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

16th Rencontres du Vietnam

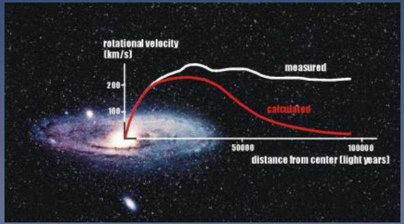
Theory meeting experiment

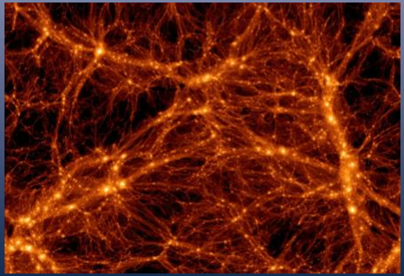
January 8, 2020 – Quy Nhnon - Vietnam

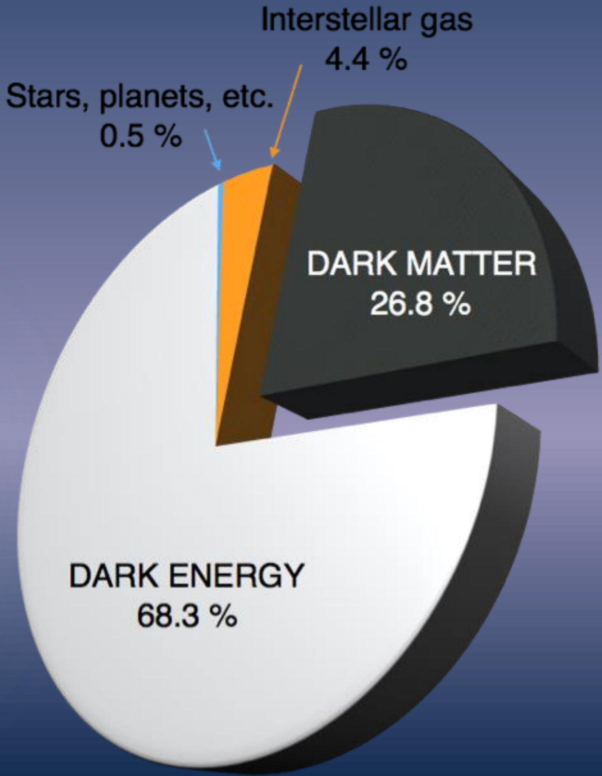
Antonio D'Addabbo

