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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

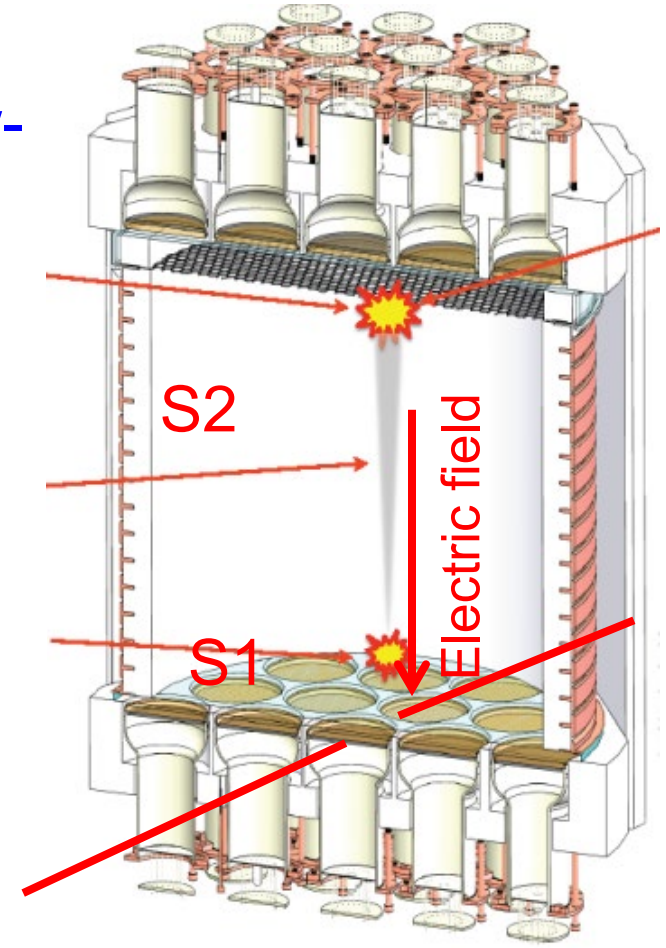
TAUP2025, Xichang, China
August 28th, 2025

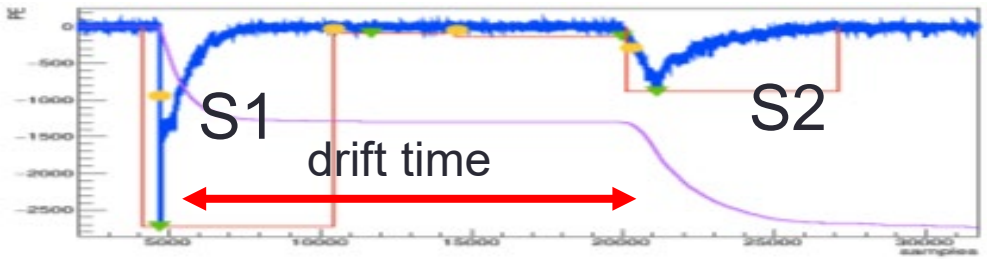
DARKSIDE

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**)



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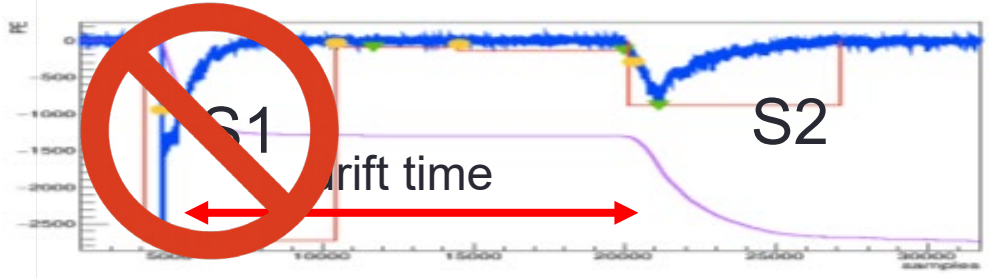
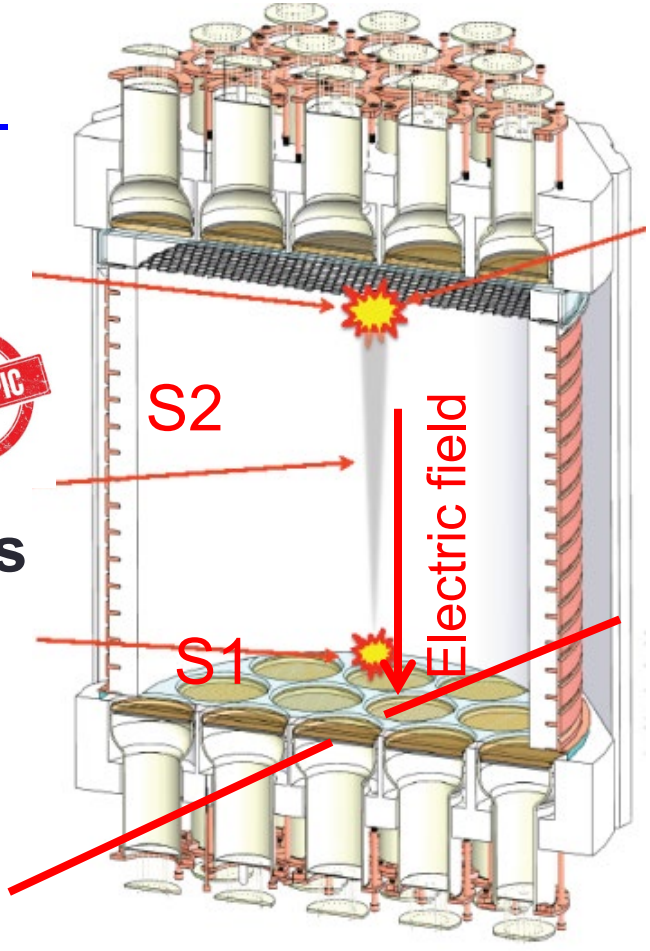
    - Novel light readout with SiPM
  - Pave way for next-generation (**ARGO**)
- Technology sensitive to **low-mass WIMPs**
  - A few GeV instead of the "standard" 100's GeV
  - Slower recoil, O(1 keV) instead of 20-100 keV
  - **Challenging!** S1 too small, S2-only



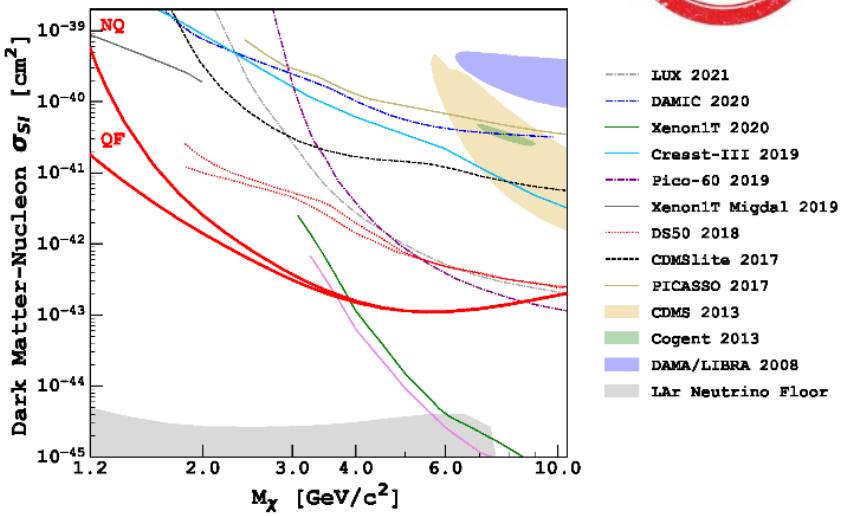




Talks by W. Bonivento, M. Wada & A. Jamil

# The search for low-energy WIMPs

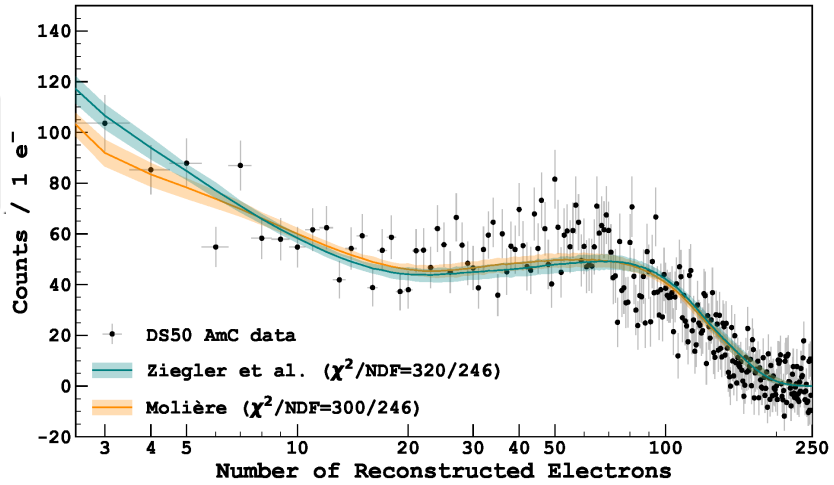

- Analysis sensitive to **ionization yield** for keV NRs
  - **Poorly known** for Ar (data at ~7 keV)
- Measurement within **DS-50**, with AmC and AmBe neutron sources
  - Combined fit with direct measurements (ARIS, SCENE)
  - Constrains from small low-energy sample from the AmC calibration
  - Custom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

