CHARACTERIZATION OF LOW-ENERGY RECOILS WITH THE RED EXPERIMENT

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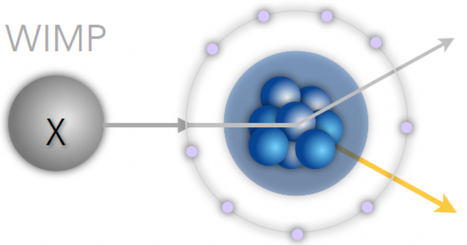
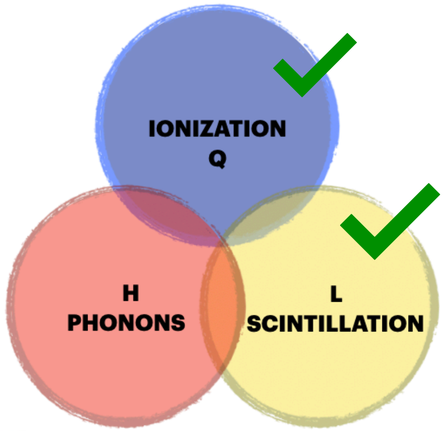
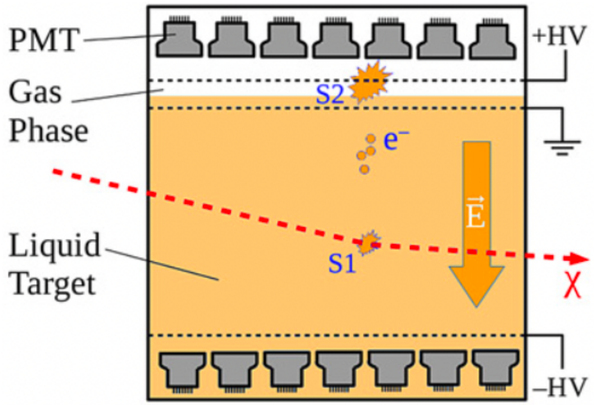
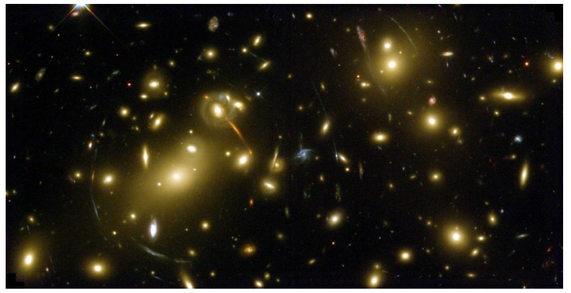
DIRECT DETECTION OF DARK MATTER

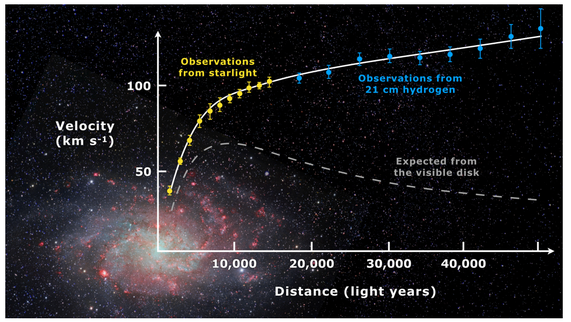
- **WHO?**
  - Weakly Interacting Massive Particles (WIMPs)
- **WHAT?**
  - WIMP-induced Nuclear Recoils (NRs)
- **WHERE?**
  - Dual-phase Time Projection Chambers (TPC) filled with liquefied noble elements (Ar or Xe) (*but other detector technologies are also used*)
- **HOW?**
  - Signals from **scintillation** and **ionization**
- **WHY?**
  - Solve the puzzle of this unknown constituent of the Universe







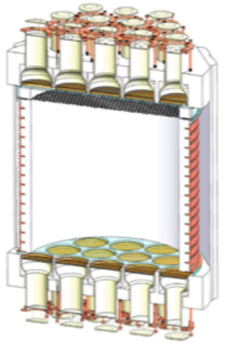




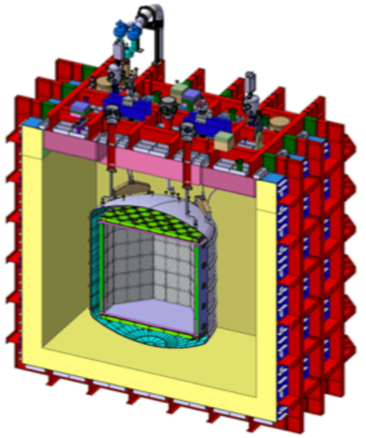
THE GLOBAL ARGON DARK MATTER COLLABORATION EFFORT

- Liquid Argon multi-tonnes experiments
- Push sensitivity down to neutrino fog

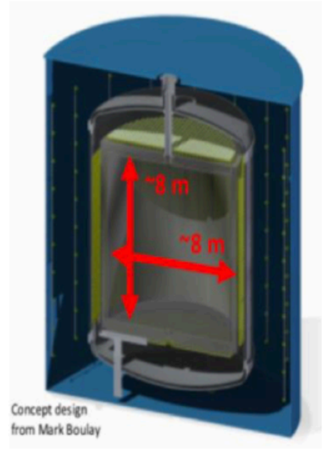
2013 - 2019 → 2026 - 2035 → 2030s - ...