Gran Sasso Science Institute and
Laboratori Nazionali del
Gran Sasso - INFN

The dark matter problem

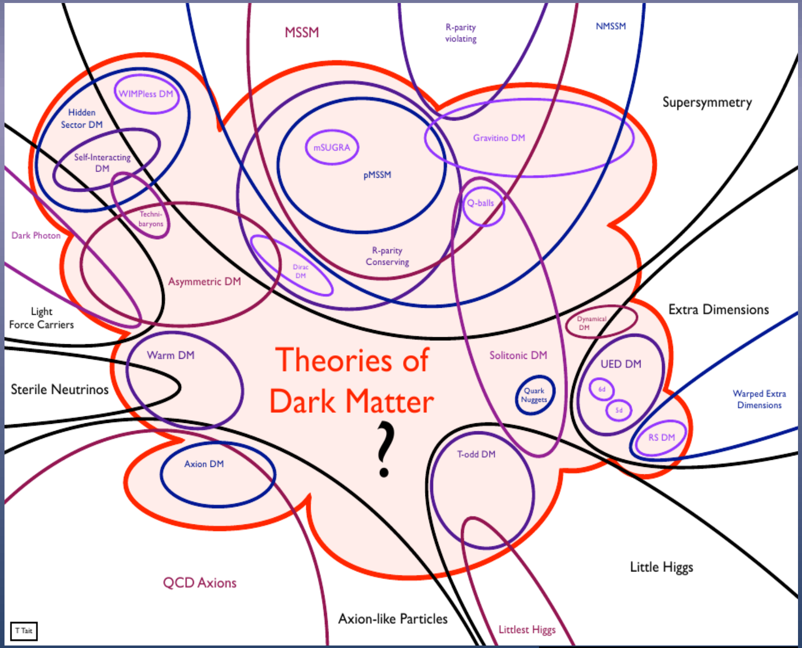






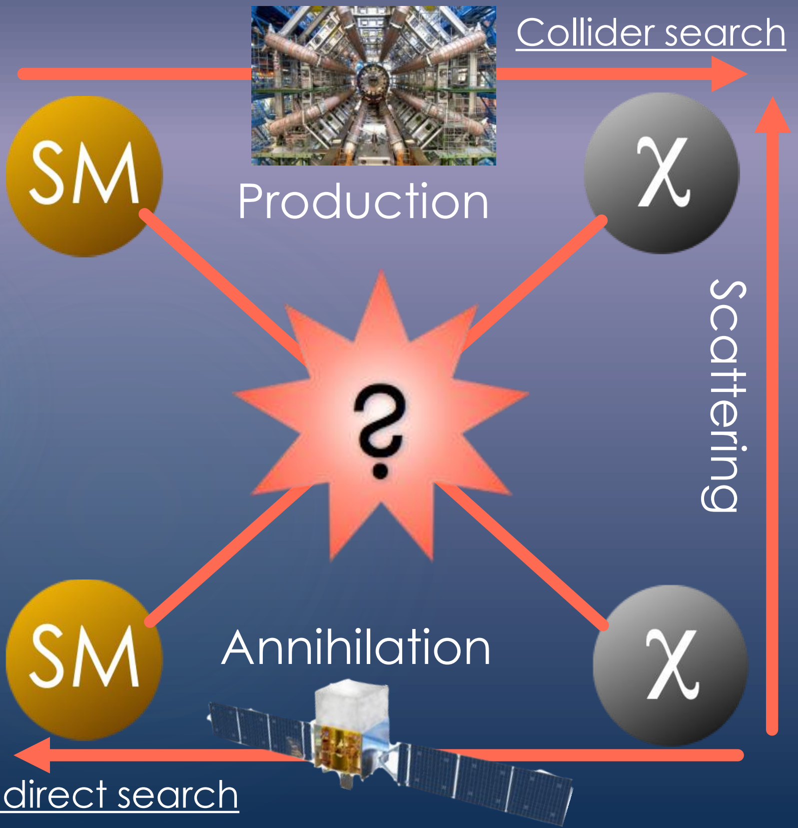
After 80 years…

- **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**
- **Stable (or extremely long-lived)**



