Probing dark matter interactions with a RES-NOVA prototype cryogenic detector

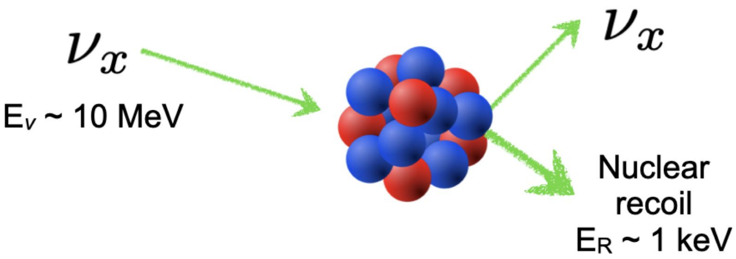
RES-NOVA

- **RES-NOVA** comes from Latin and means *“new things”*
- Its main goal is to study astrophysical sources of neutrinos and DM

www.res-nova.unimib.it

RES-NOVA detection channel

coherent elastic neutrino–nucleus scattering



- Equally sensitive to all ν-flavors
- High interaction cross-section

$$Q_W = N - Z\overbrace{(1 - 4\sin^2\theta_W)}^{\sim 5\%}$$

$$\underbrace{\sigma_{CE\nu NS}}_{\text{cross-section}} = \frac{G_F^2}{4\pi}\,\underbrace{F^2(q^2)}_{\text{Nuclear Form factor}}\,\underbrace{E_\nu^2}_{\text{Neutrino energy}}\,\underbrace{Q_W^2}_{\text{Weak nuclear charge}}$$

RES-NOVA target

$$\sigma_{CE\nu NS} \propto N^2$$

cross-section　　　Neutron number

Pb ideal target

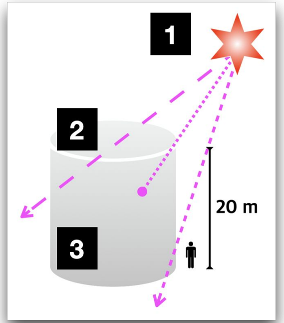
highest neutron number

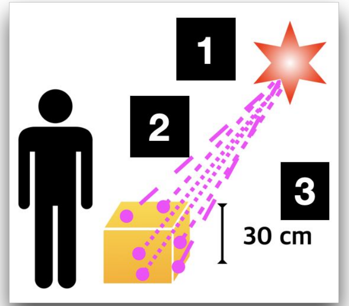
Highest nuclear stability

Roman-Pb

High radiopurity < **1mB/kg**

x10^4 better than commercial **low-background Pb**





Status quo:

1. detection of ~1/6 SN flux
2. small cross-section
3. large volume detectors

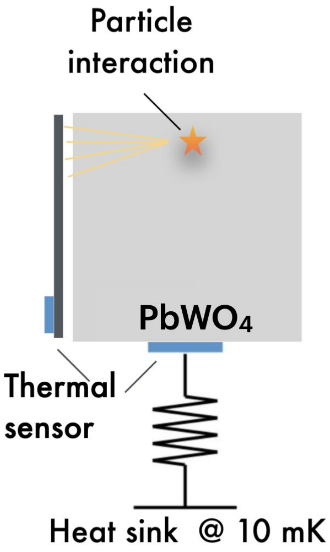
Opportunities:

1. detection of full SN ν flux
2. highest cross-section
3. cm-scale ν telescope

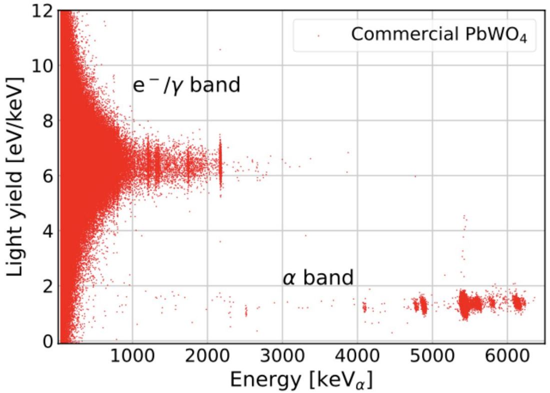
L. Pattavina et al., Phys. Rev. D 102, 063001 (2020)

