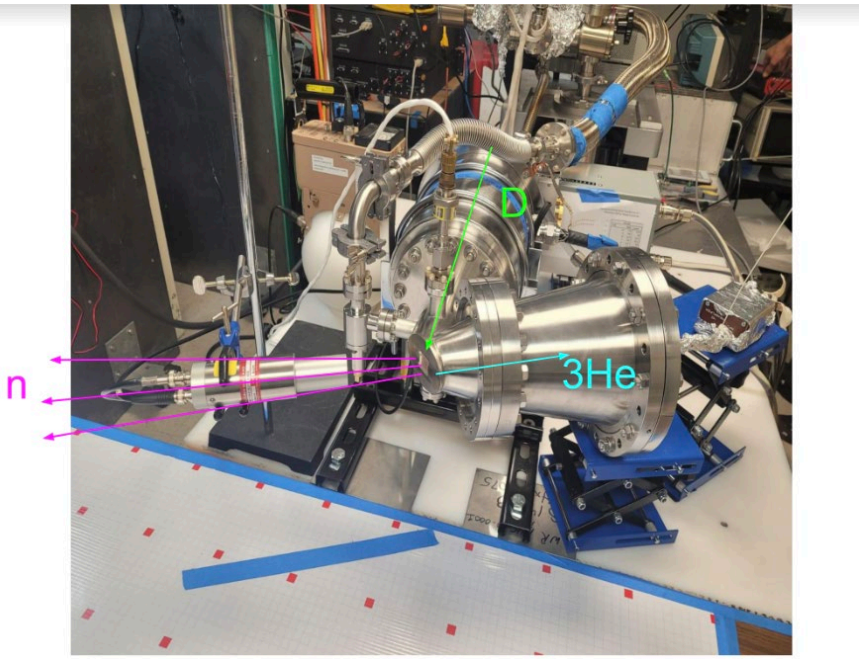
- ReD+ measurements (Cf & DD gun) both **require**:
  - New TPC, bigger than the old one (and cylindrical)
    - TPC being redesigned and built, SiPM readout (UniNA & LNS-INFN)
  - Refurbishment of the cryogenic system: ongoing in Naples
  - Larger neutron spectrometer (18 more PSci bought, UniCT)
  - Reduce the accidental background:
    - Improvement in the source shielding on the front side (UniCT)
    - Reduction of the passive volumes using new mechanical supports for Psci (UniCT)
  - Funding available under the PRIN_2022JCYC9E (LP: 6%)
- Comparable **timelines** for the two measurements
  - ReD+: Oct 2023- Mar 2026 (PRIN) → **March 2026**
  - DD gun: 2026-2027
  - Need of a "radioprotected" experimental area at LNS → Sala 40°
- Push sensitivity down to **0.2 keV$_{nr}$**

DD-Gun

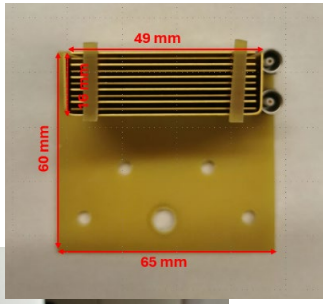
- Joint project with University of Sao Paulo (FAPESP grant)

$$^{2}_{1}\mathrm{D} + ^{2}_{1}\mathrm{D} \rightarrow ^{3}_{1}\mathrm{T}\,(1.01\ \mathrm{MeV}) + p^{+}(3.02\ \mathrm{MeV}) \quad 50\%$$
$$\rightarrow ^{3}_{2}\mathrm{He}\,(0.82\ \mathrm{MeV}) + n^{0}(2.45\ \mathrm{MeV}) \quad 50\%$$

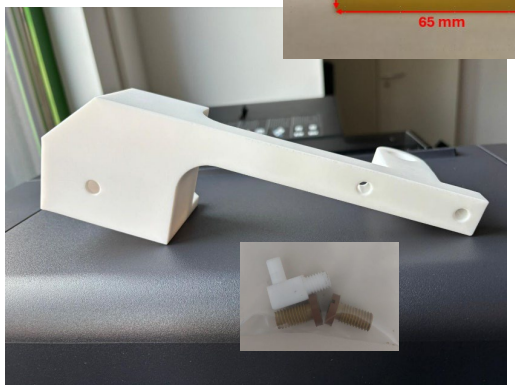
- **DD-gun**: up to 10^7 n/s of quasi-monochromatic neutrons (2.4 MeV)
  - Commercial (tabletop) device by Adelphi
  - Very small x-ray background
  - Delivered to USP in 2024: **being commissioned** now
  - **Neutron tagging** by detecting the accompanying ^{3}He with a Si detector (demonstrated @Adelphi and @USP)
  - Different systematics and higher rate than ^{252}Cf
  - Will be shipped to LNS within 2025