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




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

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



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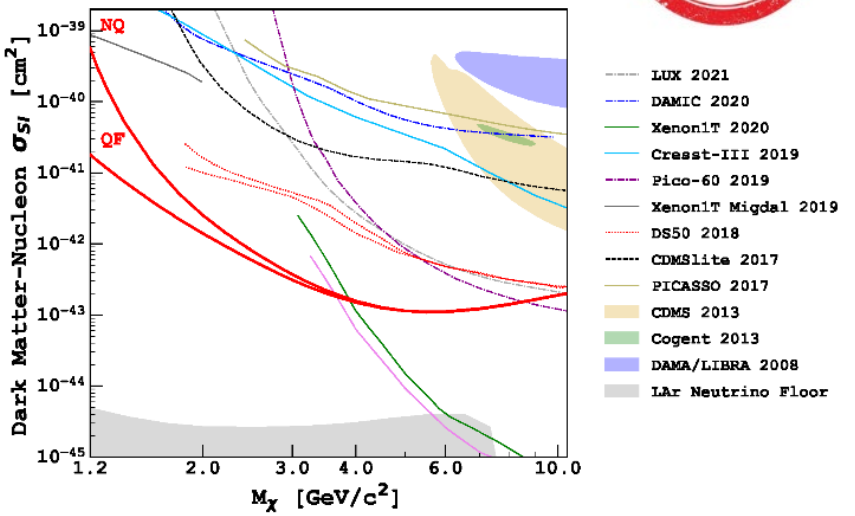
- Different screening models for $s_n$
- **Strong case** for a LAr **direct measurement** at **1-5 keV**

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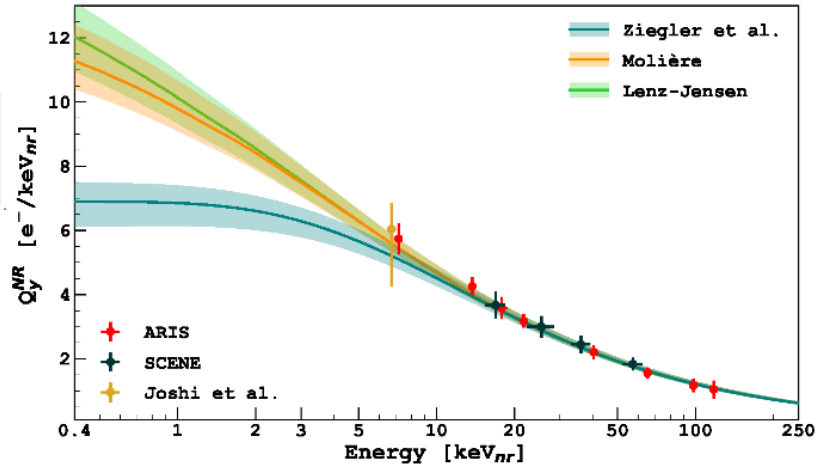
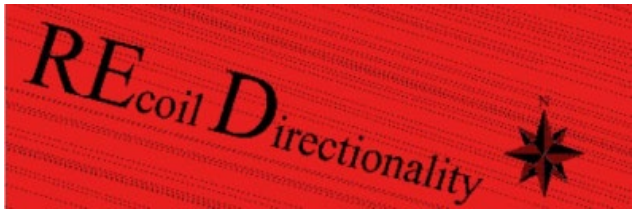
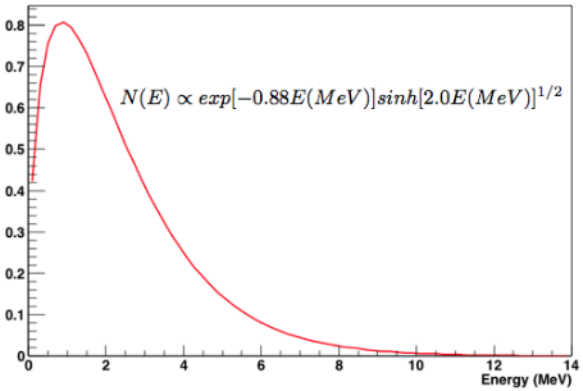


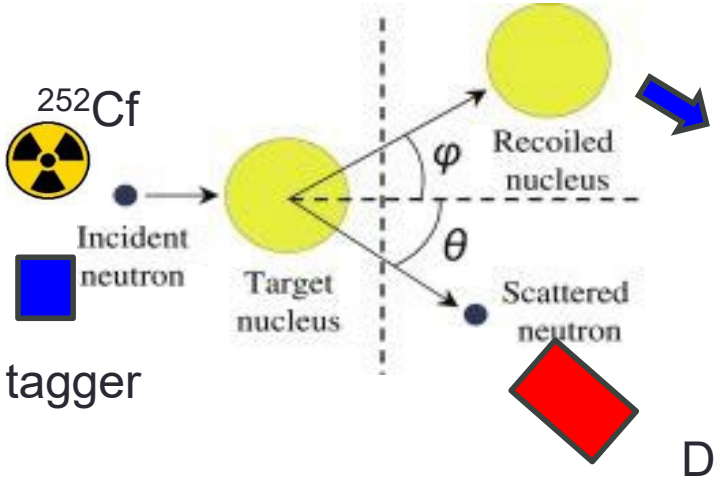
# The ReD project




- 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



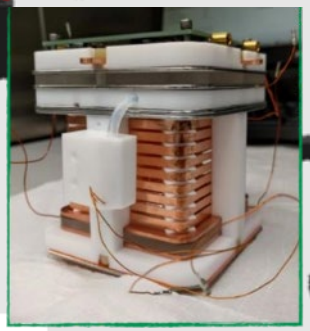

$$E_{NR} = 2KE_{neutron}\frac{m_n m_{Ar}}{(m_n + m_{Ar})^2}(1 - cos\theta_{scatt})$$