DarkSide-50



DarkSide-20k @LNGS

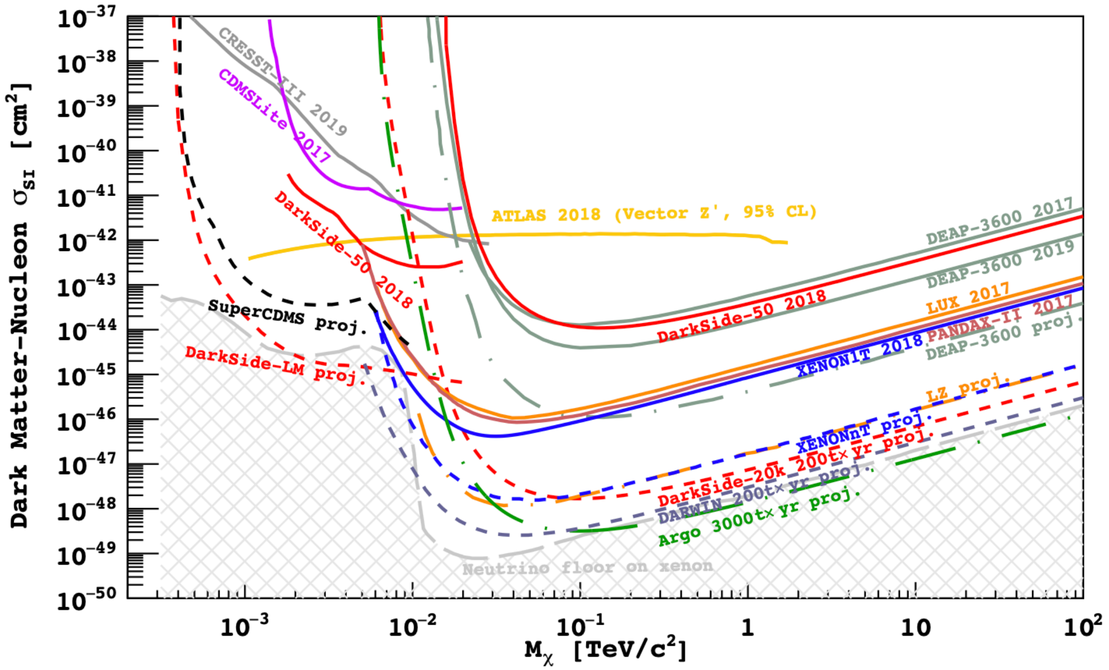


ARGO @SNOLAB

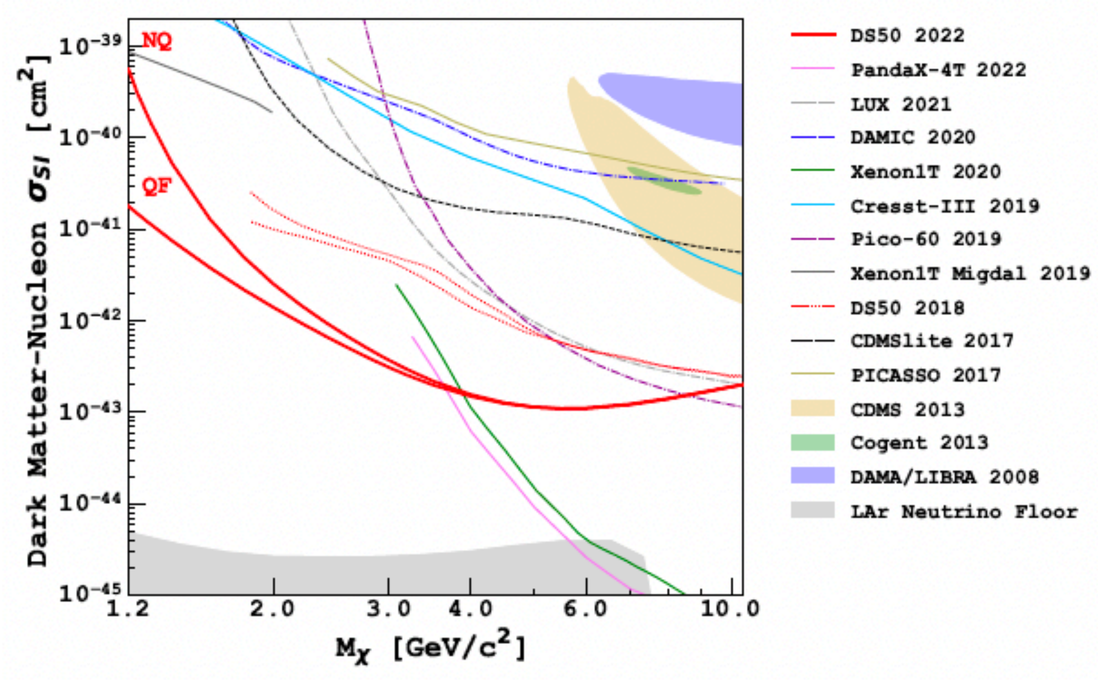
Intense R&D phase

REcoil Directionality

Global Argon Dark Matter Collaboration, European Strategy on Particle Physics Dec 2018



WHY DO WE LOOK FOR LOW-ENERGY RECOILS IN LAR TPC?



Phys. Rev. D **107**, 063001 (2023)

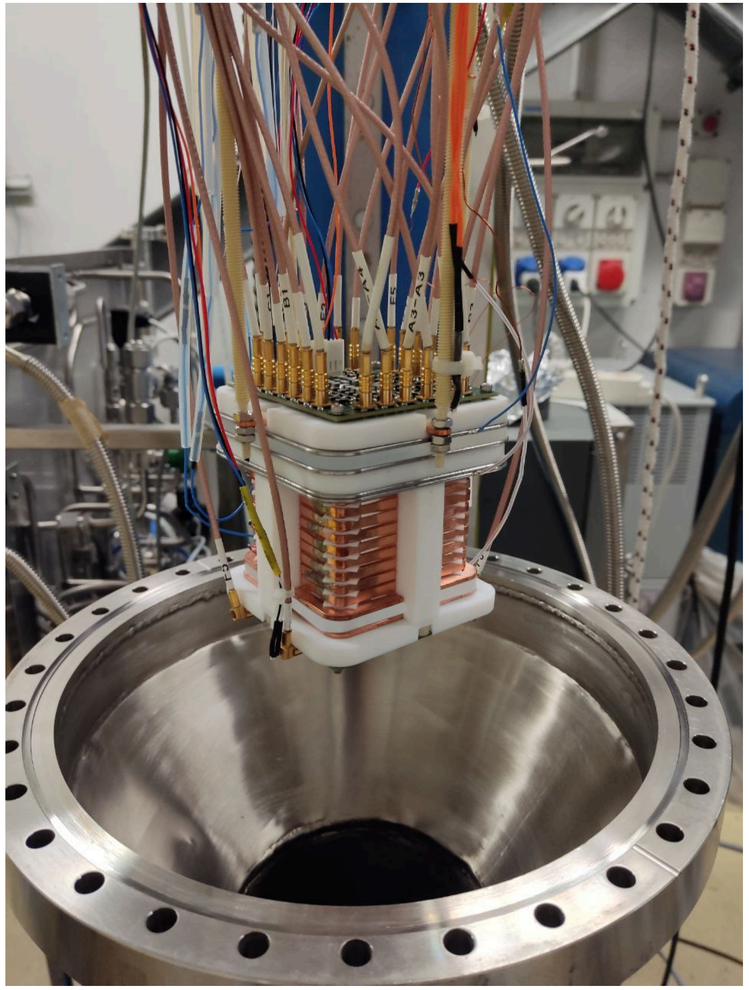
- In 2018 DarkSide-50 extended its physics case to lighter Dark Matter
- ***Challenging*** → ionization is the only detection channel available since the ***efficiency for detecting scintillation signal is low***
- No signal for WIMPs → current 90% CL exclusion limit set for spin independent WIMPs with mass in [1.2, 3.6] GeV/c^2
- Dedicated calibration with neutron sources mandatory to improve and better constrain response model at the keV scale

REcoil **D**irectionality experiment aims to characterize the response of a dual-phase LAr TPC for NRs down to the **unexplored range of 2-5** keV_{nr} to study the charge yield vs the energy of the recoil (E_{NR})

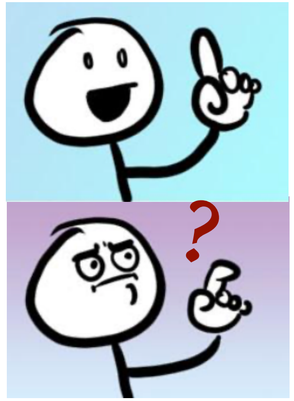
RECOIL DIRECTIONALITY (RED) EXPERIMENT

- R&D project within the *Global Argon Dark Matter Collaboration*
- Double-phase, Liquid Argon Time Projection Chamber
- Three scientific objectives in view of the future **DarkSide-20k**

1. Test the optical readout system consisting in cryogenic Silicon Photomultipliers (SiPMs) *[P. Agnes et al., Eur. Phys. J. C (2021) 81,1014]*
2. Investigate the directional sensitivity via the recombination effect *[paper in preparation]*
3. Characterization of low-energy Nuclear Recoil signals



HOW TO GET AWAY WITH DATA

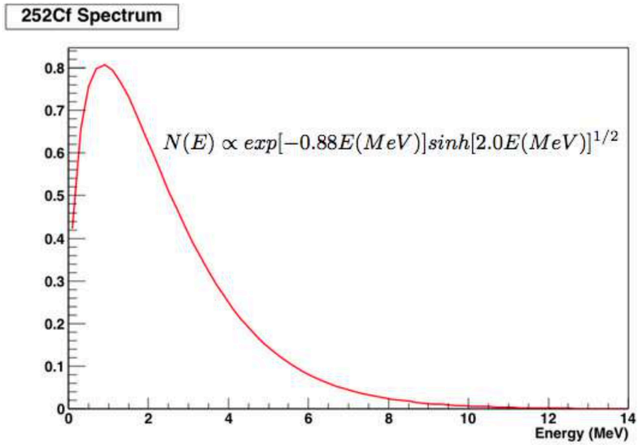


Nuclear Recoils of known energy in the region of interest (a few keV)

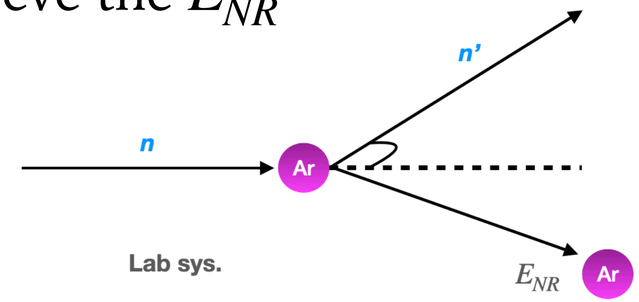
Neutrons produced by a spontaneous fission (SF) source: ^{252}Cf

