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

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Gran Sasso - INFN

The 15th International Conference on the
DARK SIDE OF THE UNIVERSE

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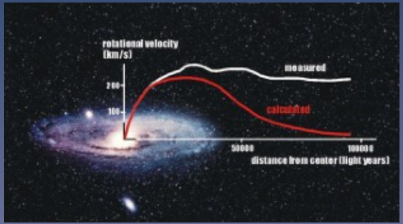
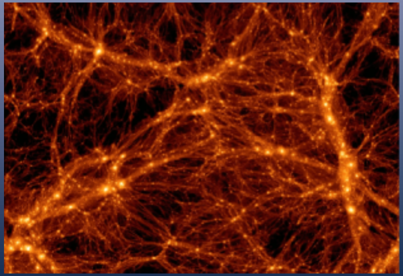
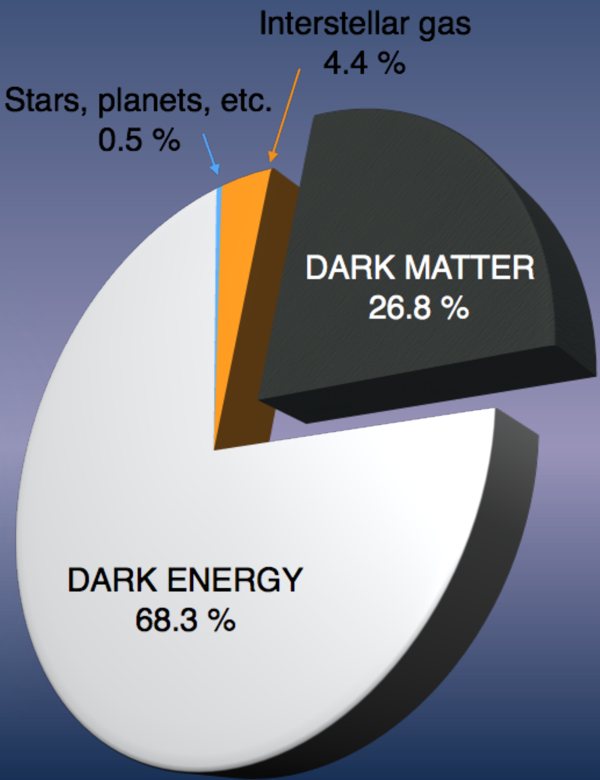
The dark matter problem

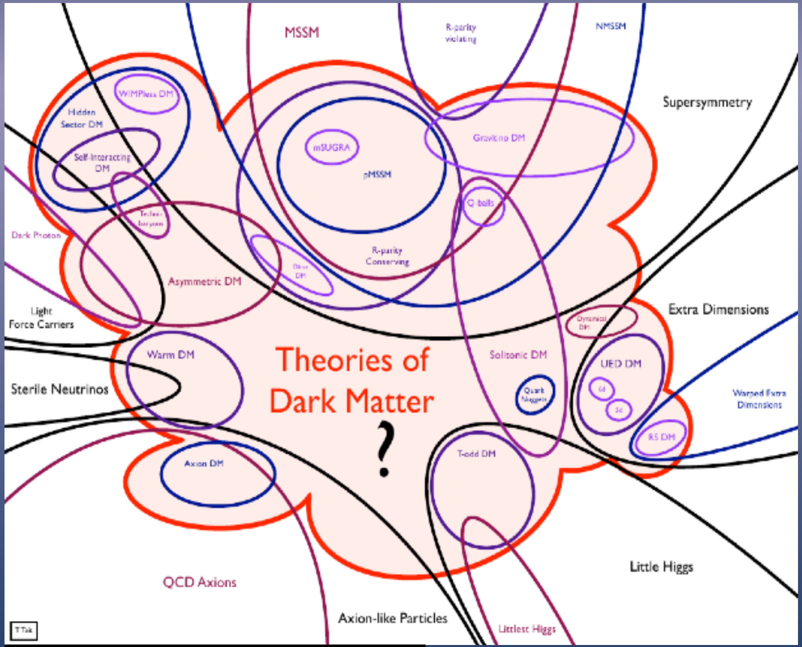






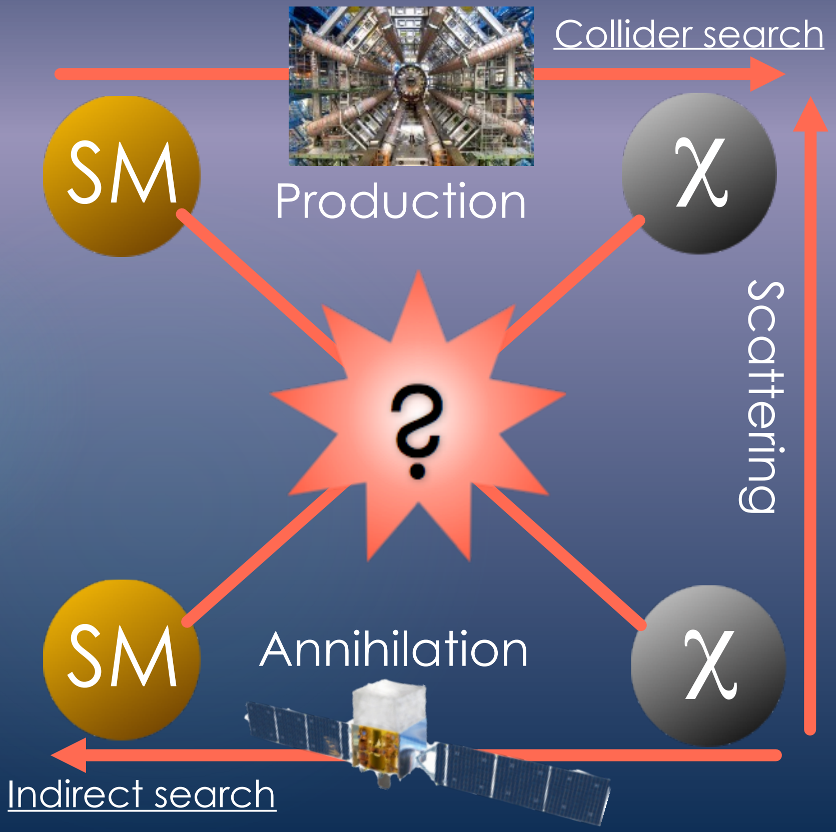
After 80 years…

- **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**
- **STILL HERE!**
  - Stable (or extremely long-lived)

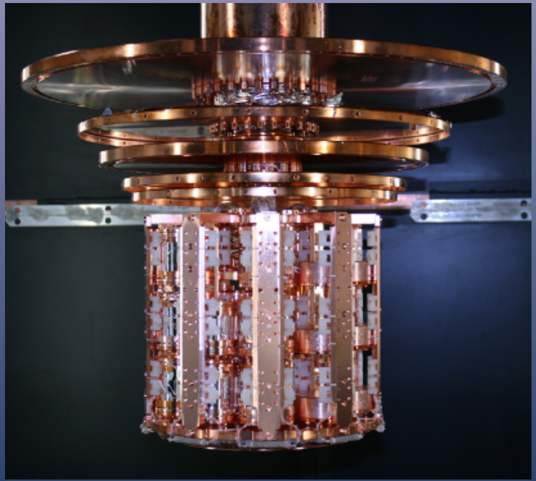


T. Tait at UCLA DM 2016

The hunt for dark matter



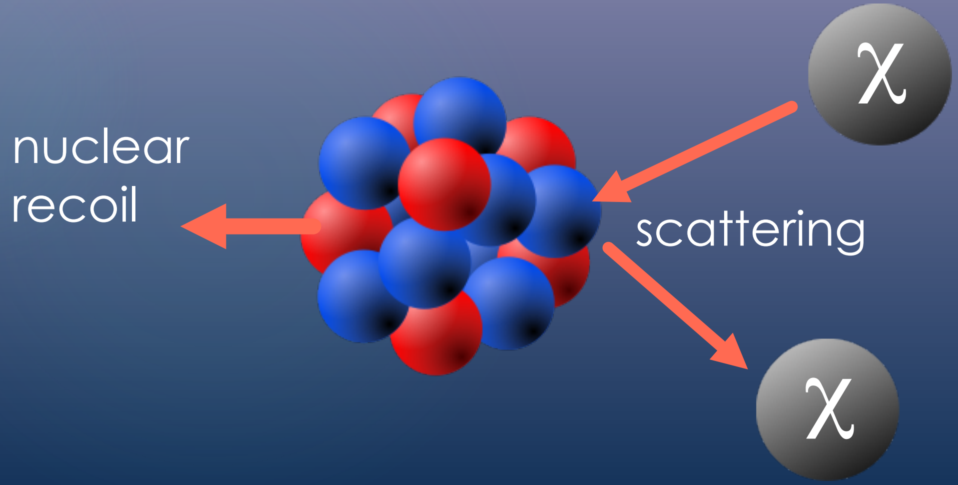
Direct search



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

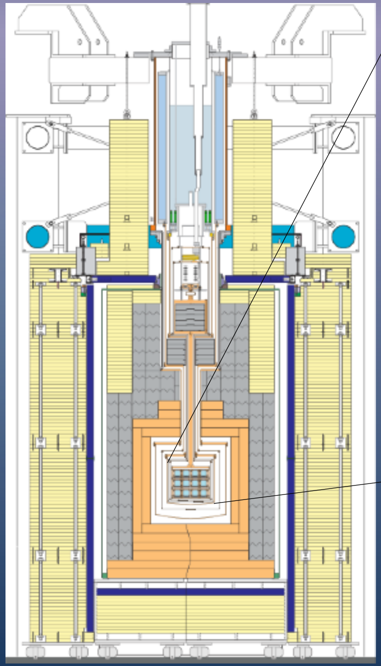


Dark matter particles scatter
- off nuclei
- elastically
- coherently: $\sim A^2$

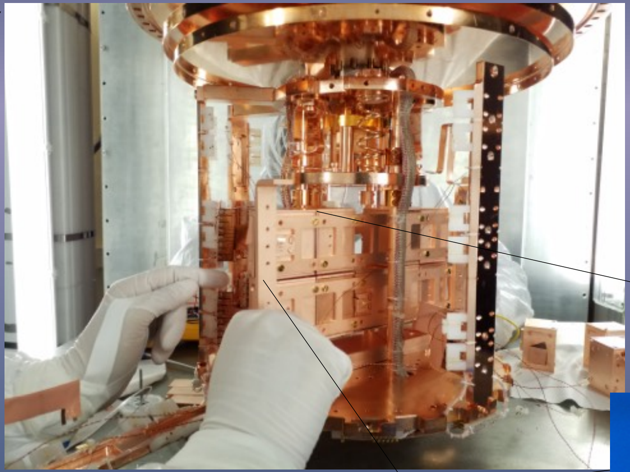
The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

Setup?

