



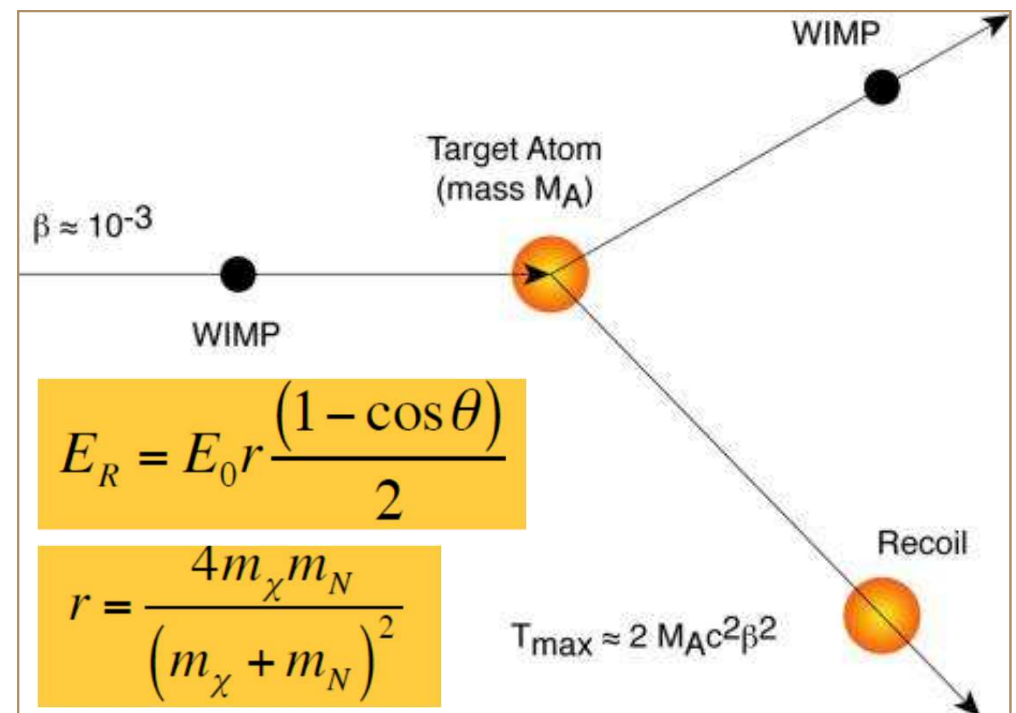
L. Pandola (LNS)

on behalf of the DarkSide LNS Group

Gruppo 2 Local Meeting, June 25th 2024

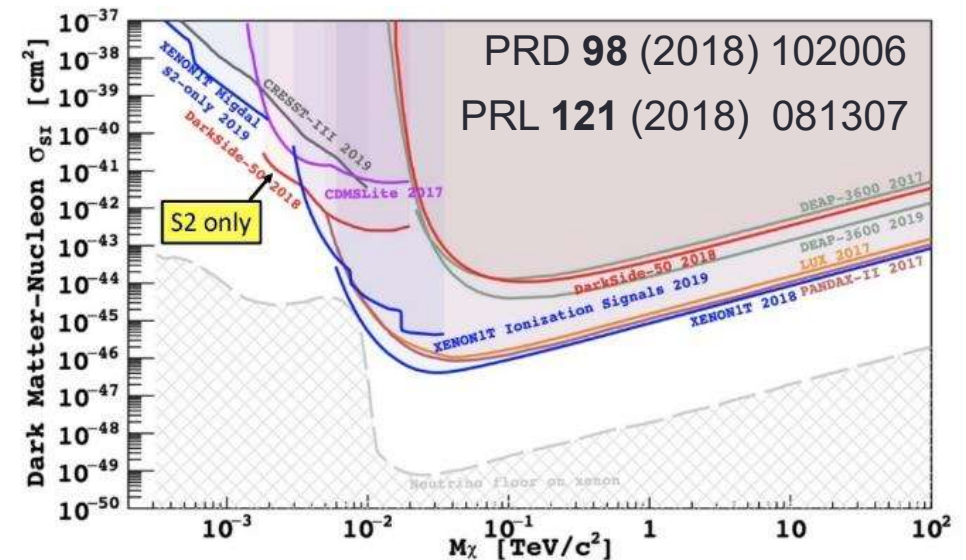
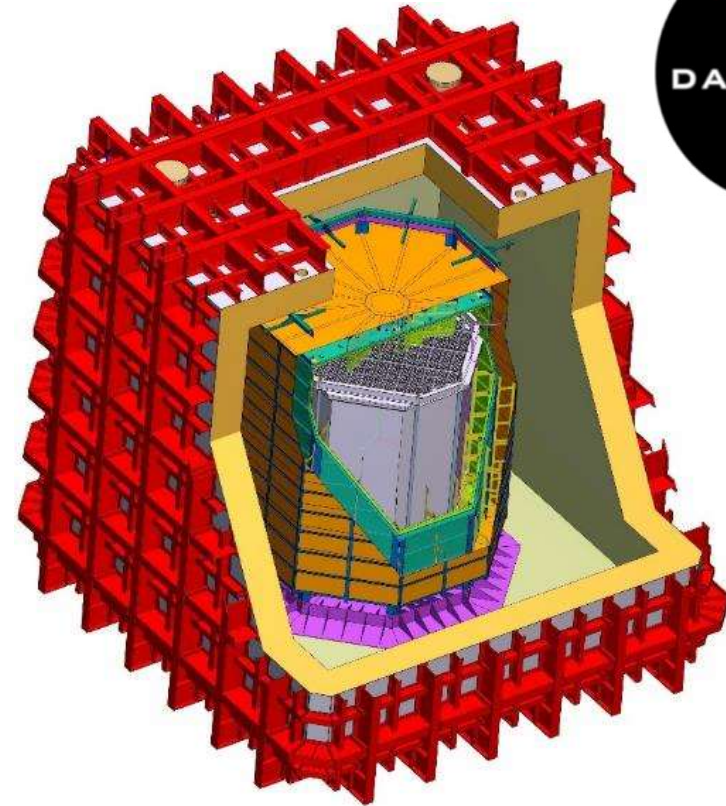
Physics background

- 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)



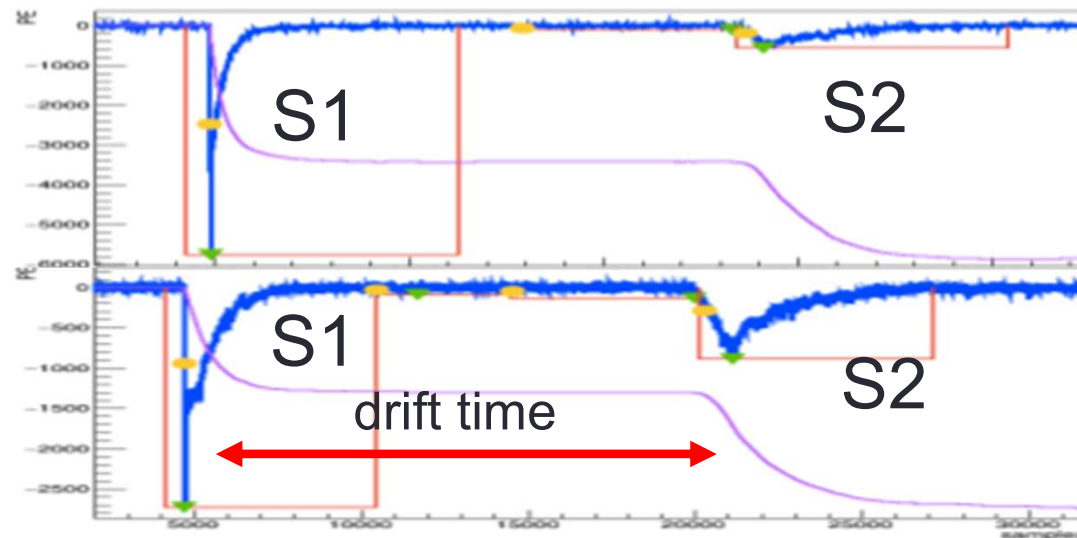
Physics background

- **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 $10^{-47} \text{ cm}^2 @ M_W = 1 \text{ TeV}/c^2$
 - Next-next step: global worldwide effort (ARGO, 300 ton LAr)
- More sensitive to **low-mass WIMP** than Xe, due to the **lighter target**