T. Tait at UCLA DM 2016

The hunt for dark matter

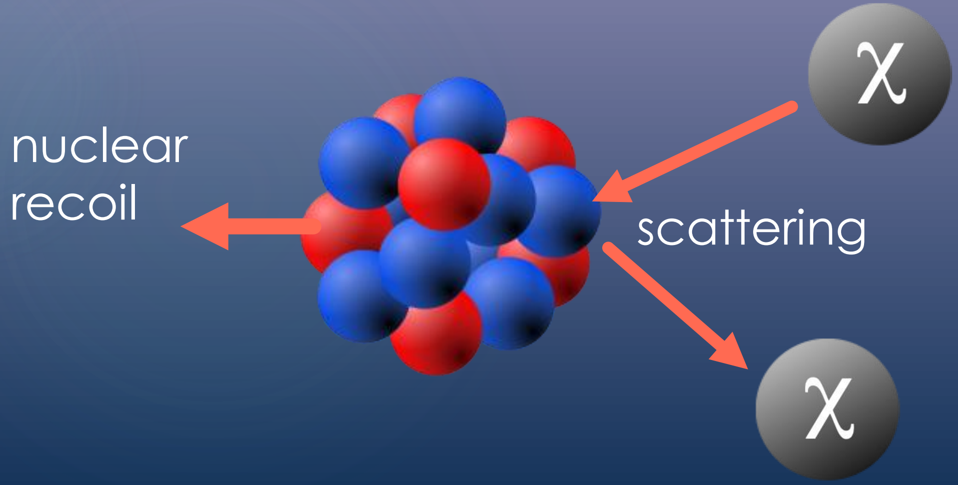


Direct search

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



<u>Dark matter particles scattering</u>

- off nuclei
- elastic
- coherent: ~A^2
- spin-independent

The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

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

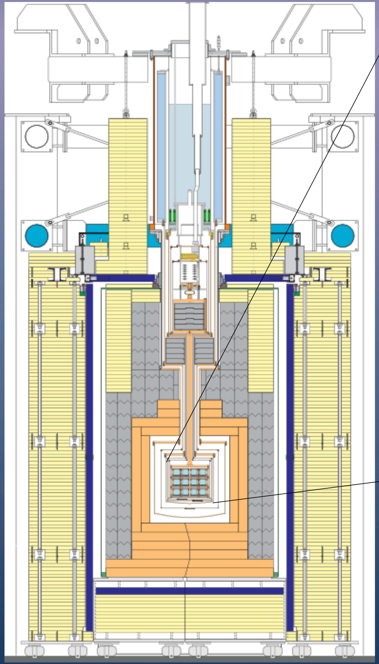
Background suppression

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

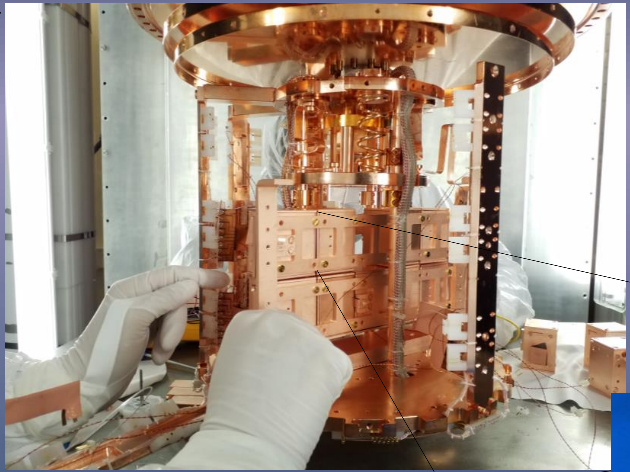
The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

Setup?

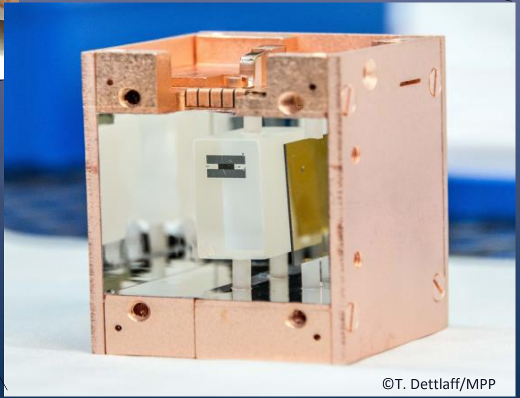


Dilution cryostat with shielding/vetoing



Cold box housing the detectors (Carousel)

Detector module with targets at 15 mK

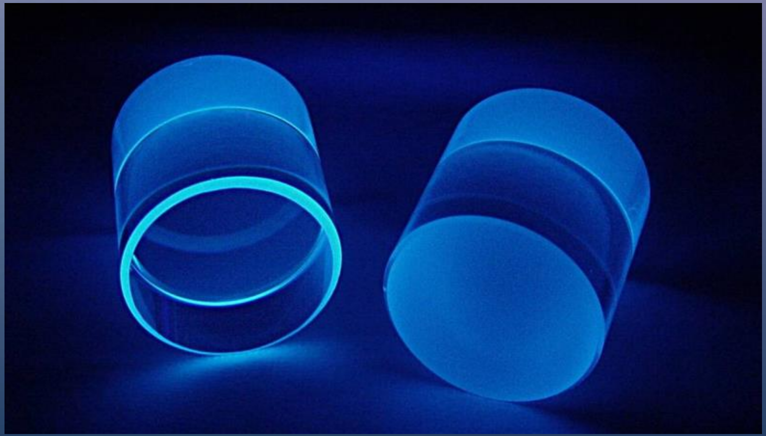


Low temperature and low background environment

The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

Target? **Scintillating $CaWO_4$** crystals

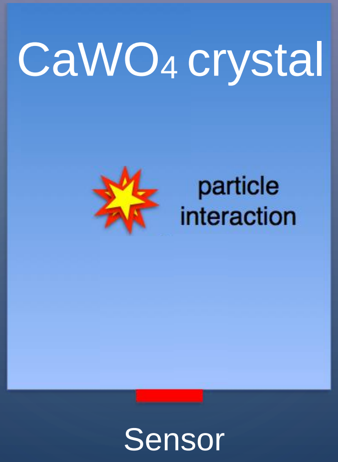


- 3 nuclei: O, Ca and W
- Light targets to maximize sensitivity for low mass dark matter
- Each particle interaction implies **phonon signal** + **light signal**