RES-NOVA technology

- **Low-temperature calorimeters** based on **$PbWO_4$ crystals**
- **TES (Transition Edge Sensors)** used as thermal sensors
- Key advantages:
  - Excellent energy resolution
  - Low-energy threshold
  - No energy quenching
- **Double read-out** (heat + light signal) for efficient **particle identification**

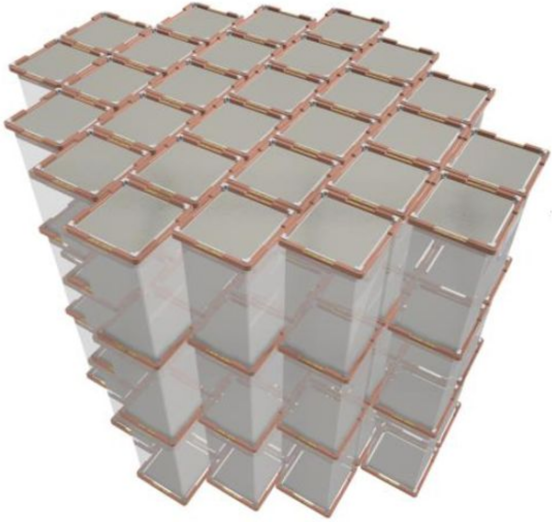


Detector energy spectrum of a cryo-$PbWO_4$

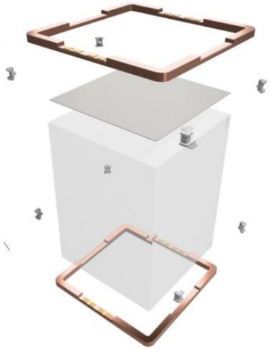


J.W. Beeman et al., Eur. Phys. J. A 49, 50 (2013)

RES-NOVA Detector Concept



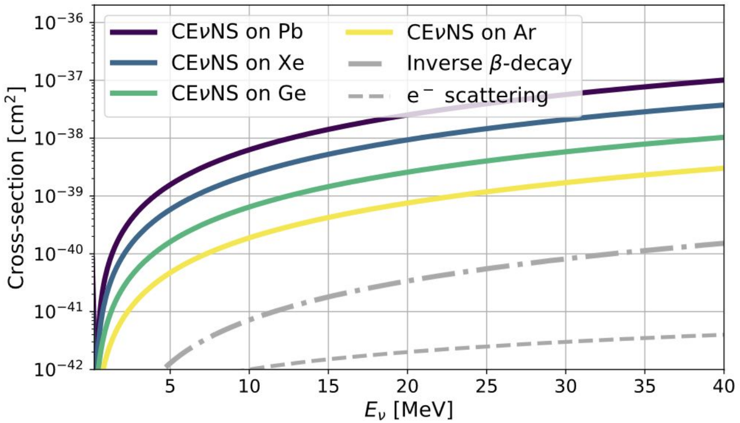
- **TES sensors** will be used as the thermal sensors of the experiment
- The final demonstrator aims for a ∽ 1 **keV energy threshold**
- Detector demonstrator:
  - **84 $PbWO_4$ modules**
  - Total mass of **~160 kg**
  - Arranged in **3 layers of 28 modules**
- Each module consists of:
  - a **$PbWO_4$ crystal** (heat channel)
  - a **Ge light detector** for scintillation readout
- Target background rate in the RoI: 10^{-3} c/keV/ton/s
- The demonstrator will serve as a stepping stone toward **RES-NOVA-1**, with a target mass of **1.7 t**



Sensitivity DM with RES-NOVA

Assuming that the time-integrated DM-induced event rate equals the CEνNS rate from SN neutrinos, we obtain:

$$R_{CE\nu NS} \sim \sigma_{CE\nu NS} \cdot T(10\ s) \sim N^2 \cdot 10\ s$$
$$R_{DM} \sim \sigma_{DM} \cdot T(1\ y) \sim A^2 \cdot 3 \times 10^7\ s \sim (2N)^2 \cdot 3 \times 10^7\ s$$
$$R_{DM} \simeq R_{CE\nu NS} \rightarrow \sigma_{DM} \sim 10^{-7} \cdot \sigma_{CE\nu NS}$$



This simplified scaling argument suggests that RES-NOVA can probe SI DM cross-section to the 10^{-45} cm^2 scale

