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Characterization of low-energy Argon recoils with the ReD Experiment

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on behalf of ReD working group (GADM Collaboration)

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Dark Wave

National Science Centre Poland

European Funds

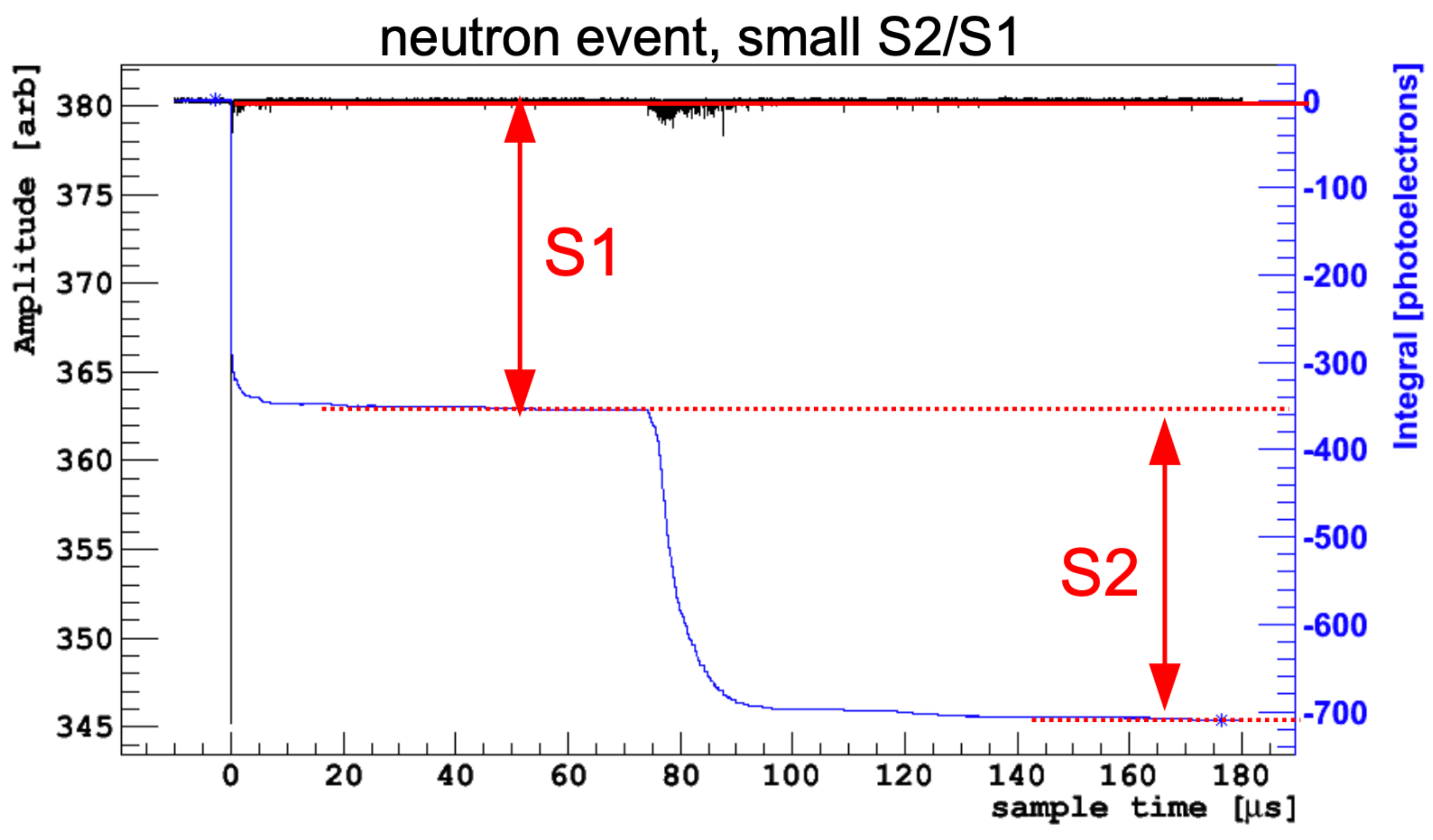
Republic of Poland

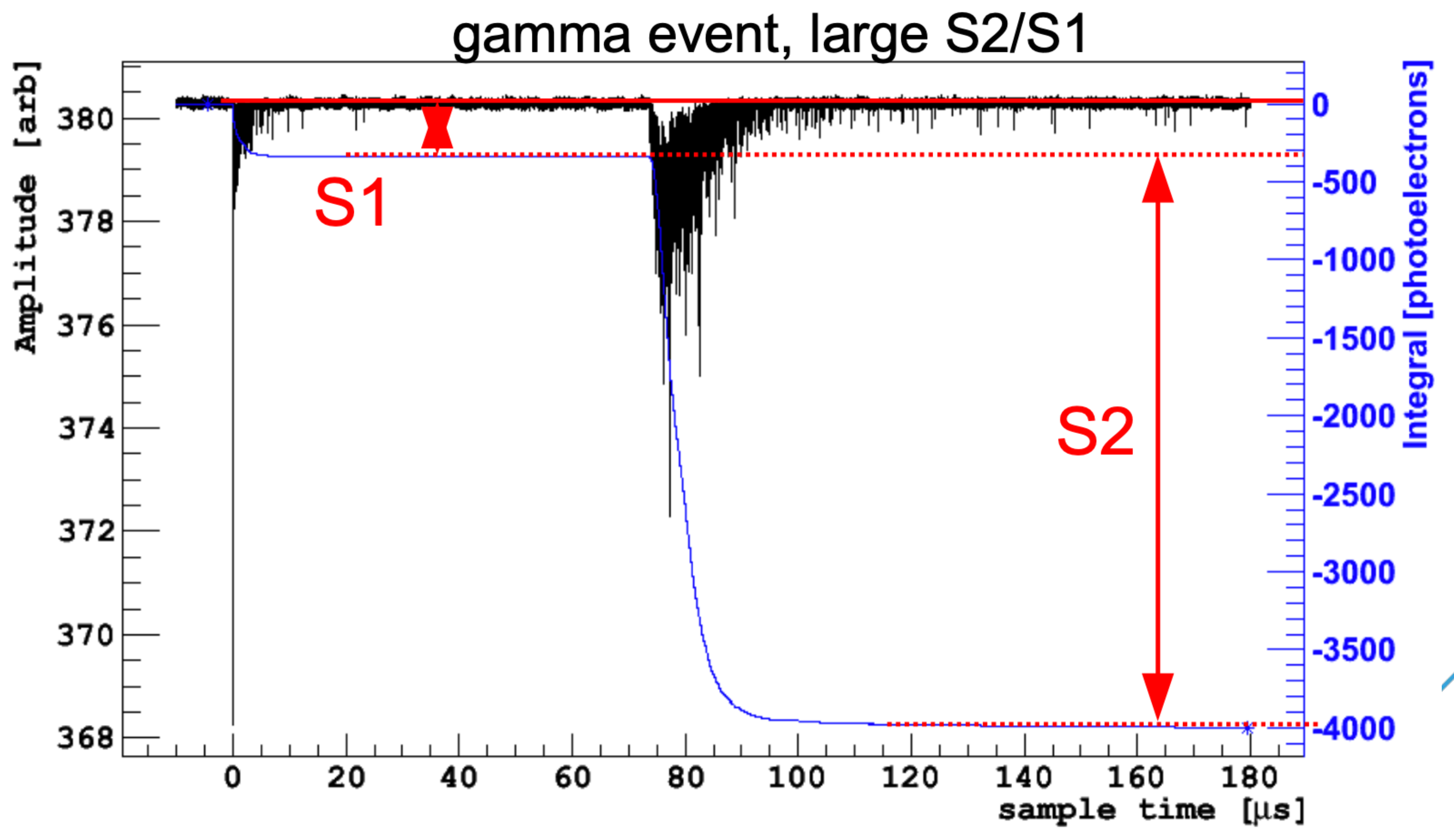
FNP Foundation for Polish Science

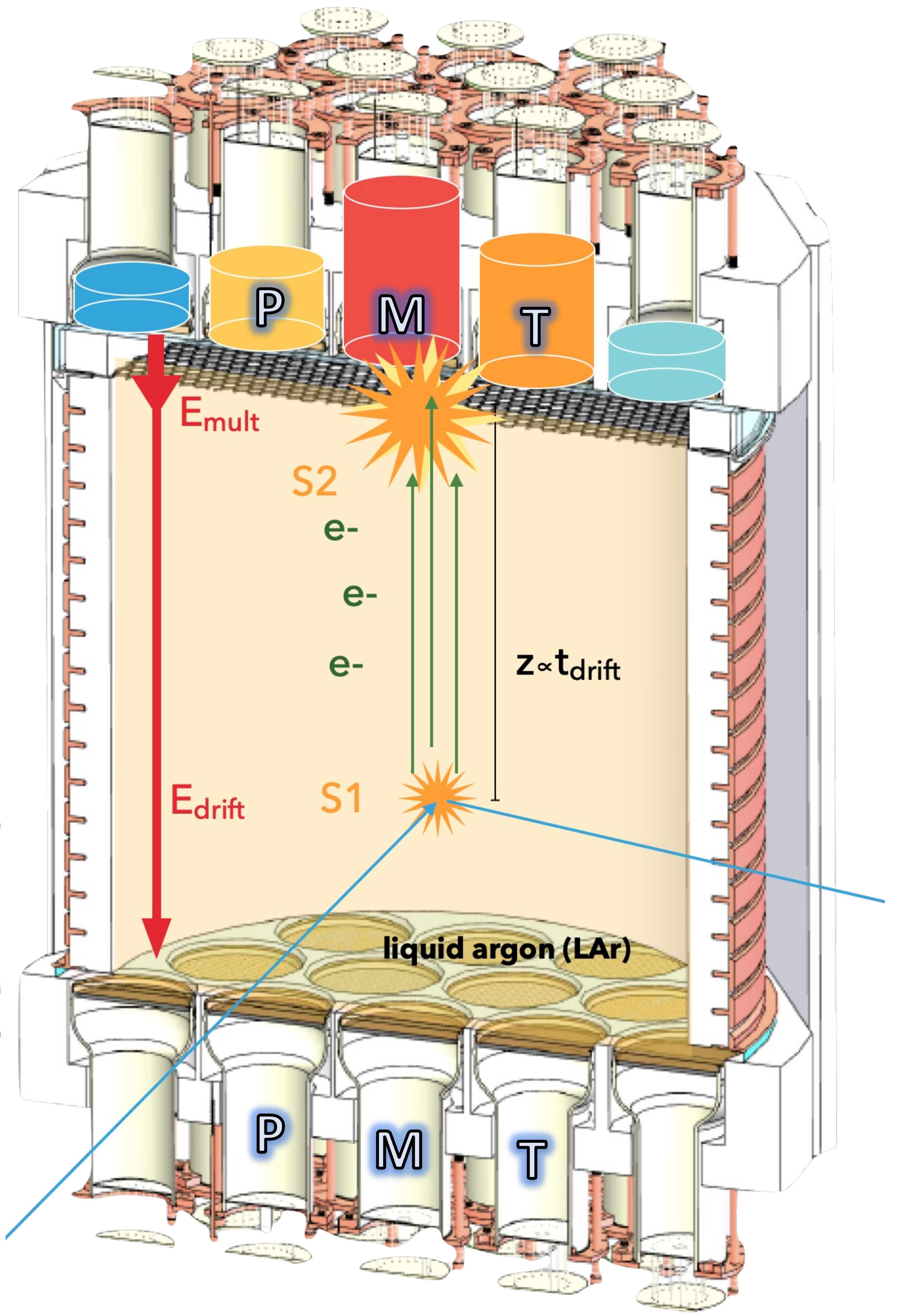
European Union

Dual-phase TPCs Concept

- Looking for dark matter in our galaxy **elastically scattering** off argon atoms inside the TPC.
- **WIMPs** produce **NRs** while **β and γ-rays** produce **electron recoils (ERs).**
- Primary **scintillation** (S1) and secondary **electroluminescence** (S2) signals detected by light detectors.
  - **3D position** reconstruction from $\Delta T_{S1\text{-}S2}$ + S2 light pattern
  - **ER/NR** pulse shape discrimination (PSD) in **f_{prompt} vs S1** parameter space.