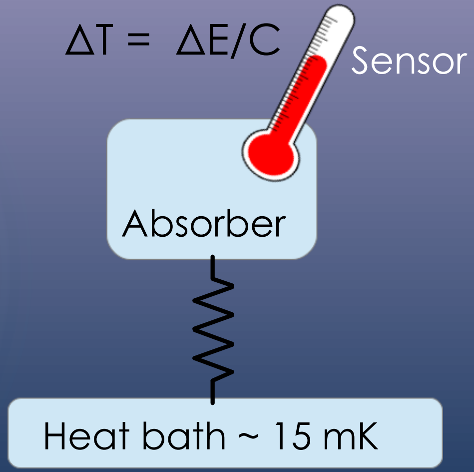
The CRESST experiment

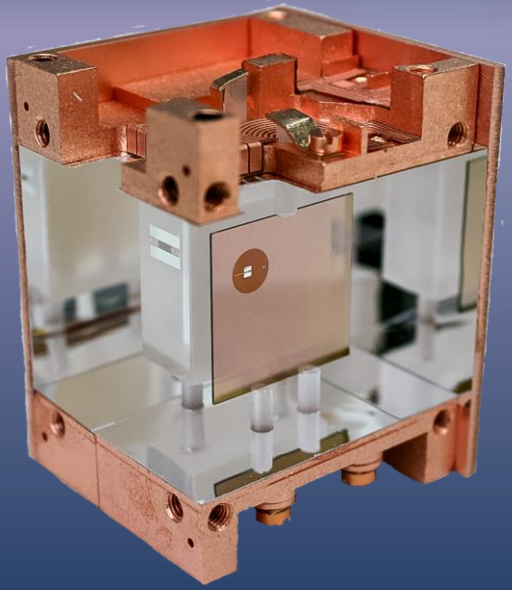
Cryogenic Rare Event Search with Superconducting Thermometers

Detector?



Crystals operated as **cryogenic calorimeters**



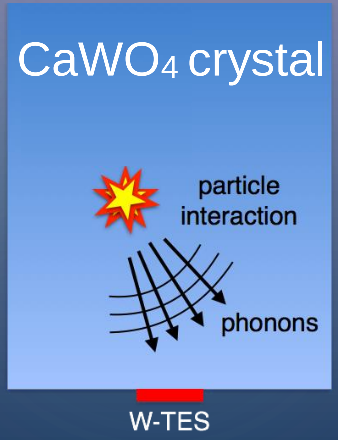


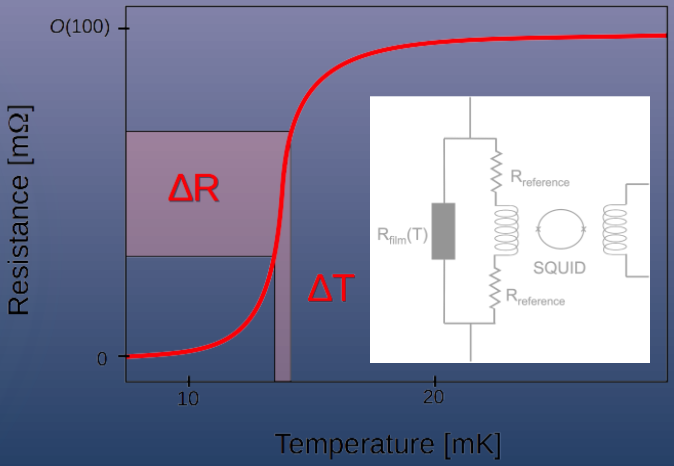
The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

Sensor?

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

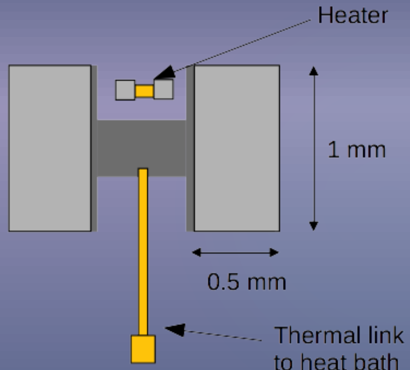
Stability?