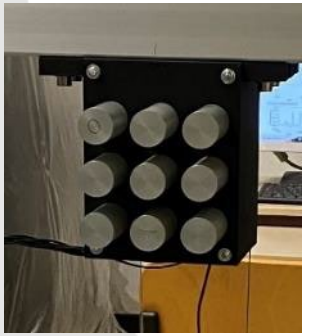
Time of flight

Fixed by geometry

**Two-body kinematics!**

# The ReD conceptual layout

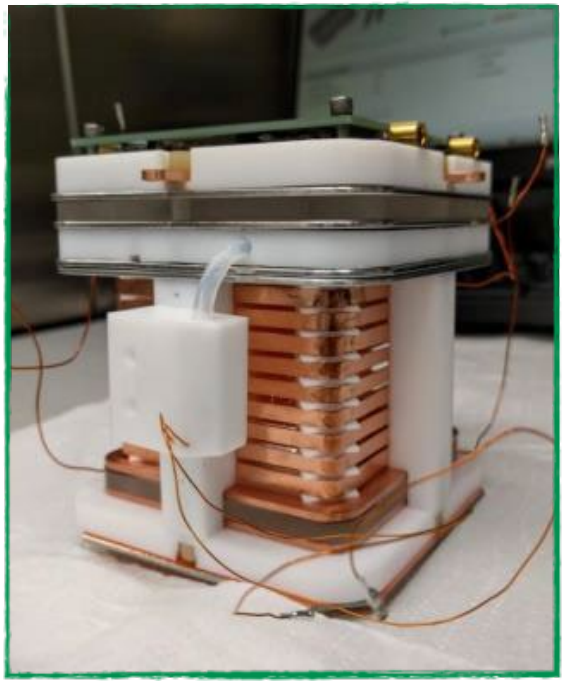




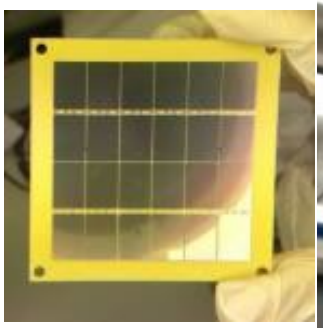


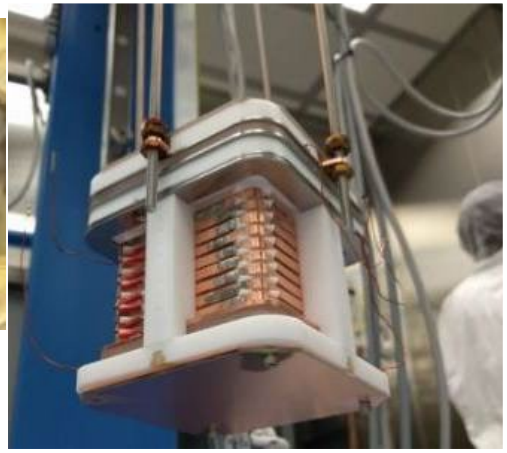

- Design sensitivity in the range **2-5 keV$_{nr}$**

# 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





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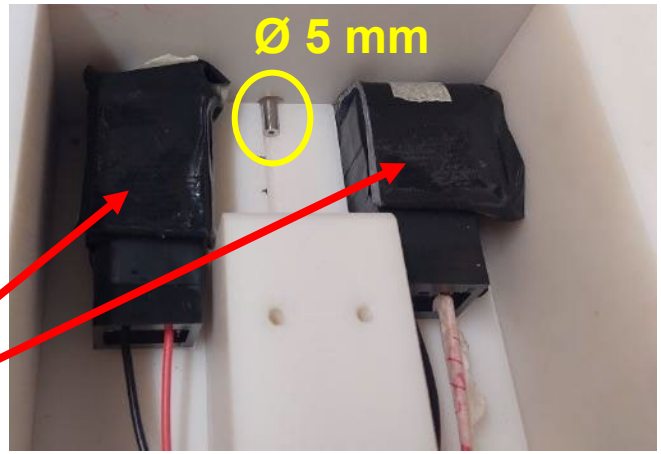
# … and all the rest

- **$^{252}$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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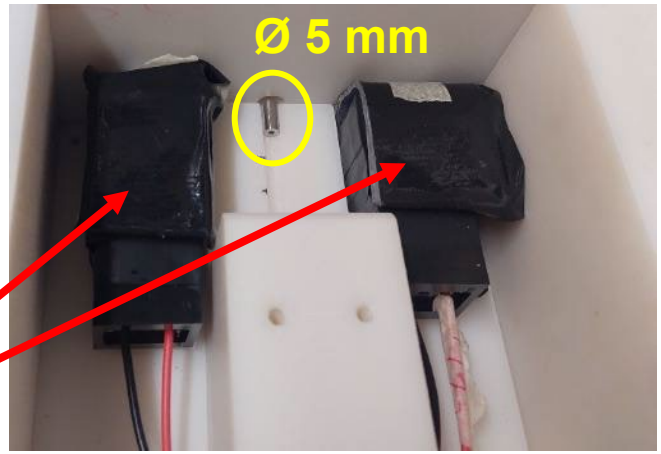
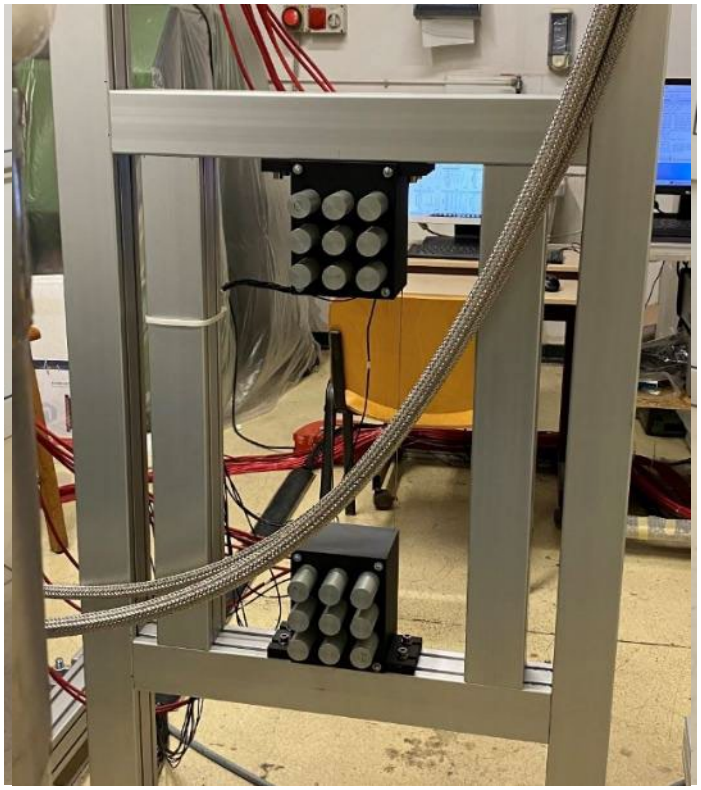
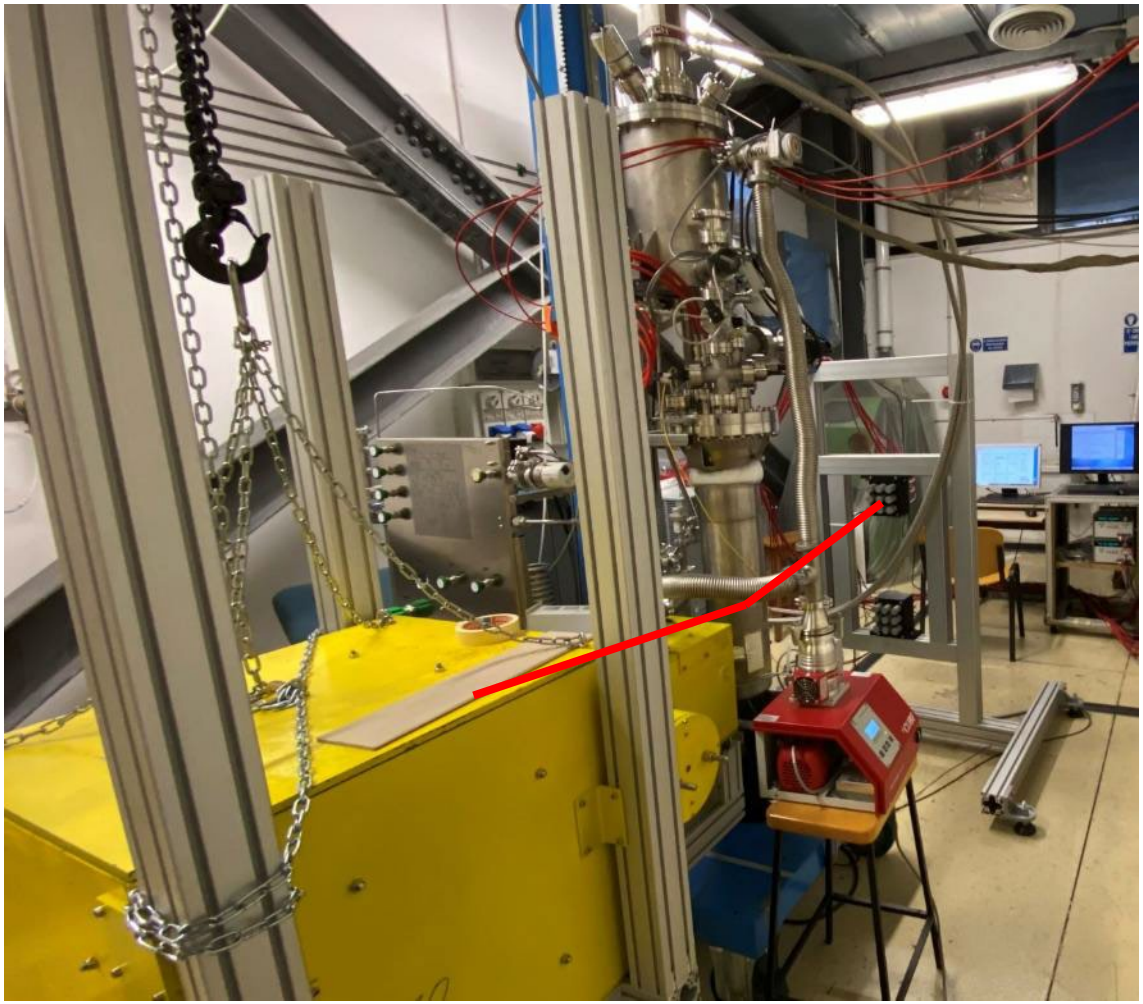
- Two **$BaF_2$ detectors** to tag fission products
  - Fast (high source rate, pile-up)
  - START for time of flight
- **Neutron spectrometer**: two 3x3 arrays of EJ276 **plastic scintillators** («PSci»)
  - STOP for time of flight
  - Features n/γ discrimination
  - 1 m downstream the TPC
  - Symmetric deployment
  - **θ ~ 12°-17°** in order to **avoid direct neutrons** from the source
- Tag Ar recoils down to **~1-2 keV$_{nr}$**



