First results from the CRESST-III low-mass Dark Matter detector

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The dark matter problem

- Dark matter: 26.8%
- Dark energy: 68.3%
- Interstellar gas: 4.4%
- Stars, planets, etc.: 0.5%

First results from the CRESST II low-mass dark mater detector
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After 80 years...

- **Non-baryonic**
  Height of acoustic peaks in the CMB
  Power spectrum of density fluctuations
  Primordial nucleosynthesis

- **Cold (non-relativistic)**
  Structure formation

- **Electrically neutral**

- **Interacts via gravity and (maybe) some sub-weak scale force**

- **Stable (or extremely long-lived)**
The hunt for dark matter

Production

SCATTERING

Annihilation

Collider search

Direct search

Indirect search
The CRESST experiment
Cryogenic Rare Event Search with Superconducting Thermometers

What? Direct detection of dark matter particles via their scattering off target nuclei in cryogenic detectors operated at ~15 mK

Dark matter particles scattering
- off nuclei
- elastic
- coherent: $\sim A^2$
- spin-independent
The CRESST experiment
Cryogenic Rare Event Search with Superconducting Thermometers

Where? Laboratori Nazionali del Gran Sasso (LNGS) underground facility, Italy

Background suppression
- Underground site
- Shielding/vetoing
- Radon mitigation
- Purity of materials
- Material handling
- Event discrimination
The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

Setup?

Cold box housing the detectors (Carousel)

Detector module with targets at 15 mK

Low temperature and low background environment

Dilution cryostat with shielding/vetoing
The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

Target?

Scintillating CaWO₄ crystals

- 3 nuclei: O, Ca and W
- Light targets to maximize sensitivity for low mass dark matter
- Each particle interaction implies phonon signal + light signal
The CRESST experiment
Cryogenic Rare Event Search with Superconducting Thermometers

Detector?

Crystals operated as cryogenic calorimeters

\[ \Delta T = \frac{\Delta E}{C} \]

Sensor

\( \text{CaWO}_4 \text{ crystal} \)

\( \text{particle interaction} \)

Sensor

Absorber

Heat bath \( \sim \) 15 mK
The CRESST experiment
Cryogenic Rare Event Search with Superconducting Thermometers

Sensor?

CaWO$_4$ and SOS crystals readout by W-Transition Edge Sensors (TES)

Energy deposition in the absorber $\sim$keV

Temperature rise in the TES $\sim$μK

Resistance change $\sim$mΩ
The CRESST experiment
Cryogenic Rare Event Search with Superconducting Thermometers

Stability?

Calibration?

Thresholds?

W-TES equipped with heaters

- Stabilization of detectors in the operating point
- Injection of heat pulses for calibration and determination of trigger threshold
The CRESST experiment
Cryogenic Rare Event Search with Superconducting Thermometers

Phonon signal ($\geq 90\%$)

- independent of particle type
- precise measurement of the deposited energy

CaWO$_4$

W-TES
The CRESST experiment
Cryogenic Rare Event Search with Superconducting Thermometers

Silicon on Sapphire (SOS) crystal

**Scintillation light (few %)**
- particle-type dependent
- \( \rightarrow \) LIGHT QUENCHING

Phonon signal (\( \geq 90 \% \))
- independent of particle type
- precise measurement of the deposited energy

particle discrimination

deposited energy

reflective and scintillating housing
The CRESST experiment
Cryogenic Rare Event Search with Superconducting Thermometers

Crystals operated as cryogenic calorimeters (~ 15 mK)

\[ \Delta T = \Delta E/C \]

\(~ 1 \text{ keV}/\mu\text{K}~\)
The CRESST experiment
Cryogenic Rare Event Search with Superconducting Thermometers

[Diagram showing a schematic of the CRESST experiment]

- Silicon on Sapphire (SOS) crystal
- W-TES
- Deposited energy
- Light Yield = \( \frac{\text{energy detected in light channel}}{\text{energy detected in phonon channel}} \)

[Graph showing light yield vs. energy]
The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

Precise determination of QFs for O, Ca & W @mK temperatures

Values (in ROI)
- O: $(11.2 \pm 0.5)\%$
- Ca: $(5.94 \pm 0.49)\%$
- W: $(1.72 \pm 0.21)\%$