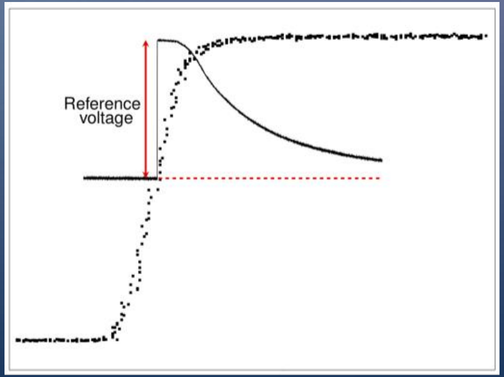
Calibration?

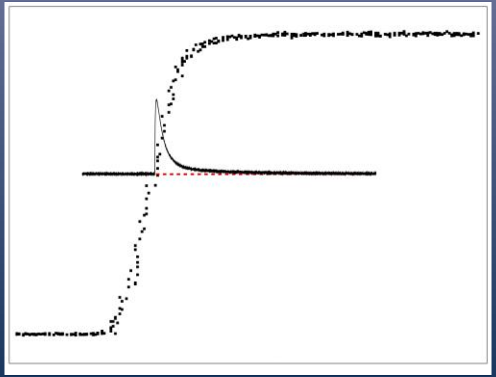
Thresholds?

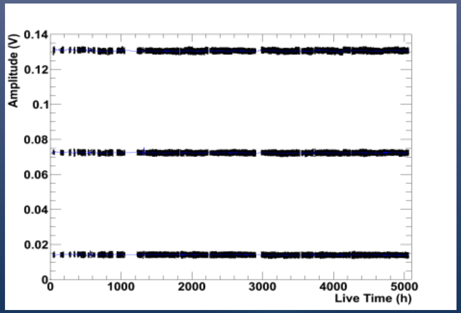
W-TES equipped with heaters

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



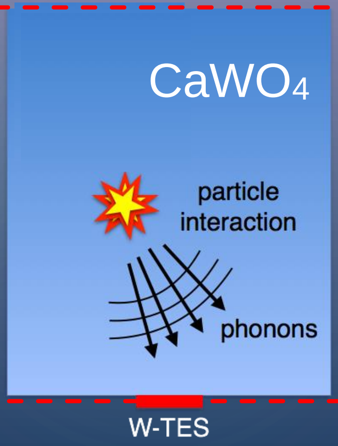






The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers



Phonon signal (≳90 %)

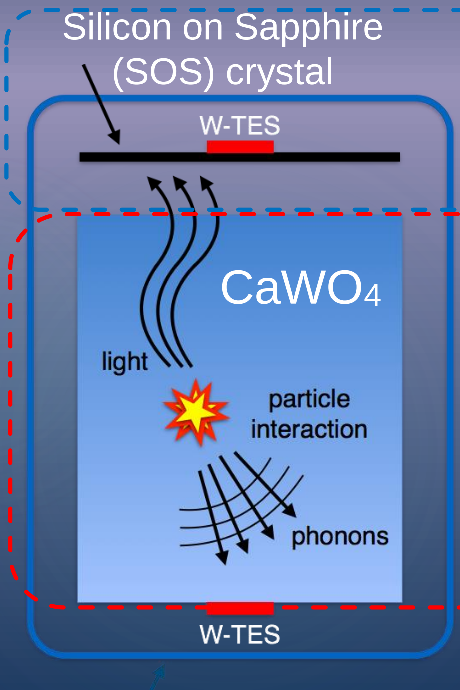
independent of particle type

precise measurement of the deposited energy

deposited energy

The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers



Scintillation light (few %)
particle-type dependent
→ LIGHT QUENCHING

particle discrimination

Phonon signal (≳90 %)