Continuous energy spectrum for neutrons from ^{252}Cf

Need to close the kinematics

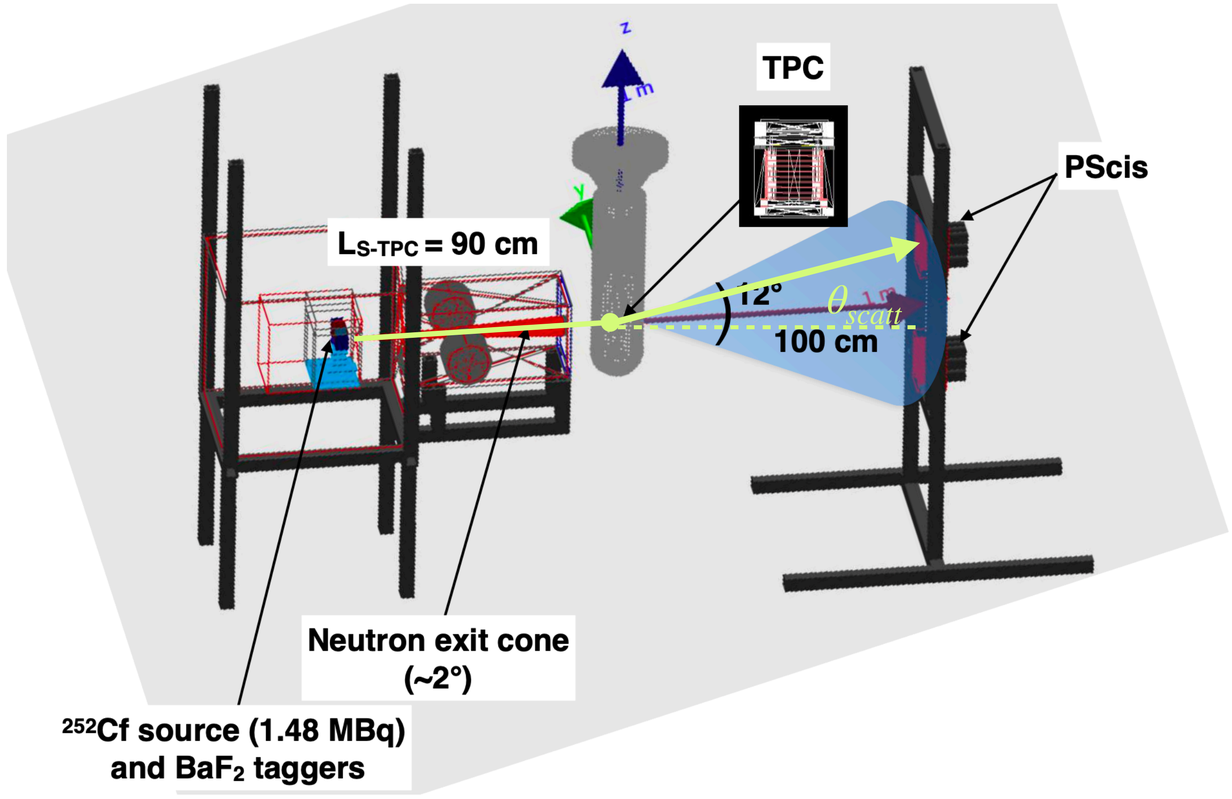


Measure the **kinetic energy** of each initial neutron and **fix the scattering angle** by setup geometry to retrieve the E_{NR} from two body kinematics calculations



STRATEGY

- Neutrons of O(2 MeV) produced by the ^{252}Cf source
- Looking for **ionization** events offline (TPC acquired in *slave mode*)
  - **Time of Flight** (**ToF**) measurements to retrieve the **kinetic energy** of the initial neutron
  - Tagger detectors
    - BaF_2 crystals facing the source and detecting γs form SF → **START**
    - Plastic Scintillators (**PScis**) in a neutron spectrometer → **STOP**
  - Two body kinematics to calculate E_{NR}

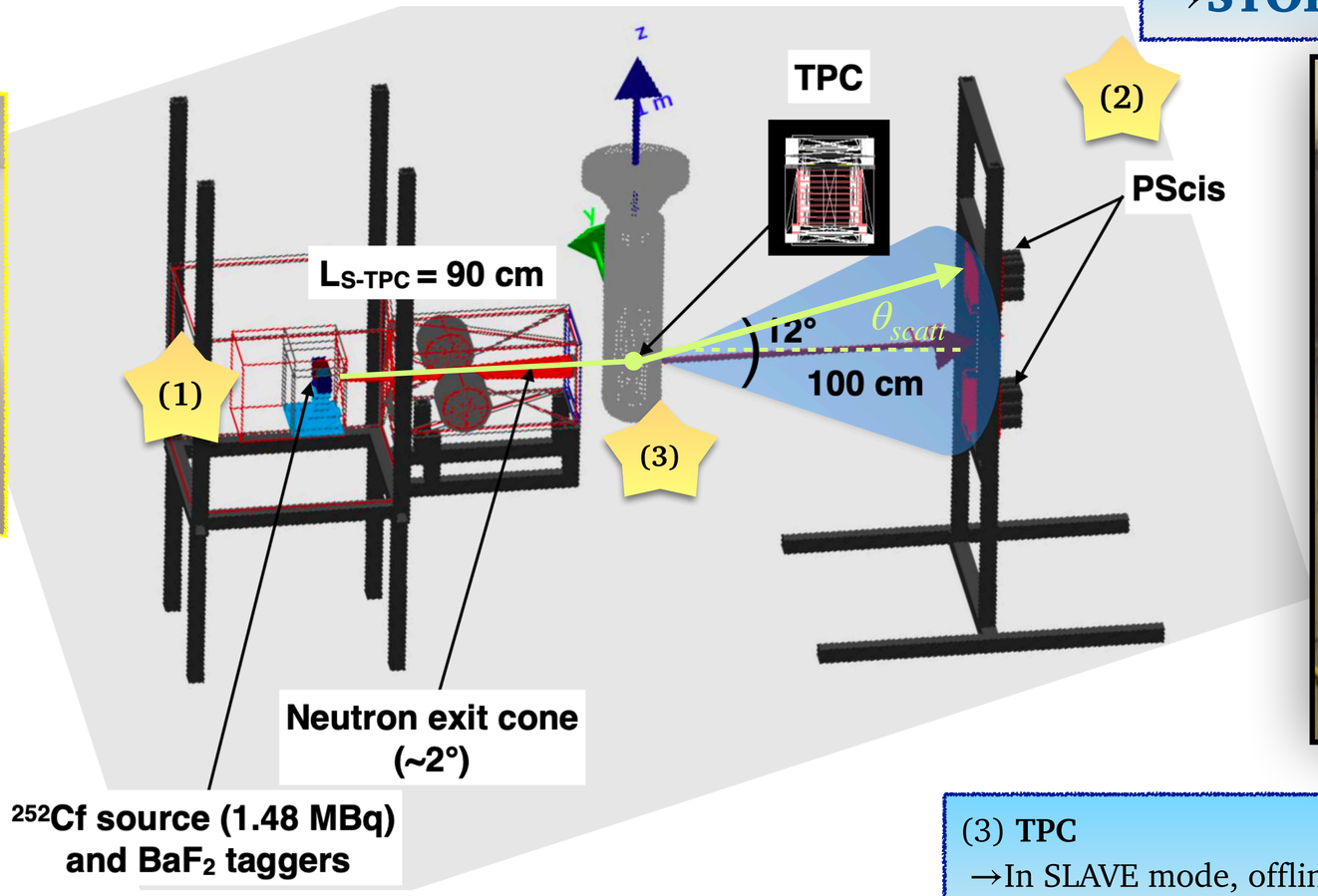


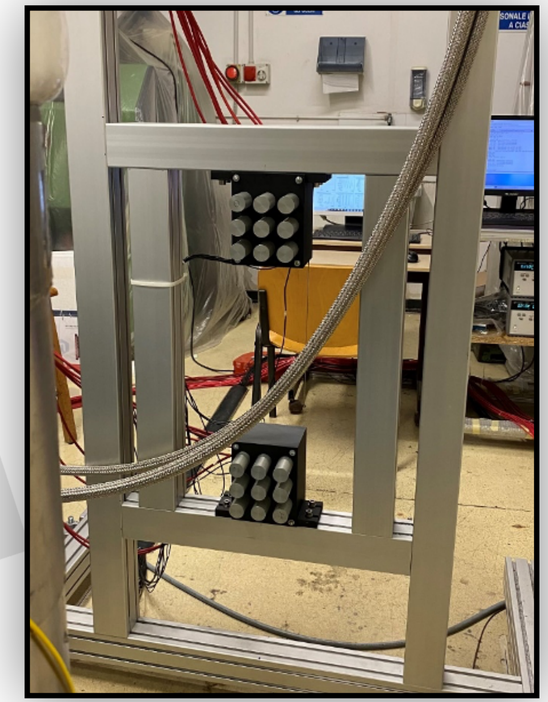
$$E_{NR} = 2E_{Kin}\frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - \cos\theta_{scatt})$$

EXPERIMENTAL SETUP

(1) BaF_2
→**START**

(2) PScis
→**STOP**

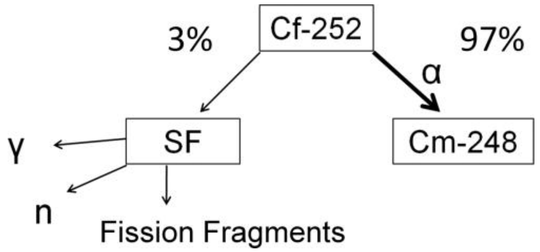


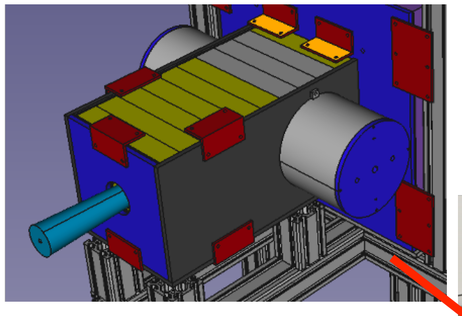


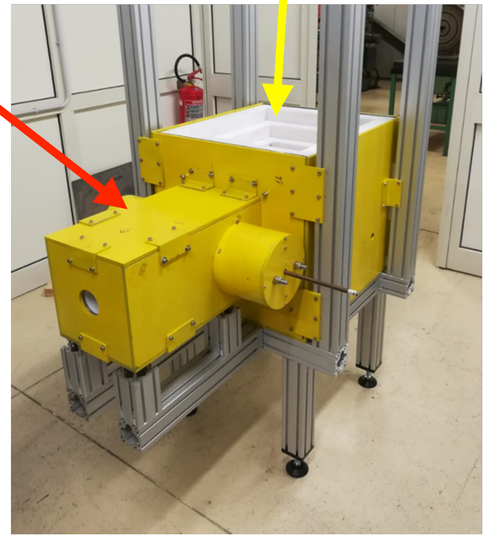
(3) TPC
→In SLAVE mode, offline analysis