Low-mass Dark Matter Search

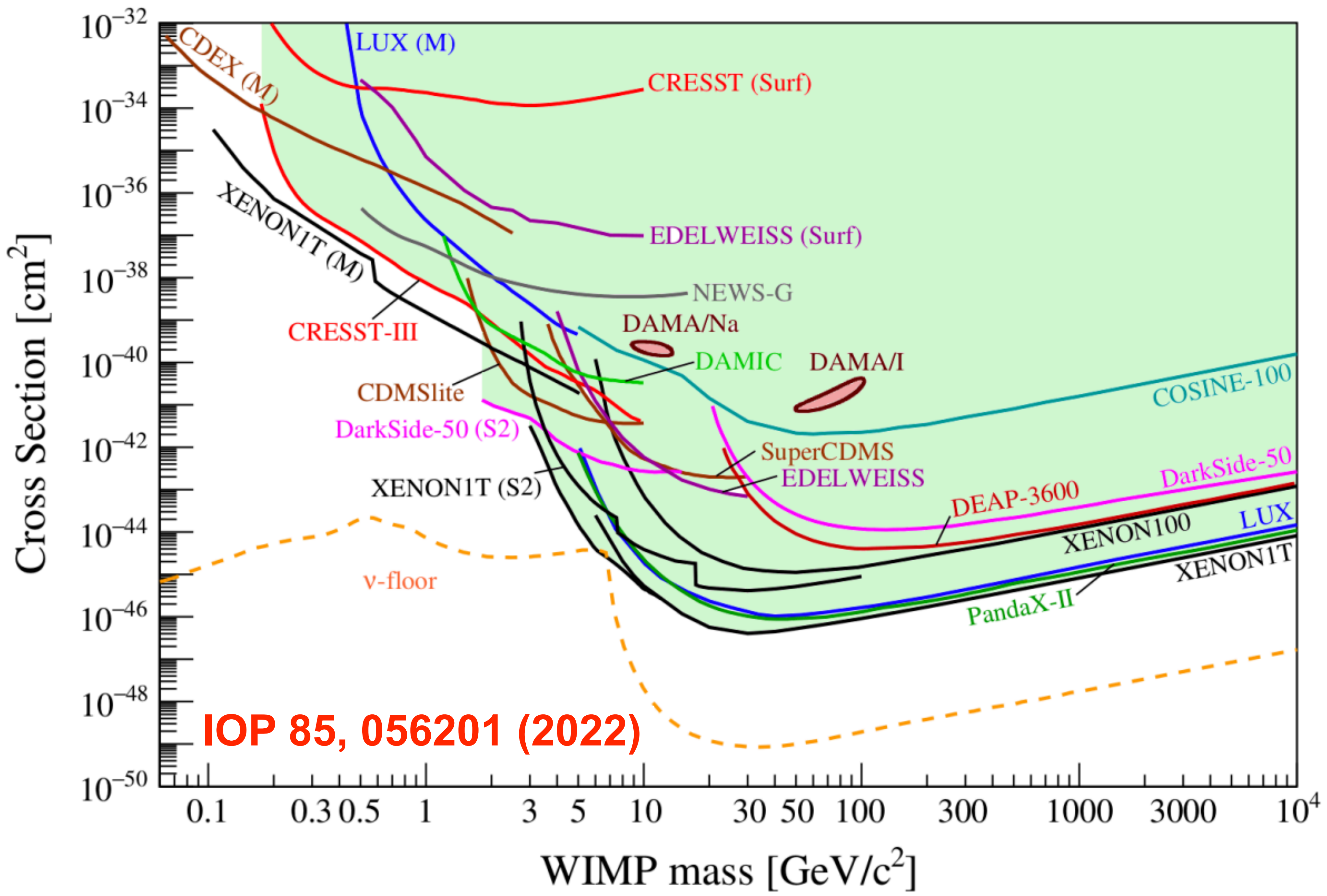
The race to detect Dark Matter is going to lower energies:

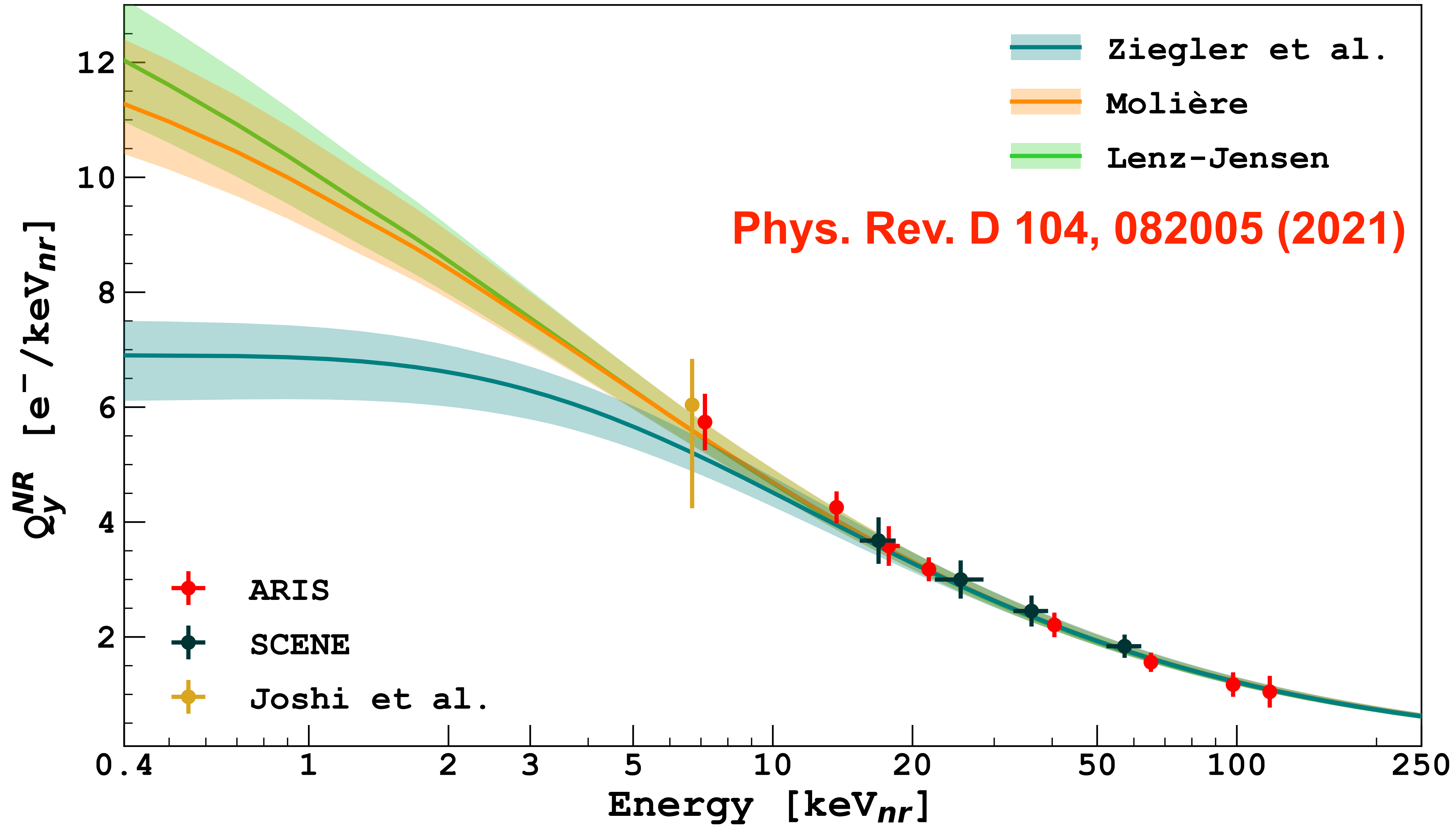
- **WIMP Mass:**
  O(few GeV/c²) vs. O(100 GeV/c²)
- **Recoil Energy:**
  O(few keV) vs. 20-100 keV

The **argon response for nuclear recoils (NRs)** in the low-energy range is yet **to be explored**.

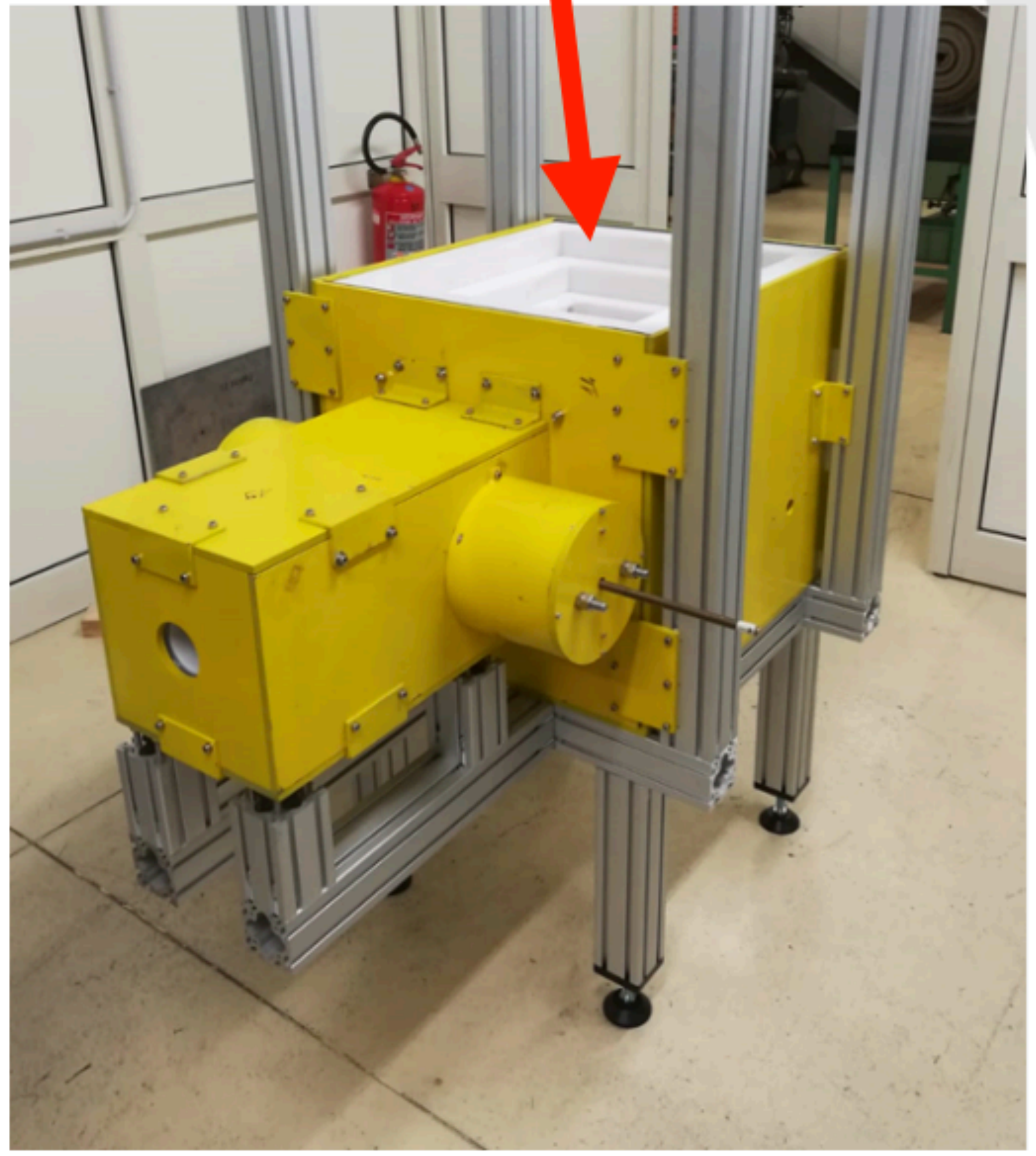
- To date, the energy calibration below **6.7 keV$_{nr}$** relies on the limited sample from the AmC calibration of DS-50, which is not closed by 2-body kinematics.