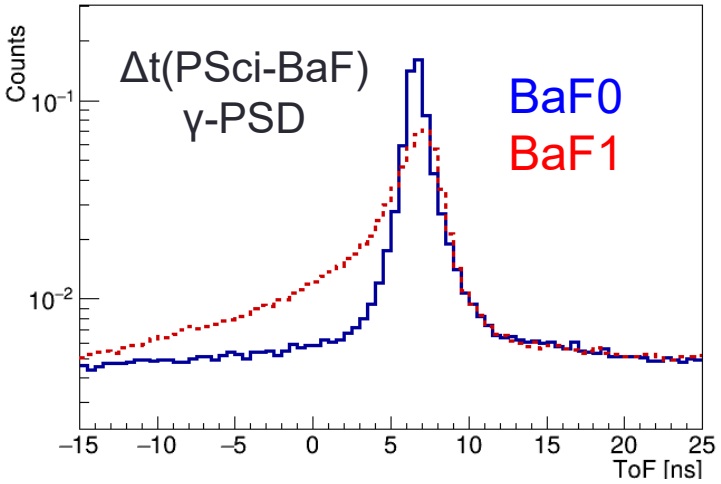
# The real thing at

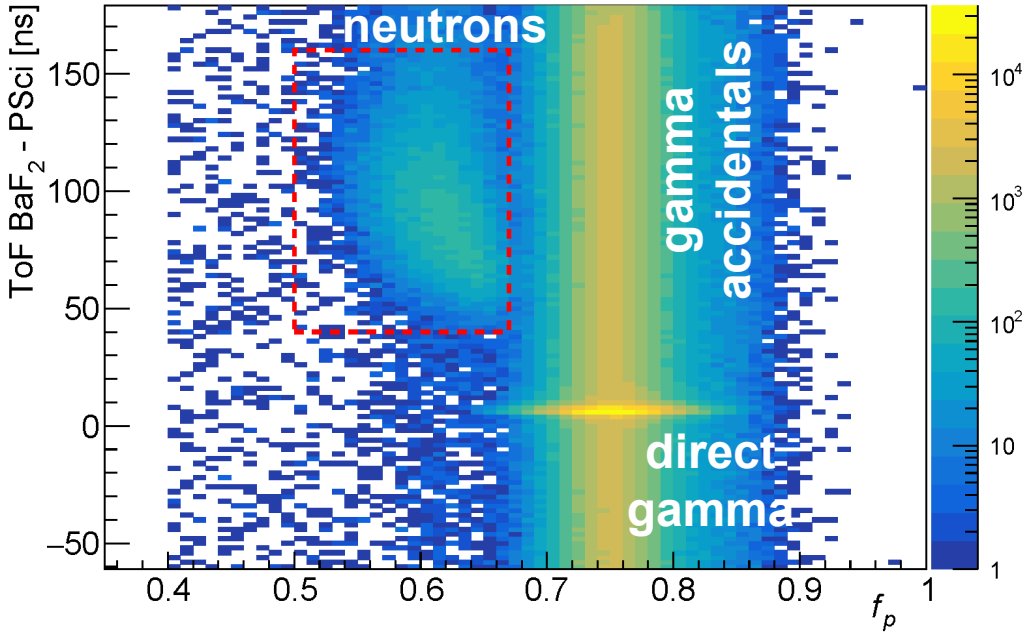
INFN Catania
Istituto Nazionale di Fisica Nucleare



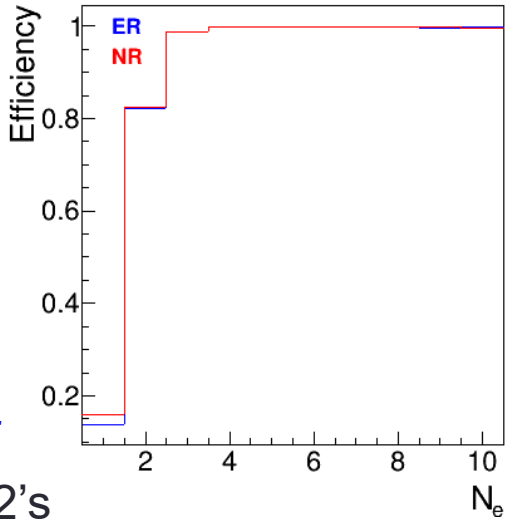
# Data taking: finding neutrons…

- Data taking with $^{252}$Cf from **Jan to Mar, 2023** (about 75 days)
  - Weekly calibrations with $^{241}$Am and laser
- 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 0.4% of total triggers
- ToF resolution **0.6-1.3 ns** rms
  - Event-by-event $E_n$ at <5%

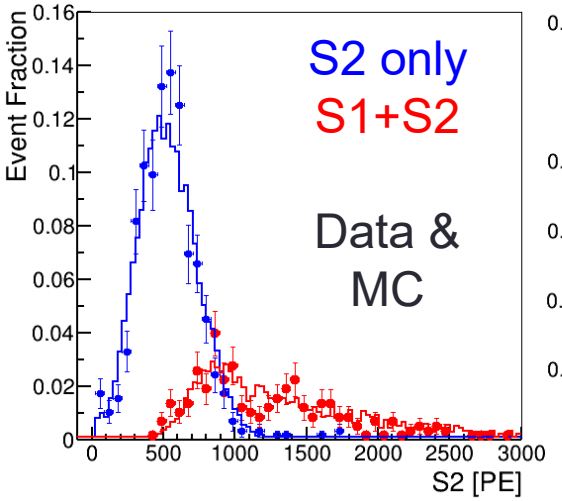


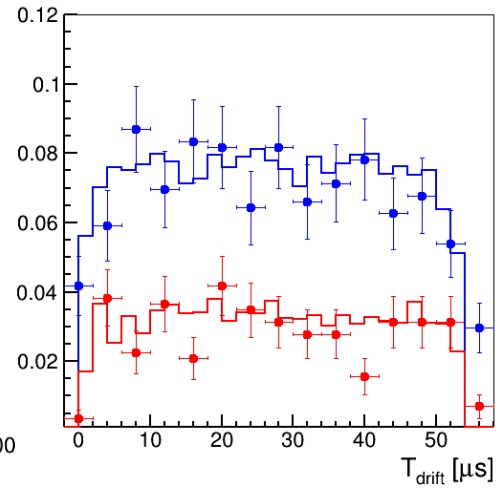
# … interacting in the TPC




- Look for TPC events **offline**
  - Pulse finder fully **efficient** for S1 > 25 PE, **S2 > 4 e-**
  - **Additional 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
- Detailed end-to-end **MC simulation** available
  - Produce synthetic data → same analysis flow than real data
  - Validated on calibration, use to check reconstruction algorithms!
- 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 **$E_{NR}$** from time of flight (and geometry) down to **1-2 keV**
  - Select 1-10 keV due to kinematics
  - Uncertainty 9% @ 2 keV (6% @8 keV), driven by PSci solid angle

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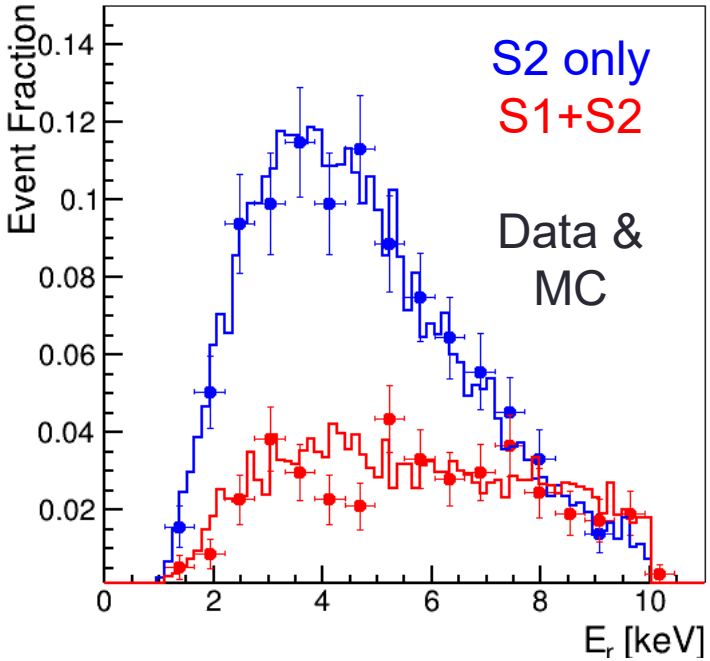