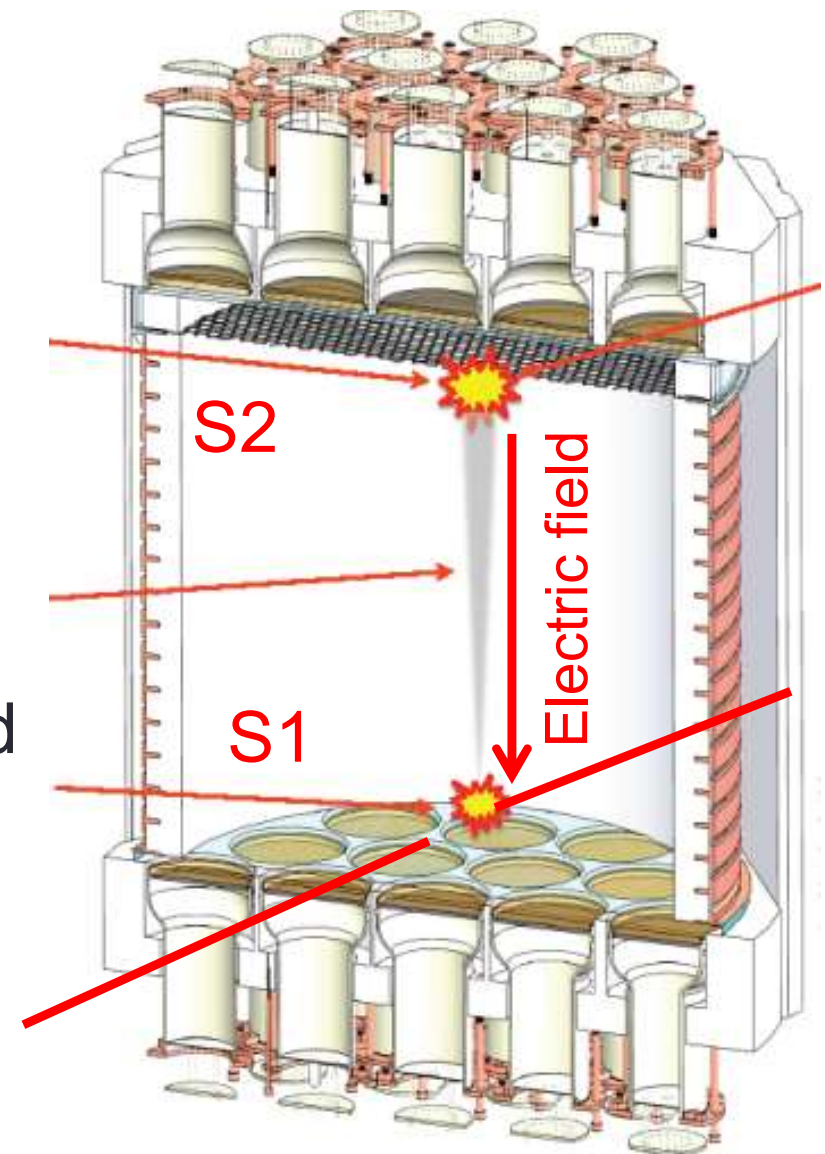


Dual-phase Ar TPC & low-mass WIMPs De

- The working principle...

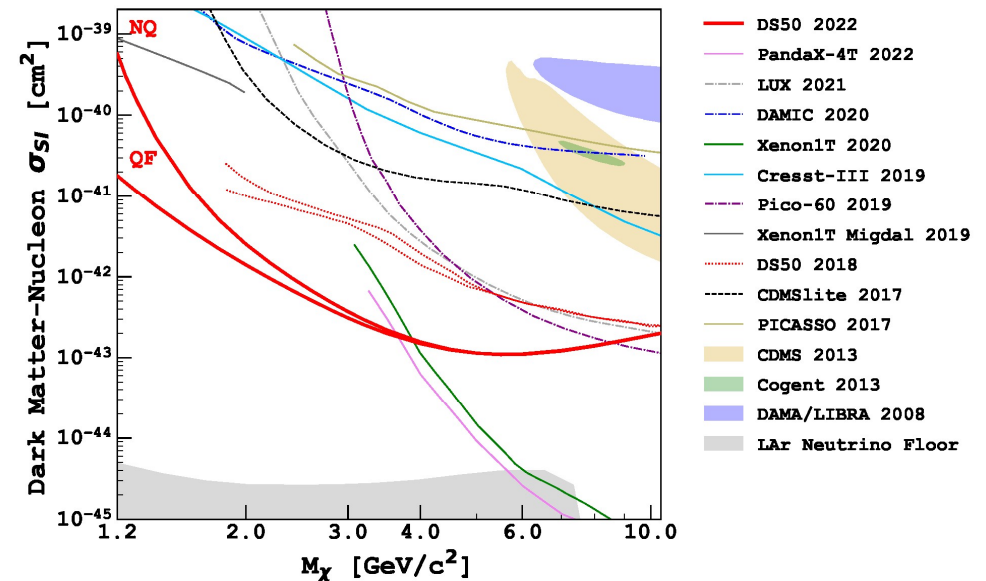


- Allows for full **3D reconstruction** (and hence fiducialization)
 - (X, Y) from the **$S2$ light pattern** in the top sensors
 - Z from the **drift time** between $S1$ and $S2$
 - Many 10's or 100's of μs
- Designed for optimal sensitivity to "**standard**" (100 GeV) WIMPs