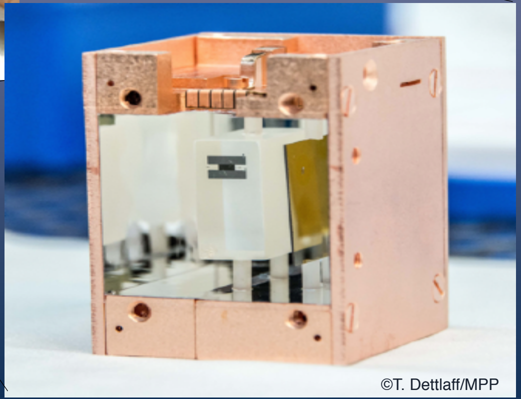


Dilution Refrigerator



Scintillating $CaWO_4$ crystals as target

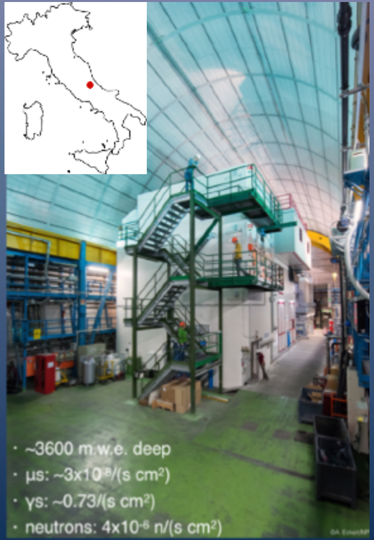
Separate **cryogenic light detector**



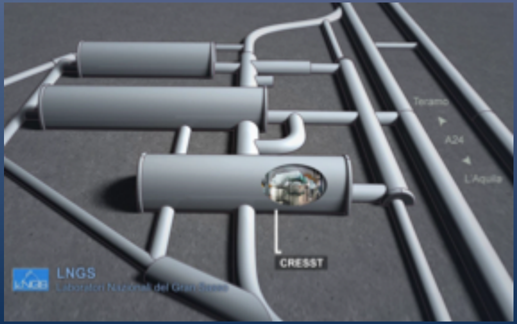
The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

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



Background suppression

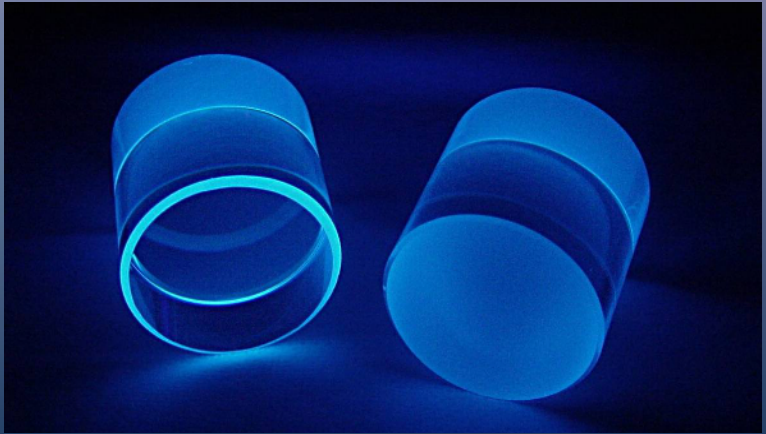


- Underground site
- Shielding/vetoing
- Radon mitigation
- Purity of materials
- Material handling
- Event discrimination

The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

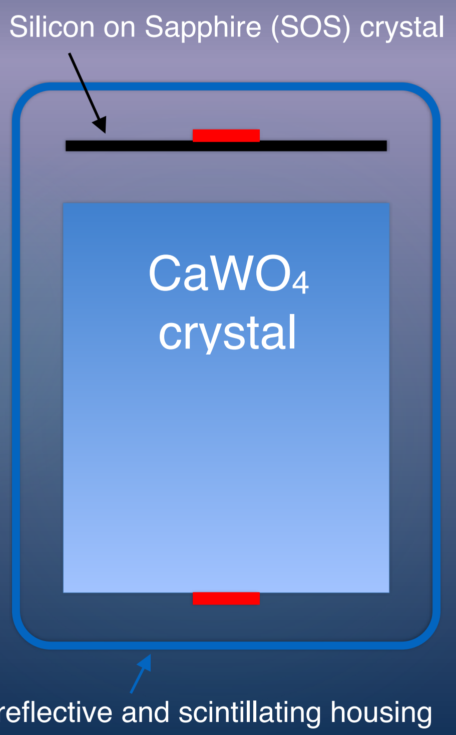
Target? **Scintillating $CaWO_4$** crystals



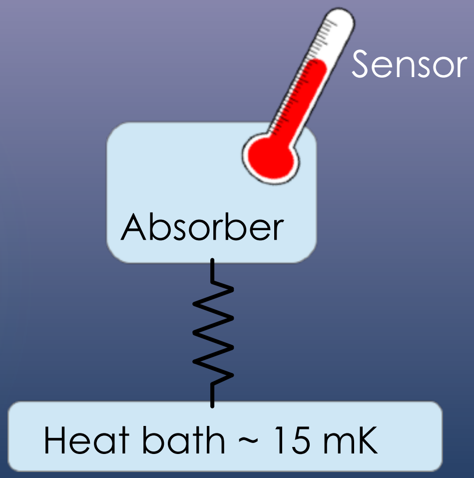
- 3 nuclei: O, Ca and W
- Light targets to maximize sensitivity for low mass dark matter
- Each particle interaction implies **phonon signal** + **light signal**

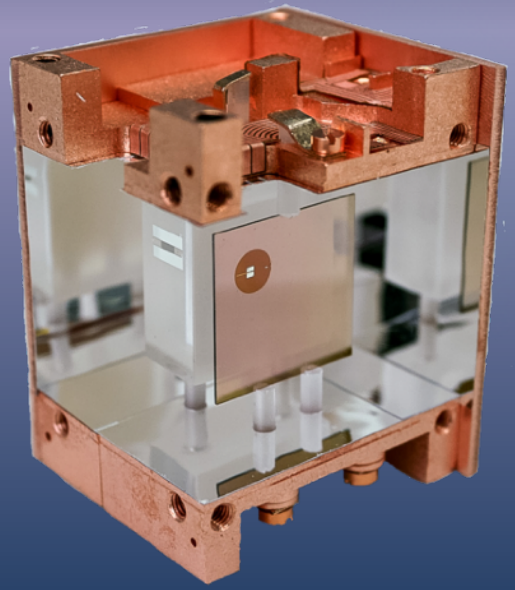
The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers



Crystals operated as **cryogenic calorimeters**

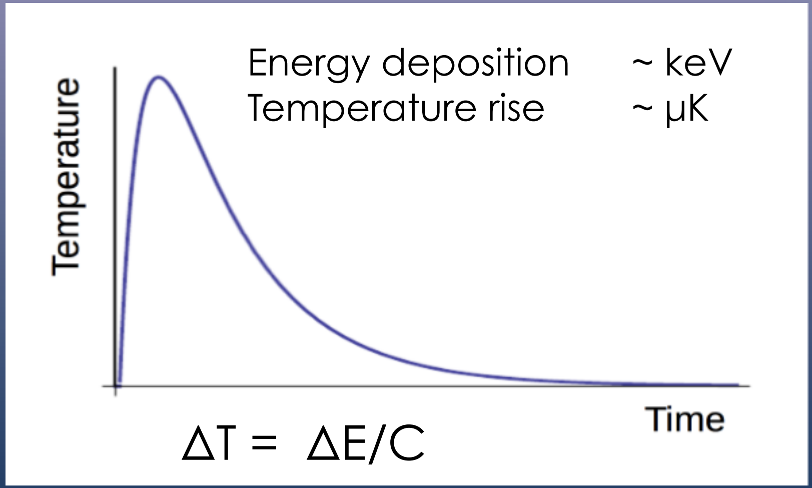




The CRESST experiment

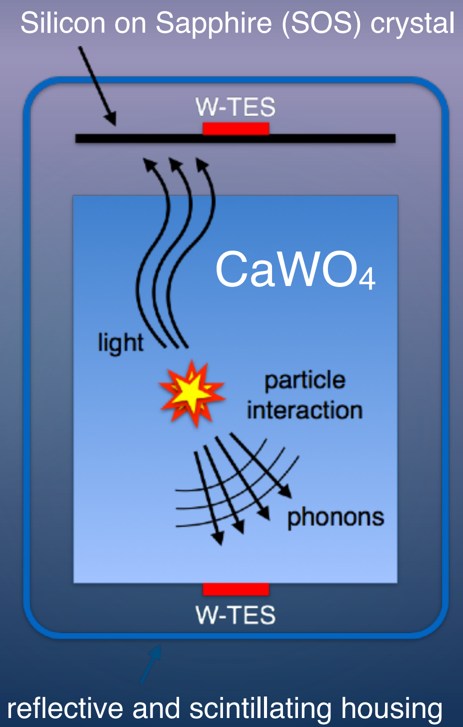
Cryogenic Rare Event Search with Superconducting Thermometers

Crystals operated as
cryogenic calorimeters (~ 15 mK)

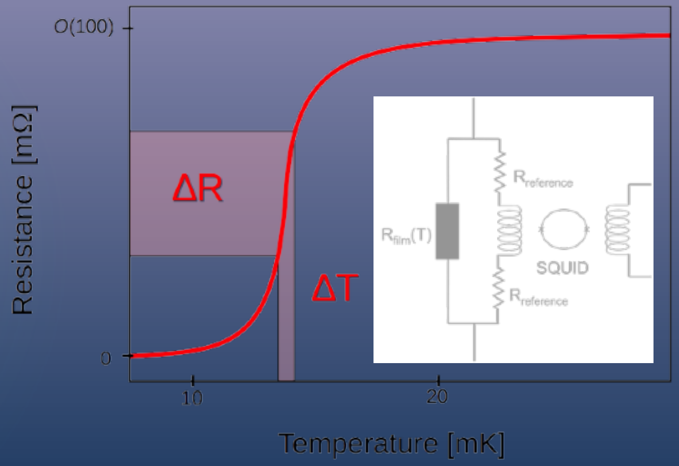


The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers



CaWO4 and SOS crystals readout by **W-Transition Edge Sensors (TES)**



Energy deposition in the absorber ~keV

↓

Temperature rise in the TES ~μK

↓

Resistance change ~mΩ

The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

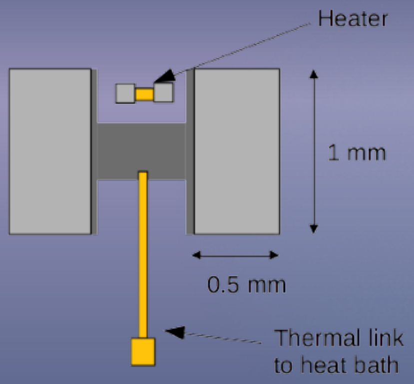
Stability?

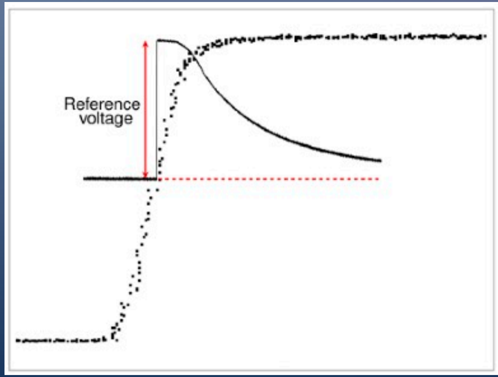
Calibration?

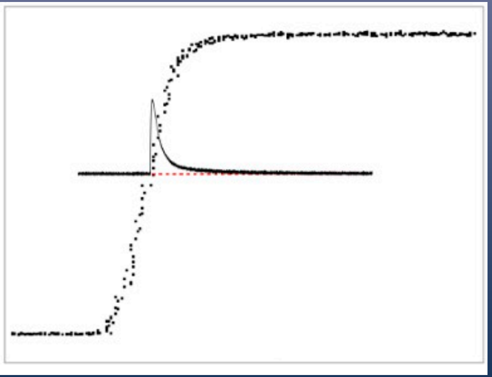
Thresholds?