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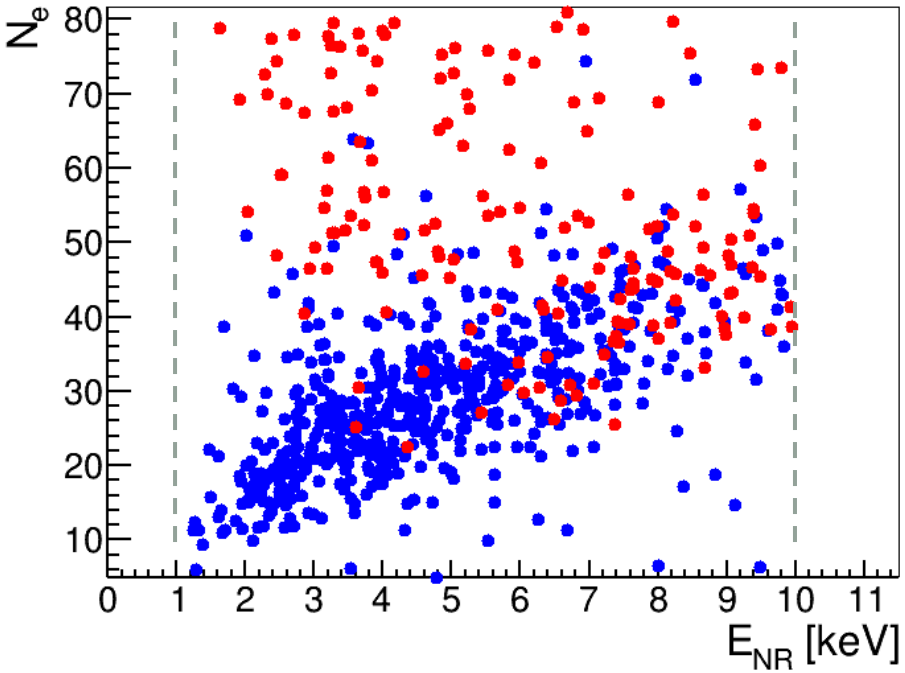
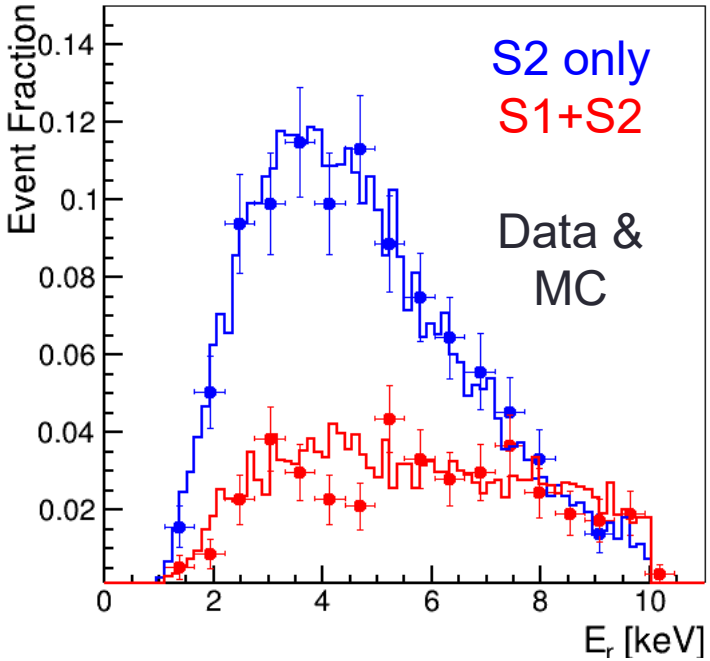
- S2 converted into **$N_e$** via ionization gain **$g_2$ = (18.6 ± 0.7) PE/e-**
  - From $^{241}$Am calibration, checked with «echo» events
  - $^{241}$Am to constrain TPC vertical alignment Δz = (0.23 ± 0.95) cm
- **$N_e$ resolution** 12% at $N_e$=10 (7% for $N_e$ >40)