The **ionization channel** provides access to the **lowest energy sensitivity** of Liquid noble-gas detectors.





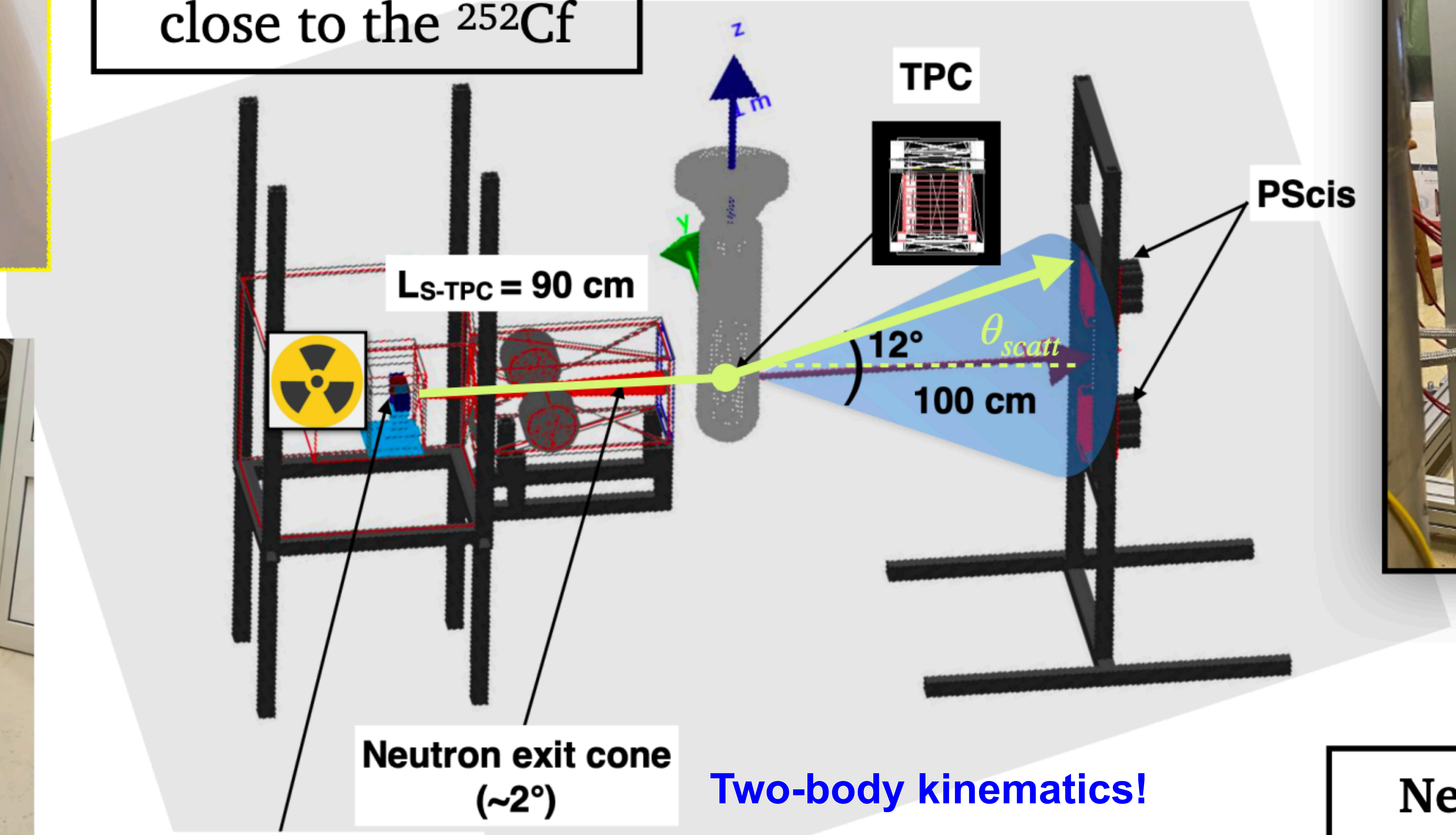
ReD Experimental Layout



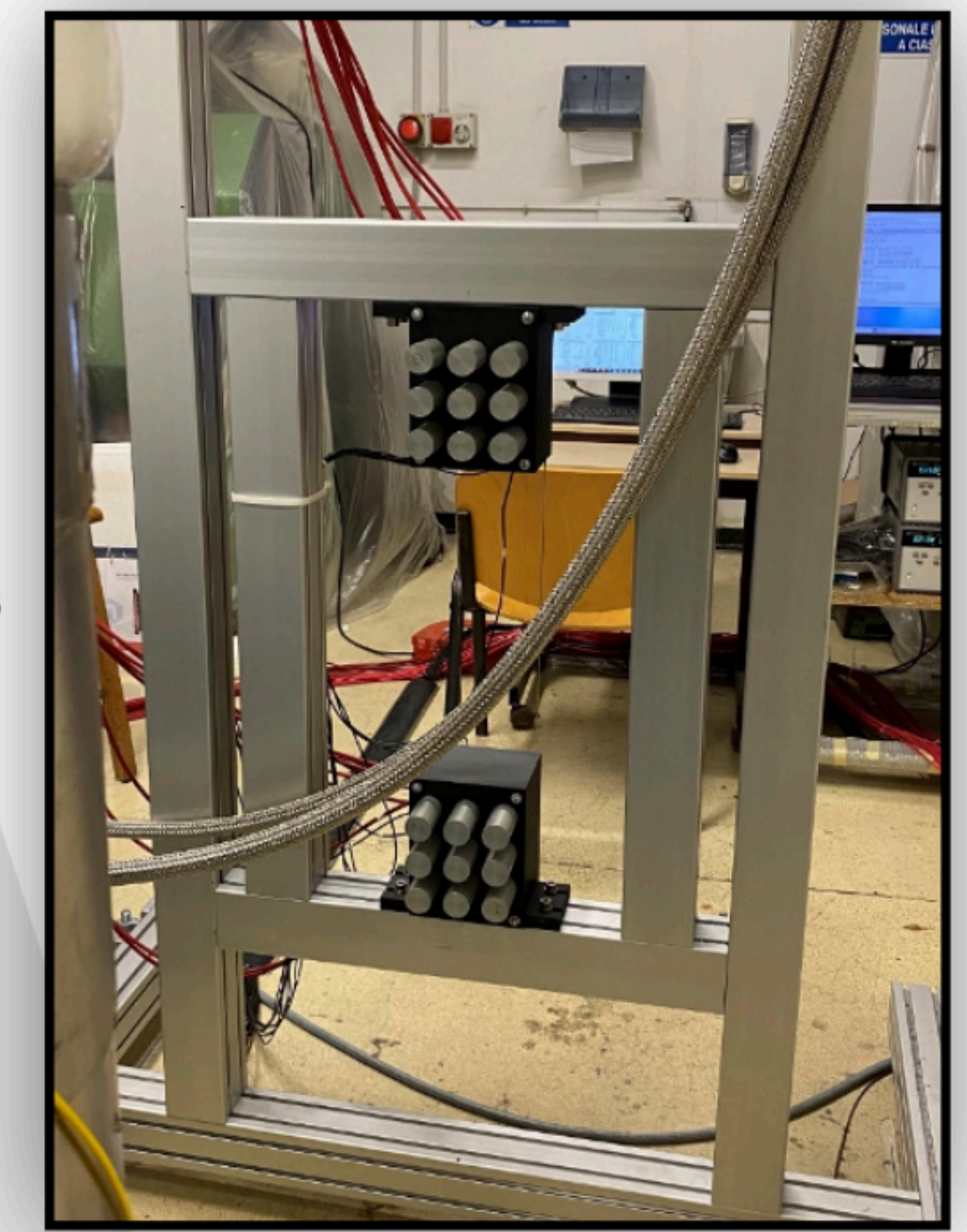
START

BaF$_2$ scintillators close to the ^{252}Cf

TPC in SLAVE mode
→ **offline analysis**



^{252}Cf source (1.48 MBq) and BaF$_2$ taggers



Two-body kinematics!