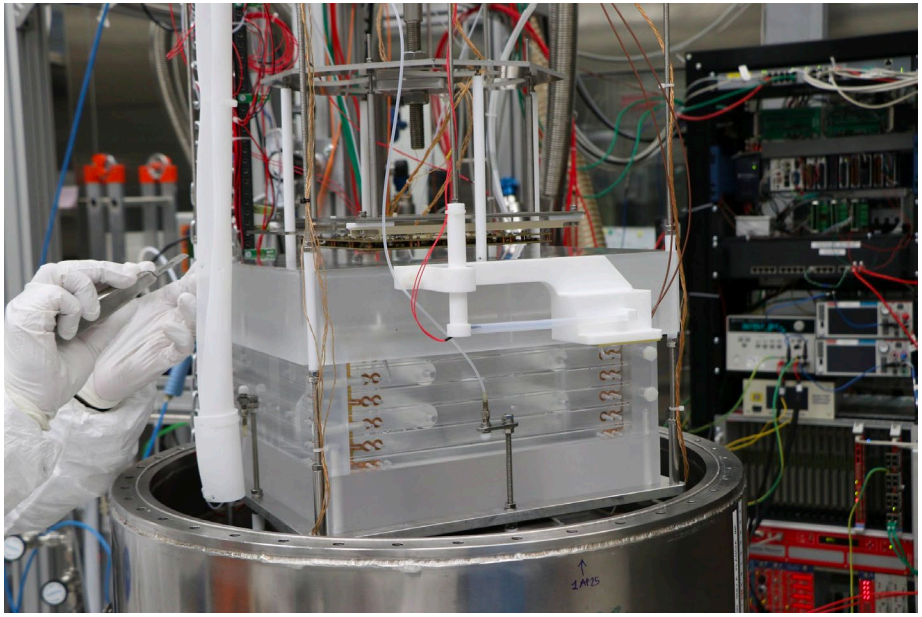
Activities in 2024/5: Proto-0 @ Na



- Operating a **TPC** (7 kg active mass), equipped with the very same **readout SiPM tiles** developed for DS-20k
- LNS contributing by **design** and realization of **mechanical parts** to host a **capacitive levelmeter**
  - Important to monitor the level of liquid argon → *not available* in ReD

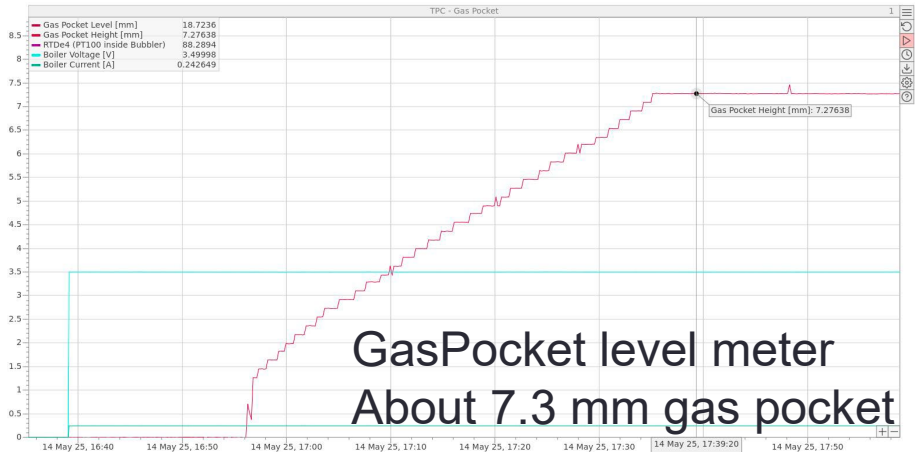


- First **cooldown** in July 2024
  1) Campaign-1 (ended on December 2024)
  2) Campaign-2 *ongoing*
- LNS **contributed** to:
  - Data taking shifts (3 weeks)
  - MC simulation studies
  - Data analysis
  - ^{83m}Kr source procurement



Proto-0 @ Na

Gas pocket formation:
boiler ON @ 0.84 W –
about 1h to get the GasPocket-meter at constant value



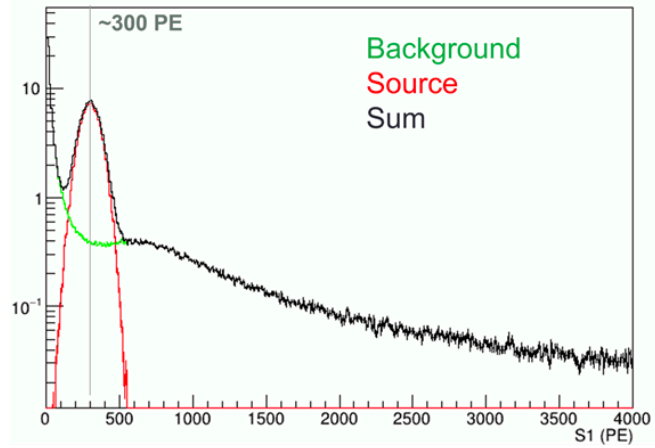
GasPocket level meter
About 7.3 mm gas pocket