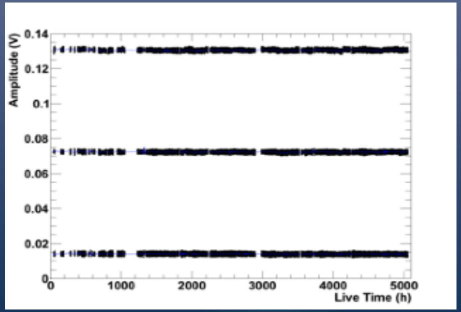
W-TES equipped with heaters

- Stabilization of detectors in the operating point
- Injection of heat pulses for calibration and determination of trigger threshold







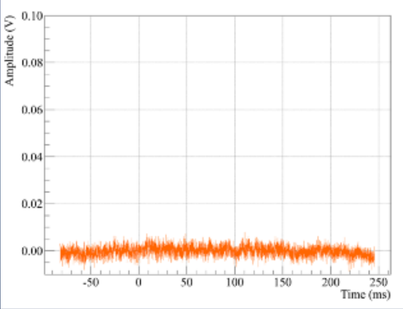


The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

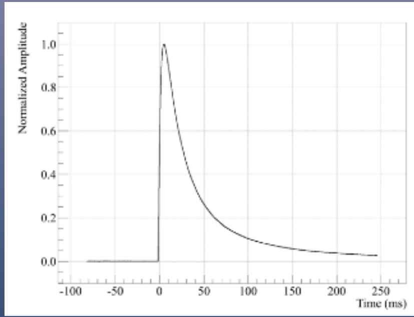
Efficiency?

Simulated pulses (of desired energies) passed through analysis chain



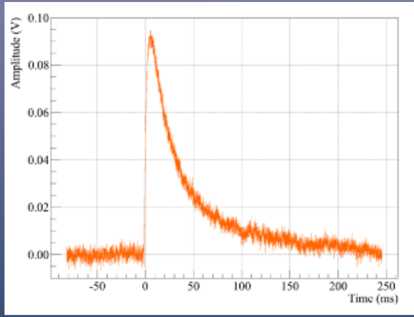
Empty baseline

+



Averaged pulse

=

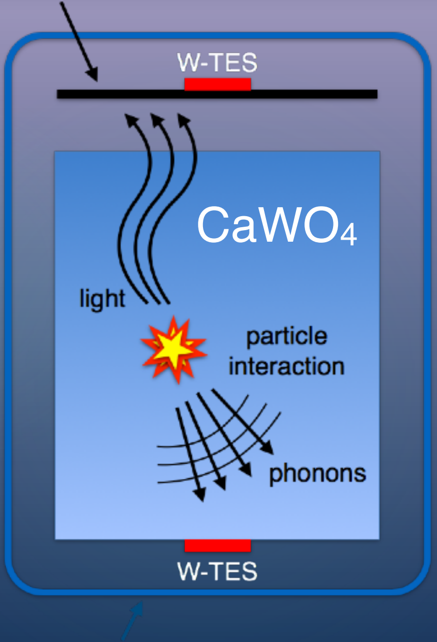


Simulated pulse

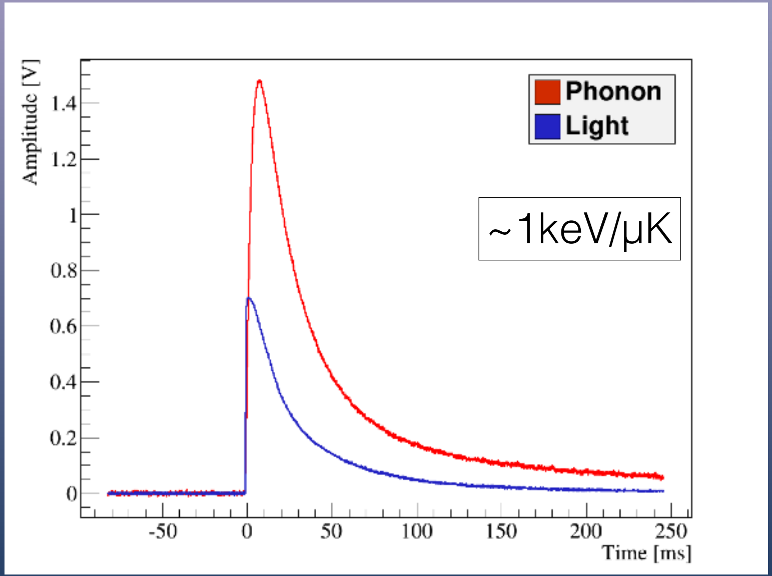
The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

Silicon on Sapphire (SOS) crystal

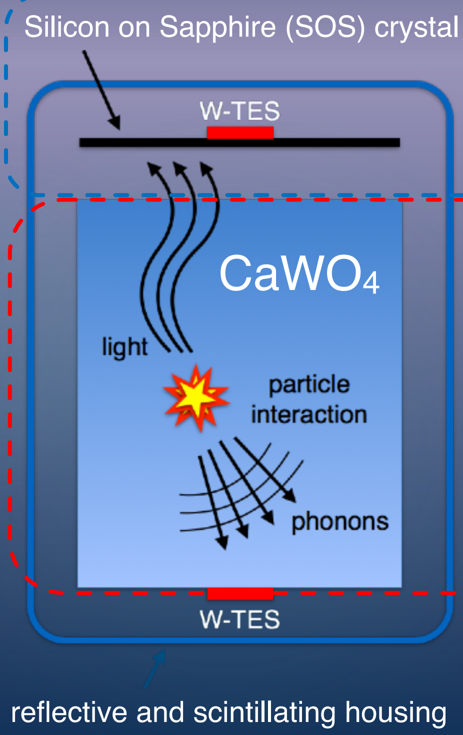


reflective and scintillating housing



The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers



<u>Scintillation light</u> (few %)

particle-type dependent

→ LIGHT QUENCHING

particle discrimination

<u>Phonon signal (≳90 %)</u>

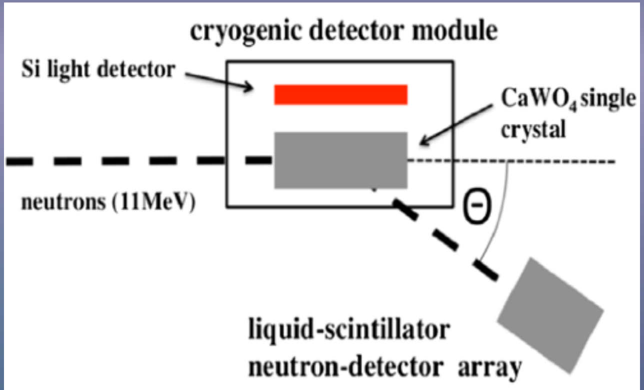
(almost) independent of particle type

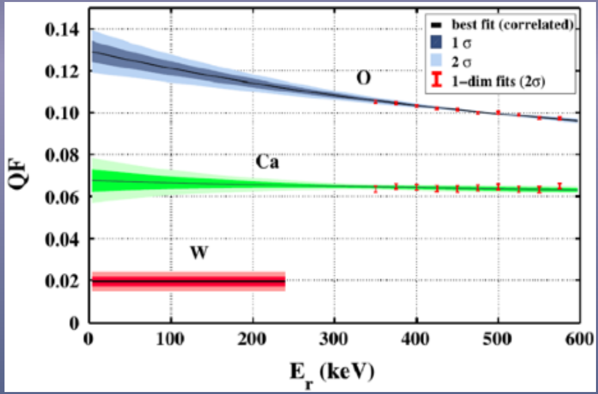
precise measurement of the deposited energy

deposited 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 ± 0.5)%
- Ca: (5.94 ± 0.49)%
- W: (1.72 ± 0.21)%

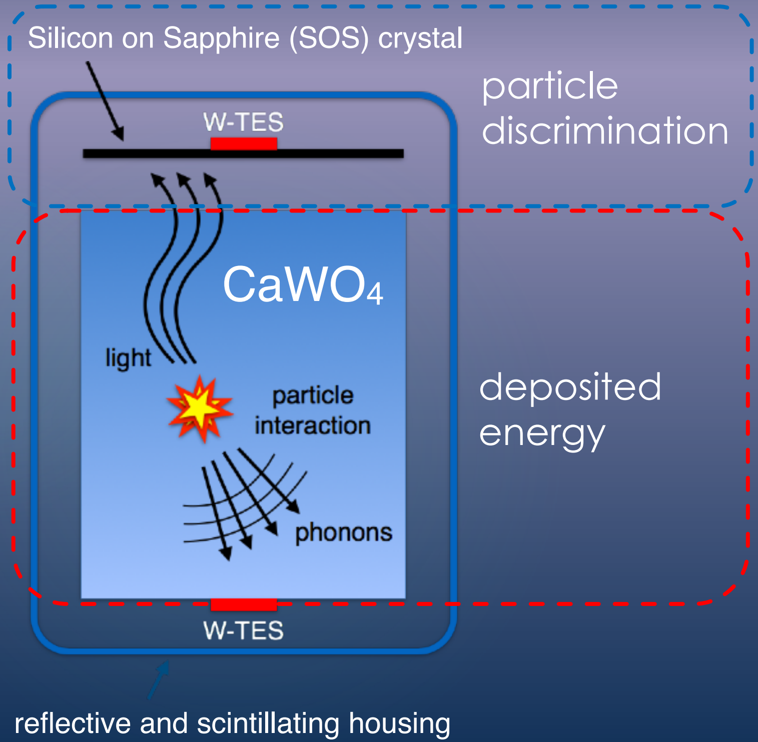
Queching factor measurements
@ accelerator of Maier-Leibnitz-Laboratorium

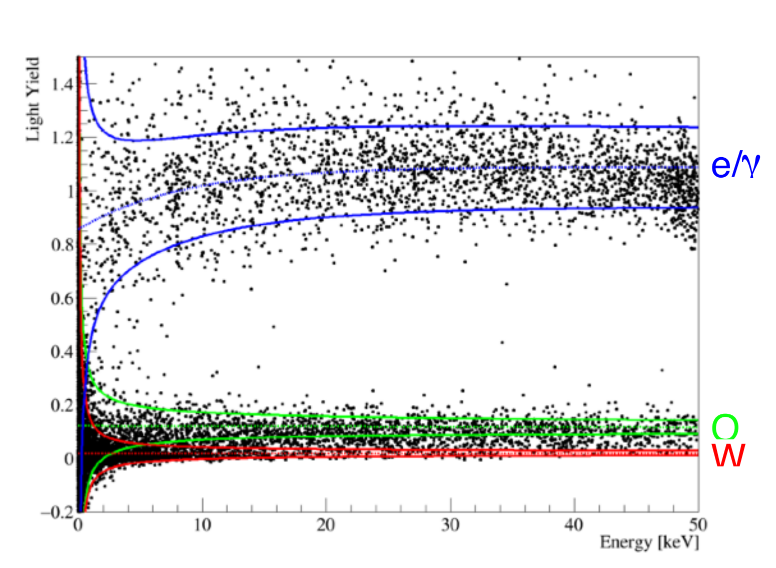
EPJ C (2014) 74:2957

The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

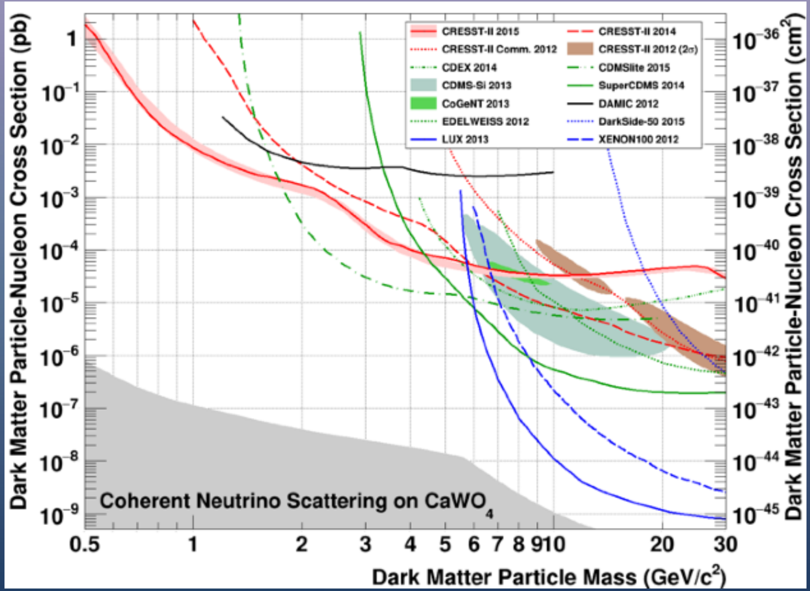
Light Yield = $\frac{\text{energy detected in light channel}}{\text{energy detected in phonon channel}}$