Queching factor measurements
@ accelerator of Maier-Leibnitz-Laboratorium

R. Strauss et al., EPJC 74: 2957 (2014)
CRESST-II results

Crystal: Lise (mass 300 g)
Background level ~ 8.5 counts/(keV kg day)
Threshold: 307 eV, Resolution: \( \sigma = 62 \) eV @ 0 eV
Exposure: 52 kg day

G. Angloher et al., EPJC 76: 25 (2016)
CRESST-II results

Crystal: Lise (mass 300 g)
Background level ~ 8.5 counts/(keV kg day)
Threshold: 307 eV, Resolution: $\sigma = 62$ eV @ 0 eV
Exposure: 52 kg day

Hunting light dark matter requires a low threshold!

G. Angloher et al., EPJC 76: 25 (2016)

World leading experiment below 1.7 GeV/c$^2$
Low threshold detectors
Exploring new parameter space below 0.5 GeV/c²

Dark matter recoil spectrum: CaWO₄ target, ideal detector
Low threshold detectors
Exploring new parameter space below 0.5 GeV/c²

Dark matter recoil spectrum: CaWO₄ target, ideal detector

Challenges

- Small recoil energies
  ~ sub-keV range
Low threshold detectors
Exploring new parameter space below 0.5 GeV/c²

Dark matter recoil spectrum: CaWO₄ target, ideal detector

Challenges

- Small recoil energies
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- Featureless spectrum
Low threshold detectors

Exploring new parameter space below 0.5 GeV/c²

Dark matter recoil spectrum: CaWO₄ target, ideal detector

Challenges

- Small recoil energies
  ~ sub-keV range

- Featureless spectrum

- Very rare
  current limit*
  $\mathcal{O}(0.01)$ counts/tonne day
Low threshold detectors

Exploring new parameter space below 0.5 GeV/c$^2$

Dark matter expected rate: CaWO$_4$ target, ideal detector

Challenges

- Small recoil energies
  ~ sub-keV range
- Featureless spectrum
- Very rare
  current limit*
  $\mathcal{O}(0.01)$ counts/tonne day
The CRESST-III strategy: go for small

Exploring new parameter space below 0.5 GeV/c²

To improve sensitivity to low masses a radical change of strategy:

Smaller crystals: 250g → 24g

Threshold goal: 300eV → 100eV

G. Angloher et al., EPJC 76: 25 (2016)
CRESST-III low-threshold detector

Exploring new parameter space below 0.5 GeV/c²

**CRESST-III**

detector dimensions scaling down

- \((20 \times 20 \times 10)\) mm\(^3\)
- Mass \(\sim 24\) g
- Threshold goal \(\sim 100\) eV
- Self grown crystals \(\sim 3\) counts/(keV kg day)
- Fully scintillating housing
- Instrumented sticks

**CRESST-II**

- \((40 \times 40 \times 40)\)
- \((\sim 300)\)
- \((\sim 300)\)
- \((\sim 8.5)\)
- no
- no

Surface related background vetoing

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Exploring new parameter space below 0.5 GeV/c²

(CRESST-II)
CRESST-III Phase 1
CRESST-III Phase 1

Data taking started July 2016

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Det A – Full dataset analysis

Selection criteria

Objective
Accept events where a correct determination of the amplitude (energy) is guaranteed

Unbiased (blind) analysis
1. Design cuts on non-blind training set (≤20% of DM data)
2. Apply without change to blind DM data set

Rate:
noise condition (14% of measuring time)

Stability:
Detector(s) not in operating point (3% of measuring time)

Data quality:
Non-standard pulse shapes (e.g. i-Stick events and pileup)

Coincidences:
with μ-veto (7.6% of measuring time), i-Sticks and other detector modules

Detector A

Data taking: 10/2016 – 01/2018
Non-blind data: 20% randomly selected
Target crystal mass: 23.6 g
Gross exposure (before cuts): 5.689 kg days
Analysis threshold: 30.1 eV
Resolution: $\sigma = 4.6$ eV @ 0 eV

A. H. Abdelhameed et al., PDR 100:102002 (2019)
Det A – Full dataset analysis

Pulse height evaluation

The **Gatti-Manfredi filter** is an **Optimum Filter** (OF) which maximises the ratio between the amplitude of the treated pulse and the noise RMS.
Det A – Full dataset analysis

Pulse height evaluation

The Gatti-Manfredi filter is an Optimum Filter (OF) which maximises the ratio between the amplitude of the treated pulse and the noise RMS.