NOA @ LNGS

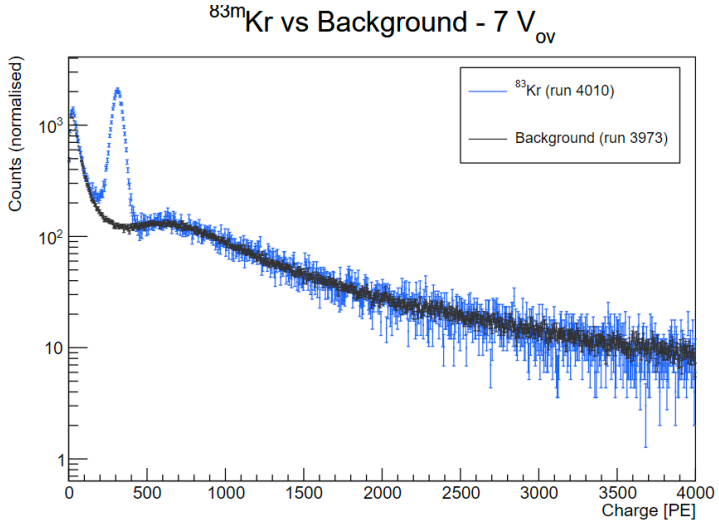
LNS contribute to **production shifts**:

- VETO: vTiles production completed,
  Goal: complete vPDU characterization by Oct!
- TPC: 10% of PDU production completed, test ongoing in Naples

^{83m}Kr source in single phase
Diffuse source decaying with two β emission (32.1 + 9.4) keV



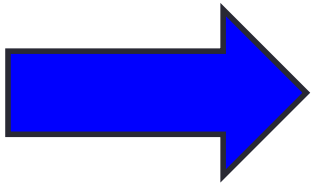
MONTE CARLO (NO OPTICS) + BKGD DATA



Attività e richieste 2026 – gruppo LNS

- Il progetto ReD in DarkSide è **in conclusione**. Attività 2026:
  - Preparazione pubblicazione, presentazione risultati conferenze
  - Non sono previste spese
- Attività legate al PRIN **ReD+** e al progetto **DDgun**
  - Finanziamenti extra-CSN2
- Anche **Proto-0 termina** nel 2025 per la CSN2
  - Attività di analisi dati, etc.
- Attività 2026 sotto l'ombrello di **DarkSide CSN2:**
  - **Contributo** all'attività sperimentale di testing per le TPC-PDU **a Napoli**
  - **Sviluppo software** (offline, Monte Carlo, analisi) e **fenomenologia** per DarkSide-20k
  - Possibili **turni a NOA**
- Richieste finanziarie ridotte
  - Missioni per meeting ed attività a Napoli e LNGS
  - Da integrare per eventuale turnistica

Preliminary



Richieste 2026 – gruppo LNS

M. Gulino **(Resp Loc.)**	Associato (UniKore)	70% (TBC)
L. Pandola	Ricercatore II	50% (+6% PRIN) = 56%
G. Manicò	Associato (UniCt)	40% (TBC)
N. Pino	Ass. Ricerca	0% (+100% PRIN) (end 11/2025)
TOTALE		**1.60 w/o PRIN** (1.37 nel 2025) 2.66 FTE w/ PRIN

Preliminary

Missioni	- Contatti con altri gruppi, meeting di Collaborazione, partecipazione turni misura	8 k€
Consumo	- (da definire)	TBD k€
TOTALE		**8 k€**

Richieste ai LNS

- Per la misura ReD+ con **^{252}Cf (PRIN)**
  - Richiesta di spazio sperimentale attrezzato (LAN, quadri elettrici, carroponte, uso gas in bombola …) in zona controllata, circa 4 x 10 m^2 [email: 02/04/2025]
  - **Sala 40 gradi**, concordata con Direttore, capi Div Ric e Tecnica, RSPP
    - Riscontro immediato da Divisione Ricerca (Servizio Utenti), Divisione Tecnica e Servizio Radioprotezione (**grazie**!)
    - Uso **non** esclusivo della sala
  - Supporto del Servizio Utenti (Rep. Elettronica, Rep. Apparati Sp.)
  - Supporto dei Servizi Amministrazione, Fondi Esterni, Radioprotezione
- Per le successive fasi con **DD gun**
  - Stesso spazio sperimentale (uso non esclusivo)
  - DD gun in prestito temporaneo da FAPESP, da restituire entro inizio 2028
    - Supporto Amministrazione per pratiche doganali
    - Supporto Radioprotezione per pratiche autorizzative
  - Stesse richieste di supporto ai Servizi dei LNS