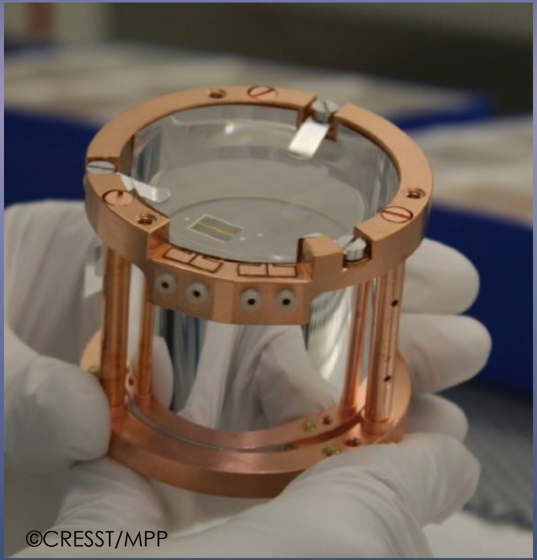
CRESST-II results

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



EPJ C (2016) 76:25

World-leading below 1.7 GeV/c²



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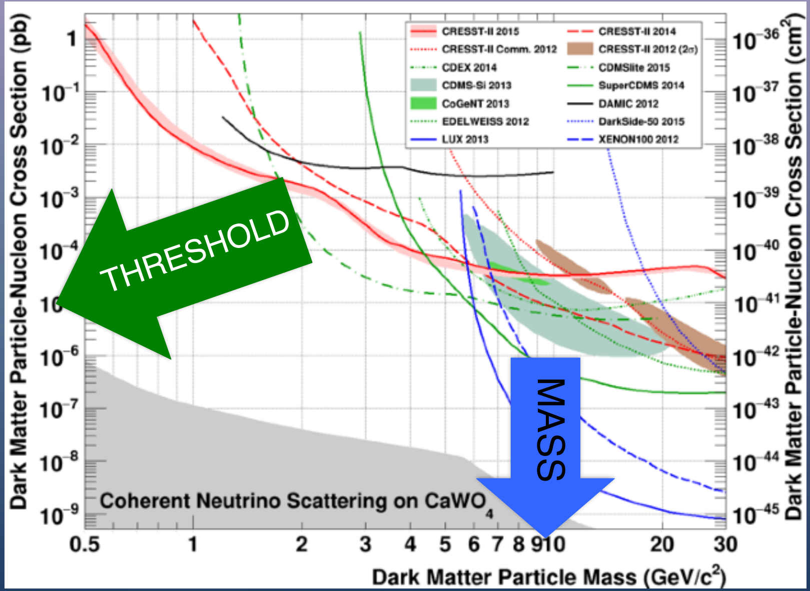
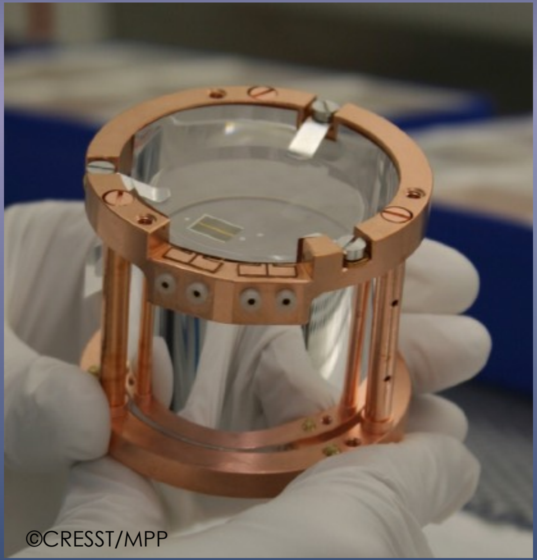


EPJ C (2016) 76:25

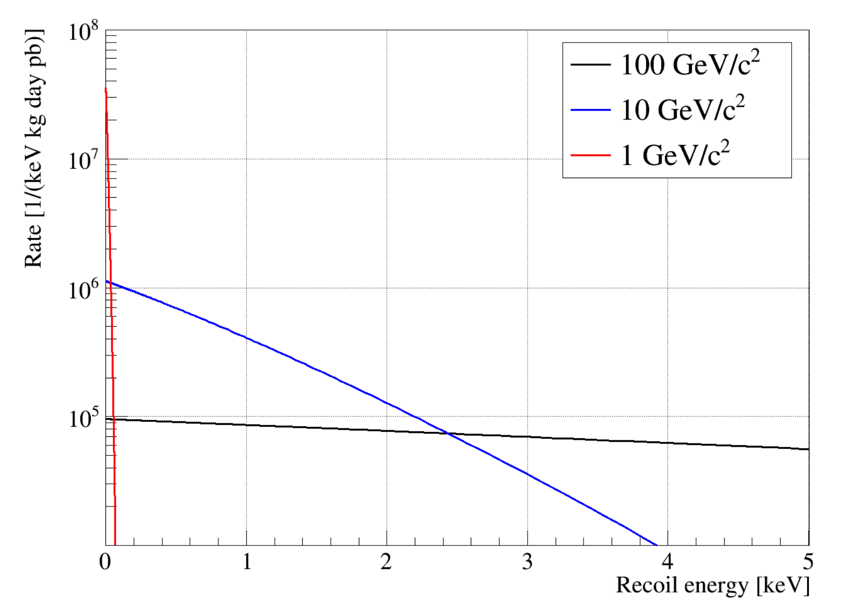


Hunting light dark matter requires a low threshold!

Low threshold detectors

Exploring new parameter space below 0.5 GeV/c²

Dark matter recoil spectrum: $CaWO_4$ target , ideal detector



Low threshold detectors

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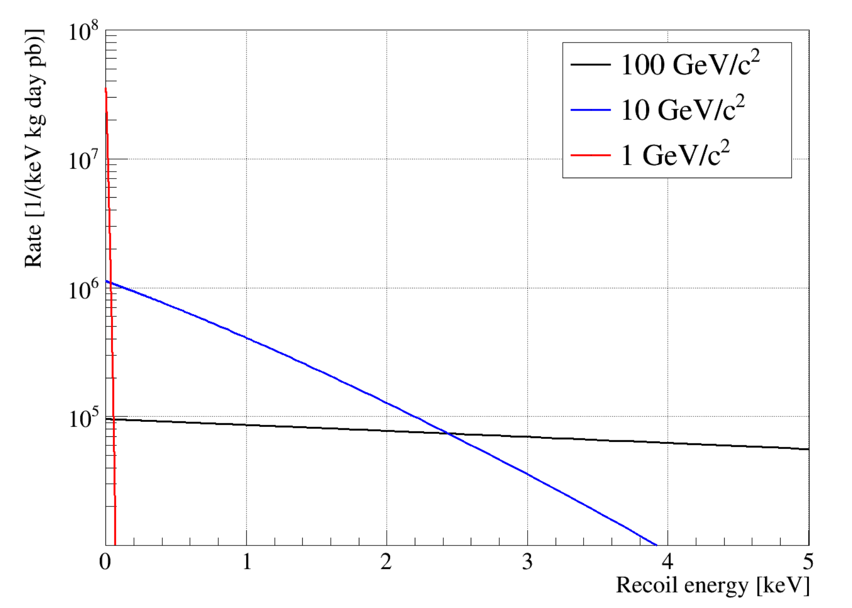

Challenges

- Small recoil energies

  ~ keV range

Low threshold detectors

Exploring new parameter space below 0.5 GeV/c²

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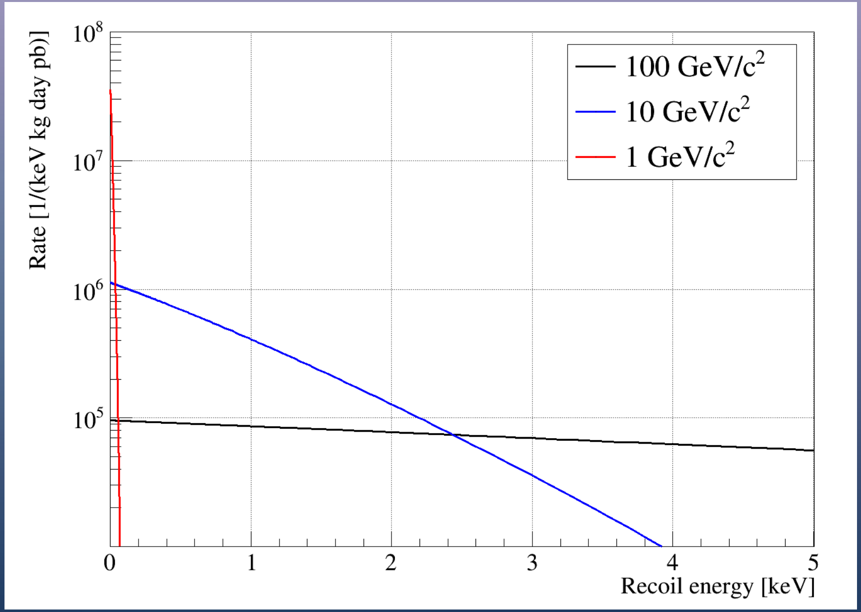


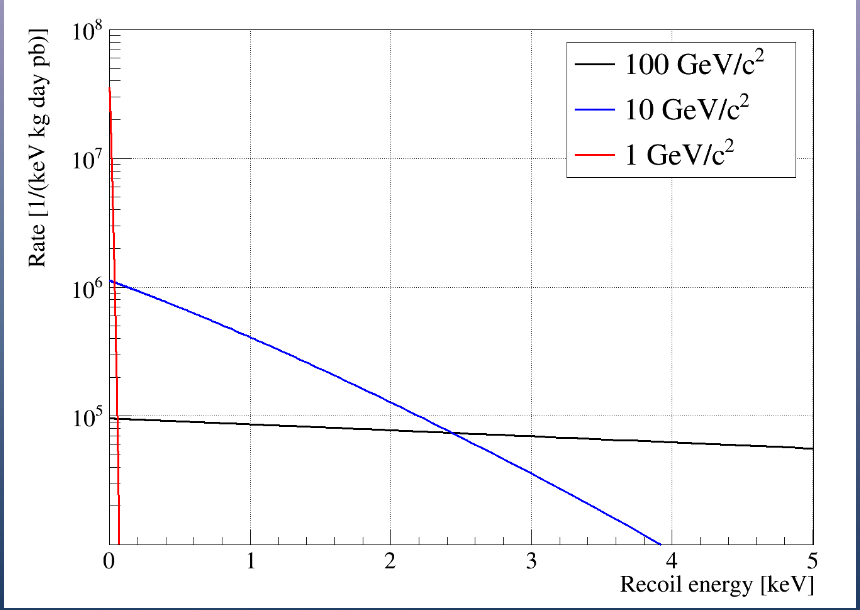
<u>Challenges</u>

- Small recoil energies
  ~ keV range
- Featureless spectrum

Low threshold detectors

Exploring new parameter space below 0.5 GeV/c²

Dark matter recoil spectrum: $CaWO_4$ target , ideal detector



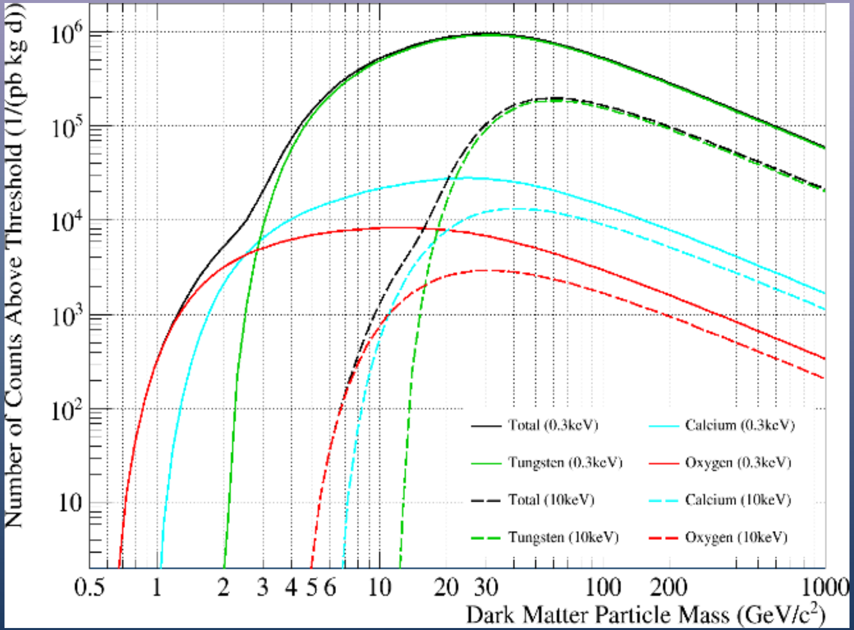
<u>Challenges</u>

- Small recoil energies
  ~ 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