Sensitivity DM with RES-NOVA

The DM differential cross-section is described as follows:

$$\frac{d\sigma}{dE_R} = \frac{m_N}{2v^2\mu_n^2}\,\sigma_{\text{DM-N}} \cdot A^2 \cdot |F(q)|^2$$

relative velocity

DM-nucleus reduced mass

DM-nucleon cross-section

Atomic number

Nuclear form factor

The combination of heavy and light nuclei in the target material, RES-NOVA is sensitive to a broad range of dark matter masses

DM SD interaction

In addition to the SI DM interaction, RES-NOVA can also provide insights into the spin-dependent (SD) interaction channel through

- ^{207}Pb (natural isotopic abundance of 22.1%, $J^{\pi} = 1/2^{-}$)
- ^{17}O (natural isotopic abundance of 0.037%, $J^{\pi} = 5/2^{+}$)

$$\frac{d\sigma^{SD}}{dq^2} = \frac{\sigma^{SD}_{\text{DM-N}}}{3\mu_n v^2} \frac{\pi}{(2J+1)} S_n(q)$$

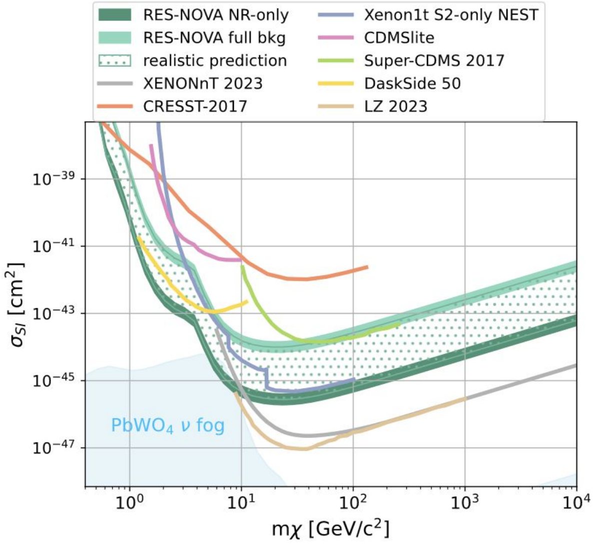
target nuclear spin

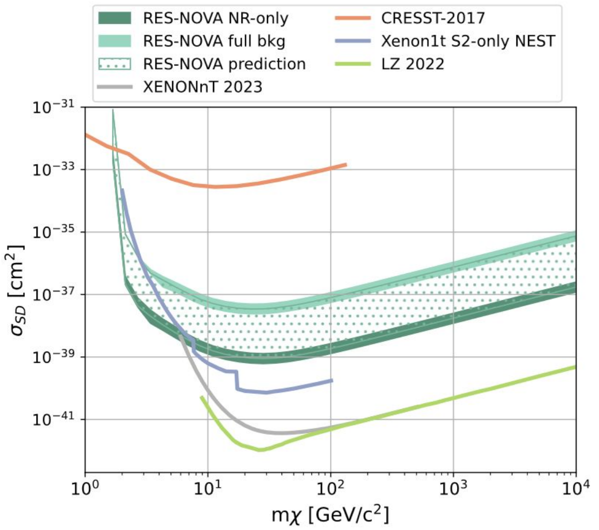
spin-matrix element for the interaction on neutrons

Sensitivity DM with RES-NOVA

Sensitivity calculations were performed within the standard thermal relic WIMP framework

- spin-independent
- spin-dependent
- Input bkg model: >40 bkg sources
- Exposure of 170 kg·y





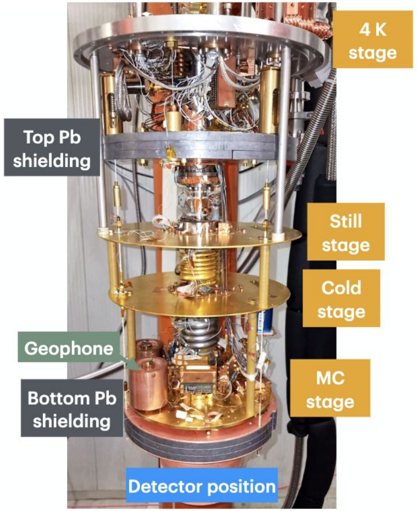
RES-NOVA Coll., Phys. Rev. D 111, 103050 (2025)