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

STOP

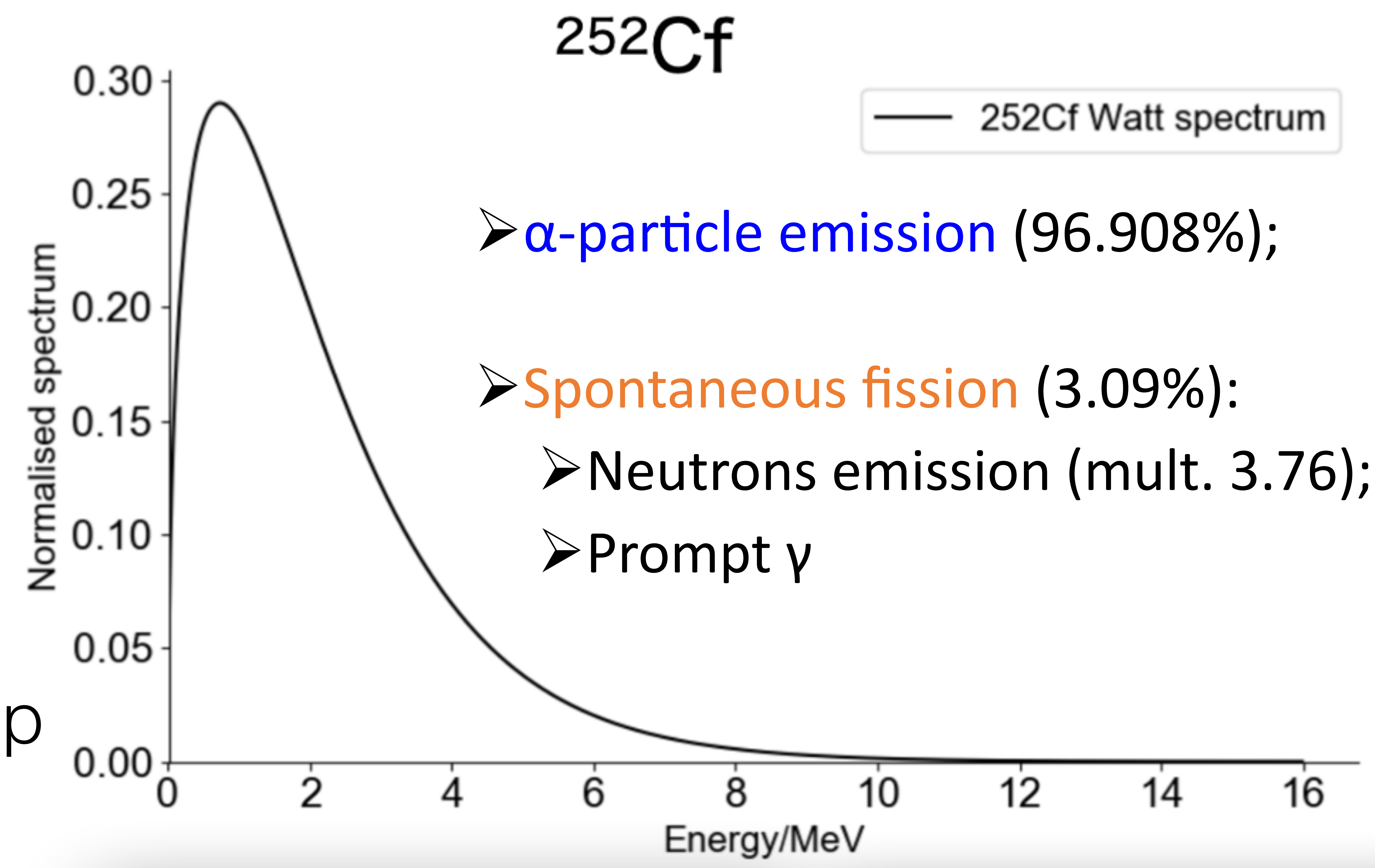
Neutron spectrometer:
18 Plastic Scintillators
(PScis)

Experiment Components

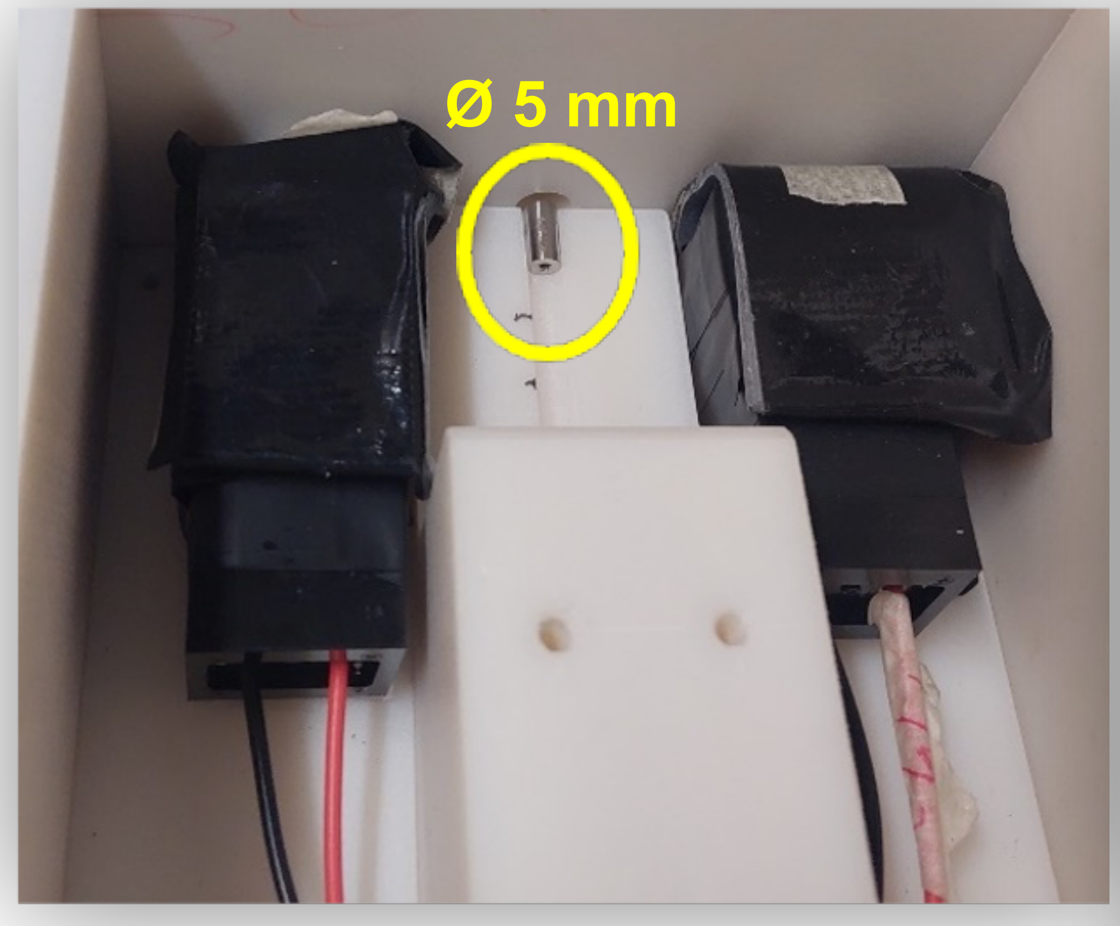
- **^{252}Cf source** (26 kBq fission)
  - ✦ Hosted inside a B-loaded PE, Fe, and Pb shields.
  - ✦ The shield features a 2° collimator for even TPC illumination at a 1 m distance

- Two **BaF_2 detectors** to tag fission products
  - ✦ Fast scintillation (0.8 ns decay constant)
  - ✦ Capable to withstand the source rate, without pileup
  - ✦ **START** for the time of flight measurement

- **Neutron Spectrometer**:
  - ✦ Two 3x3 arrays of EJ276 **plastic scintillators**
  - ✦ **1"-Diameter** —> Better 3D neutron reconstruction
  - ✦ **Time Resolution < 1 ns**
  - ✦ **STOP** for the time of flight measurement
  - ✦ Features **n/γ discrimination**
  - ✦ **θ ~ 12°-17°** to avoid direct neutrons from the source
  - ✦ **Symmetric** deployment to **control systematics** due to alignment



- ➤ α-particle emission (96.908%);
- ➤ Spontaneous fission (3.09%):
  - ➤ Neutrons emission (mult. 3.76);
  - ➤ Prompt γ