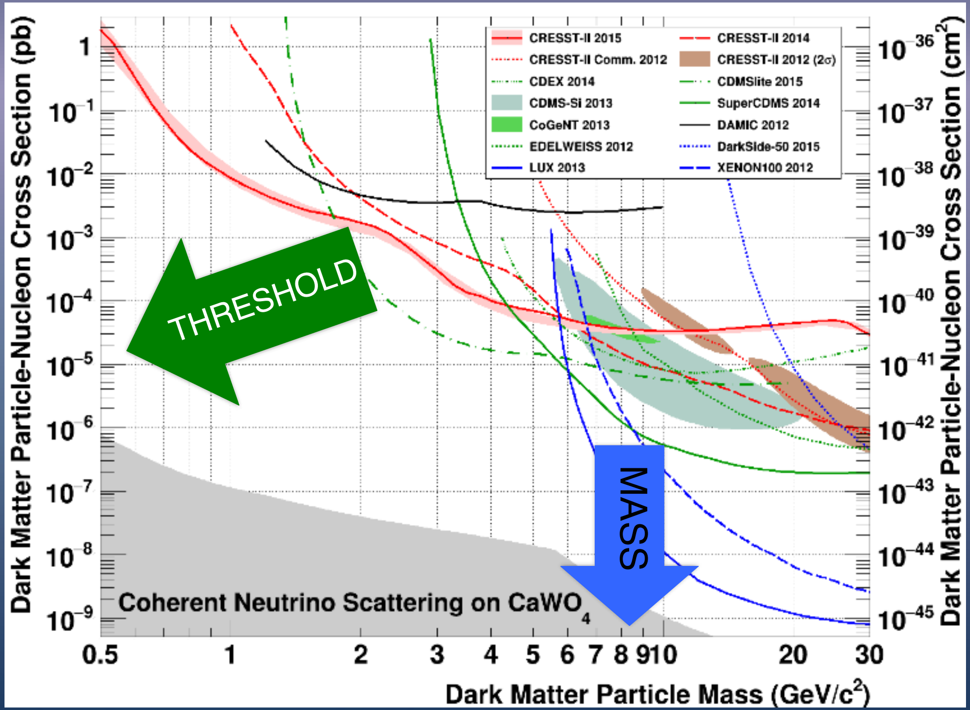
Dark matter expected rate: $CaWO_4$ target , ideal detector



Challenges

- Featureless spectrum
- Small recoil energies
  ~ keV range
- Very rare
  current limit*
  $\mathcal{O}$(0.01) counts/tonne day

The CRESST-III strategy: go for small



EPJ C (2016) 76:25

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

Smaller crystals:
250g → 24g

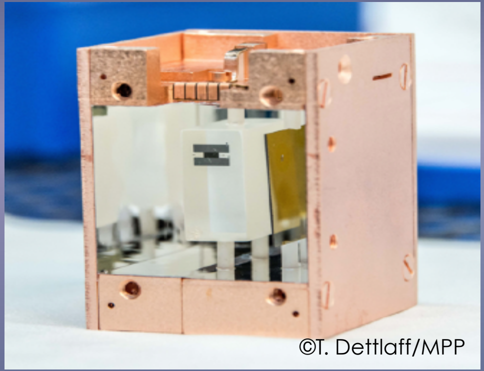
Threshold goal:
300eV → 100eV

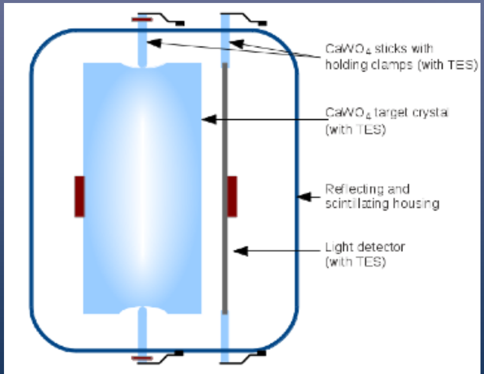
CRESST-III low-threshold detector

Exploring new parameter space below 0.5 GeV/c^2

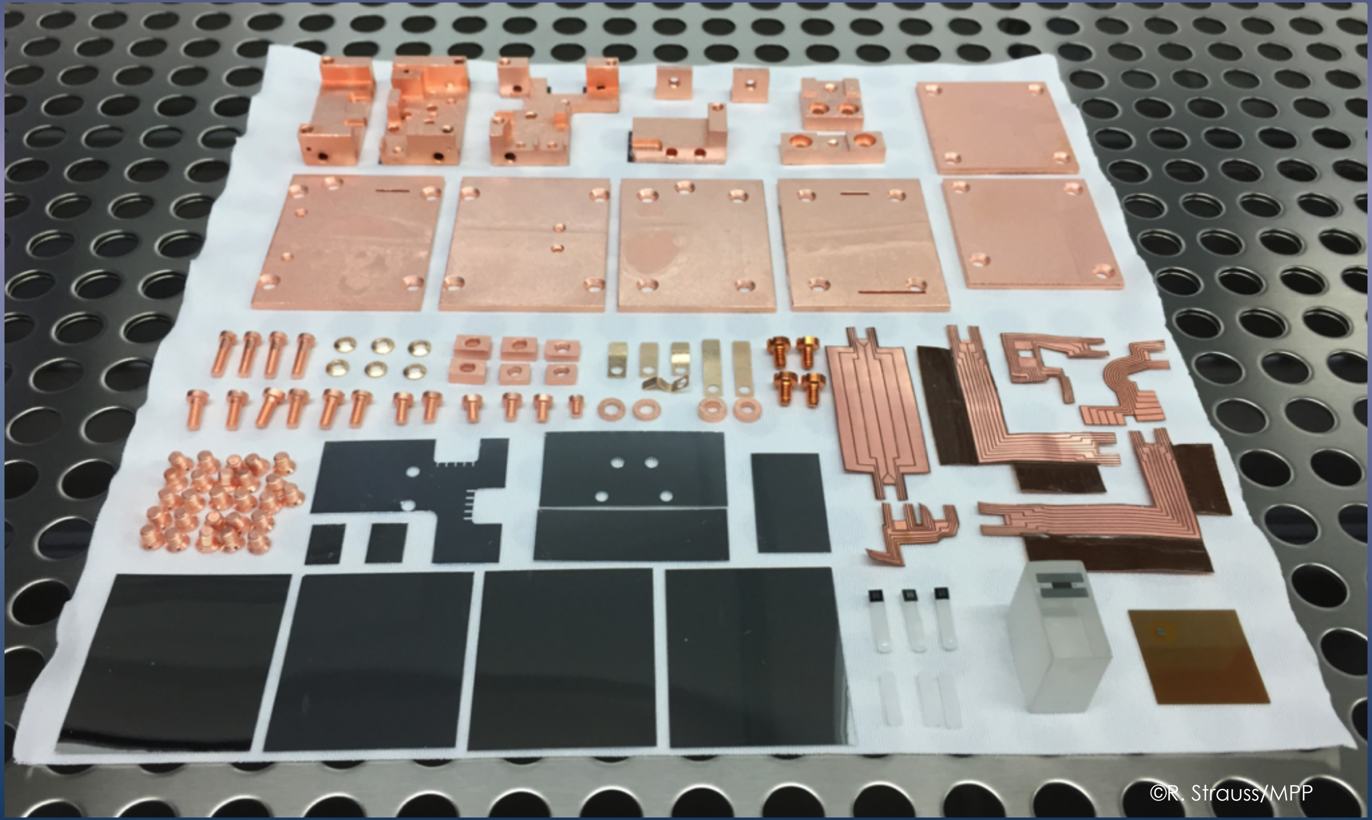
CRESST-III detector dimensions scaling down	**(CRESST-II)**
• $(20\times20\times10)$ mm^3	$(40\times40\times40)$
• Mass ~ 24 g	(~300)
• Threshold goal ~ 100 eV	(~300)
• Self grown crystals ~ 3 counts/(keV kg day)	(~8.5)
• Fully scintillating housing	no
• Instrumented sticks	no