M. Mancuso et al., JLTP 193: 441, (2018)

Typical improvement in resolution by using the OF factor ~2-3
Det A – Full dataset analysis

Optimum filter for threshold analysis

Study the noise distribution after OF in order to set the thresholds (Optimum Trigger)

- Analytical description of amplitude distribution in empty baselines
- Threshold optimised based on noise triggers in a given exposure
- Allowed 1 noise trigger per kg day surviving selection criteria

Detector A
30.1 eV threshold
Det A – Full dataset analysis

Efficiency/signal survival probability

Simulated pulses of desired energies passed through analysis chain

Empty baseline + Averaged pulse = Simulated pulse
Det A – Full dataset analysis

Efficiency/signal survival probability

≥60% efficiency over broad energy range

Simulated by artificial pulses placed at random positions in the data stream

Includes trigger and cuts

A. H. Abdelhameed et al., PDR 100:102002 (2019)
Det A – Full dataset analysis

Neutron calibration - bands fit

- Unbinned Maximum Likelihood fit
- Calculation using QFs from MLL neutron beam measurement
Det A – Full dataset analysis
Dark Matter data - energy spectrum

Analysis optimized for very low energies: 30 eV $\rightarrow$ 16 keV
Cosmogenic activation $\rightarrow$ $^{179}$Ta + e$^-$ $\rightarrow$ $^{179}$Hf + $\nu_e$ (1.8y)

A. H. Abdelhameed et al., PDR 100:102002 (2019)
Det A – Full dataset analysis

Dark Matter data - acceptance region

Analysis optimized for very low energies: 30 eV $\rightarrow$ 16 keV
Acceptance region fixed before unblinding

A. H. Abdelhameed et al., PDR 100:102002 (2019)
Det A – Full dataset analysis

Dark Matter data - acceptance region

Zoom of acceptance region: 30 eV $\rightarrow$ 1 keV

Unexpected rise of event rate for $E < 200$ eV

A. H. Abdelhameed et al., PDR 100:102002 (2019)
Det A – Full dataset analysis

Results

Energy spectrum of accepted events

Yellin method

Simulated Dark Matter energy spectrum
Det A – Full dataset analysis

Results

Energy spectrum of accepted events

Yellin method

Expected energy spectrum

A. H. Abdelhameed et al., PDR 100:102002 (2019)
More than one order of magnitude improvement at 0.5 GeV/c²

A. H. Abdelhameed et al., PDR 100:102002 (2019)
Results

More than one order of magnitude improvement at 0.5 GeV/c²

Reach of CRESST-III experiment extended to 0.16 GeV/c²

A. H. Abdelhameed et al., PDR 100:102002 (2019)
Det A – Full dataset analysis

Results

- More than one order of magnitude improvement at 0.5 GeV/c^2
- Reach of CRESST-III experiment extended to 0.16 GeV/c^2
- Unexpected rise of event rate at E < 200 eV

A. H. Abdelhameed et al., PDR 100:102002 (2019)
Conclusion

- The CRESST-III det-A collected an exposure of 5.689 kg days
- The CRESST-III det-A reached a nuclear recoil threshold of 30.1 eV
- More than one order of magnitude improvement at 0.5 GeV/c$^2$
- Reach of CRESST-III experiment extended down to 0.16 GeV/c$^2$
- Competitive direct dark matter experiment below 1.7 GeV/c$^2$
- Unexpected rise of event rate at E < 200 eV
A second CRESST-III run has been done: upgraded detector modules with dedicated hardware changes to investigate the origin of the background excess.

Preliminary analysis shows that excess is present also in sapphire crystals.
A third CRESST-III run is under preparation

Run start foreseen in February 2020

More studies to understand background excess

Additional active magnetic field compensation with three pair of coils for x, y & z-axes
This is a new starting point for light DM search.

We are crossing a door and we have no idea of what we will find on the other side.

New frontiers
New potential
New challenges...
The CRESST collaboration

Thanks for your attention!