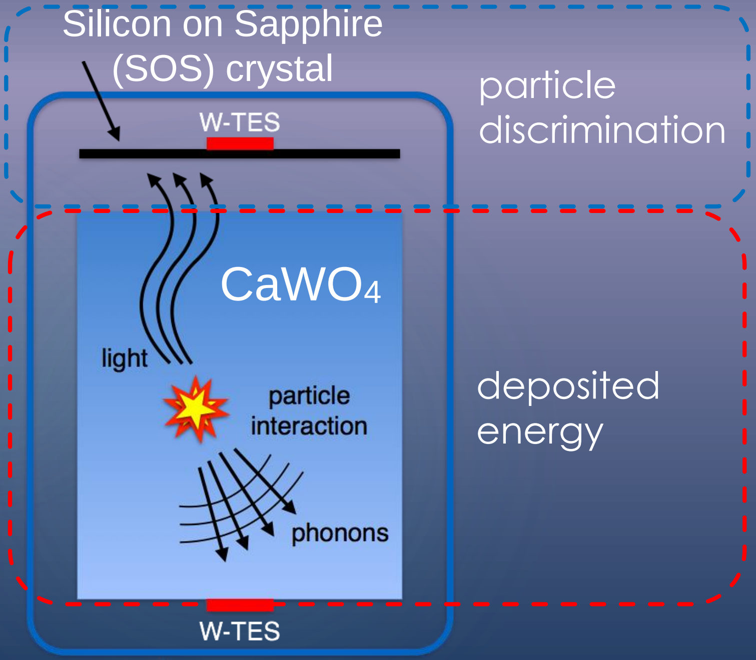
independent of particle type

precise measurement of the deposited energy

deposited energy

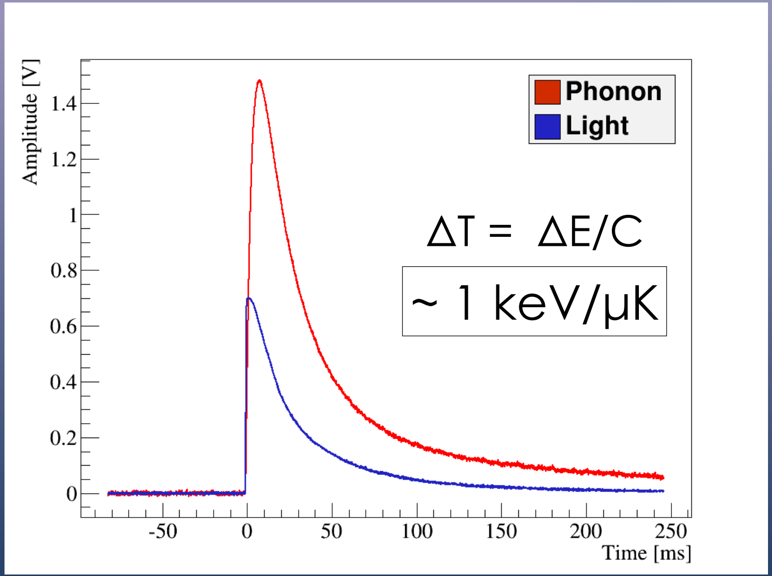
The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers



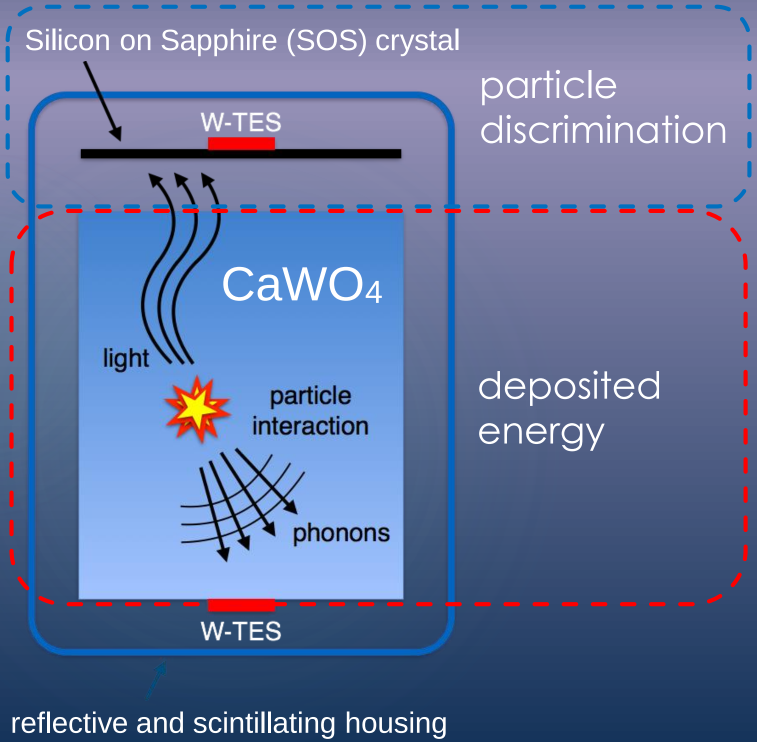
reflective and scintillating housing

Crystals operated as
cryogenic calorimeters (~ 15 mK)