THE SOURCE INSIDE ITS SHIELD

- ^{252}Cf source
  - **0.86 MBq** (1/1/2023)
  - **26 kBq** SF
- Shield made of B-loaded PE (15 cm), Fe and Pb
- Collimator “nose”: 50 cm of B-loaded PE, opening angle **~2°**
- Designed to irradiate the entire TPC at 1 m distance



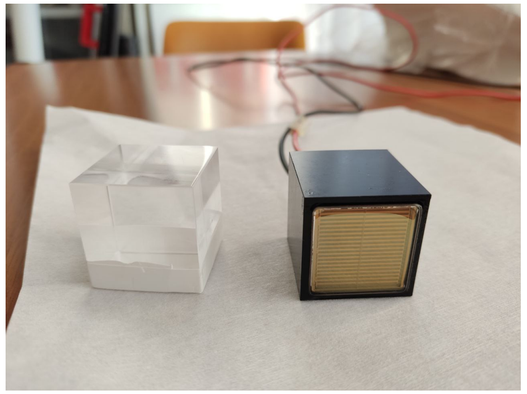




THE TAGGER DETECTORS

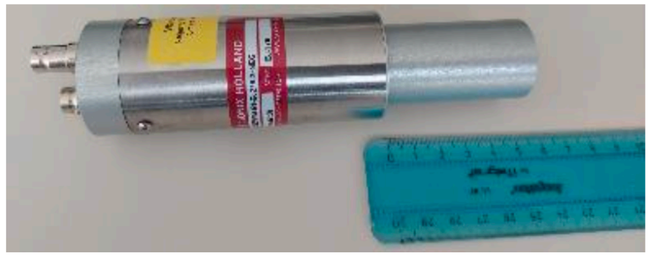
BaF_2 scintillators

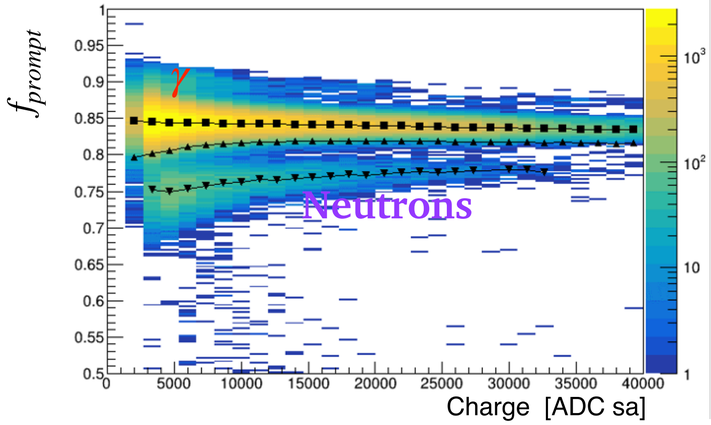
- Coupled with Hamamatsu PMT
- Fast scintillation (0.8 ns but @220 nm)
- Featuring e-/ion discrimination
- Detect the accompanying radiation of the SF



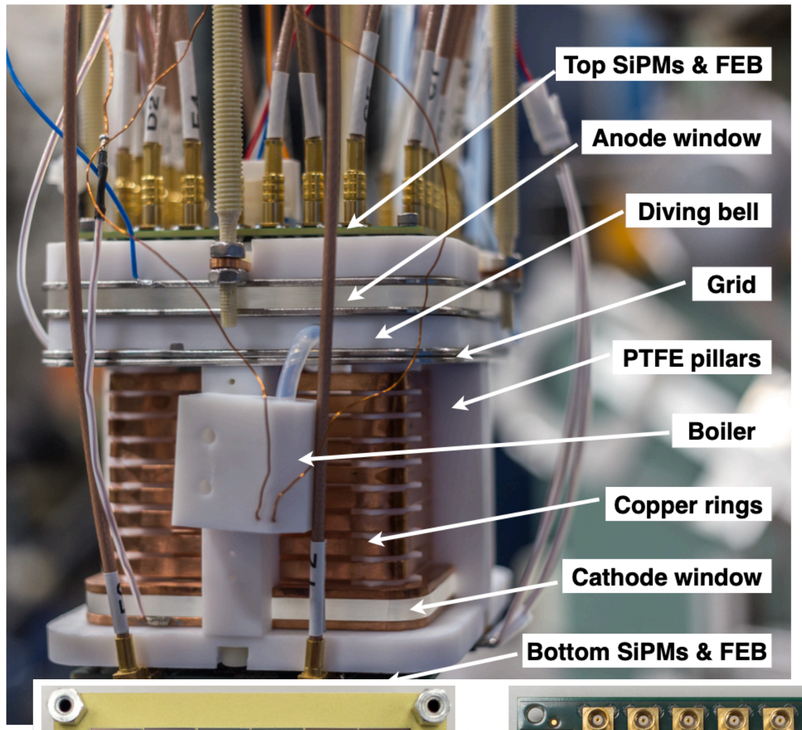
Neutron spectrometer

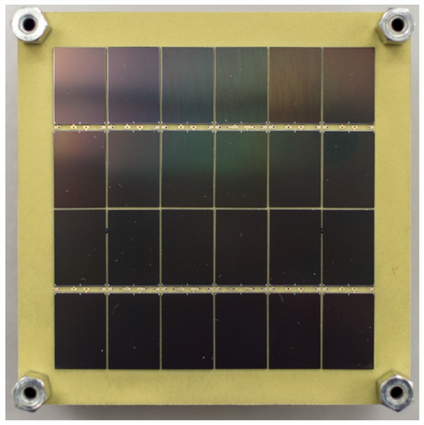
- **18 1-in** EJ-276 Plastic Scintillators + PMTs
- 2 matrices 3x3 placed at $\theta_{scatt} \sim$ **12°-17°** wrt the TPC position in the cryostat
- Fast timing (1 ns rms)
- Featuring n/γ discrimination

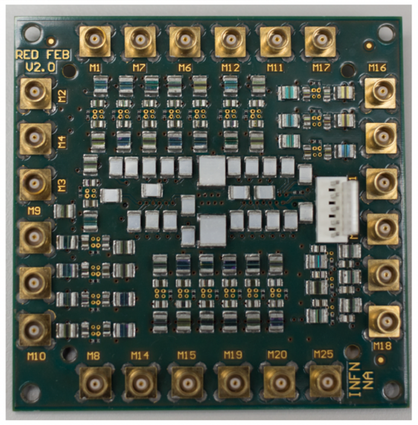




THE HEART OF THE EXPERIMENT



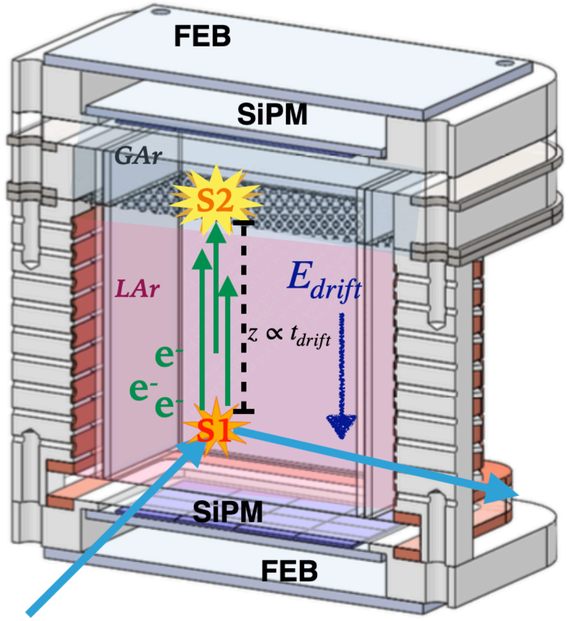


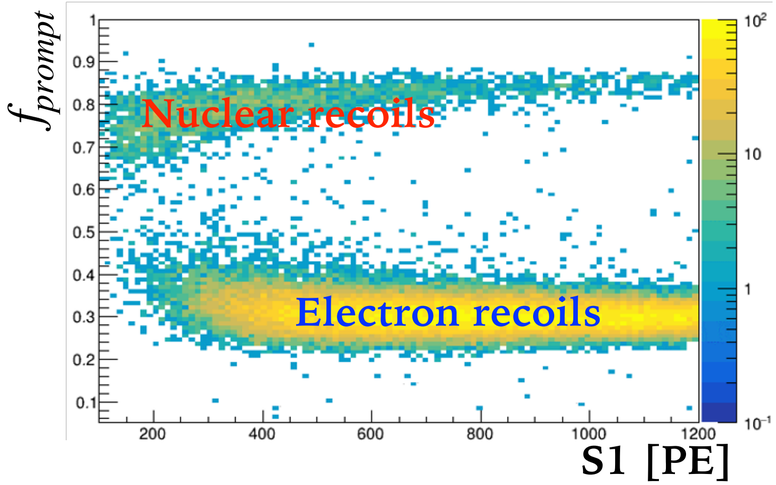


- Active volume of **5(l) x 5(w) x 6(h)** cm^3
- Liquid Argon bulk + *7-mm-thick* ***gas layer***
- Conductive layer of ITO on Anode and Cathode windows
- **Cryogenic SiPM** readout: two 5x5 cm^2 tiles with 24 devices
    1. Top : 24 channels
    2. Bottom: 4 channels