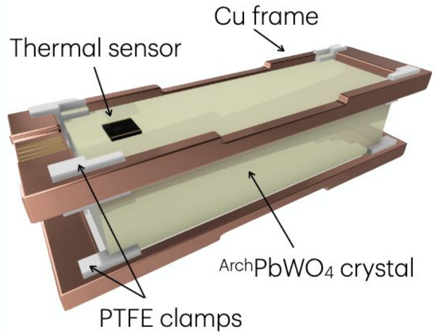
Experimental set-up

- The crystal had a mass of **13 g** and dimensions of **0.7 × 0.7 × 4 cm^3**

- The measurement was performed in IETI a **pulse-tube** assisted dilution refrigerator at **LNGS**
    - Not optimized for ultra-low-background measurements
    - Optimized for mechanical stability and vibrational isolation

- The crystal was equipped with an **NTD** sensor





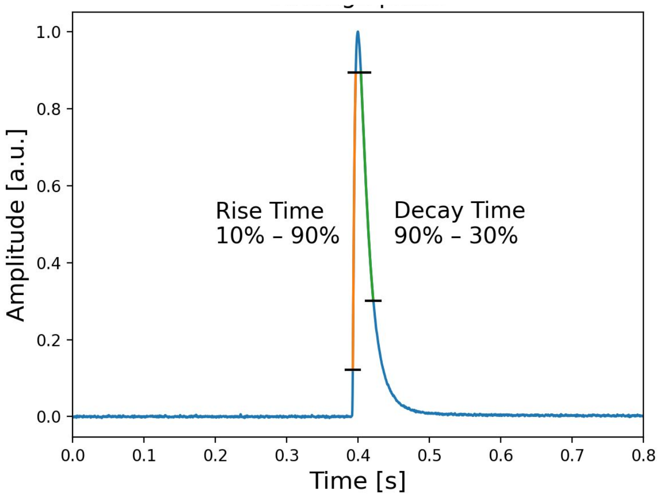
Data analysis

The continuous datastream, accounting for a total exposure of 32.4 g·day.
From the datastream we identify relevant signal events and several basic parameters are computed:

- Baseline level, slope, RMS
- Rise time
- Decay time
- Average pulse

Energy estimator:

- **OF** - maximises signal to noise ratio
- **MLE** – models the detector response through pulse-shape fitting