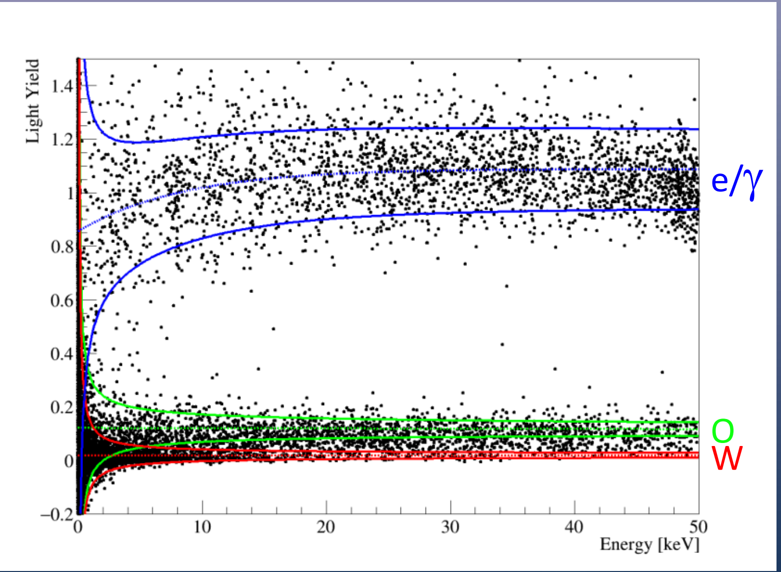


The CRESST experiment

Cryogenic Rare Event Search with Superconducting Thermometers

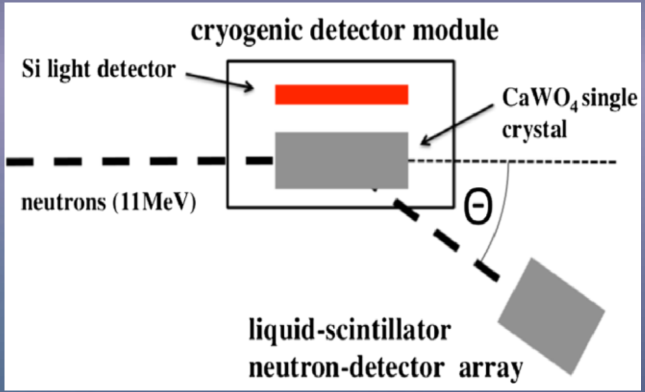


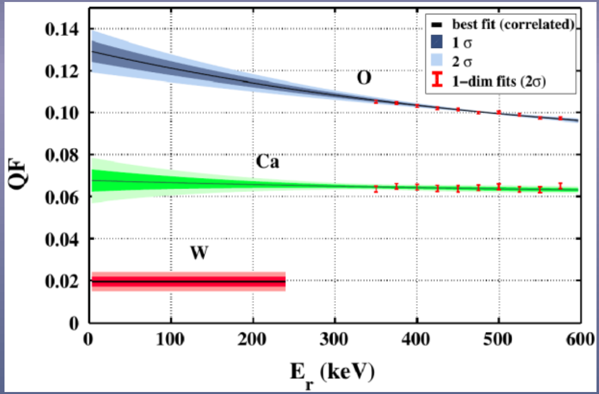
$$\text{Light Yield} = \frac{\text{energy detected in light channel}}{\text{energy detected in phonon channel}}$$