Scan for the paper

SIGNALS IN A DUAL-PHASE LAR TPC





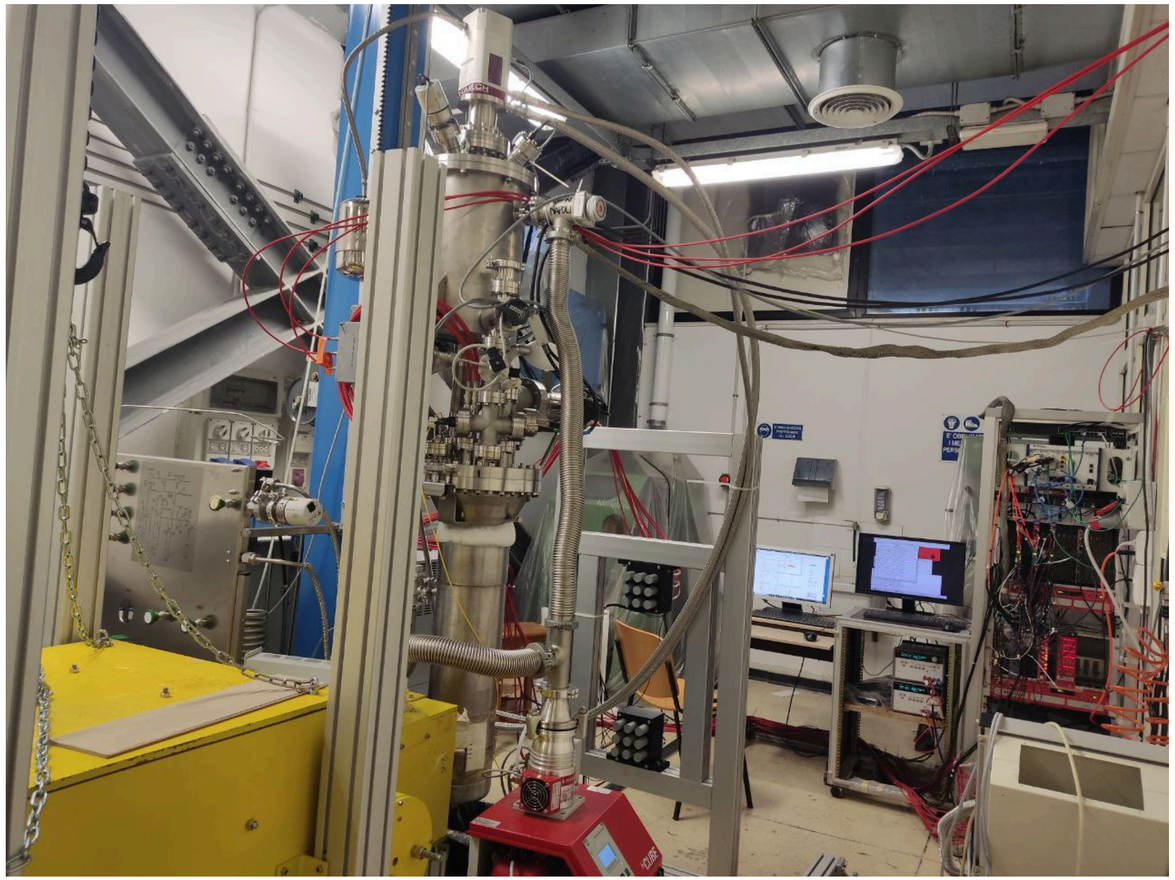
- NR event → Energy deposit
  - Prompt **scintillation light** (**S1**)
  - Creation of electron-ion pairs due to ***ionization***
  - e⁻ drifting toward the top of TPC thanks to E_{drift} and extracted in the gas layer

    → delayed **electroluminescence** signal (**S2**)
- Time difference **S2 -S1**

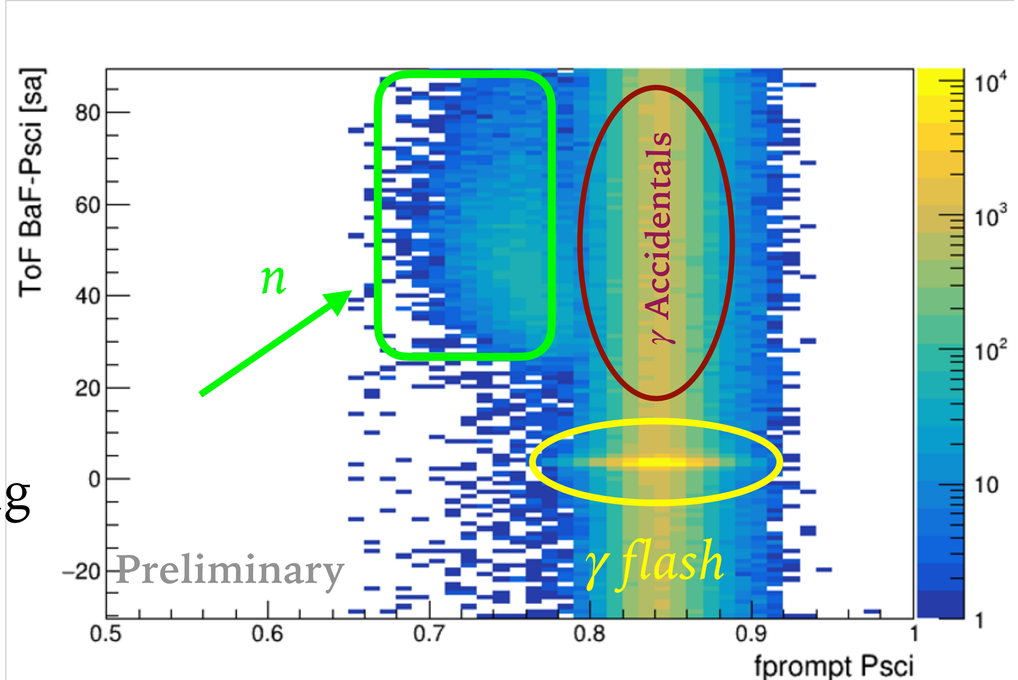
  → **drift time** and *z coordinate of the event*
- **Spatial reconstruction** on *x-y plane* thanks to **S2** pattern
- **S1** ***Pulse Shape Discrimination*** (**PSD**) of the Nuclear Recoil events wrt Electron Recoils (**ERs**)

DATA TAKING AT INFN Catania

Istituto Nazionale di Fisica Nucleare



- ^{252}Cf data campaign
  - Signal rate of **1.7 cph**
  - Taking data for *2 months*, from January to March 2023
- Calibration with ^{83m}Kr
- Data analysis ongoing



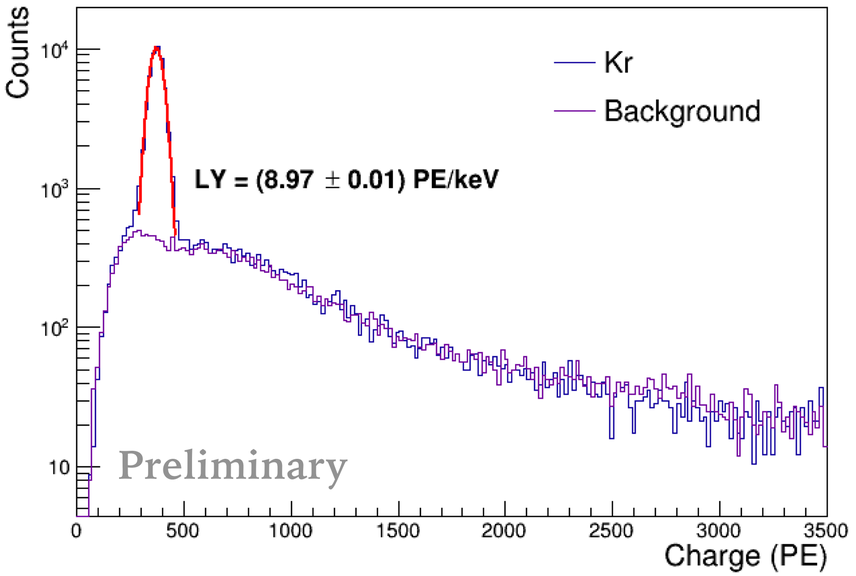
ER CALIBRATION WITH ^{83M}KR

- Calibration point at **low energy** with a **source uniformly distributed inside** the TPC