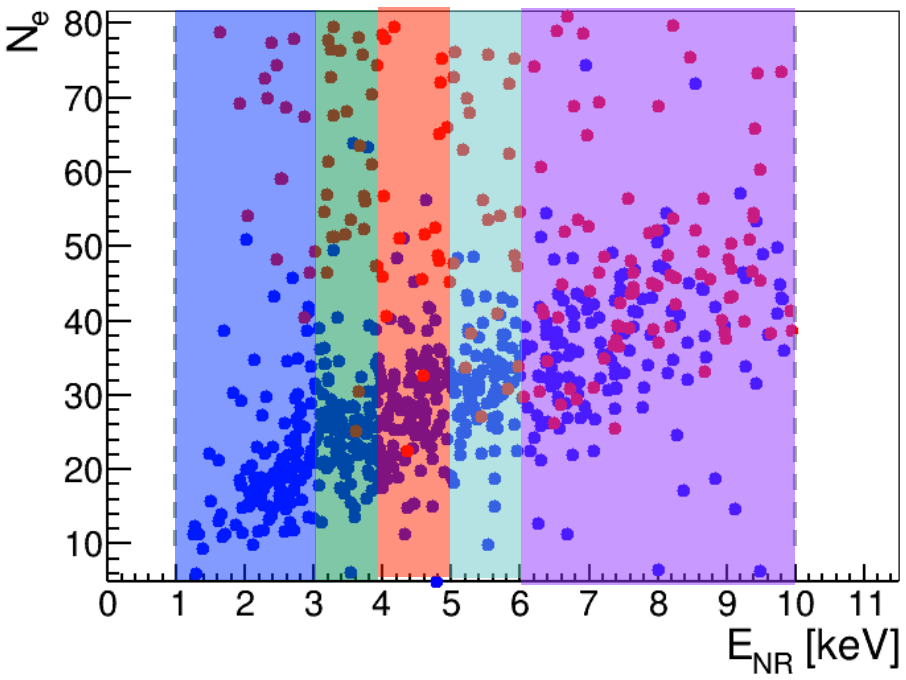


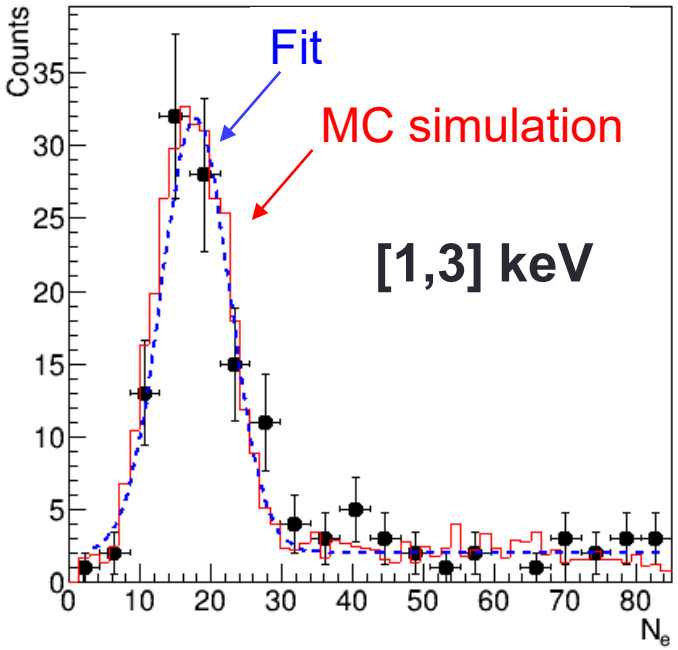

S2 only
S1+S2



# 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

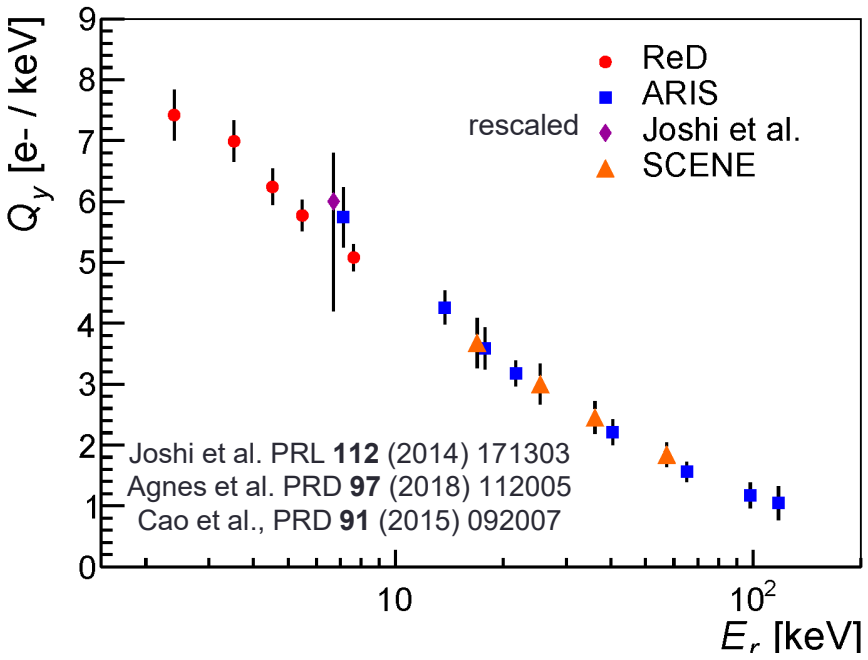


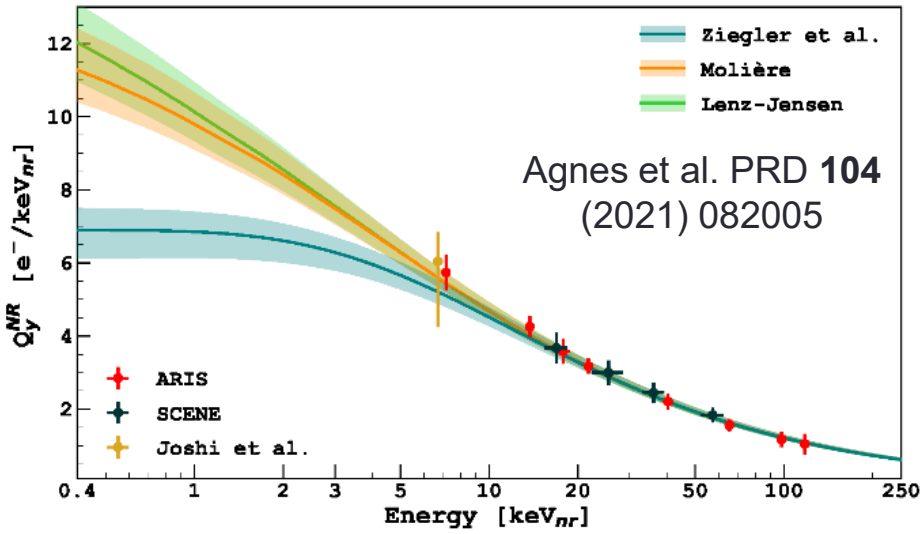




- $Q_y = N_e / \langle E_{NR} \rangle$
- Procedure validated with the MC-generated data sets
  - Unbiased, provided S1+S2 events kept
  - MC nicely describes $N_e$ distribution → potential sensitivity to fluctuations
- Total $Q_y$ uncertainty 4.5% - 6%
  - Mostly systematic, driven by $\Delta g_2$

# Results and more…

- ReD in **agreement** with **existing data** above 7 keV
- Trend of **increasing Qy** at lower energy
  - Compatible with Lenz-Jensen, but not with Ziegler
  - Problem with Moliere parametrization from literature→ miscopied parameters in the Sigmund book



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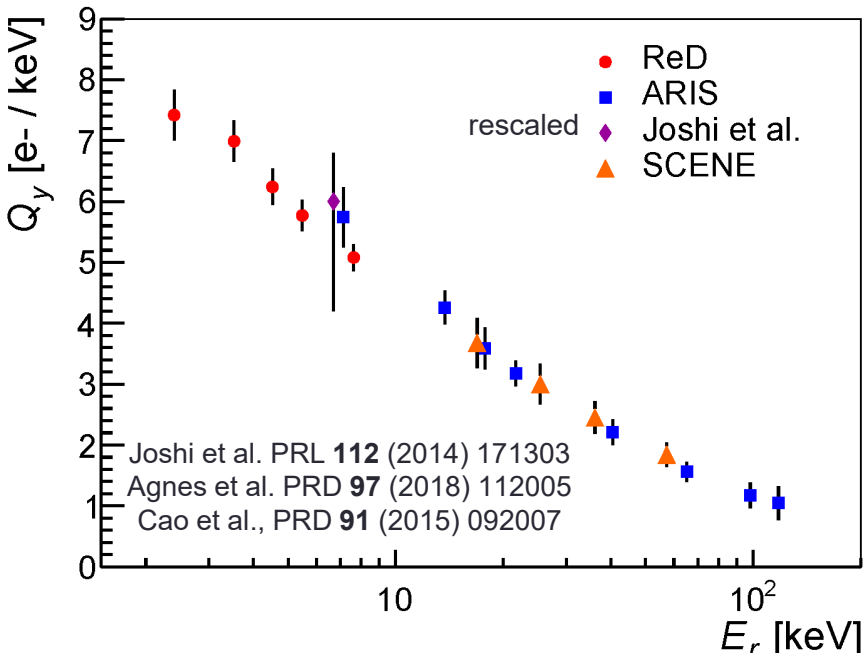
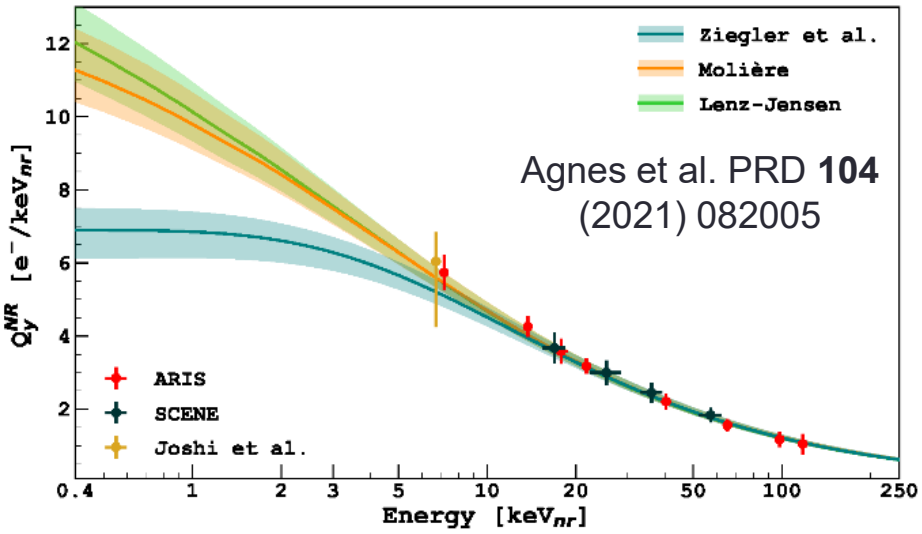
- Repeat the **global fit** with DS-50, ARIS and SCENE, **w/ the ReD data points**
  - Ziegler, Lenz-Jensen and (*correct*) Moliere screening functions
- Bonus: marginalization on $g_2$ and $\Delta z$ for ReD data
  - $Q_y$ uncertainty 3.0% - 4.5%