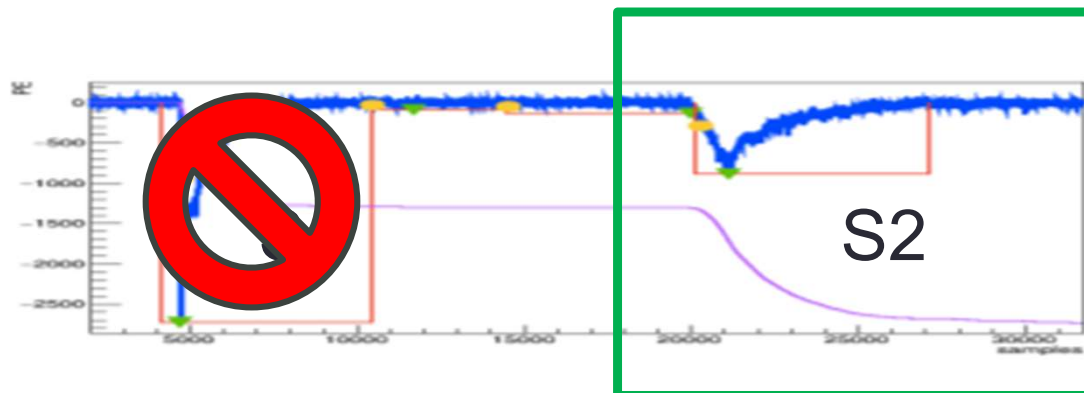
The search for low-energy WIMPs

- 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



The ReD project

- **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

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

EPJ C 81 (2021) 1014
 THE EUROPEAN PHYSICAL JOURNAL C

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

P. Agnes¹, S. Albergo^{2,3}, I. Albuquerque⁴, M. Arba², M. Ave⁴, A. Boiano⁶, W. M. Bonivento⁵, B. Bottino^{7,8}, S. Bussino^{9,10}, M. Cadeddu², A. Caminata⁷, N. Canci¹¹, G. Cappello^{2,3}, M. Caravati^{5,12}, M. Carliello⁷,

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

EPJ C 84 (2024) 24

THE EUROPEAN PHYSICAL JOURNAL C

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

DarkSide-20k Collaboration*

PS PROCEEDINGS OF SCIENCE

Characterization of low-energy argon recoils with the ReD experiment

INFN

CHARACTERIZATION OF LOW-ENERGY ARGON RECOILS WITH THE RED EXPERIMENT

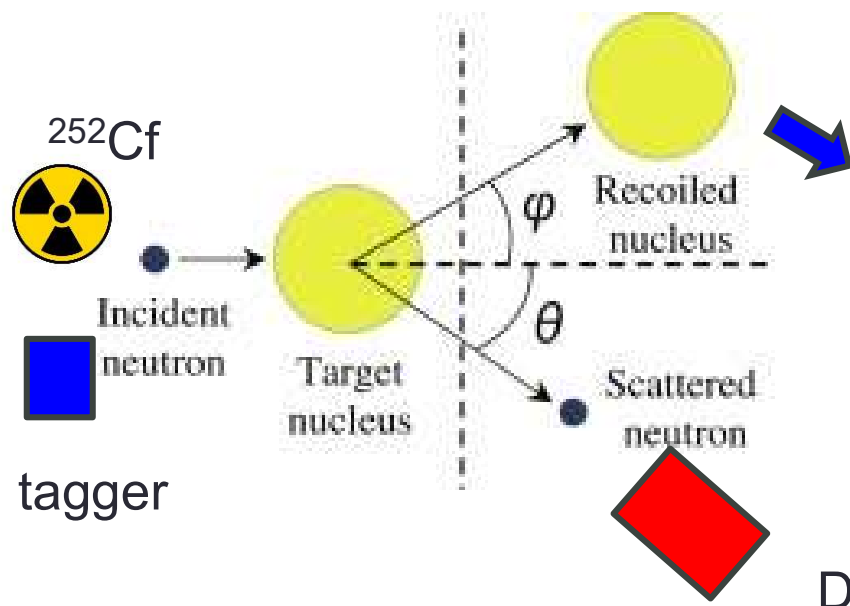
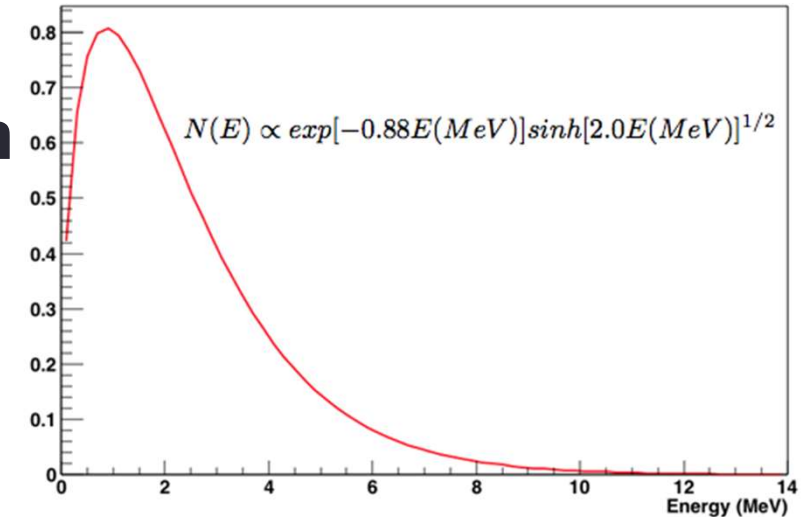
L. Pandola (LNS)
 on behalf of the ReD Working Group
 (GADM Collaboration)

TAUP 2023, Wien
 August 29th, 2023

REcoil Directionality

The working principle

- Strategy: Produce **Ar recoils of known energy** in the TPC by (n,n')
- Neutrons from a **²⁵²Cf fission source**
 - Neutrons **O(2 MeV)** and up to **10 MeV**
 - Appropriate to produce NR of a few keV
- **Close detectors (BaF₂)** to tag **fission events**
- **Neutron spectrometer** to detect neutrons scattered off-Ar



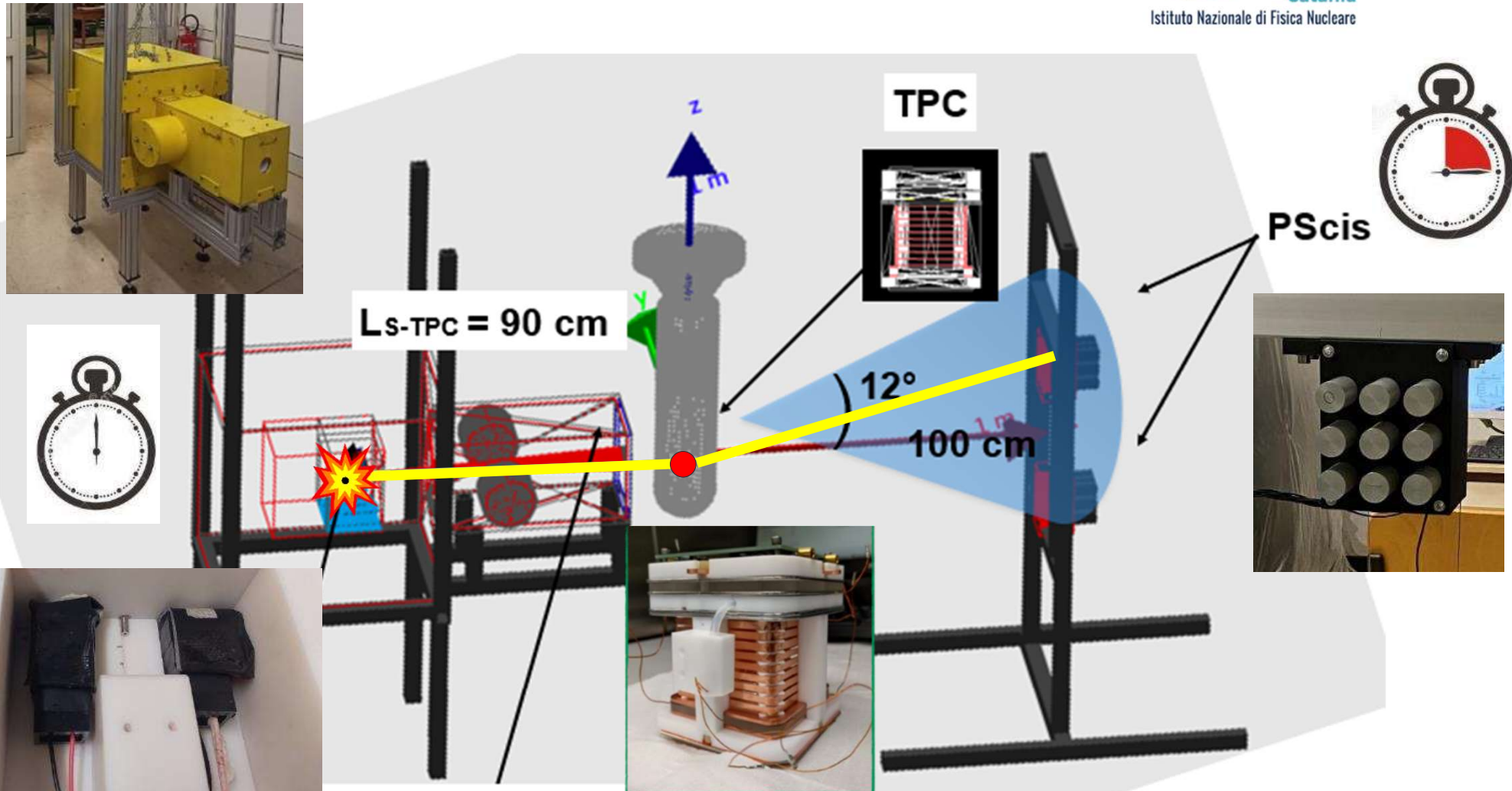
$$E_{NR} = 2K E_{neutron} \frac{m_n m_{Ar}}{(m_n + m_{Ar})^2} (1 - \cos\theta_{scatt})$$