  → study of the *XYZ response*

  → corrections for inhomogeneities

- ^{83m}Kr electron source ($T_{1/2}$ = 1.83 h):
  - two emission lines at **32.15 keV** and at **9.41 keV** → emission of electrons totaling about **41.56 keV** energy
  - made by evaporating the progenitor ^{83}Rb, which decays with a half-life 86.2 d, on carbon coal grains❖



CONCLUSIONS

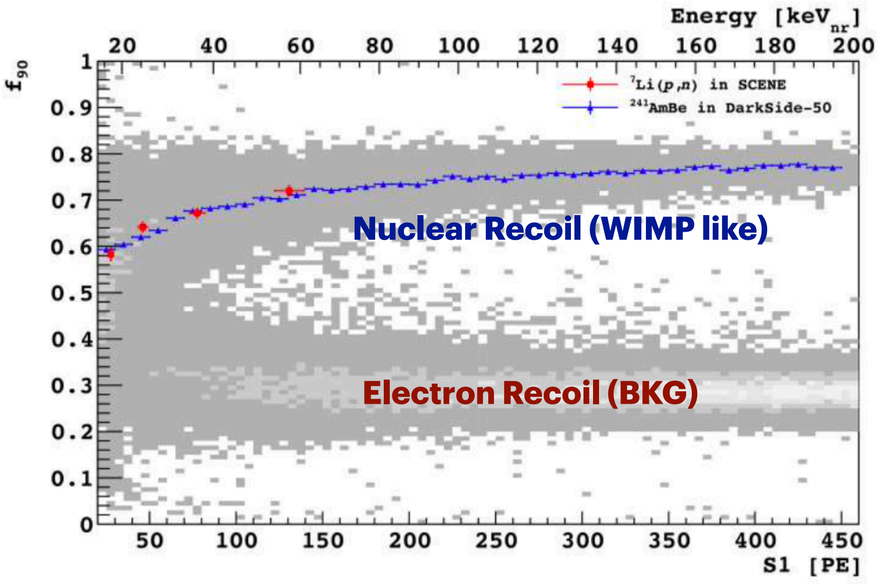
- In its third and last physics campaign the ReD experiment aims to characterize the response of a LAr TPC for NR events at low energy
  - Experimental data to validate the ionization model in Liquid Argon for low-energy recoils
  - The focus is collecting S2 pulse from NRs and derive the charge yield down to the region of 2-5 keV_{NR}
  - Data taking campaign concluded, analysis ongoing
- Future perspectives: further improve the low-energy calibration down to the sub-keV (ReD+ and DD Neutron Gun)

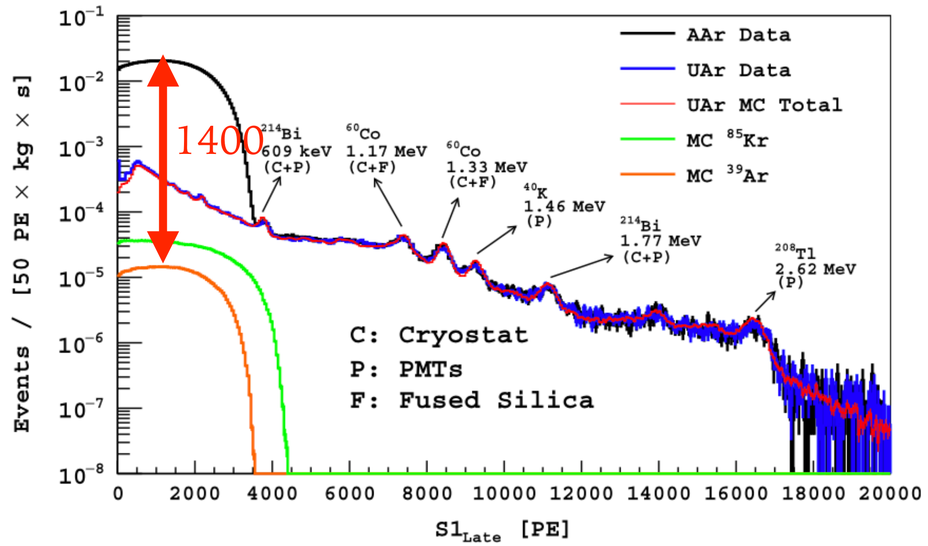
Thanks for your attention!

BACKUP

THE ROLE PLAYED BY ARGON

- High transparency to photons and electrons
- Scalability due to Liquid Ar's low cost
- Efficient background rejection :
  - Pulse Shape Discrimination (PSD) for β/γ rejection
  - Low-radioactivity due to the underground extraction
- Efficient drift and extraction of the ionization electrons
- Light nucleus allows light dark matter to produce higher-energy recoils

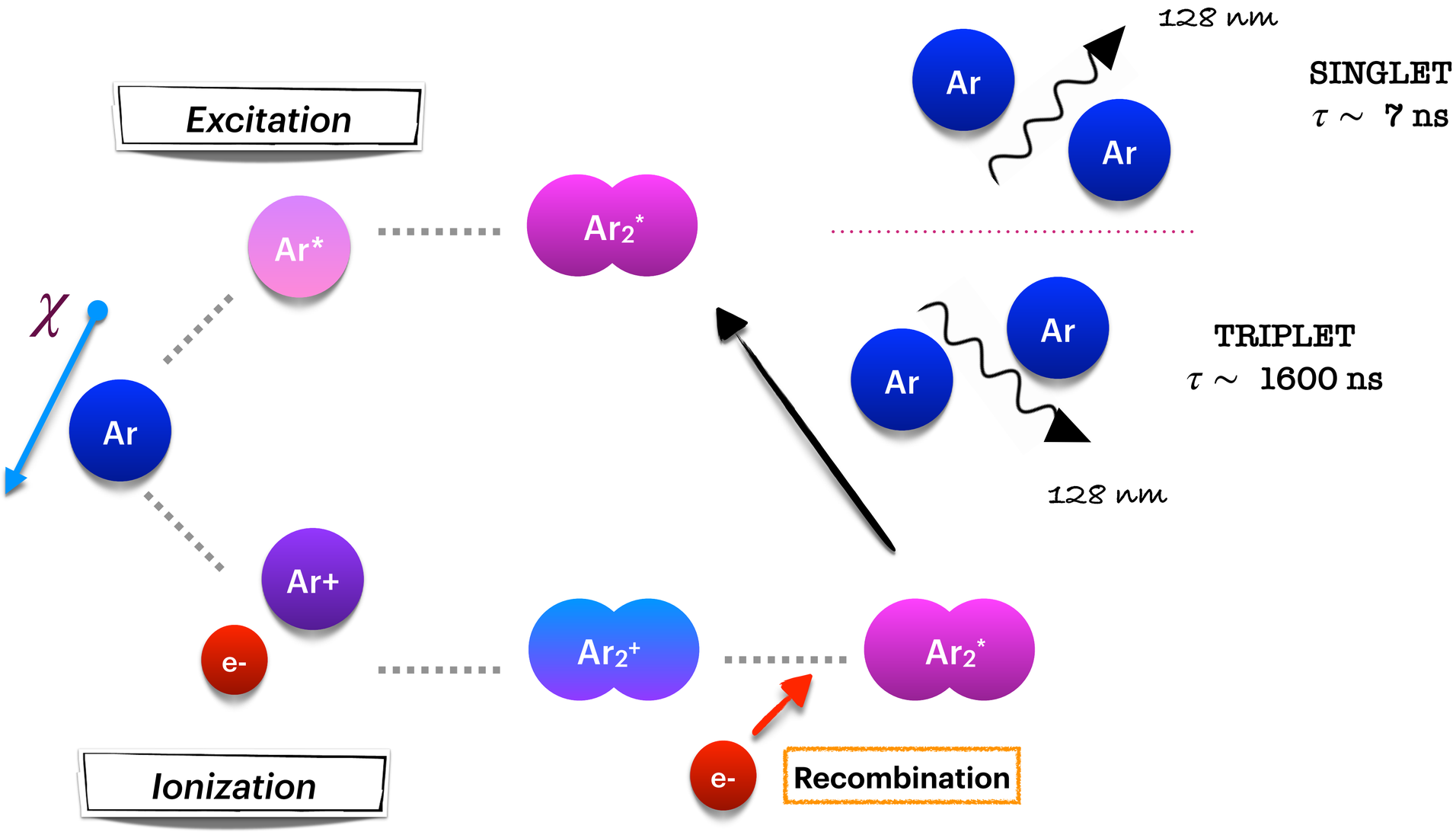




→ *all these properties enable dual-phase LAr TPC to search for dark matter into the solar neutrino fog*