Surface related background vetoing

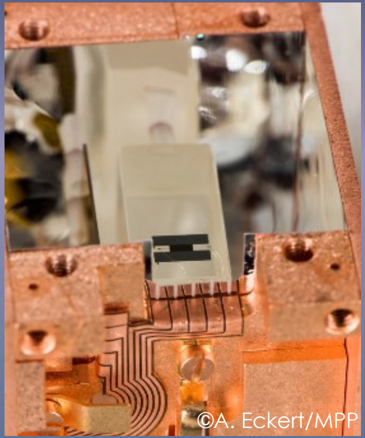


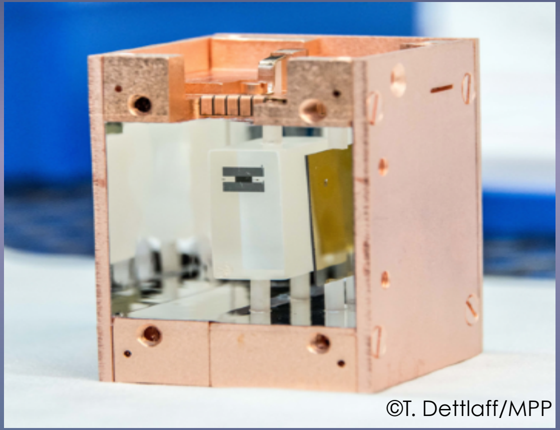


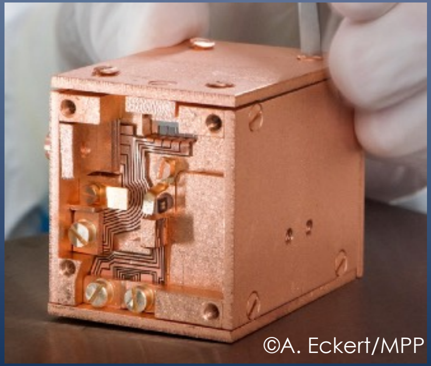
CRESST-III Phase 1

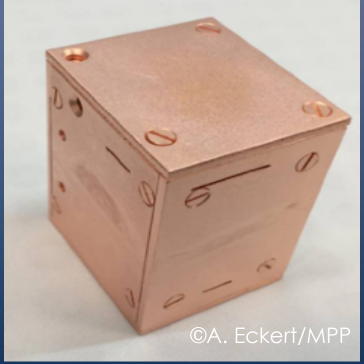


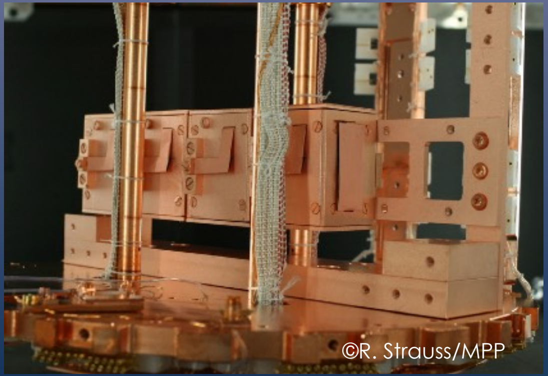
CRESST-III Phase 1









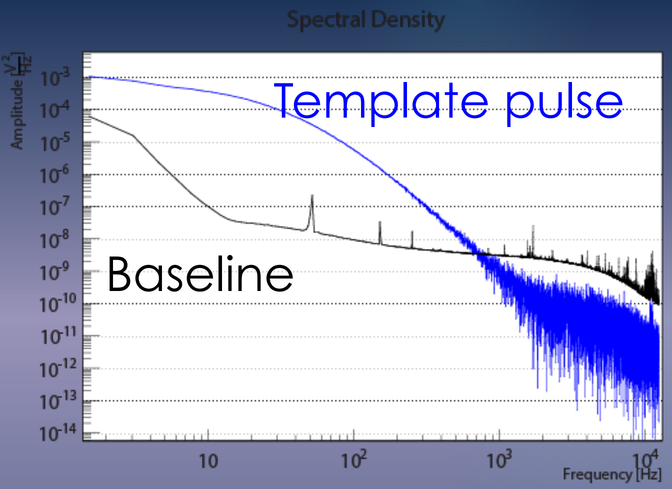


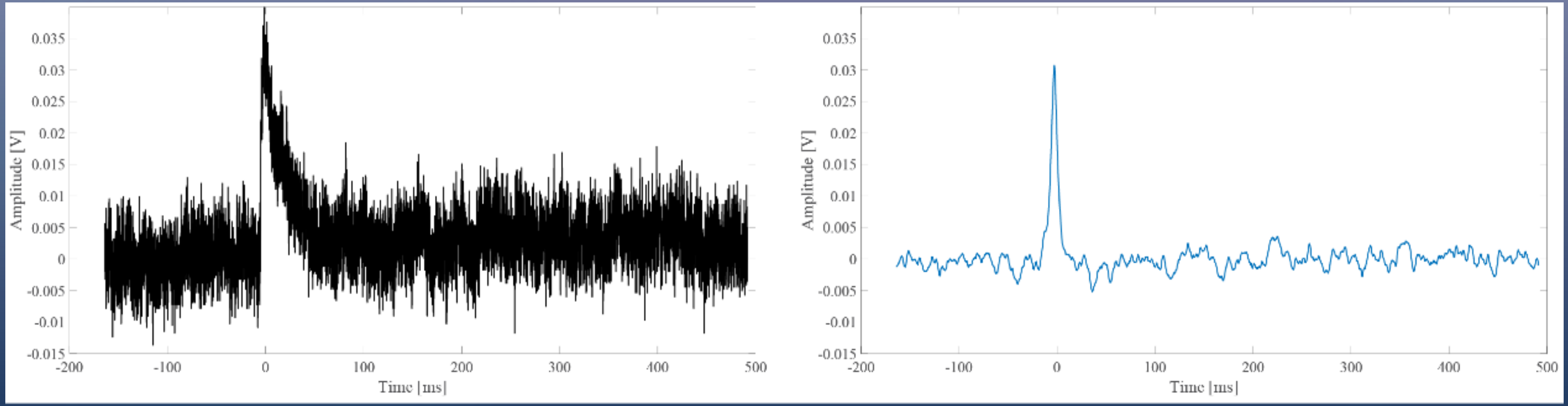
Data taking started July 2016

Optimum algorithms

Pulse height evaluation

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





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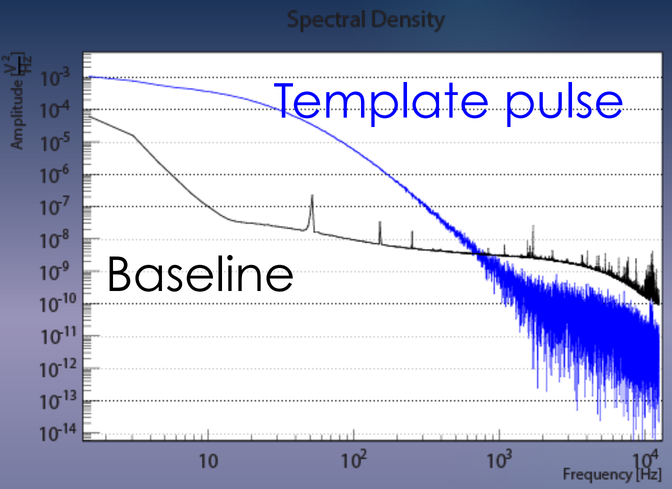
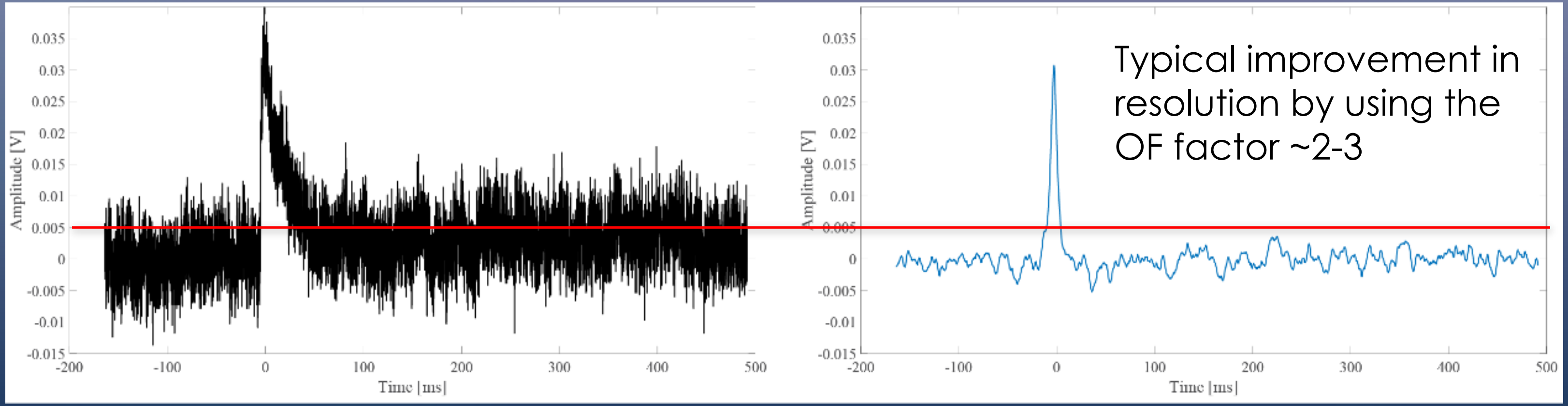




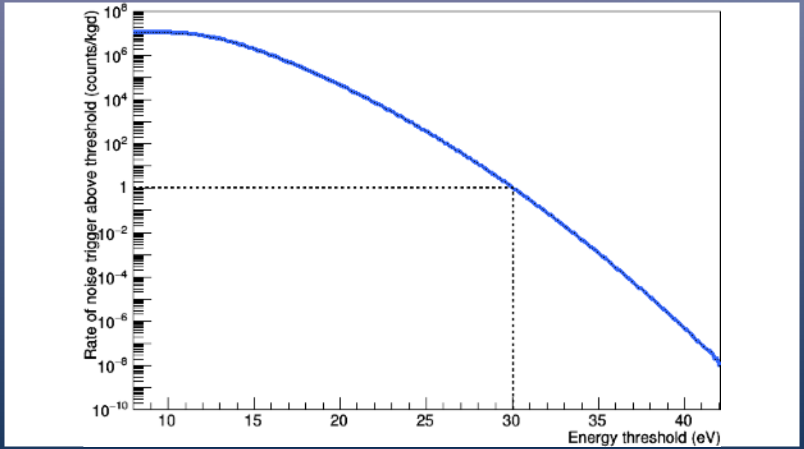
J Low Temp Phys (2019)
doi.org/10.1007/s10909-018-1948-6

Optimum algorithms

Optimum filter for threshold analysis

- Study the noise distribution after optimum filter in order to set the threshold
- Analytical description of amplitude distribution in empty baselines
- Threshold optimised based on noise triggers in a given exposure
- Study the noise distribution after OF in order to set the thresholds (Optimum Trigger)

Detector A
30.1 eV threshold



Det A – Full dataset analysis

Selection criteria

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

Objective

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

arXiv:1904.00498
submitted to PDR

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 conditions (14% of measuring time)