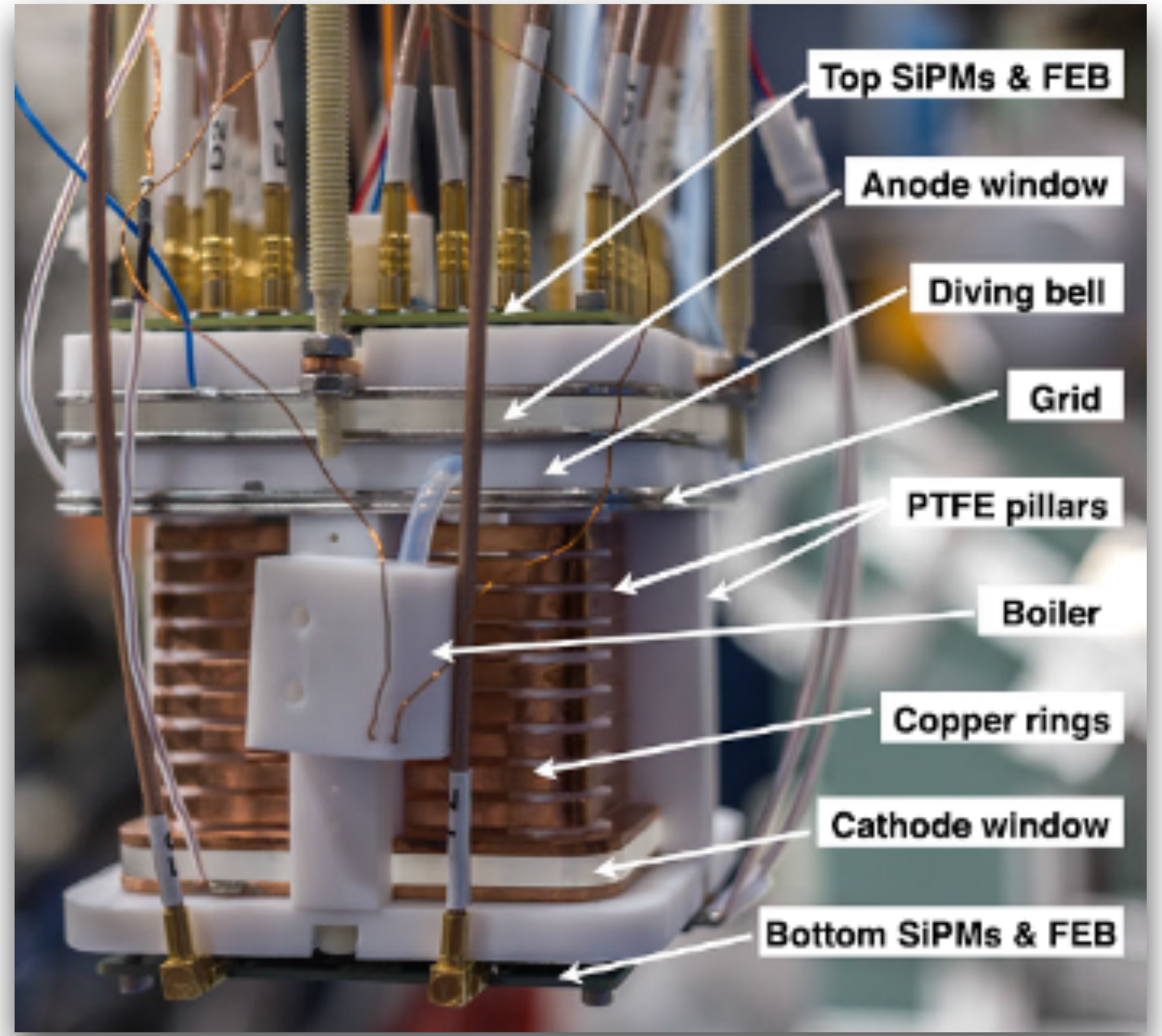
ReD TPC Performance

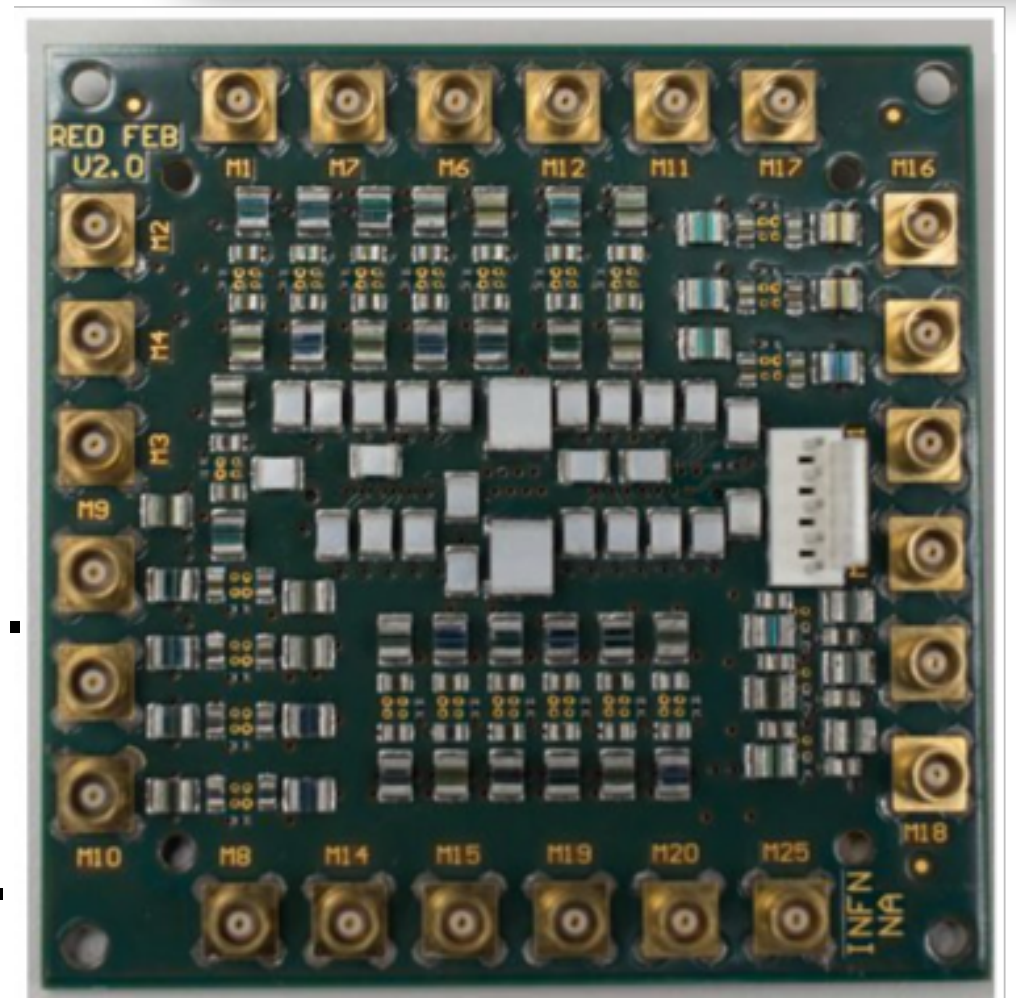
- ReD TPC is a miniaturized version of the DarkSide-20k
  - ✦ Active volume: 5(L) x 5 (W) x 6 (H) cm
  - ✦ Gas pocket thickness: 7 mm
  - ✦ Wavelength shifting (128 → 420 nm): TPB coating

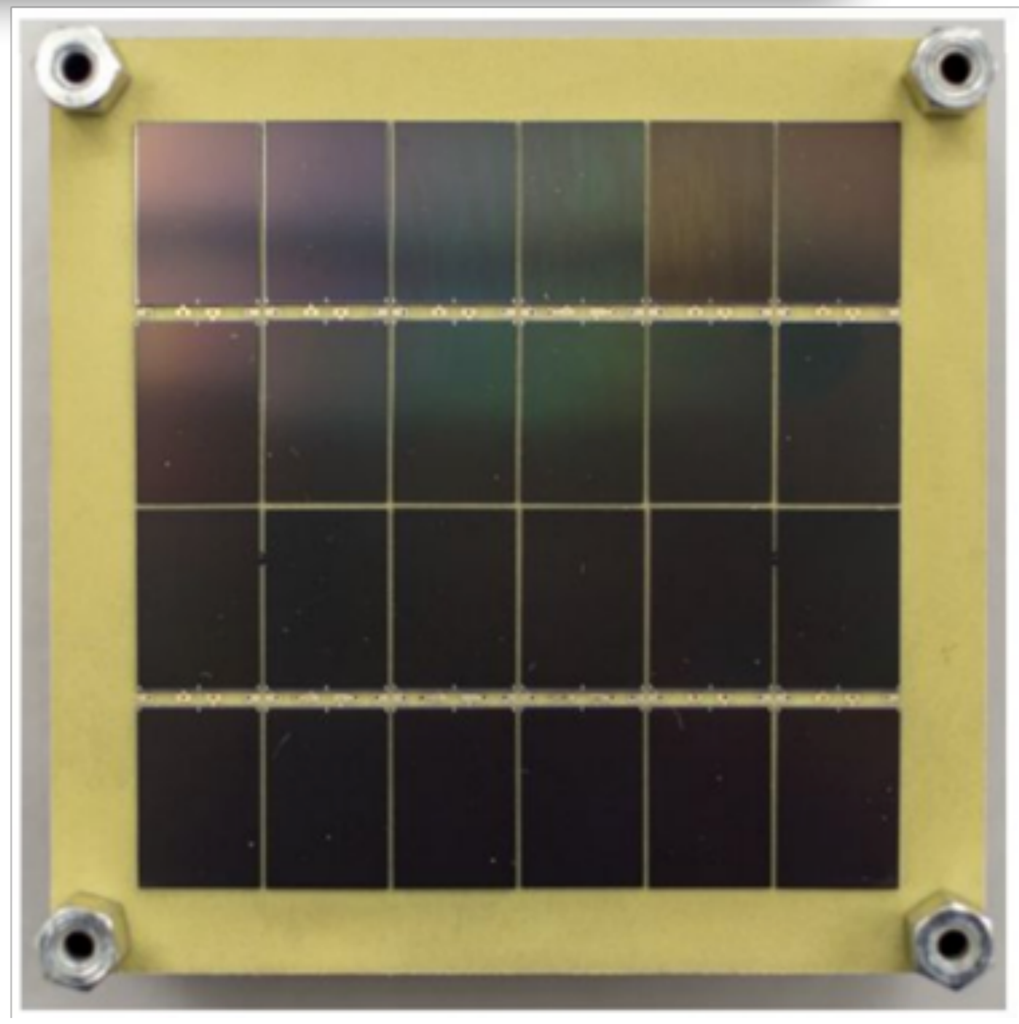
- Light readout: 5x5 cm^2 novel silicon photomultipliers (SiPMs) connected to front-end boards (as for DS-20k)
  - ✦ 24x1cm^2 SiPM 24 ch readout (top), for better (x,y) resolution
  - ✦ 24x1cm^2 SiPM, 4 ch readout (bottom)

- In this campaign:
  - ✦ SiPMs were calibrated and Single Photon Resolution was determined using laser runs.
  - ✦ Electron lifetime **> 1 ms**
  - ✦ Light Yield: **~17 PE/e-** (E_{drift} = 200 V/cm, E_{el}=5.79 kV/cm).
  - ✦ More about ReD TPC performance

Agnes et al. EPJC **81** (2021) 1014.



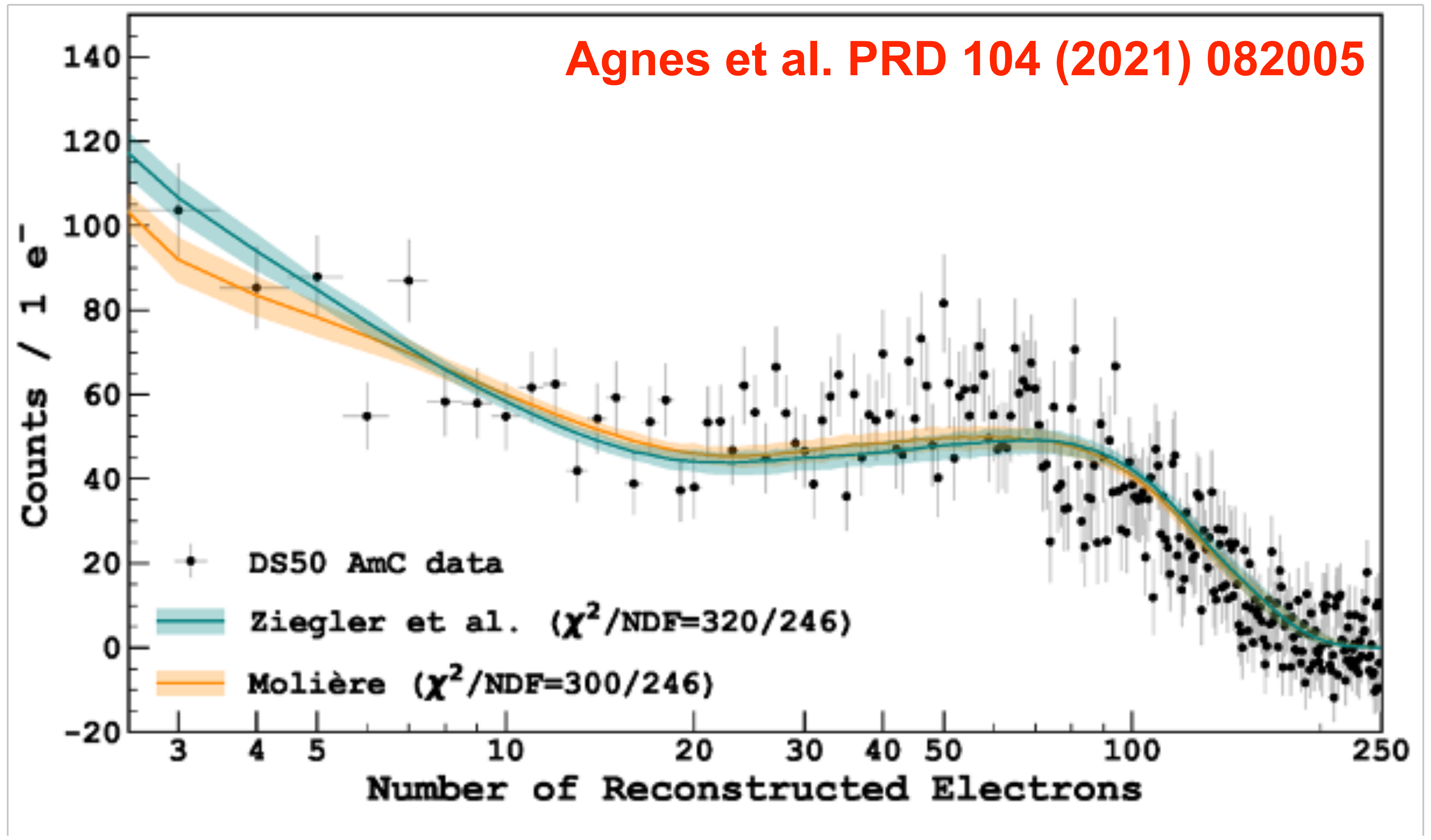




The ^{252}Cf Campaign at INFN-CT

- Data were taken from **Jan 10th to Mar 16th, 2023**
- Event rate ~ 2.5 Hz, 80 µs waveforms (600 GB/day)
- Trigger logic: **BaF_2(OR)** ∧ **PSci(OR)**
- **Tagging 60% of SF events**
- TPC acquired in **slave mode** (Difficult to trigger on S1)
- Weekly calibration with **laser**, **^{137}Cs**, and **^{241}Am** sources to correct for non-homogeneities in TPC Response.