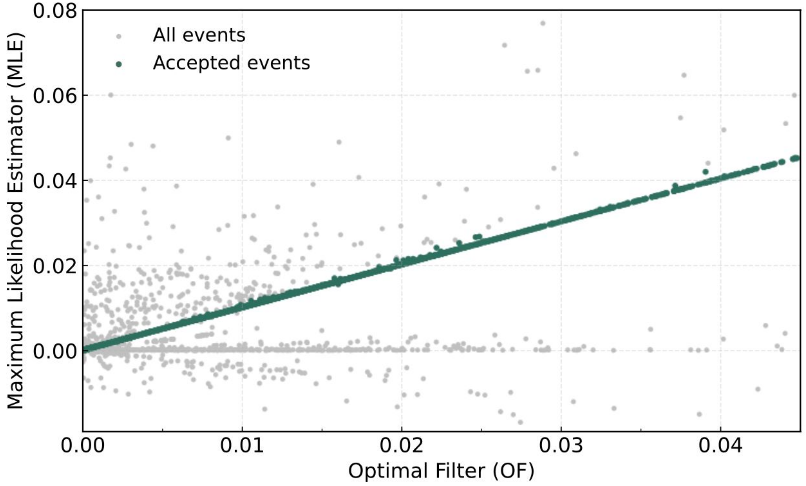
Rise time = 4 ms
Decay time = 17 ms

Applied Selection Cuts

- Comparison between pulse amplitudes reconstructed with **OF** and **MLE**

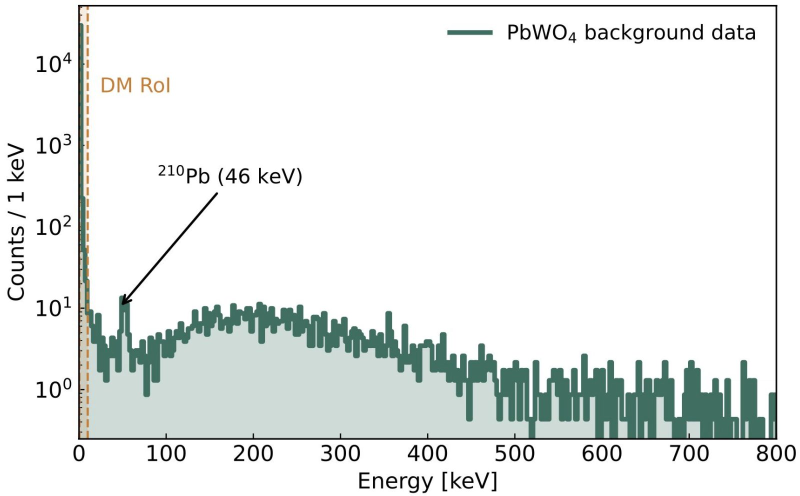
- Events passing the pulse-shape quality cuts cluster along the diagonal, showing consistency between the two estimators

- The selection band (10%) removes noise-dominated and poorly reconstructed events



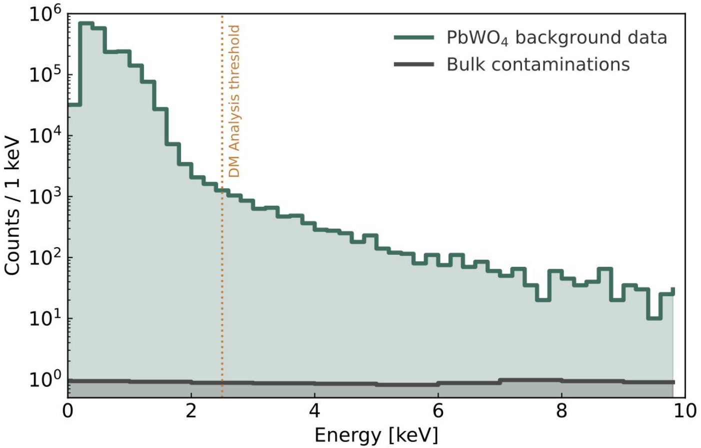
Energy Calibration

- The pulse amplitude used in the analysis is obtained with the **Optimal Filter (OF)**, providing the best energy resolution
- Energy calibration performed using the **2615 keV γ line** from ^{208}Tl
- Calibration validated through the **46 keV feature** from ^{210}Pb observed in background data
- Measured detector signal amplitude: 112 μV/MeV
- Achieved baseline energy resolution: 239 eV