Stability: Detector(s) 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

Det A – Full dataset analysis

Efficiency/signal survival probability

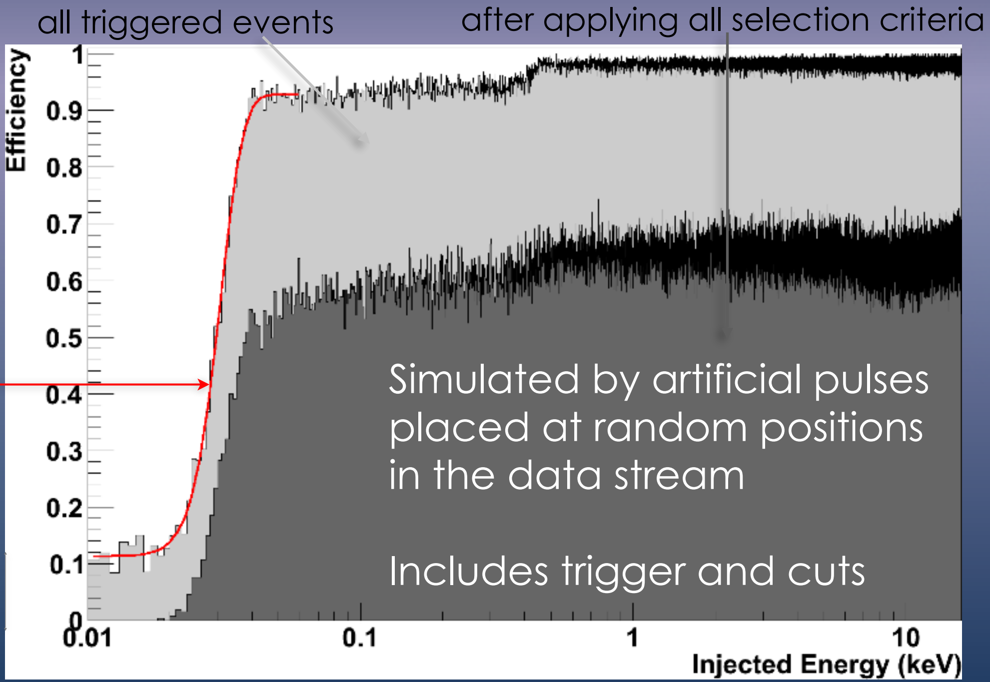
filter effect

≳60% efficiency over broad energy range

fit of the threshold with an error function

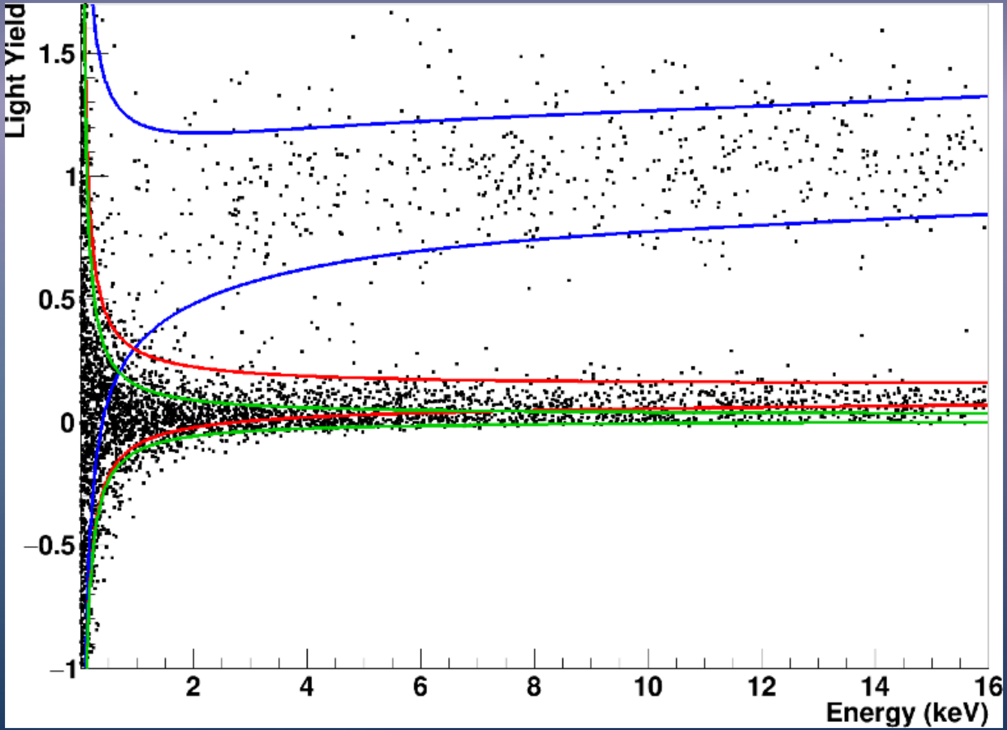
threshold fit compatible with noise analysis value 30.1 eV

pile-up



Det A – Full dataset analysis

Neutron calibration - bands fit



e/γ

O

W

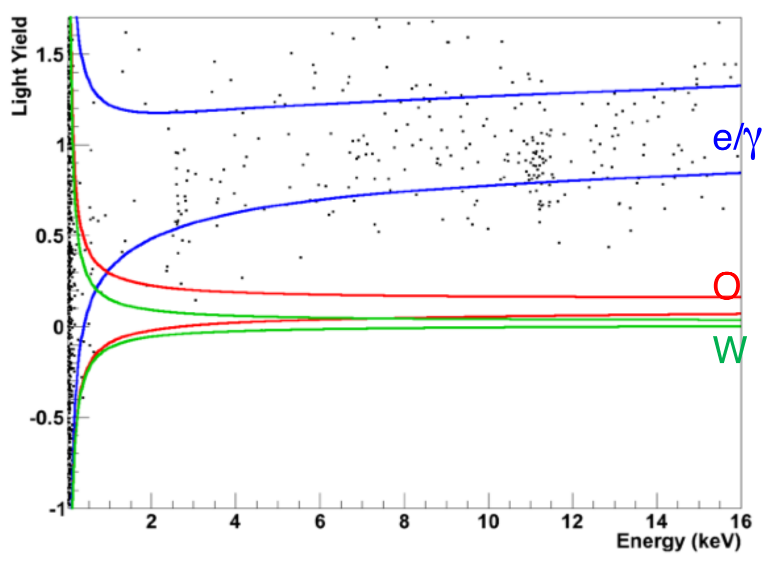
- Unbinned Maximum Likelihood fit
- Calculation using QFs from MLL neutron beam measurement

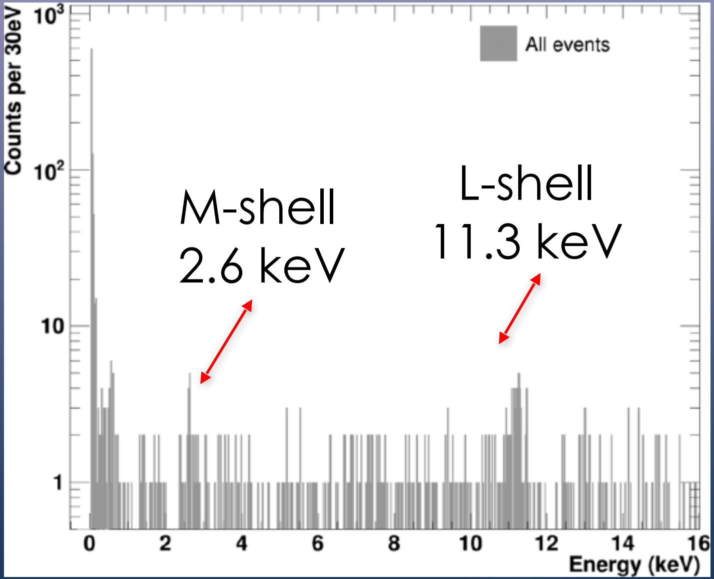
Det A – Full dataset analysis

Dark Matter data - energy spectrum

Analysis optimized for very low energies: 30 eV → 16 keV

Cosmogenic activation → $^{179}Ta + e^{-}$ → $^{179}Hf + \nu_e$ (1.8y)