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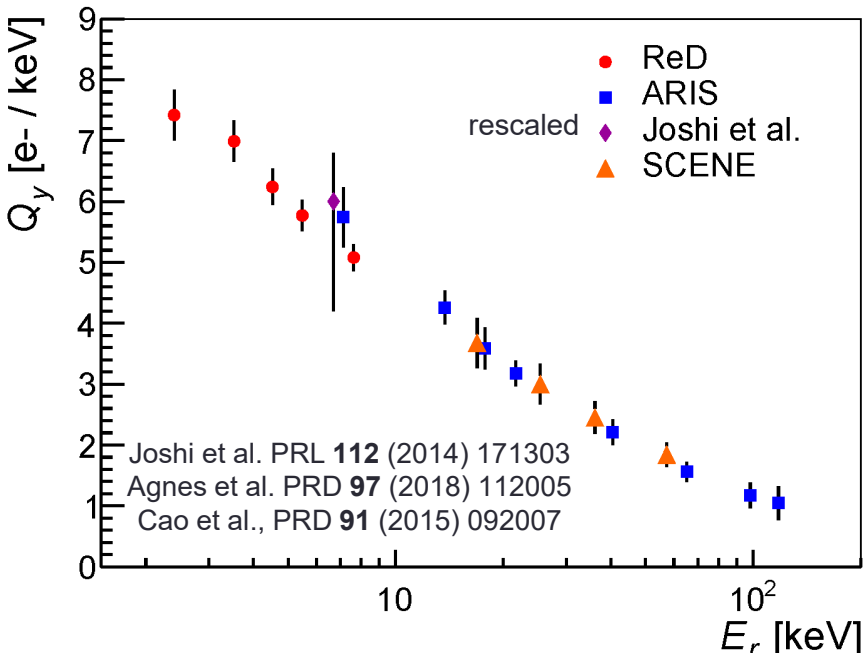
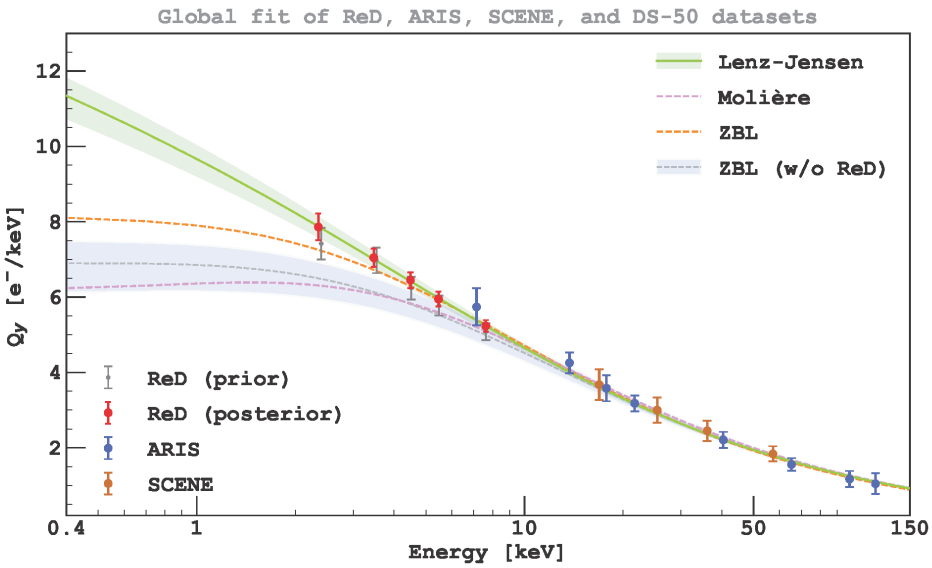
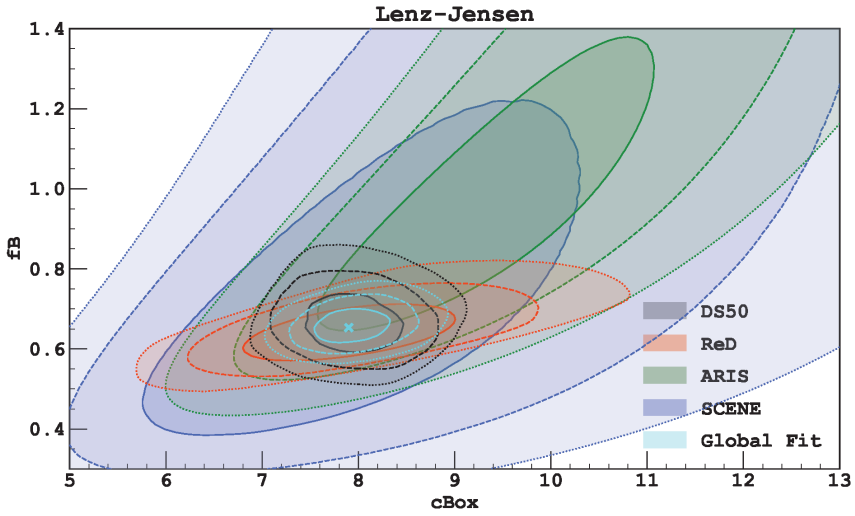
  - $Q_y$ uncertainty 3.0% - 4.5%
- Lenz-Jensen looks **best**

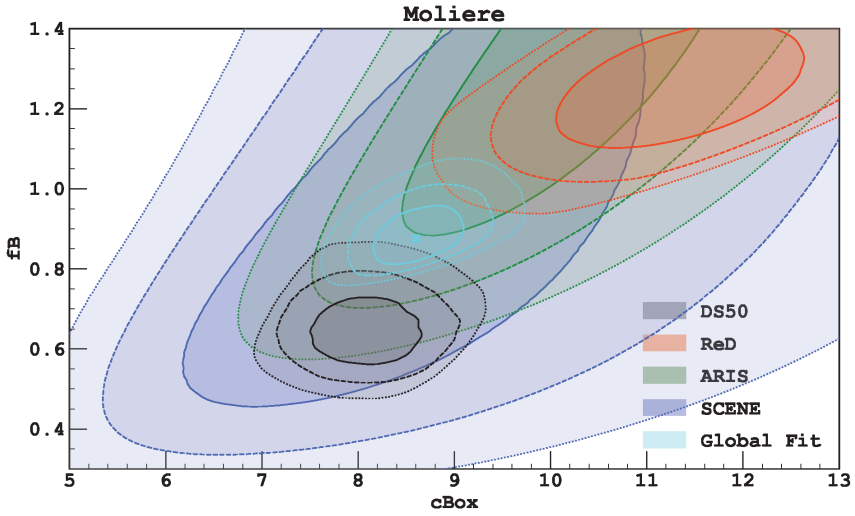


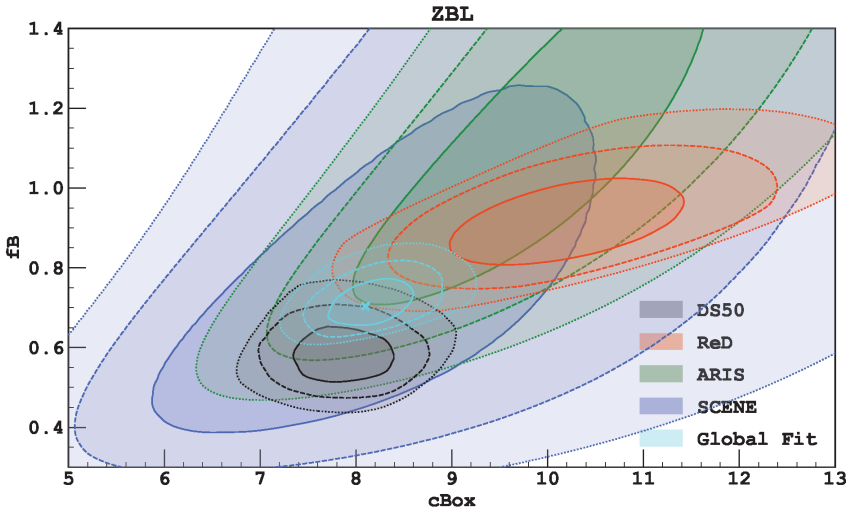



# Results & impact

- **Quantitative** comparison of models by using **Bayes Factor**
  - L-J vs. Ziegler $\log_{10}$ BF = 3.8
  - L-J vs. Moliere $\log_{10}$ BF = 7.2

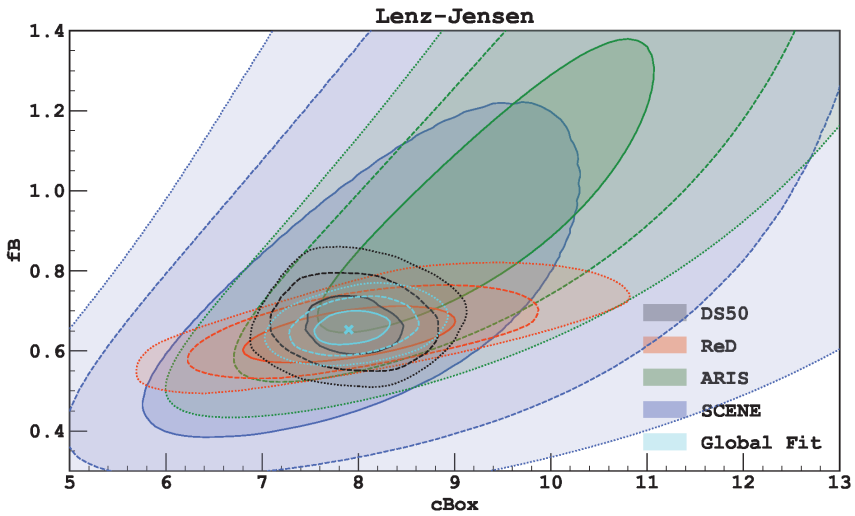


# Results & impact

- **Quantitative** comparison of models by using **Bayes Factor**
  - L-J vs. Ziegler $\log_{10}$ BF = 3.8
  - L-J vs. Moliere $\log_{10}$ BF = 7.2
- Good **agreement** of nuisance parameters with **priors**
  - $g_2$ = (18.8 ± 0.4) PE/e-
  - $\Delta z = (-0.58^{+0.05}_{-0.14})$ cm