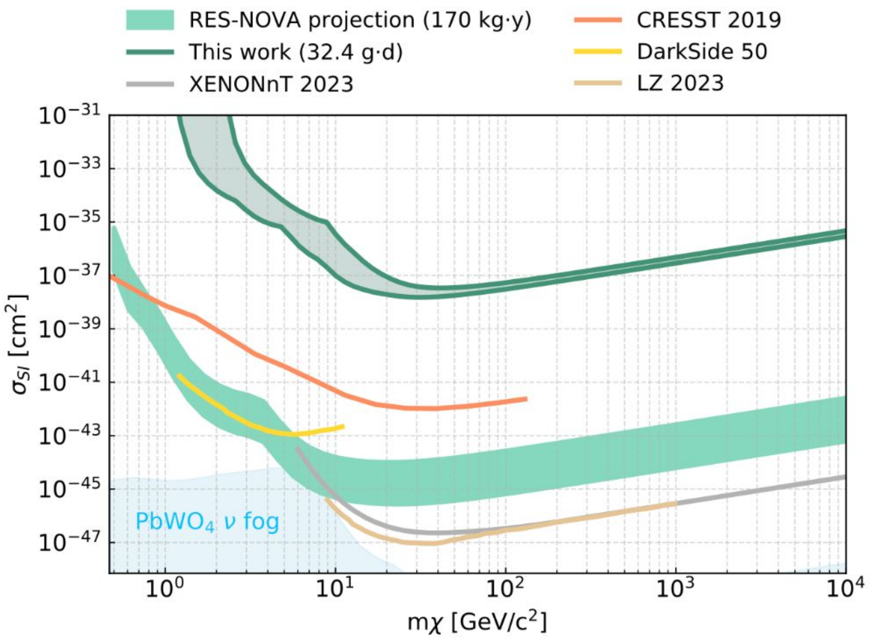


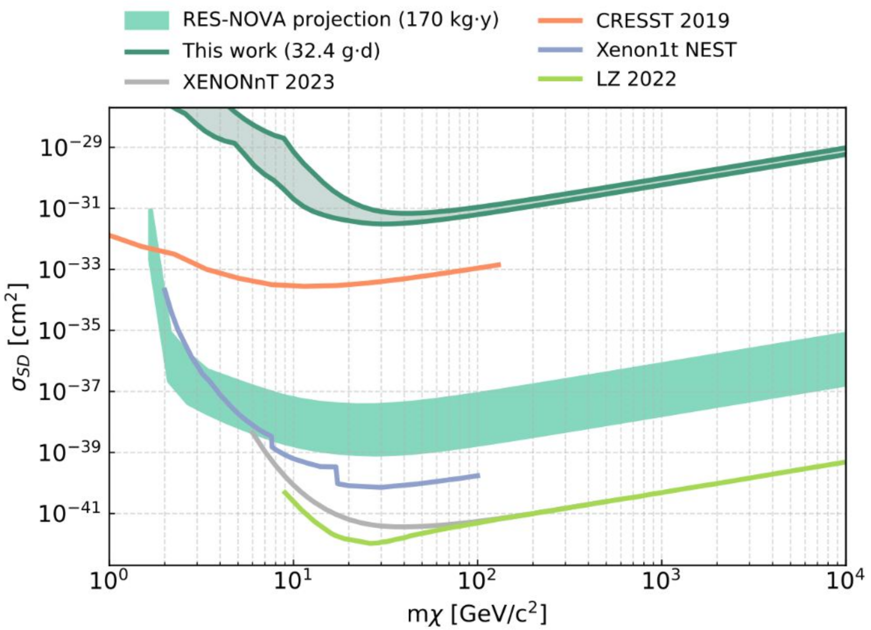
Dark Matter Sensitivity

- DM sensitivity derived by comparing the observed spectrum with the expected recoil spectrum in $PbWO_4$
- Expected spectra include detector efficiency and energy resolution effects
- Since no reliable background model is available in the ROI (2.5 keV - 10 keV) , limits are obtained using the **Yellin optimum interval method**
- Sensitivity evaluated at **90% CL**



Dark Matter limit





RES-NOVA Coll., ArXiv:2601.16251

Conclusion

- We successfully operated a cryogenic detector prototype based on a **$PbWO_4$** crystal grown from archaeological Pb
- Although the current sensitivity is not yet competitive with state-of-the-art experiments, the measurement provides a clear **proof of concept** of the detector technology
- Significant improvements are expected in future setups using **optimized low-background conditions** and **TES sensors instead of Ge-NTD thermistors**
- The developed analysis framework (noise characterization, reconstruction, and background handling) is directly applicable to **supernova neutrino detection via CEνNS**
- Overall, these results represent an important validation step toward the scientific goals of the RES-NOVA program