Measurement within **DS-50**, with AmC and AmBe neutron sources



A Dedicated **2-parameter DS-50** Model

Thomas-Imel

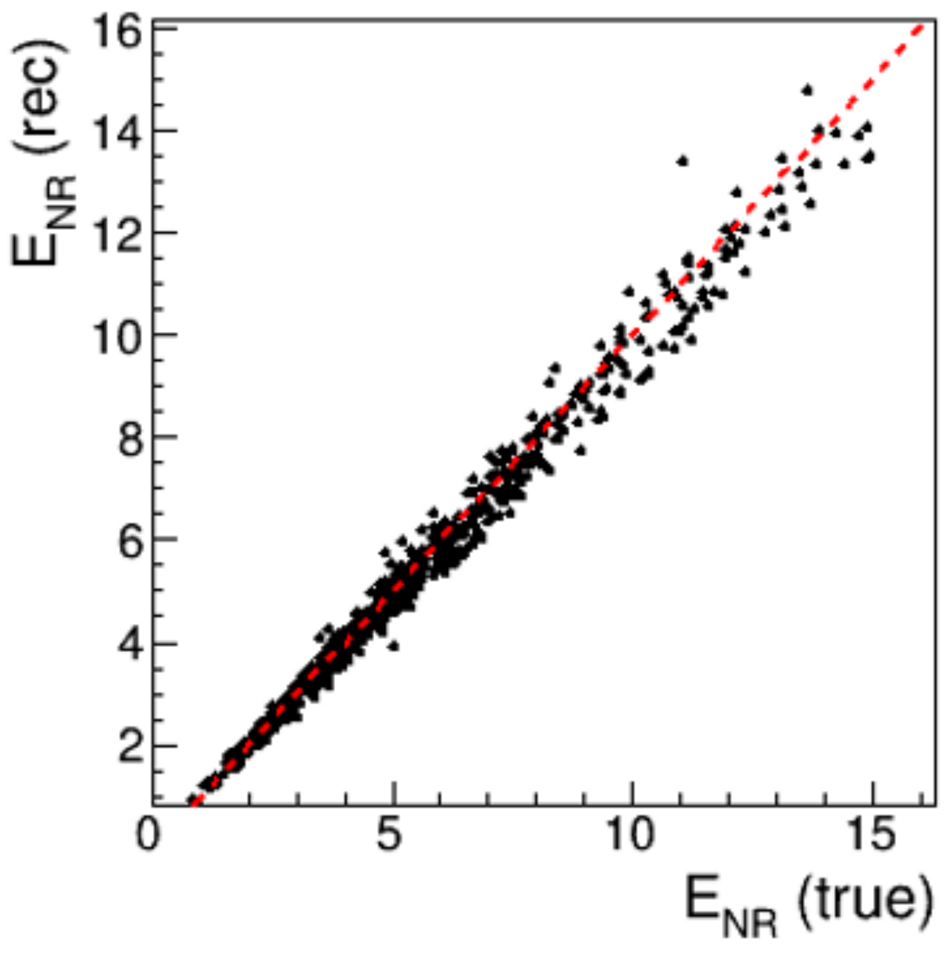
$$1 - r = \frac{1}{\gamma N_i} \ln(1 + \gamma N_i)$$

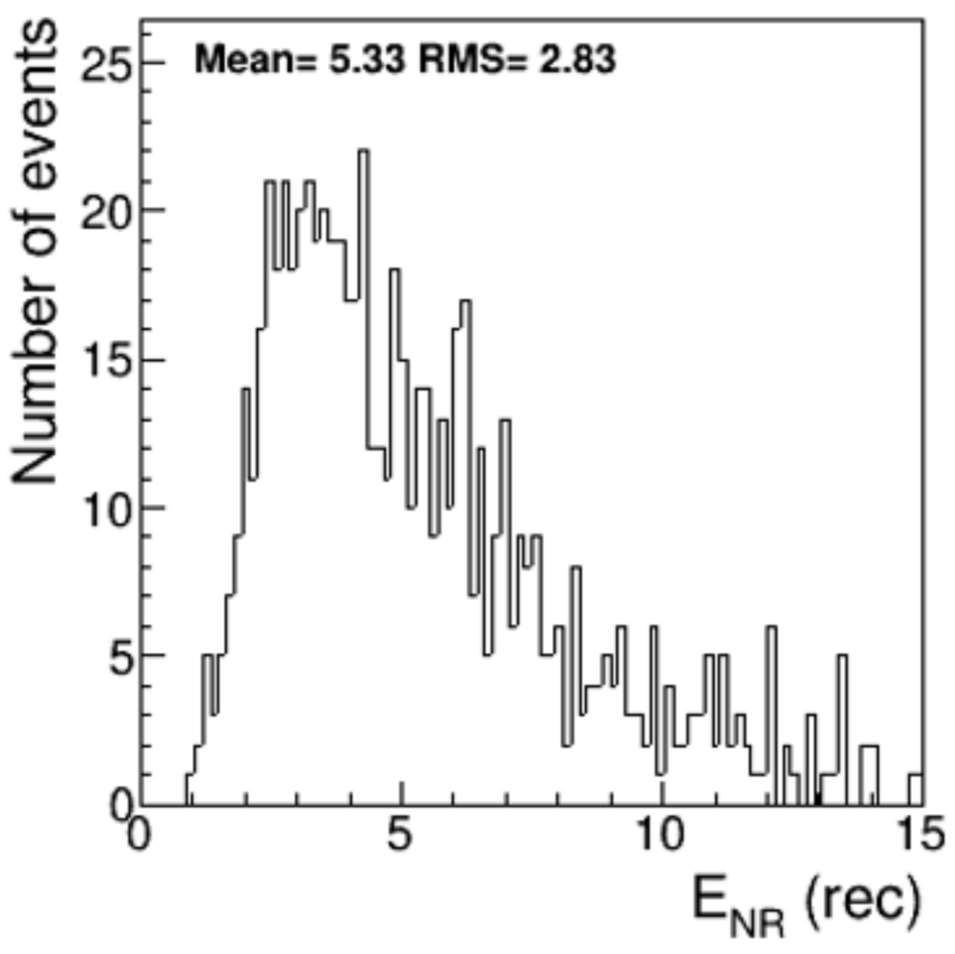
$$Q_y^{NR} = \frac{N_{i.e.}}{E_{nr}} = \frac{(1-r)N_i}{E_{nr}}$$

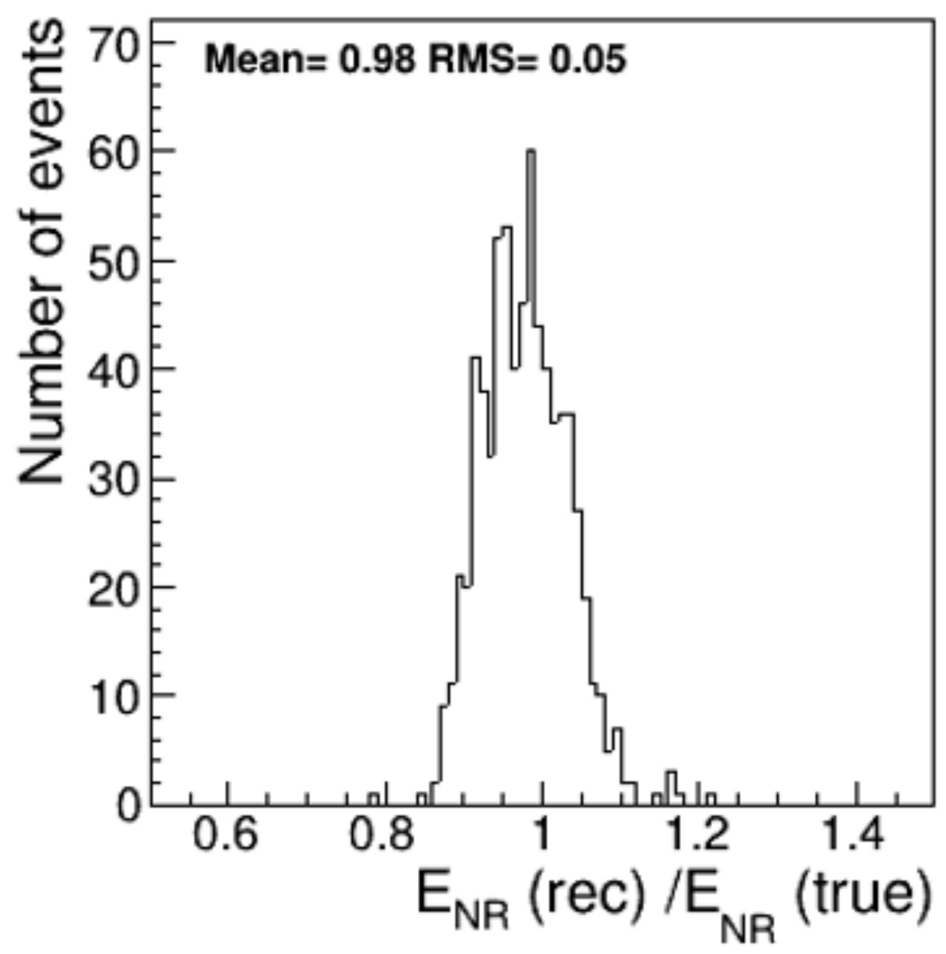
$$N_i = \beta\ \kappa(\epsilon) = \beta \frac{\epsilon\ s_e(\epsilon)}{s_n(\epsilon) + s_e(\epsilon)}$$