Time of flight

Fixed by geometry

Two-body kinematics!

The ReD conceptual layout



Ls-TPC = 90 cm

TPC

PScis

12°
100 cm

Neutron exit cone (~2°)

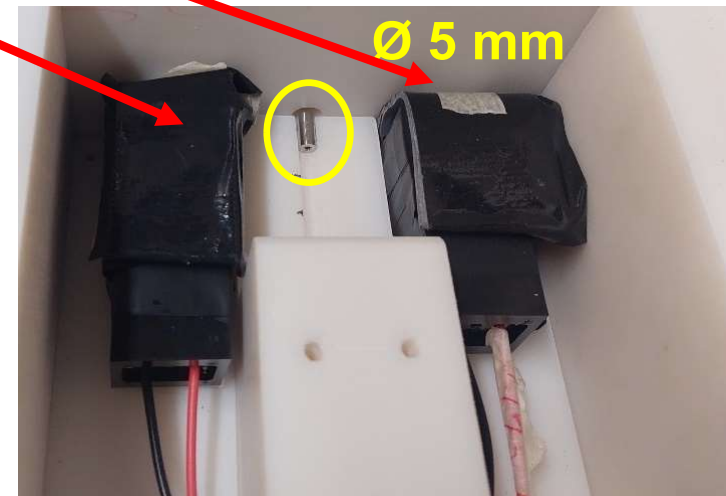
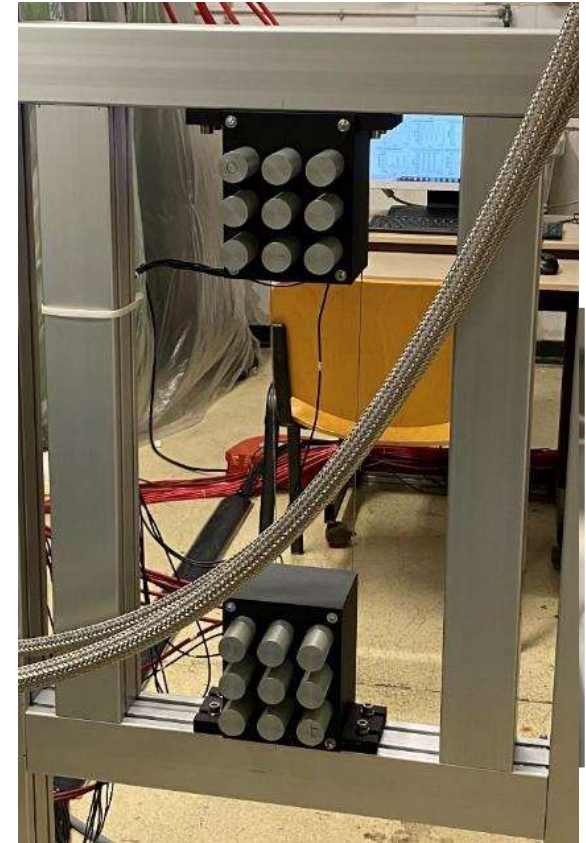
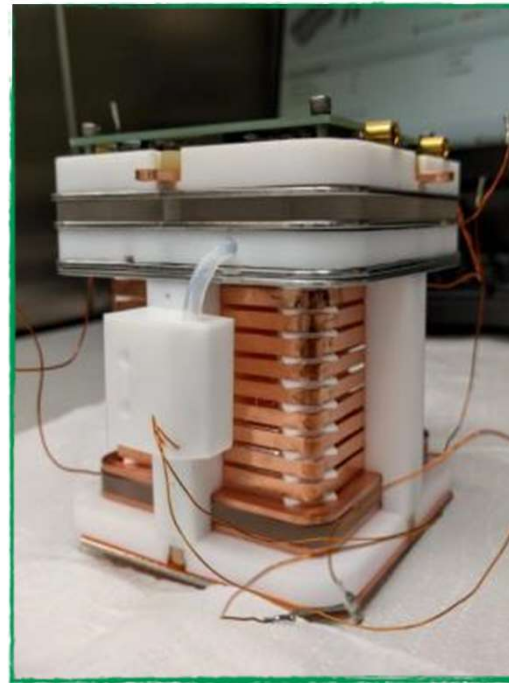
²⁵²Cf source (1.48 MBq) and BaF₂ taggers