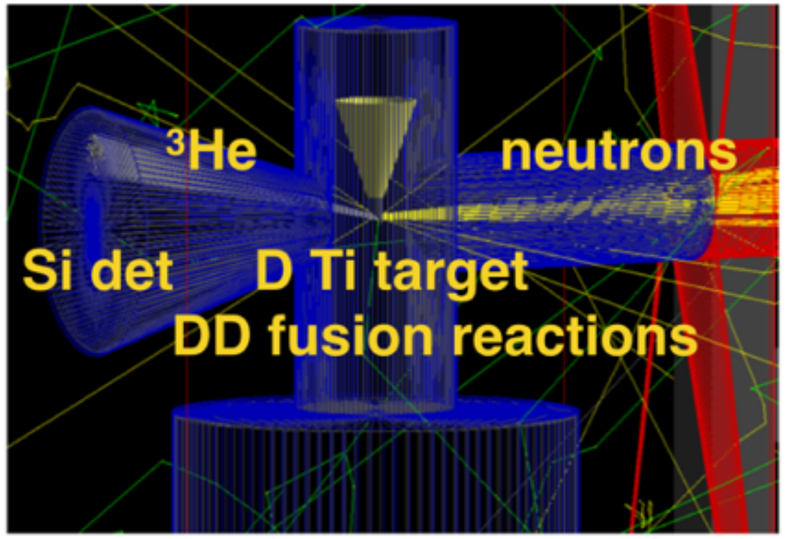
SIGNALS IN AR

Scintillation + Ionization



NEUTRON (D–D) GUN PROJECT

- Further improve the characterization for **low-energy recoils**
- Essential for low-mass analysis
- Idea: use a D-D neutron gun instead of the ^{252}Cf source
- Mono-energetic neutrons of **2.4 MeV**, flux up to 10^7 n/s (x30 wrt. source)
- Use Si detectors to tag the accompanying 3He
  - *Gun funded through a FAPESP grant to USP*
    - *In collaboration with Naples, Catania and LNS*
    - *Commissioning at IFUSP*
    - *Data taking at LNS (late 2024 and 2025)*



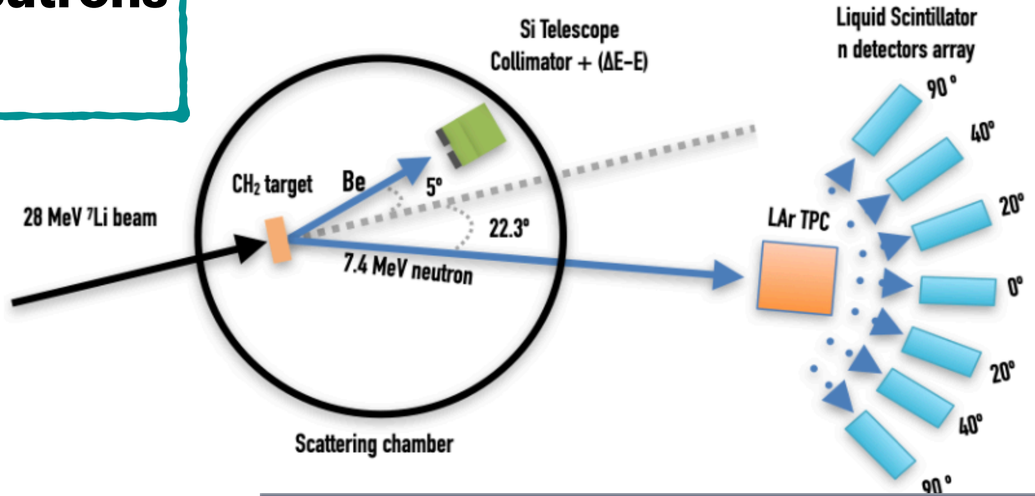
• 2.4 kHz trigger rate at Si Det

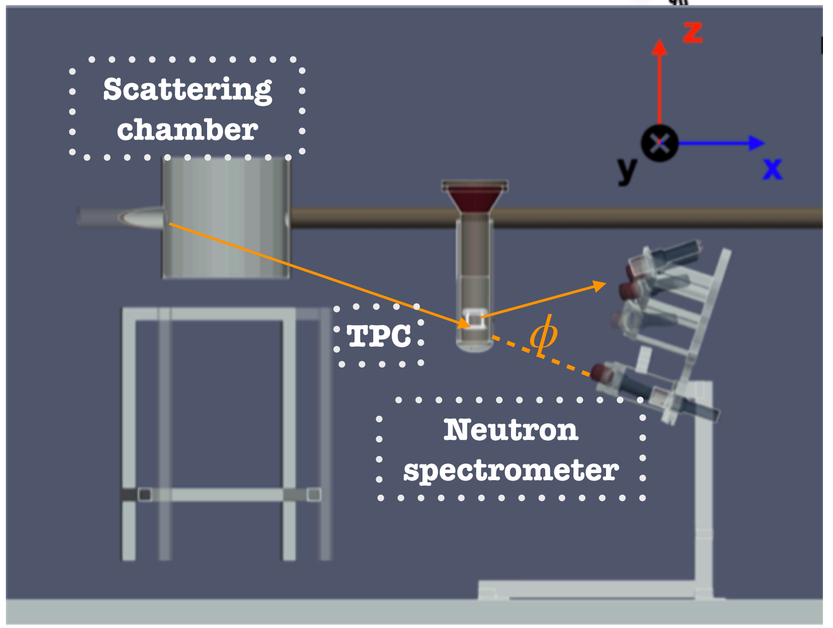
PHASE 2: DIRECTIONALITY AT INFN LNS

Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali del Sud

Irradiate a miniaturized LAr TPC with mono-energetic neutrons to produce NRs with momenta at different angles wrt ε_d

- Neutrons via the **p(⁷Li,⁷Be)n** reaction at the TANDEM accelerator
- **(n,n')** with an Ar nucleus → Nuclear Recoil
  - Two-body kinematics constrain
- n' detected by an array of Liquid Scintillator (LScis)
- Every LSci detector determine the ***energy*** and ***direction*** of the recoiling Ar
- NRs with the same E_{recoil} but different azimuthal angle ϕ (z-axis)

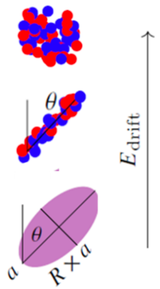


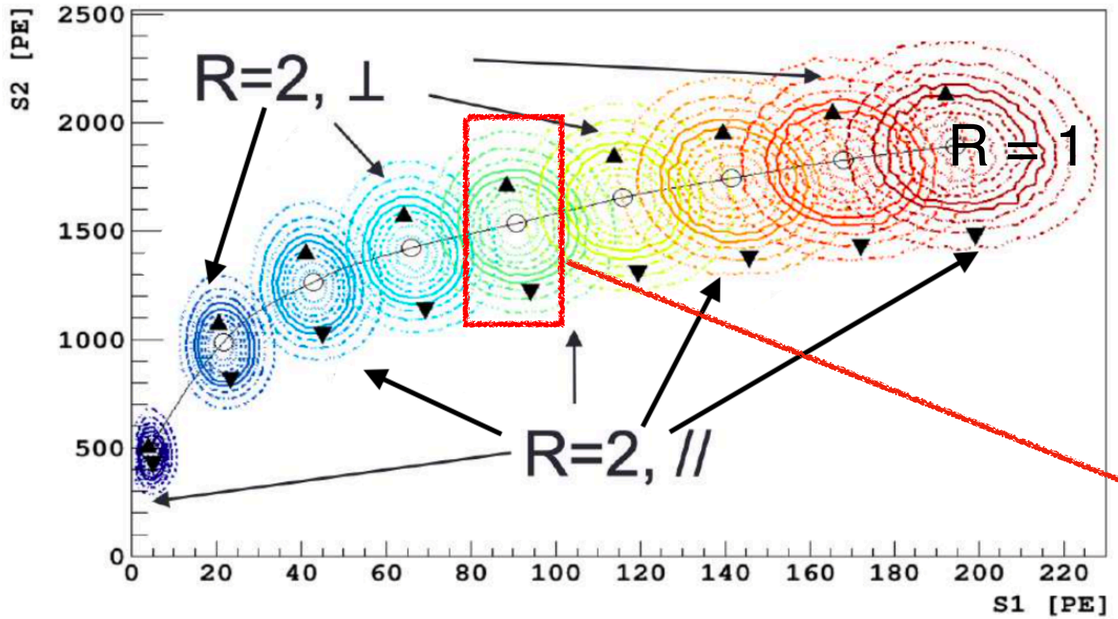


A NOVEL MODEL FOR DIRECTIONALITY

The breakthrough of the elongated ellipsoid

Model	Directional dependence
Thomas-Imel, Box ("short track") Phys. Rev. A 36 (1987) 614	None
Jaffé-Birks ("infinitely long track") Ann Phys 347 (1913) 303	$[\sin\phi]^{-1}$
Cataudella et al. **JINST 12 (2017) P12002**	$\left[\sqrt{sin^2\,\phi + cos^2\,\phi\,/R^2}\right]^{-1}$