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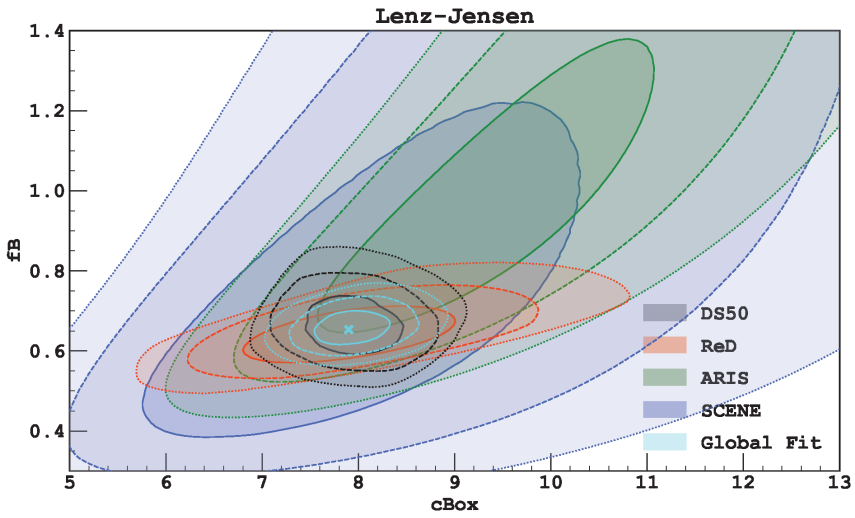
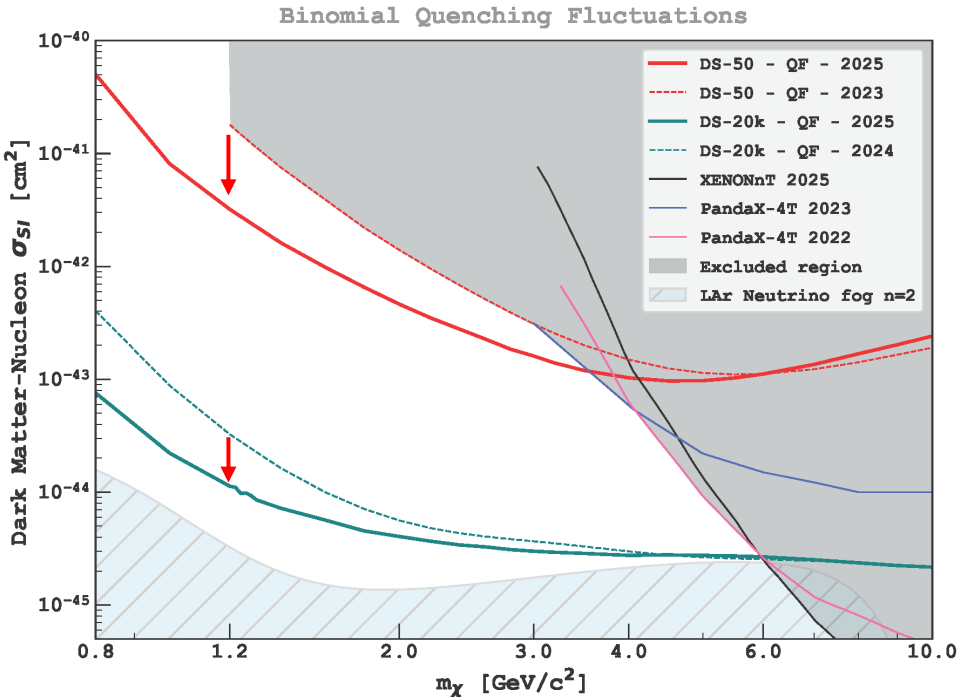
- Re-calculate **DS-50 limit** and **DS-20k sensitivity** by using **Lenz-Jensen** (w/ updated parameters)
  - Higher $Q_y$ than the previous Ziegler-based calculation → **stronger bounds**



# ReD+

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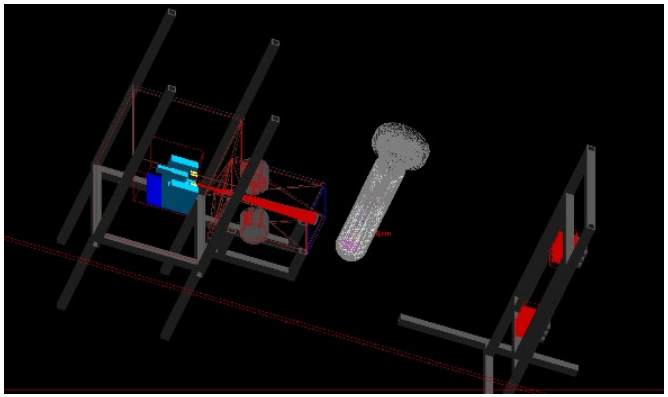
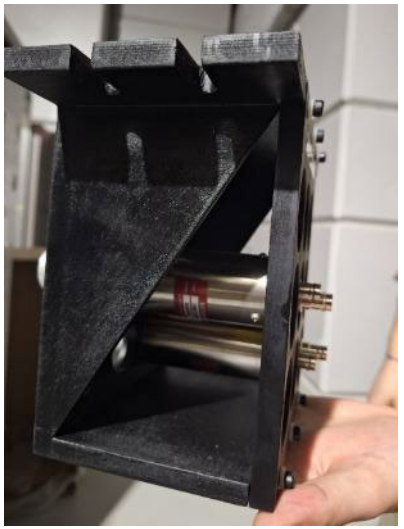
Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA
INFN

- Future project **ReD+**, funded as a PRIN project at INFN, Laboratori Nazionali del Sud
- Goal: **improve down to 0.5 keV$_{nr}$** (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





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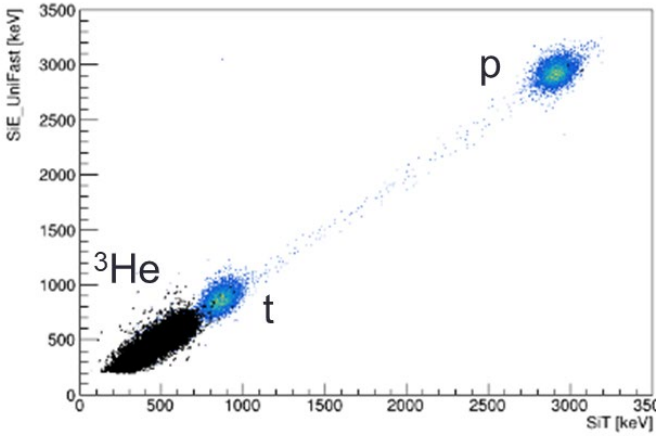
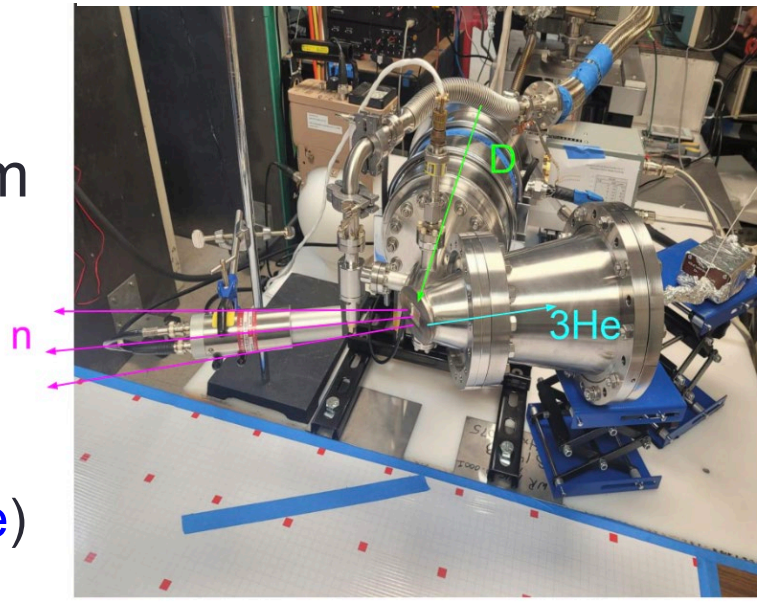
  - Redesigned TPC, larger spectrometer
  - Use the lesson learnt from ReD
  - Pilot run in winter 2025
- After that, aim **at 0.2 keV$_{nr}$** by using 2.4-MeV mono-energetic neutrons from a commercial **DD generator** ($10^7$ n/s)
  - Joint project with University of Sao Paulo (FAPESP grant)
  - Being 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$_{nr}$** 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$_{nr}$
  - Data being used to constrain fluctuation models


- **Global fit** to constrain **screening functions**
  - Strong preference for Lenz-Jensen over Ziegler and Moliere
  - Update of DarkSide-50 low-mass limits and DarkSide-20k sensitivity
    - Higher $Q_y$ with respect to the previously-assumed Ziegler
- Future: **ReD+ @ LNS**, to cover down to **0.2 keV$_{nr}$** with $^{252}$Cf (Italian PRIN funding) and DD neutron generator (Brasilian FAPESP grant)
  - Start data talking in late 2025

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- Information crucial for **"low-mass WIMP" analysis**