- Design sensitivity in the range **2-5 keV_{nr}**

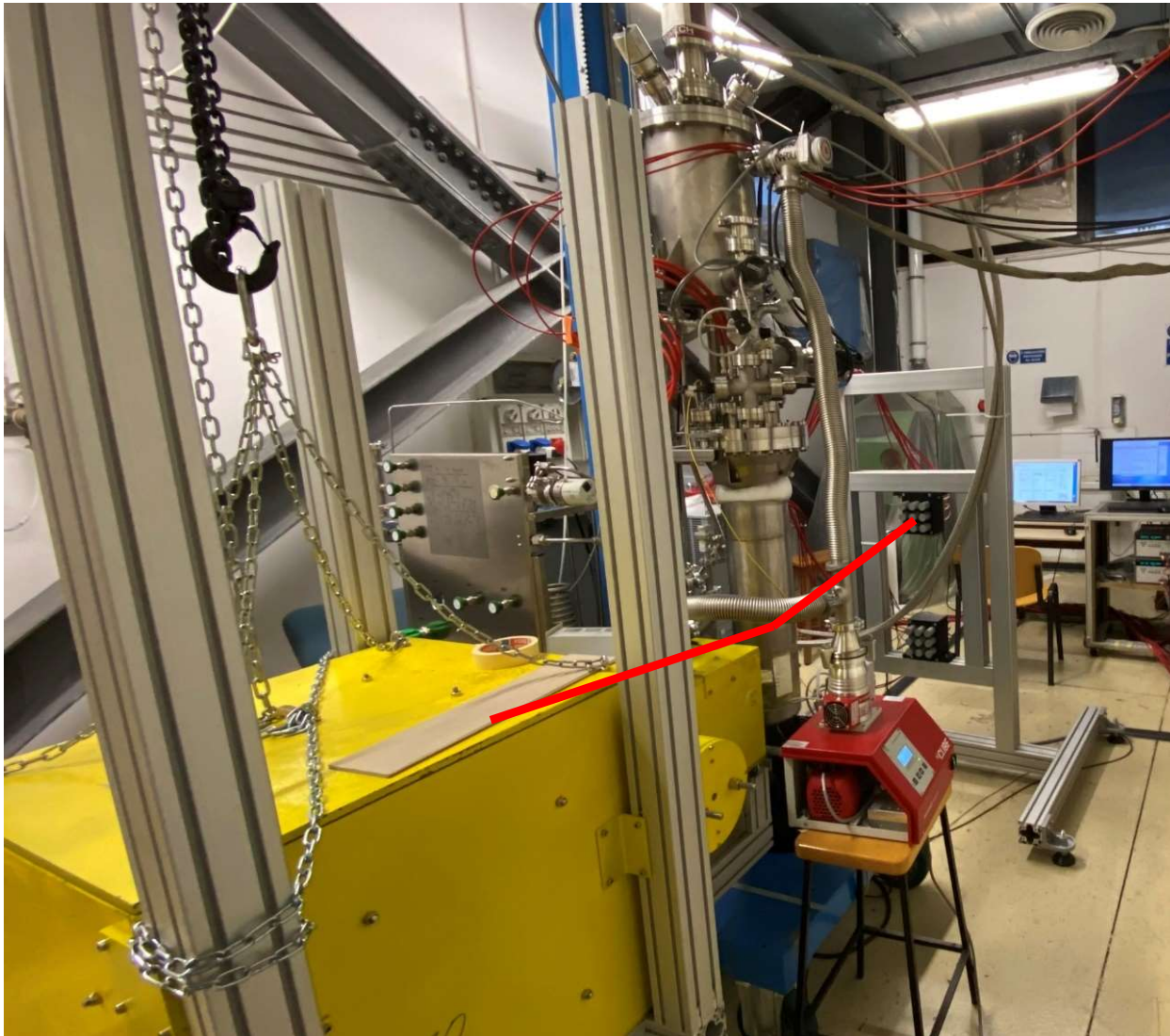
Conceptual design from University of Sao Paulo

The ingredients

- Our **ReD TPC**
 - Light readout: $5 \times 5 \text{ cm}^2$ 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 $\sim 2^\circ$**
 - Shines **the entire TPC** at 1 m distance
- Tag Ar recoils down to $\sim 1\text{-}2 \text{ keV}_{\text{nr}}$



The real thing at

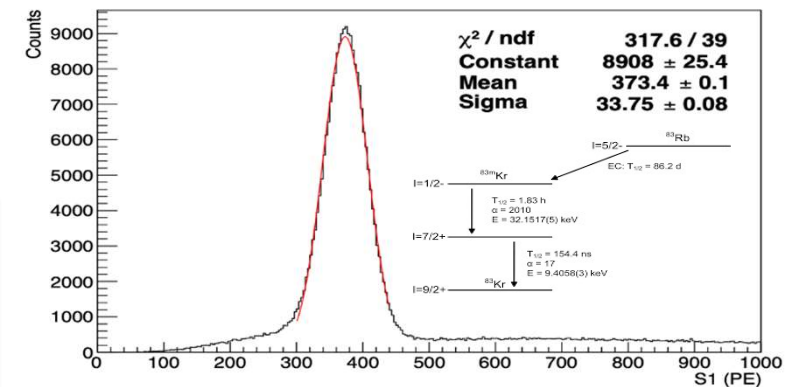
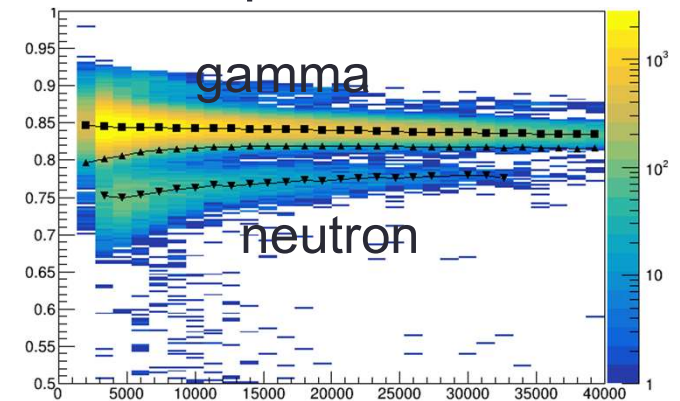


Low-energy run - timeline

- Jan – Mar 2023: Data taking with ^{252}Cf
 - Trigger logic: "any BaF" \wedge "any PSci"
 - Tagging $\sim 60\%$ of SF events
 - TPC acquired in **slave** mode (may fail to trigger in S1)
 - **Weekly calibration** with **laser** and ^{241}Am
 - Used to correct for **non-homogeneity** in the TPC response
- May 2023: Calibration with **low-energy e^-** (42 keV) from a **diffuse $^{83\text{m}}\text{Kr}$ source**
 - Study of the **TPC XYZ response** - corrections for **inhomogeneities**
- Warm up: Jun 23rd 2023
- **Decommissioning** completed
- **Data analysis** being finalized