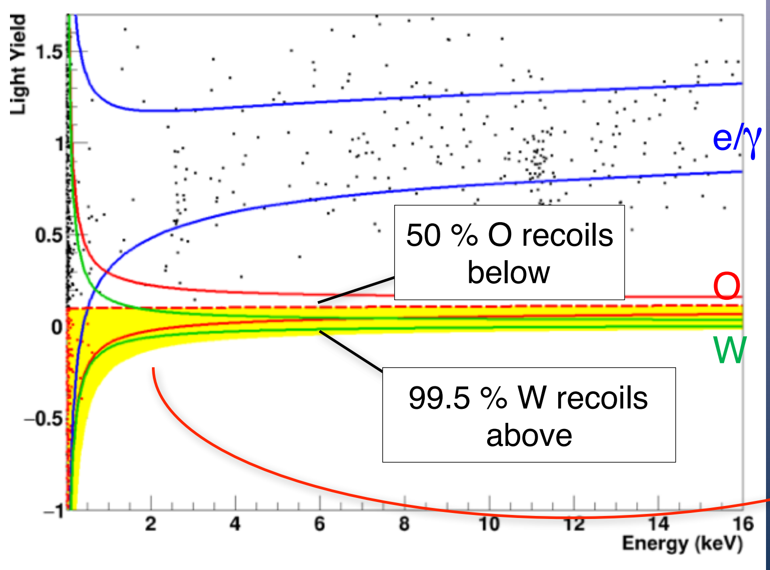


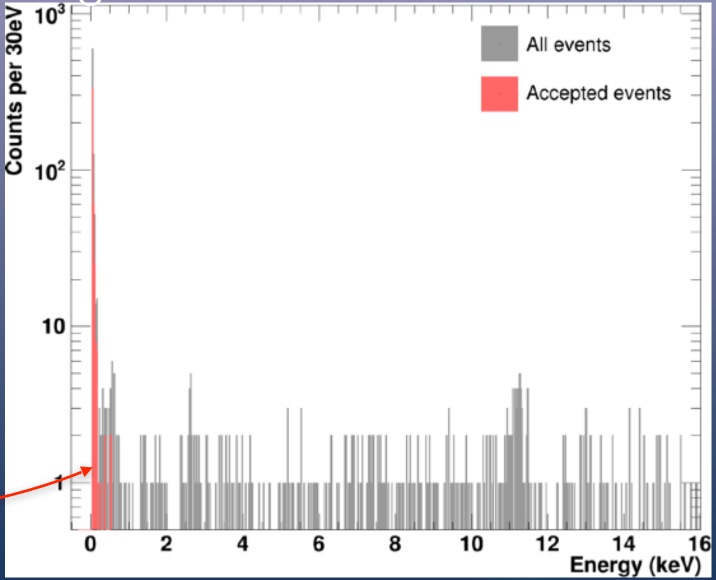
Det A – Full dataset analysis

Dark Matter data - acceptance region

Analysis optimized for very low energies: 30 eV → 16 keV

Acceptance region fixed before unblinding





Det A – Full dataset analysis

Results

Energy spectrum of accepted events

Yellin method

Simulated Dark Matter energy spectrum

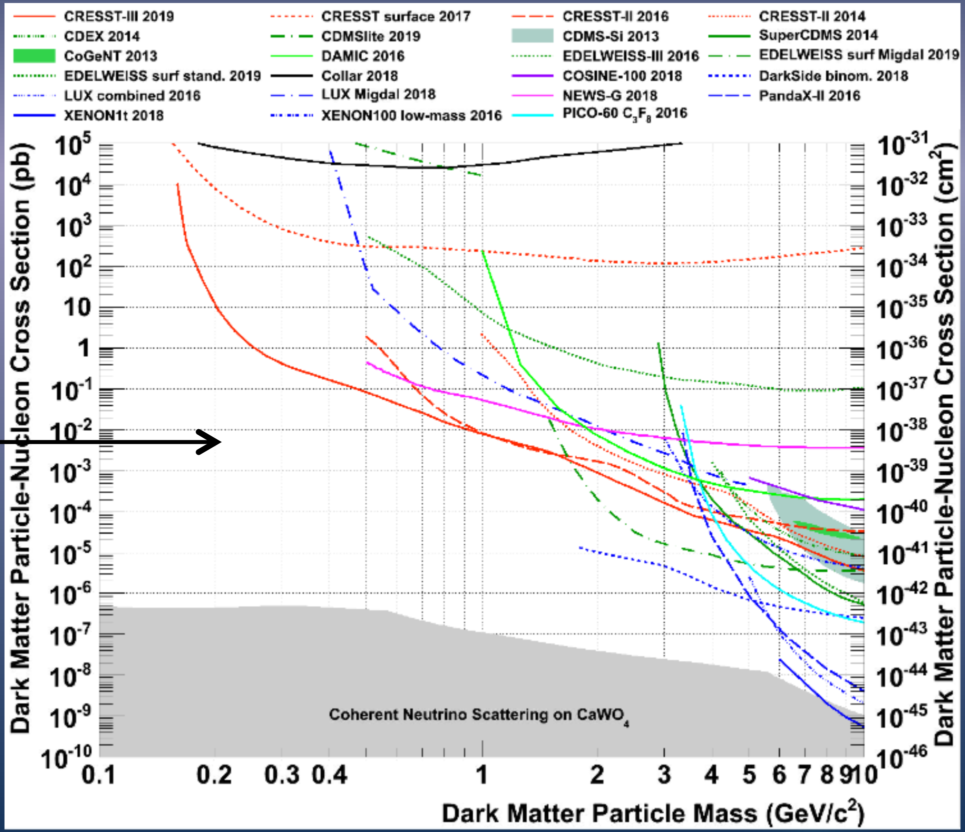
Det A – Full dataset analysis

Results

Energy spectrum of accepted events

Yellin method

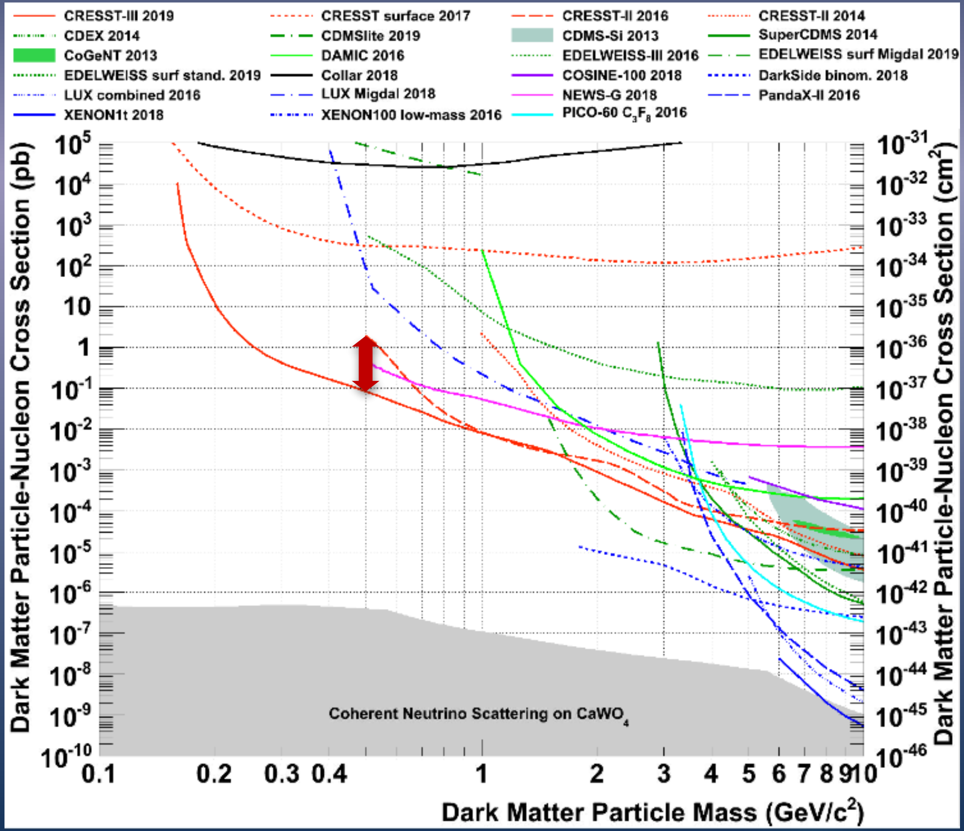
Expected energy spectrum



Det A – Full dataset analysis

Results

More than one order of magnitude improvement at 0.5 GeV/c^2

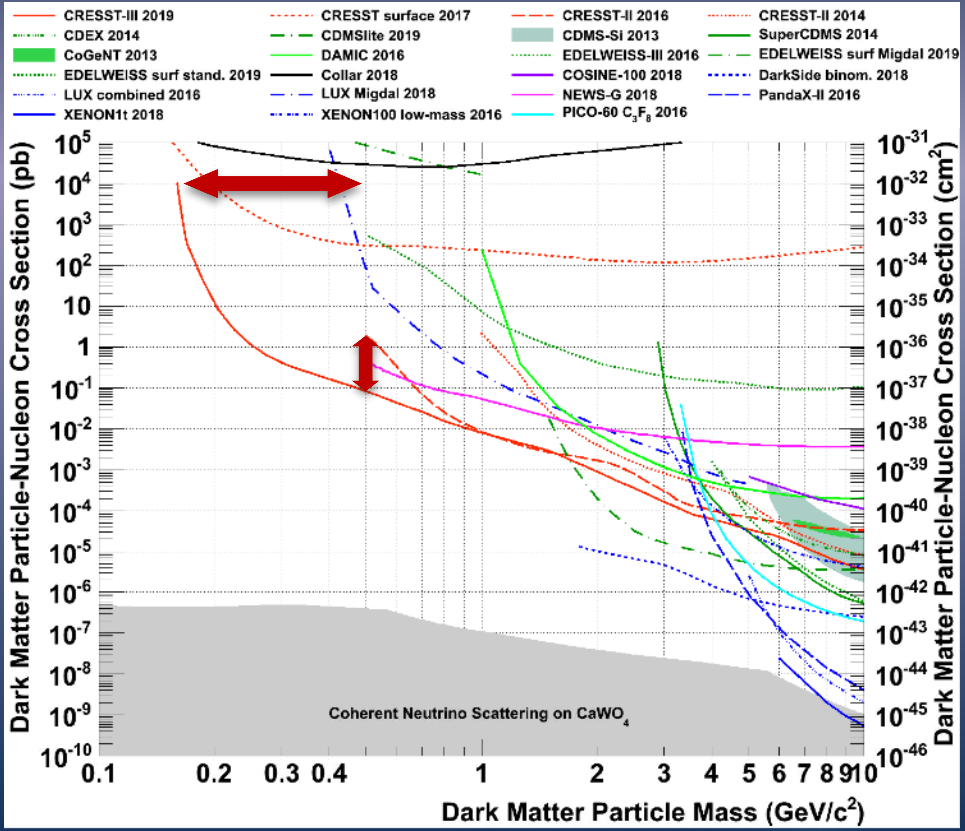


Det A – Full dataset analysis

Results

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

Reach of direct dark matter experiments extended to 0.16GeV/c²



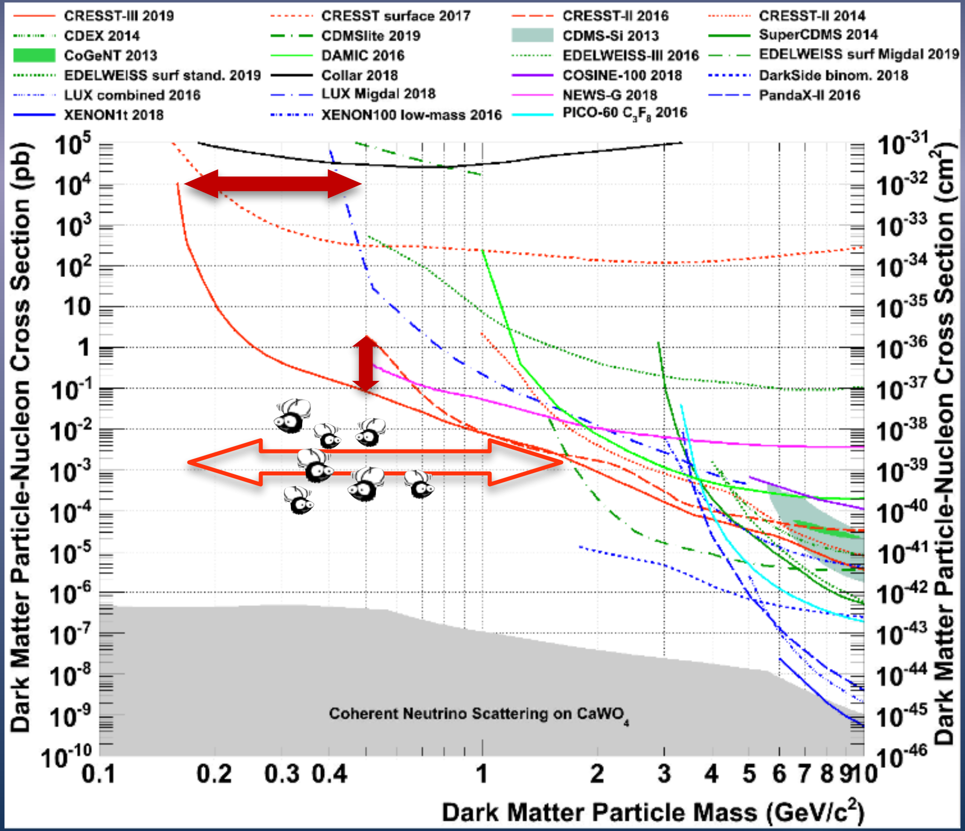
Det A – Full dataset analysis

Results

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

Reach of direct dark matter experiments extended to 0.16 GeV/c²

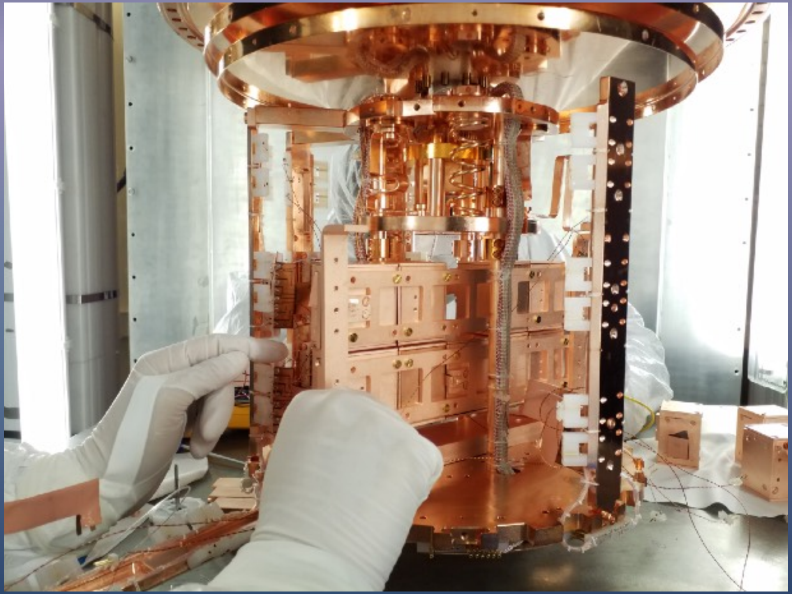
Unexpected rise of event rate at E < 200 eV



Conclusion

- The CRESST-III det-A collected an exposure of 5.689 kg days, reaching a nuclear recoil threshold of 30.1 eV
- World leading direct dark matter experiment below 1.7 GeV/c^2
- More than one order of magnitude improvement at 0.5 GeV/c^2
- Reach of direct dark matter experiment extended to 0.16 GeV/c^2
- Unexpected rise of event rate at $E < 200$ eV

~~Conclusion~~ …this is the beginning

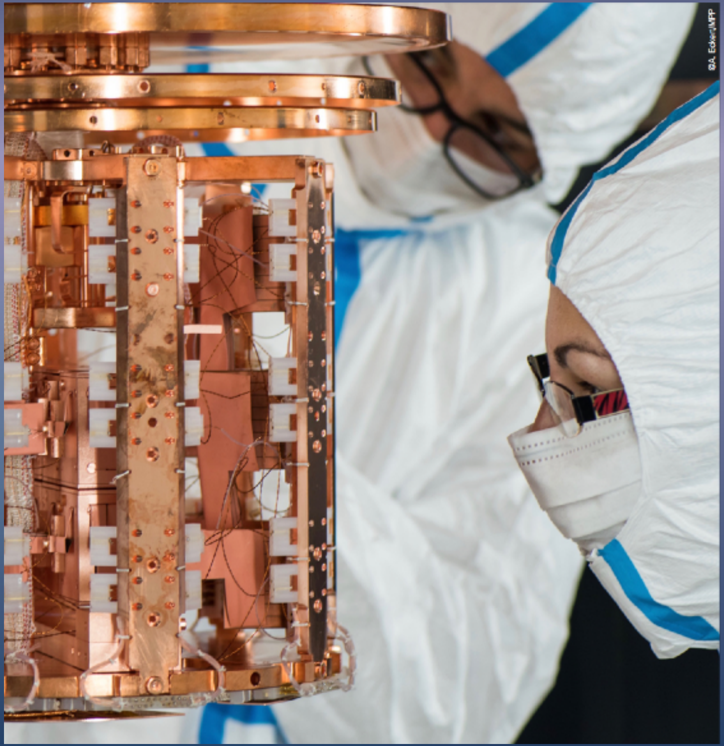


Analysis on other detectors of previous run is ongoing…

A second CRESST-III run started: upgraded detector modules with dedicated hardware changes to investigate the origin of the background excess

Additional active magnetic field compensation with three pair of coils for x,y & z-axes

~~Conclusion~~ …this is the beginning



- The cryostat is cold
- Calibrations performed
- Analysing data

~~Conclusion~~ …this is the beginning

This is a new starting point for DM search. Light DM search program complements the liquefied noble gasses and NaI programs.

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

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Thanks for your attention!