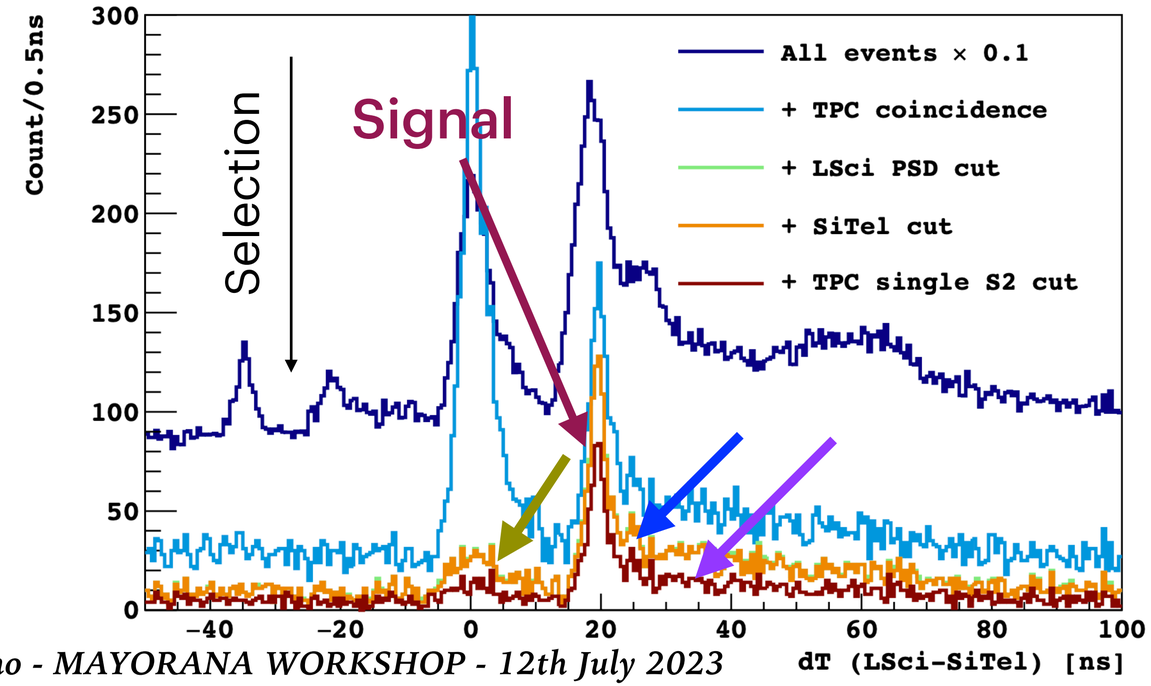
- Innovative model by **Cataudella et al.**
- Relevant parameter ***R***, the ***non-sphericity*** of the initial electron cloud
  - If **R > 1** → net directional effect
  - If **R = 1** → no directional dependence (spherical symmetry, Thomas-Imel)
- ***Contours***: detector response from mono-energy NRs (simulated data)
- Impact on detector response → change S1-S2 balance

A directional effect would cause the ***shifting of the centroid*** of the contours

SIGNALS AND BACKGROUNDS

- The TPC was irradiated for *14 days in February 2020*
- The golden-plated events are the ***three-fold coincidences***: (1) Si-Tel → (2) TPC → (3) Neutron Spectrometer
- Further **cuts** and **cleaning**: *^{7}Be tagging, timing, PSD*

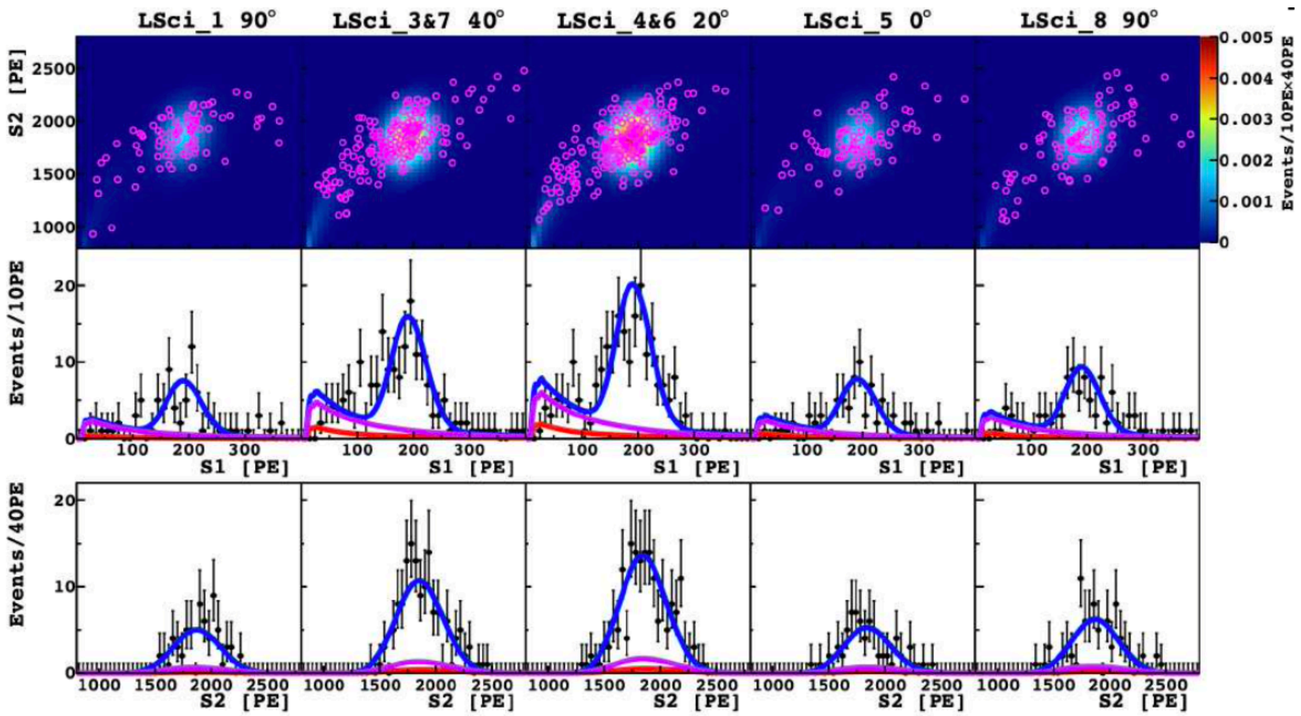
→ ~ 7000 events with proper energy (70 keV$_{nr}$) and timing , about 150 events/day

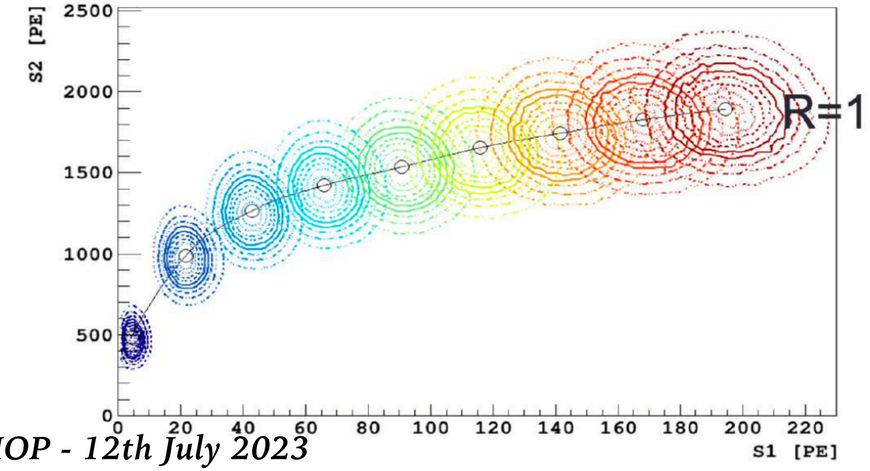


Residual Backgrounds:

- Accidentals
- (n, n') events in the TPC
- Neutrons from p(^{7}Li,^{7}Be*)n
  - 63.5 keV recoils in the TPC
- Neutrons with multi-scattering

ANALYSIS AND RESULTS





- Statistical analysis consists in an ***unbinned maximum likelihood fit***
- **Three-fold coincidence** events + **Nuclear Recoil** (SiTel ∧ TPC) sample
- Components: signal, multi scattering, accidental coincidences
- PDF from `Geant4` simulations and/or data-driven
- NR quenching in Ar → Lindhard + Mei models [**Phys Rev D. 91.092007**]
- Fitting region limited to 100-350 PE → ~ 30 - 100 keVnr

→ ***R = 1.036 ± 0.024 ⇒ No effect***