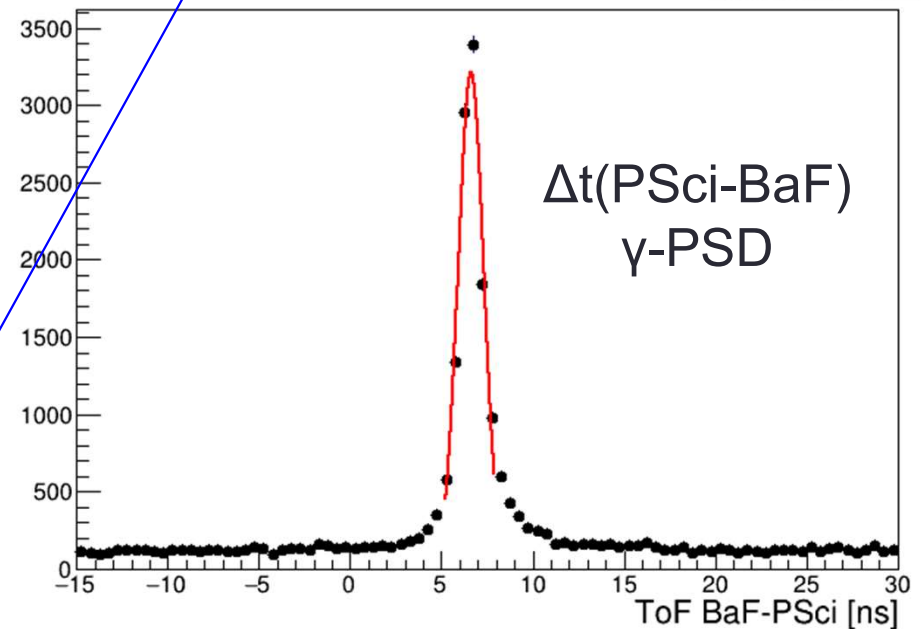
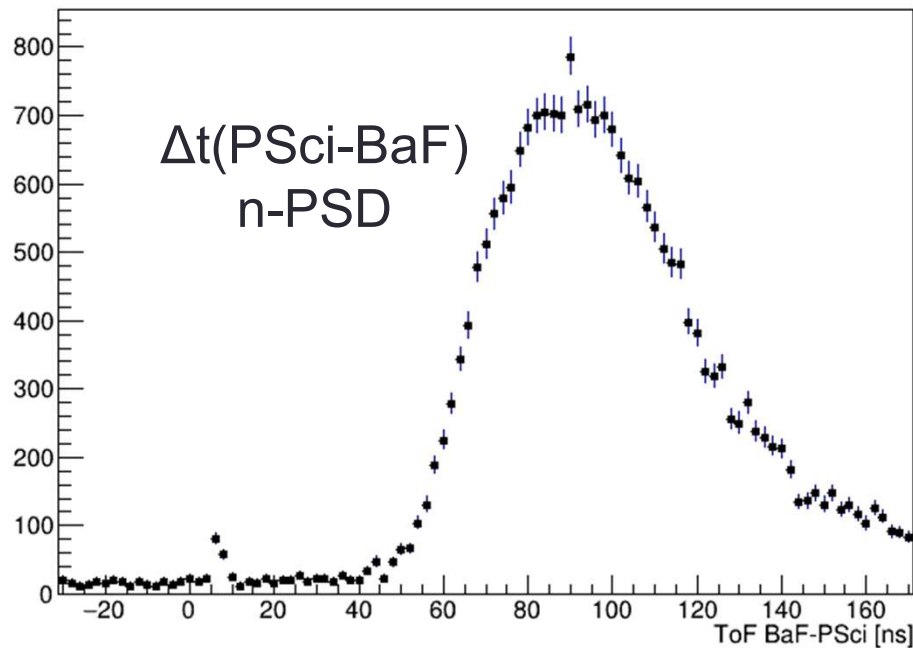
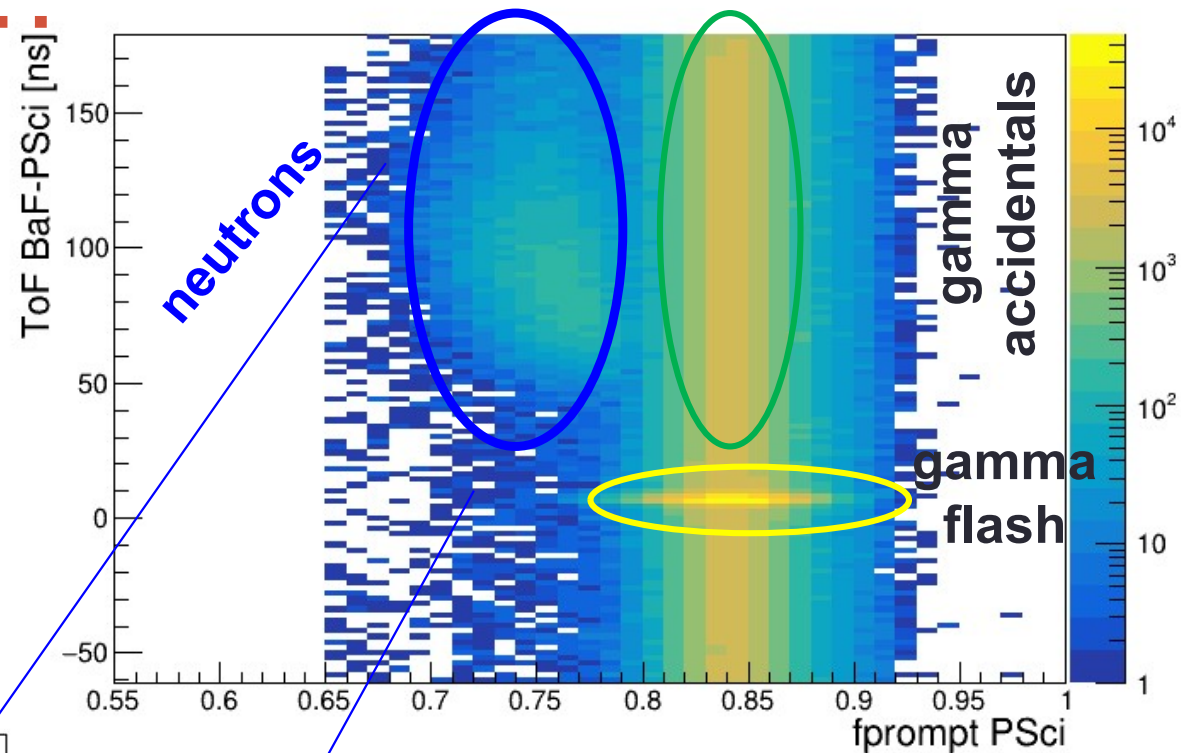
Plastic scintillators n/y separation



Finding neutrons...

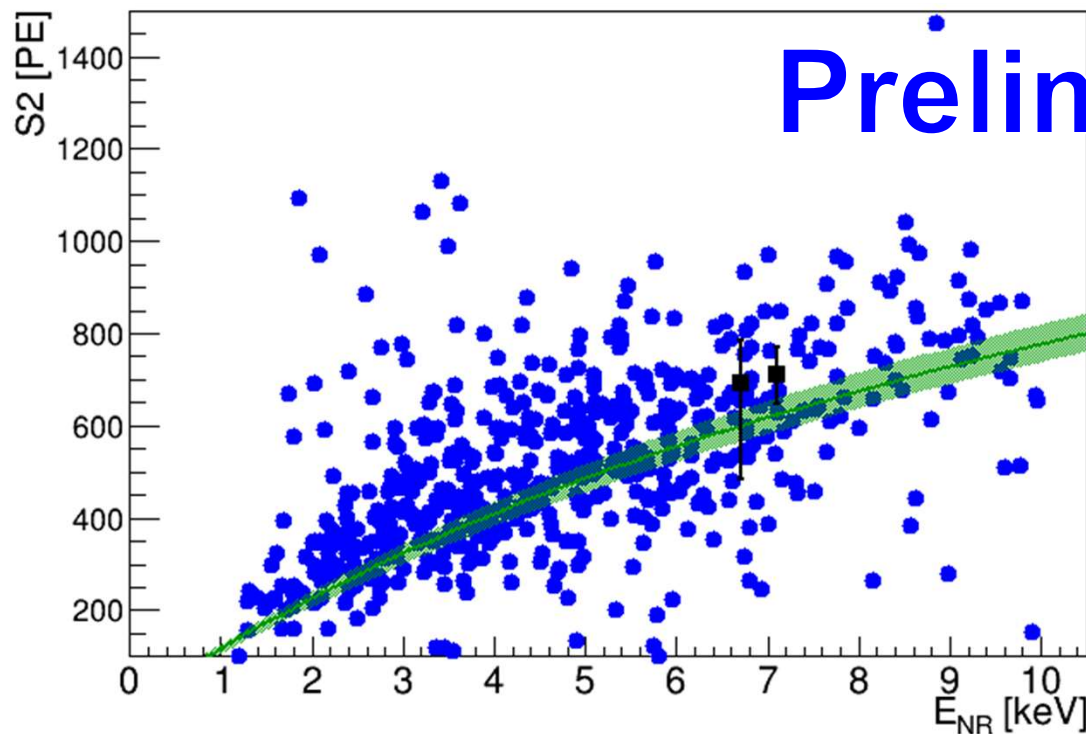
- Event rate dominated by γ -rays and accidentals
- Selection of candidate neutrons by **time of flight** and **PSD**
 - About 28 events/hour (0.3%)
- ToF resolution ~ 0.7 ns
- Event-by-event E_n at $<5\%$