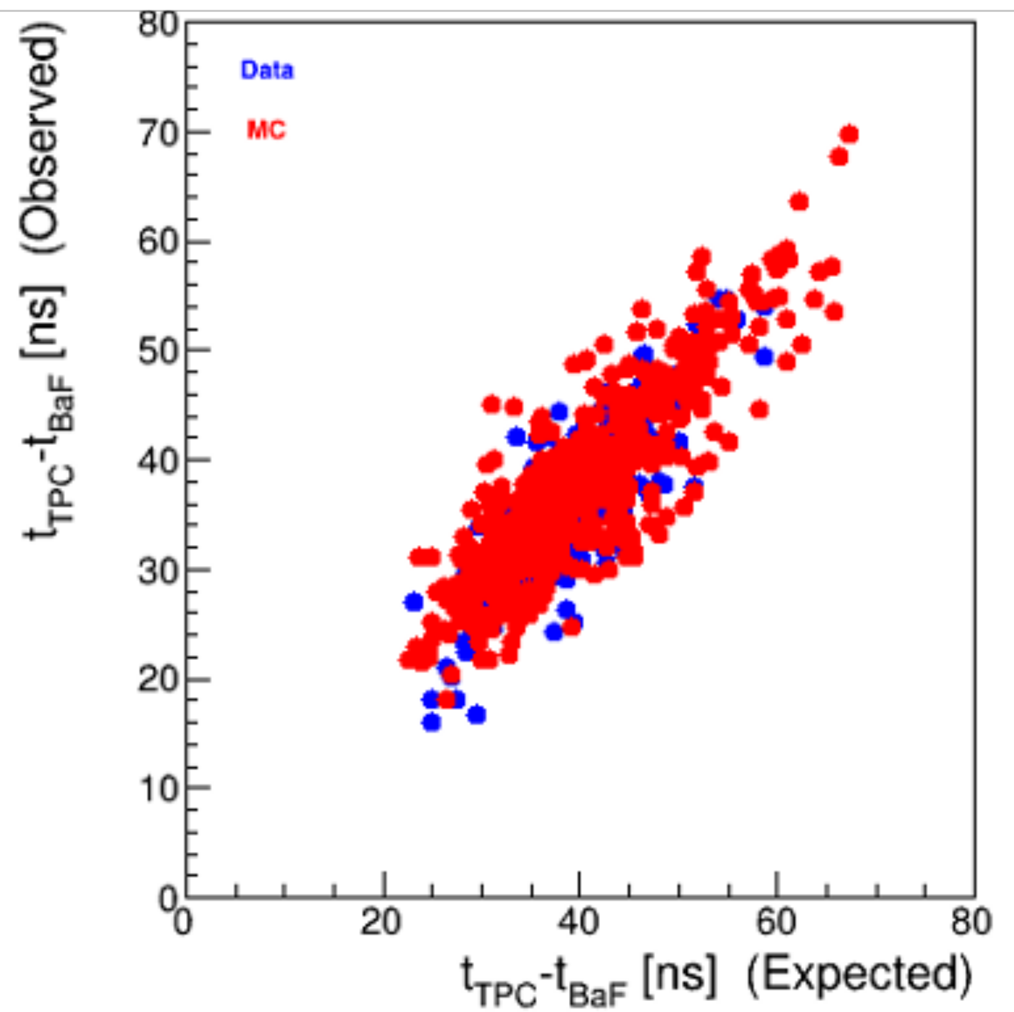
MC Validation

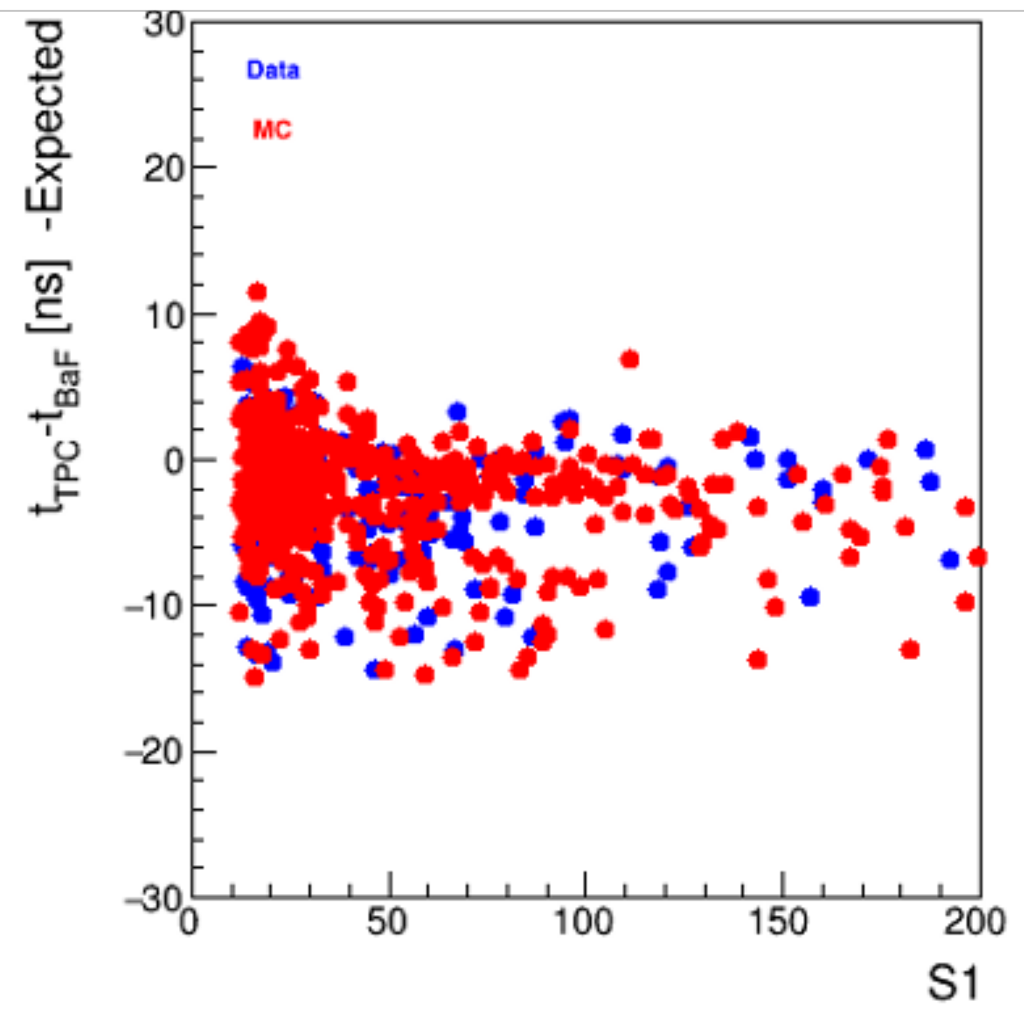
- A detailed MC Simulation was developed to verify the reconstruction algorithm
  - It produces synthetic data that go through the **same analysis flow as real data**.