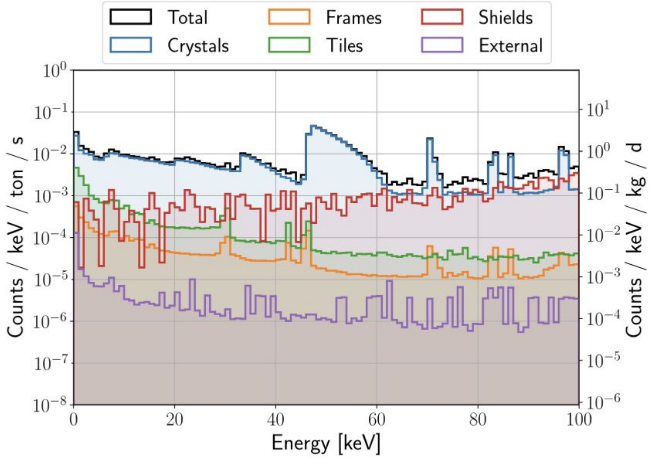
Related Posters

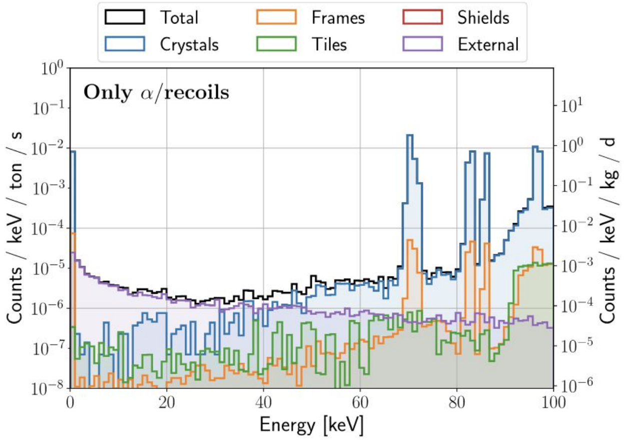
- *Axion searches with a RES-NOVA prototype cryogenic detector - L. Trombetta*
- *Energy-time signature of dark matter in RES-NOVA - N. Ferreiro Iachellini*

Thank you for your attention

Background prediction

- **Top plot:** total energy spectrum produced by background sources in the experimental setup
- **Bottom plot:** same spectrum after applying a 100% rejection of e⁻ and γ events, leaving only nuclear recoils and alphas
- Simulations indicate that **bulk contaminations in the crystal** are the dominant background source
- The collaboration is currently working on benchmarking and optimizing the **$PbWO_4$** crystal production line
- The baseline goal of the experiment is to achieve a background level of : 10^{-3} c/keV/ton/s





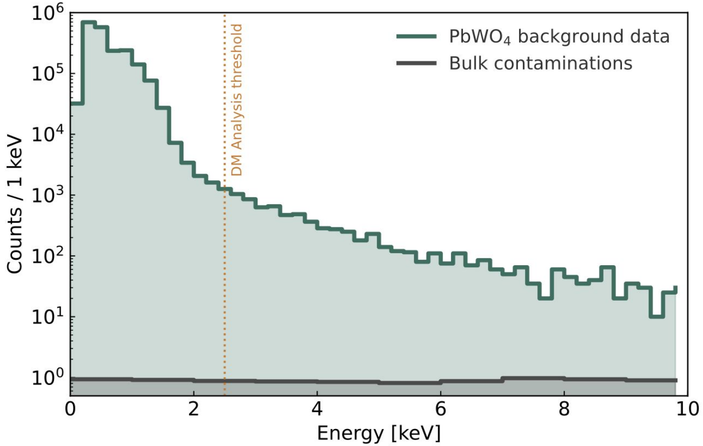
RES-NOVA Coll., Phys. Rev. D 111, 103050 (2025)

Energy Calibration Uncertainty

- No calibration points are available below **46 keV**, therefore the calibration in the RoI relies on an extrapolation
- Several polynomial calibration models were tested using the identified gamma-ray peaks:
  - 46 keV (^{210}Pb)
  - 511 keV (annihilation)
  - 583 keV and 2615 keV (^{208}Tl)
  - 1461 keV (^{40}K)
- The uncertainty is estimated from the spread of the resulting calibration functions (non-linearity envelope)
- This approach provides a **conservative estimate** of the energy-scale uncertainty in the absence of low-energy calibration lines
- Future detectors, especially those based on **TES sensors**, will benefit from dedicated **heater pulses and calibration lines within the RoI**, reducing the uncertainty associated with low-energy extrapolation.

Background in the RoI

- Sensitivity limits are derived using the **Yellin optimum interval method**, providing a conservative and largely background-independent approach
- Main background contributions in the RoI:
  - ^{210}**Bi bremsstrahlung** and shielding radioactivity: ~10^3 c/keV/kg/d
  - Environmental gamma radiation (^{222}Rn chain): ~ 10^1 c/keV/kg/d
  - Ambient neutrons: ~ 1 c/keV/kg/d
- Simulations identify **bulk crystal contamination**, particularly ^{210}**Pb decay**, as a dominant background source in the RoI.



Analysis Threshold

- A steep excess below ~ 2.5 keV is observed due to events with **signal-to-noise ratio close to unity**
- These events may include **non-physical signals** or **poorly reconstructed pulses**
- **Stricter selections** suppress noise-dominated events but reduce detection efficiency
- **Looser selections** increase efficiency but accept more low-energy noise
- Below ~ 2.5 keV, the effect of the selection becomes negligible, indicating **S/N < 1** and defining the practical analysis threshold.