$\Delta t(\text{PSci-BaF})$ vs. PSD in PSci



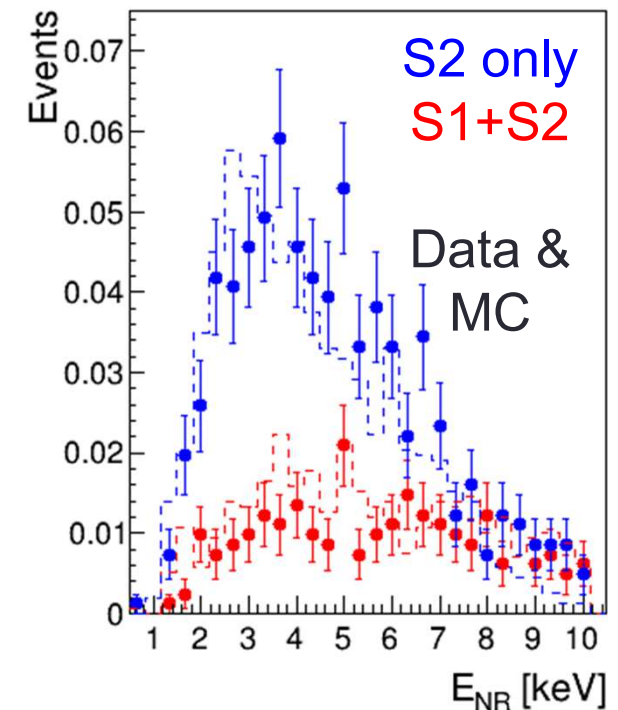
The sample of low-energy recoils

- Look for TPC events **offline**
 - Final sample: ~820 passing all cuts, out of 2300 candidates (75% are S2-only)
 - Get E_{NR} from time of flight (and geometry), uncert. $\pm 5\%$
- Using **S2-only**: E_{NR} down to 1-2 keV_{nr}
 - **Confirmed** the design sensitivity down to 2 keV_{nr} (*terra incognita*)
- Compare against **the prediction of the DS-50 model** and literature data, using a **preliminary** value of g_2



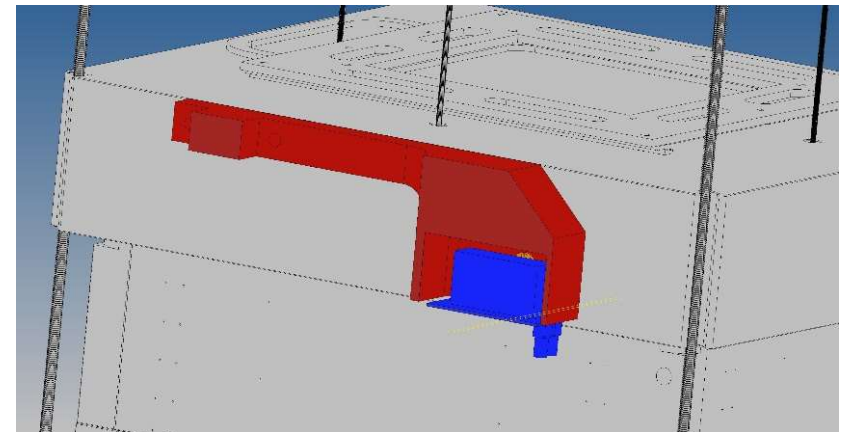
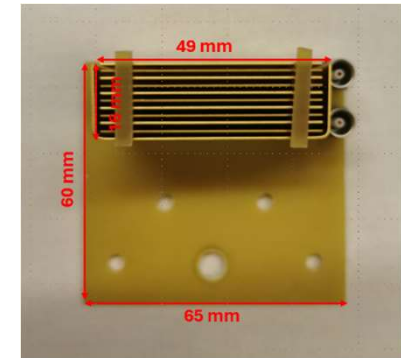
**DS-50
model**

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




Activities in 2024: Proto-0 @ Na

- Will operate 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
- Will contribute to **data taking, shifts** and **data analysis**
- ... and also **shifts at NOA** for SiPM assembly (1 week in 2024)



Next steps

- **Finalize data analysis**
 - **Confirmed** the sensitivity **down to 1-2 keV_{nr}**
 - Need to **consolidate** the measurement of g_2 and **to extract the final ionization yield (in e-/keV)** → **allows to compare with the literature**
- ReD – as a part of the TDR of DarkSide – is **completed** 
 - Collaboration **focused** on the **construction** of the **DarkSide-20k detector**
- Still the calibration of Dark Matter detectors for **very low-energy nuclear recoils** is a hot topic!
- **Two follow-ups** in Catania to further improve and push sensitivity:
 - **ReD+**: New improved calibration with ^{252}Cf
 - Funded as a two-year **PRIN project**, INFN, UniCt, UniNa (183k€)
 - Started in September 2023
 - 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: it will be commissioned and shipped to LNS



Perspectives for 2025 & further



- ReD+ and DD gun measurements both require an **improved TPC** and the **refurbishment** of the cryogenic system
 - TPC being **redesigned** and **built**, **SiPM readout** (UniNA & INFN)
 - Increase the solid angle by **doubling** the **neutron spectrometer**
 - Funding available under the PRIN
 - Use the **lessons learnt** from the ReD run of 2023
 - Reduce accidental background (which limited the ReD measurement)
 - Less passive volumes, higher g_2 , longer T_{drift}
- Comparable **timelines** for the two measurements
 - ReD+: **Oct 2023-Oct 2025** (PRIN)
 - DD gun: **early 2025**
 - Need of a **"radioprotected" experimental area** at LNS
- Push sensitivity down to **0.4 keV_{nr}**

ReD+



Finanziato
dall'Unione europea
NextGenerationEU



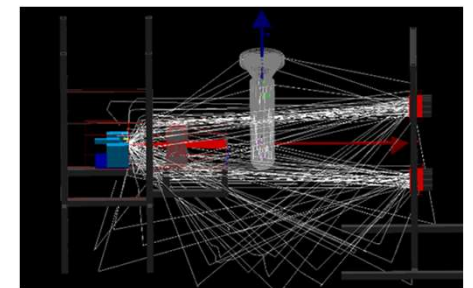
Ministero
dell'Università
e della Ricerca