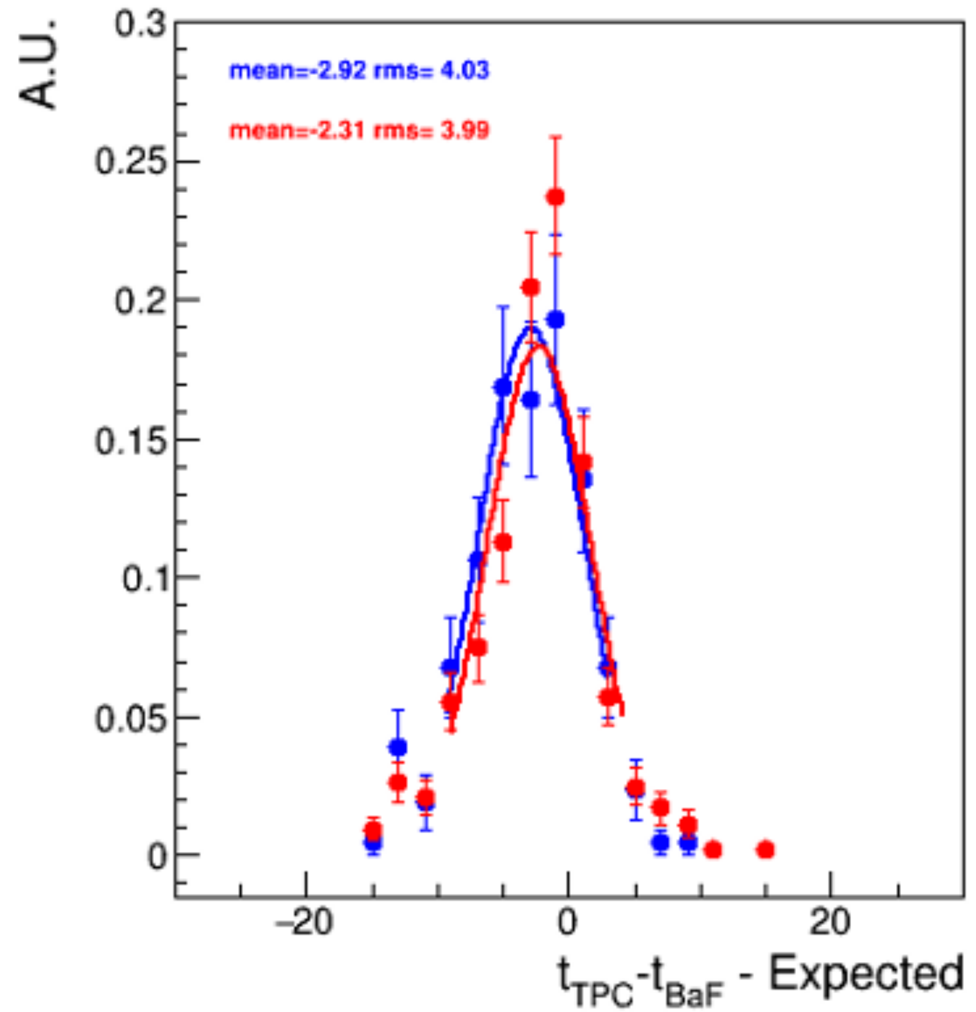




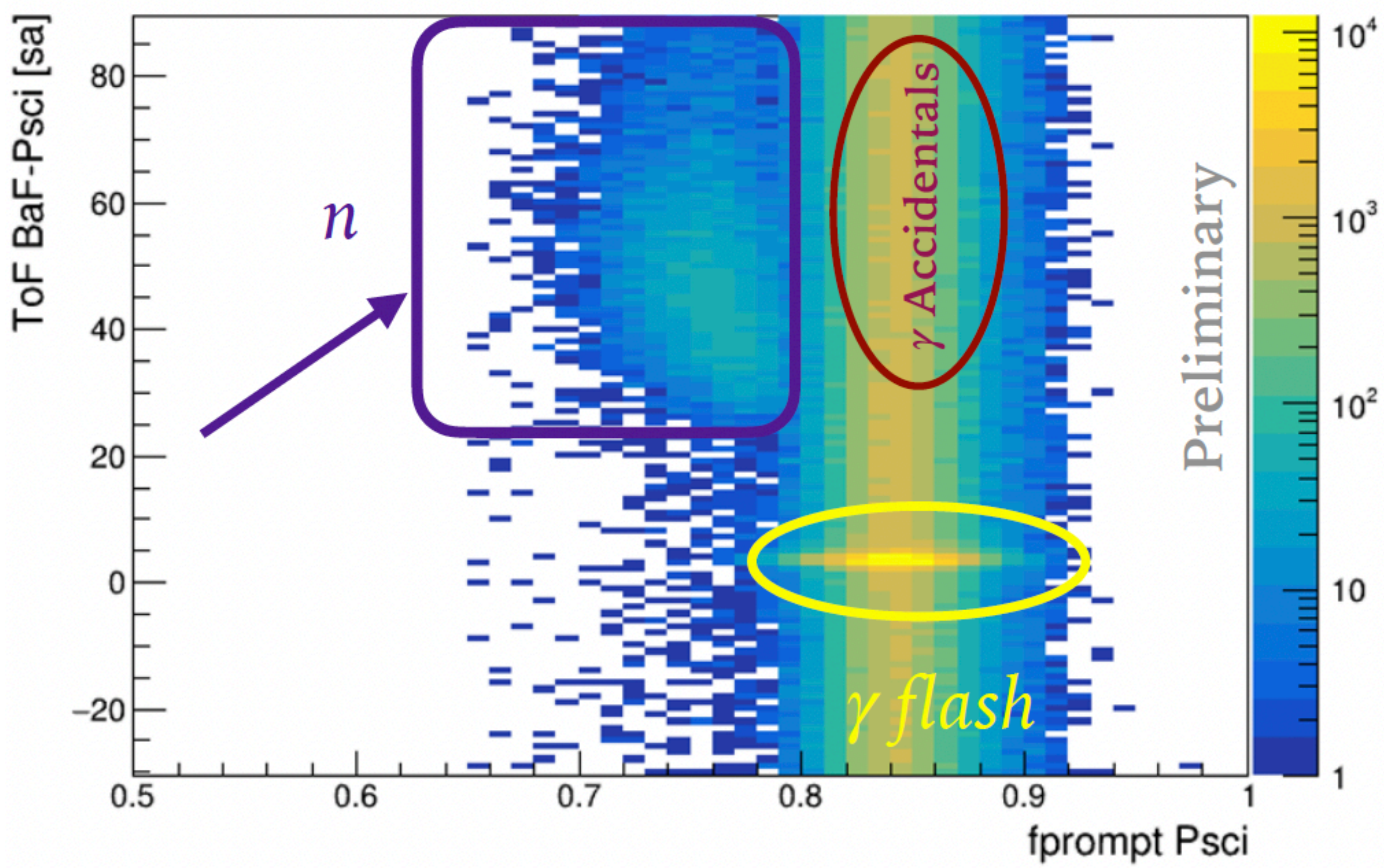




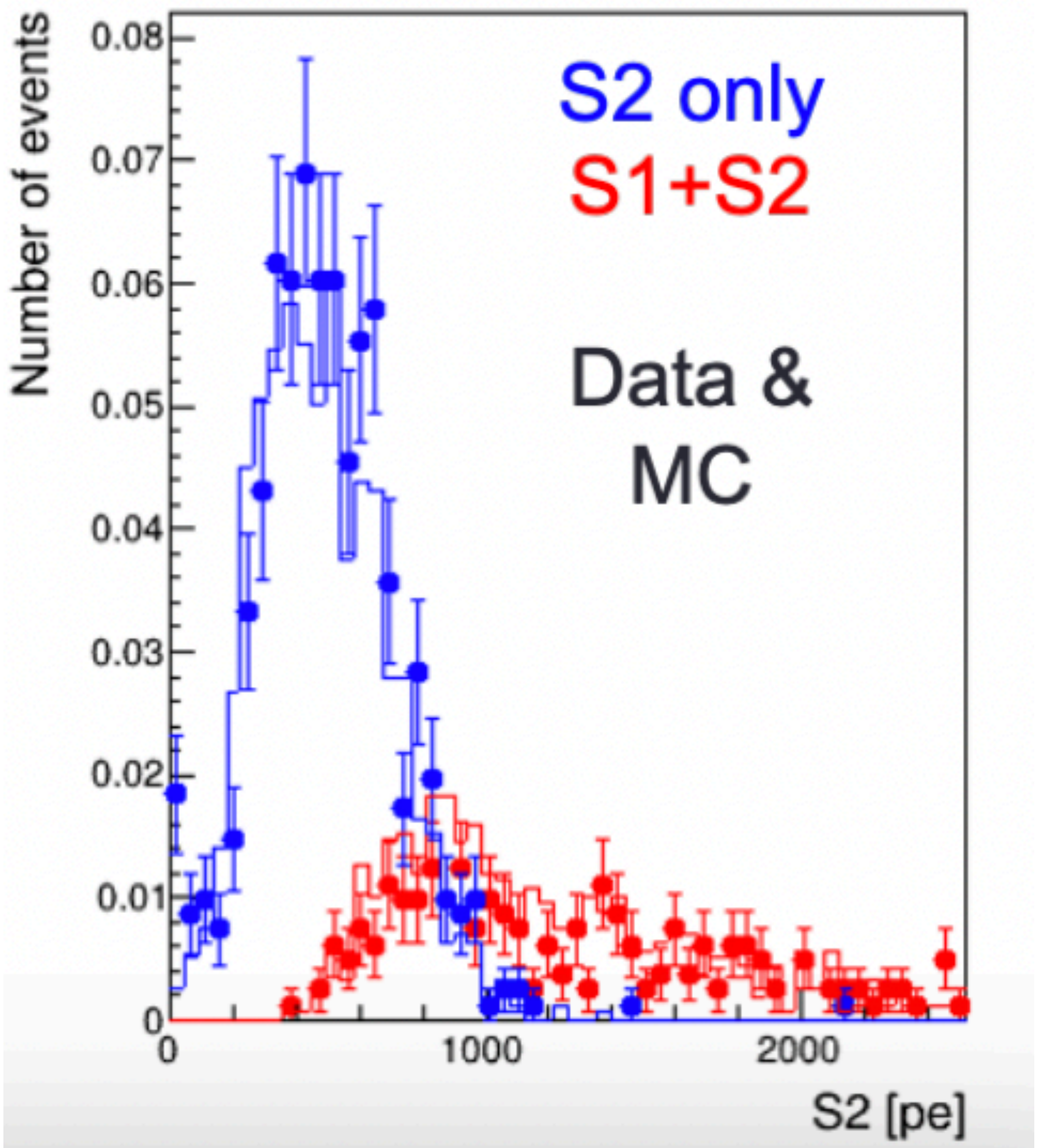




Analysis and Event Selection



- Selection of candidate neutrons by **time of flight** and **PSD**
- Event rate:
  - 28 neutrons/hour (0.3%)
  - Dominated by **γ rays and accidentals**
- ToF resolution ~ 0.7 ns
- De-convolution of SiPM response and TPC pulse finder
- Pulse finder is fully efficient for S1 > 25 PE and S2 > 4 e^-
- Selection Cuts:
  - S1 ~ 8 PE for 5 keV_{nr} —> Interesting S1 are largely missed by the pulse finder
  - Most S1+S2 events are outliers: multiple neutron scattering (as expected from MC) Therefore, removed from the analysis
  - One S2 within the coincidence window with the **BaF_2 and PSci**
  - **Fiducialization** —> the inner 4 cm



Preliminary Analysis Results

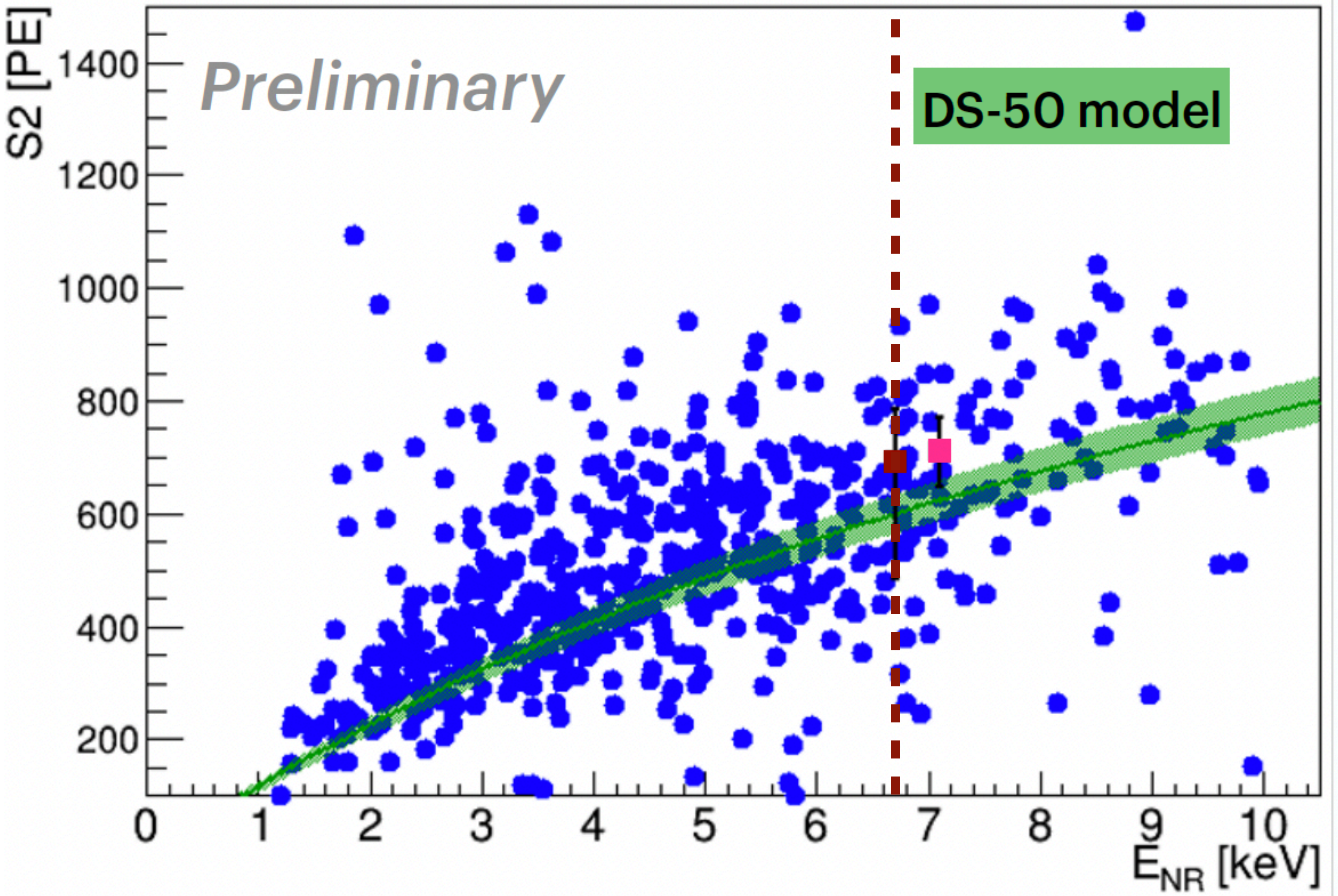
- ~ **820 passing all cuts**, out of 2300 candidate neutrons with a trace in the TPC
- 75% are S2-only (as expected from MC)
- Recoil energy was calculated on an event-by-event basis (uncertainty ± 5%)

Two-body kinematics!

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

- S2-only events: 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 = 17.2 PE/e^-**



Joshi et al. PRL **112** (2014) 171303

Agnes et al. PRD **97** (2018) 112005

Summary

- The ReD experiment aim is to characterize the response of LAr to low-energy O(keV) NRs
- We successfully took enough ^{252}Cf data (Jan-Mar 2023) and the analysis is ongoing
- Design sensitivity met: down to 1-2 keV$_{nr}$

Future Perspectives

- **Work in progress:** Infer g_2 directly from the ReD experimental data to constrain the parameters in the DS-50 ionization model (fit of data against MC distributions)
- ReD+, to cover down to 0.4 keV$_{nr}$ with ^{252}Cf (Italian PRIN funding) and DD neutron gun (Brazilian FAPESP grant)
- This information is crucial for "low-mass WIMP" analyses of current DM experiments and for the design of the next-generation detectors.

Stay Safe

Thank you!

The Future is Dark

Backup