Italiadomani
PIANO NAZIONALE
DI RIPRESA E RESILIENZA

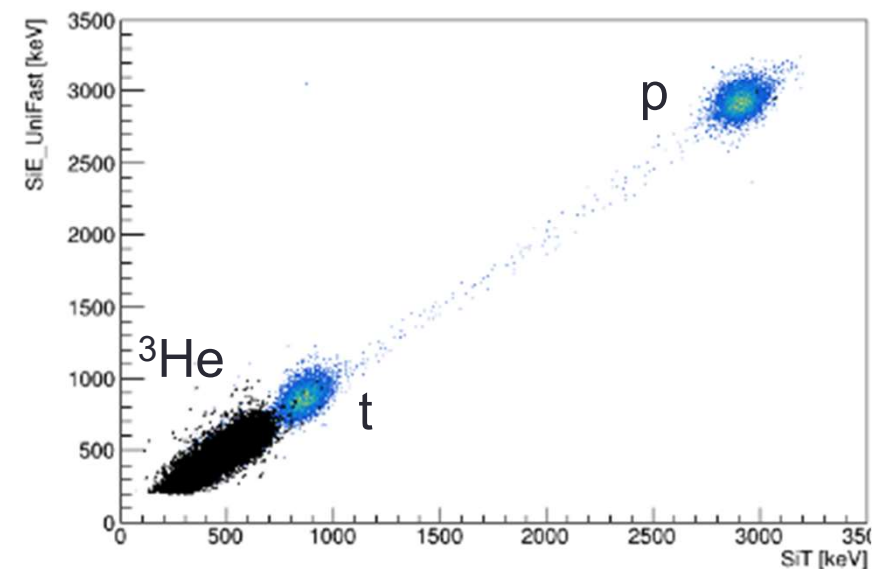
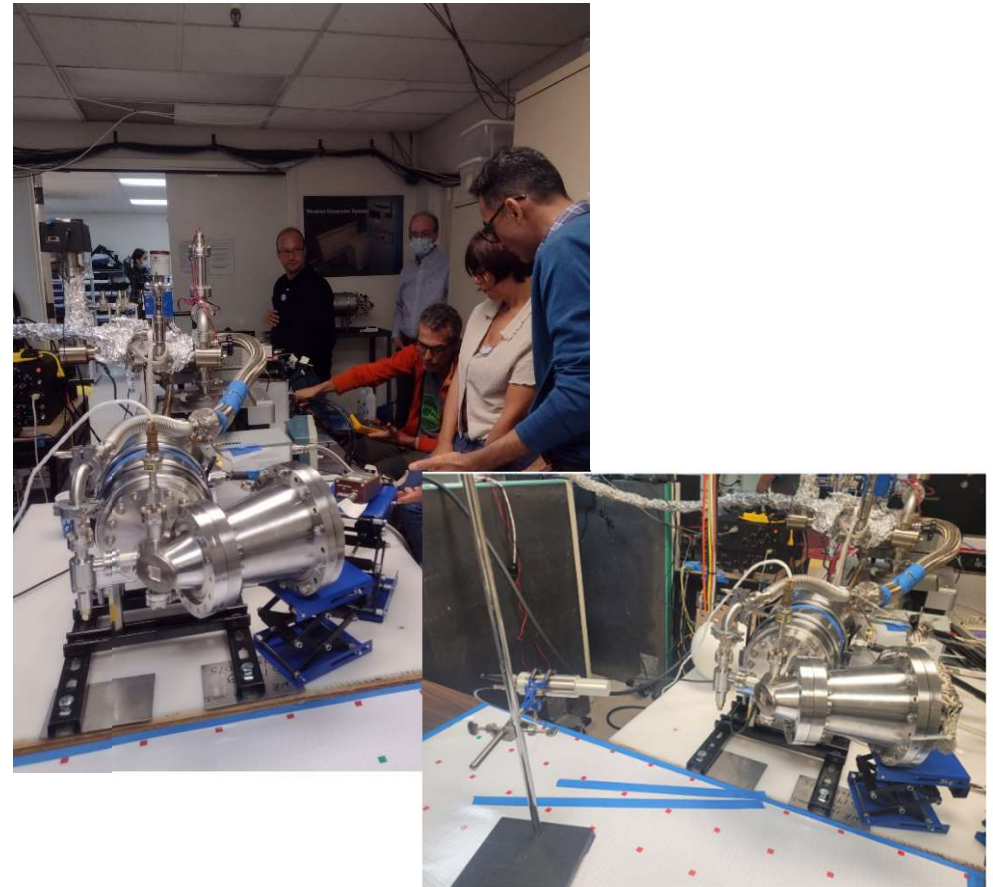


- Sigla **PRIN_2022JCYC9E** (LP: 23%)
 - INFN funding: **60k (incl. OH)**
- **Goal: Extend coverage** of ReD down to **0.4 keV** using the same approach (**^{252}Cf source**) but **optimized components**
 - **New TPC**, **bigger** than the old one (and **cylindrical**)
 - Larger **neutron spectrometer** (18 more Psci ordered)
- **Timeline:**
 - First phase: **Monte Carlo studies** to define the TPC design (now)
 - Production and characterization of the TPC (and spectrometer) in 2024
 - **Integration** of the system in **spring 2025**
- **Additional manpower:**
 - Un AdR (concorso da espletare)
- Will follow up into the **activity 3.2.G1 of DRD2**
 - "Understanding Microphysics of noble liquid (NL) response"
 - Was already **included in the proposal** (250 k€ in total, Na+LNS)



DD-Gun

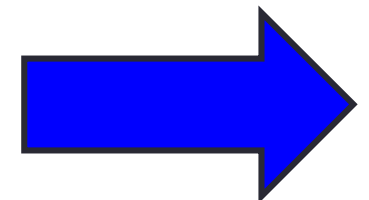
- **Commercial DD gun (Adelphi)**
- Mono-energetic **2.4 MeV**
- **Neutron tagging** via **associated ^3He**
 - **Demonstrated** → experimental tests at Adelphi on October 2023
- Very **small x-ray background**
- Assuming a conservative flux of **10^6 n/s** (achieved @Adelphi), signal rate **comparable to ReD+**
 - Different systematics
- **Delivered to USP on June 5th**
 - Could be shipped at LNS in **early 2025**



Attività e richieste 2025 – gruppo LNS

- Il progetto ReD in DarkSide è **in conclusione**. Attività 2025:
 - **Finalizzazione** analisi dati, preparazione **pubblicazione**
 - Non sono previste spese
- Attività legate al PRIN **ReD+** e al progetto **DDgun**, poi **DRD2**
 - Finanziamenti extra-CSN2
- Attività 2025 sotto l'ombrello di **DarkSide CSN2**:
 - **Contributo** all'attività sperimentale di **Proto-0 a Napoli** e test **SiPM**
 - **Sviluppo software** (offline, Monte Carlo, analisi) e **fenomenologia** per DarkSide-20k
 - Possibili **turni a NOA** (già nel 2023-4: 4 settimane)
- Richieste **finanziarie ridotte**
 - **Missioni** per meeting ed **attività a Napoli**
 - Da integrare per eventuale **turnistica**
 - Materiale di **consumo** per attività di **Proto-0** (da concordare)

Preliminary



Richieste 2025 – gruppo LNS



| | | |
|--------------------------------|---------------------|----------------------------|
| M. Gulino (Resp Loc.) | Associato (UniKore) | 60% (TBC) |
| L. Pandola | Ricercatore II | 32% (+23% PRIN) = 55% |
| G. Manicò | Associato (UniCt) | 40% (TBC) |
| TOTALE | | 1.55 (0.7 nel 2023) |

Preliminary

| | | |
|-----------------|---|--------------|
| Missioni | - Contatti con altri gruppi e meeting di Collaborazione | 7 k€ |
| Consumo | - Acquisto sorgente di calibrazione per attività di Proto-0 | xx k |
| TOTALE | | xx k€ |