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)%

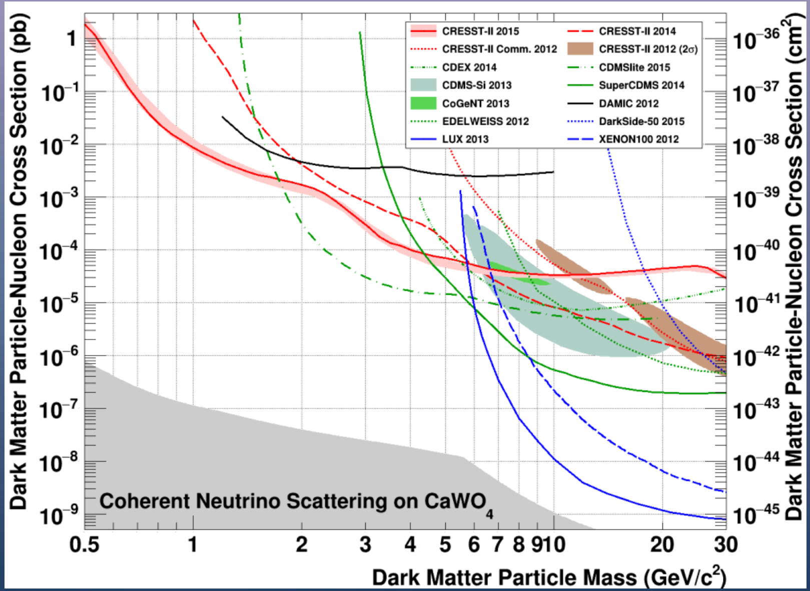
Queching factor measurements
@ accelerator of Maier-Leibnitz-Laboratorium

R. Strauss et al., EPJC **74**: 2957 (2014)

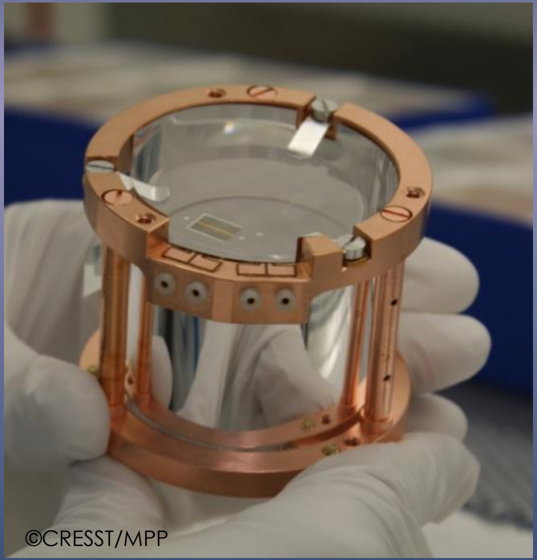
CRESST-II results

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

World leading experiment below 1.7 GeV/c^2

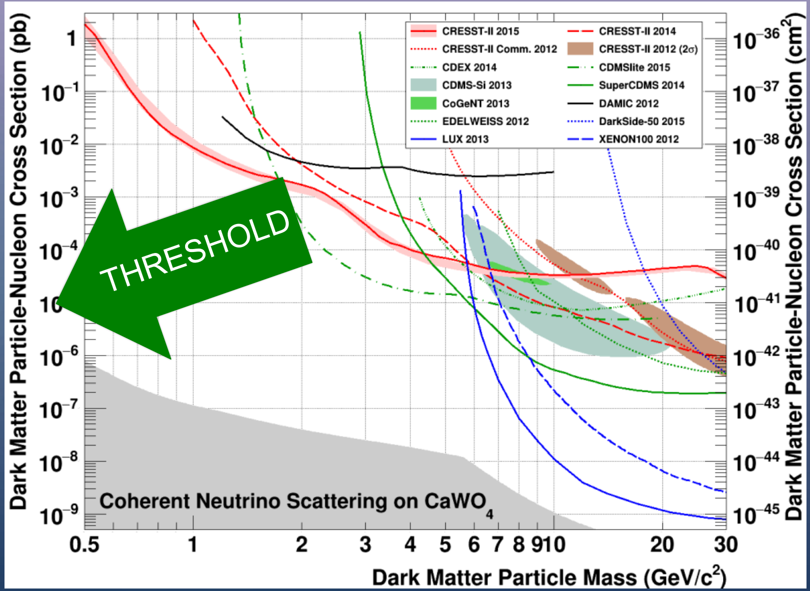


G. Angloher et al., EPJC **76**: 25 (2016)



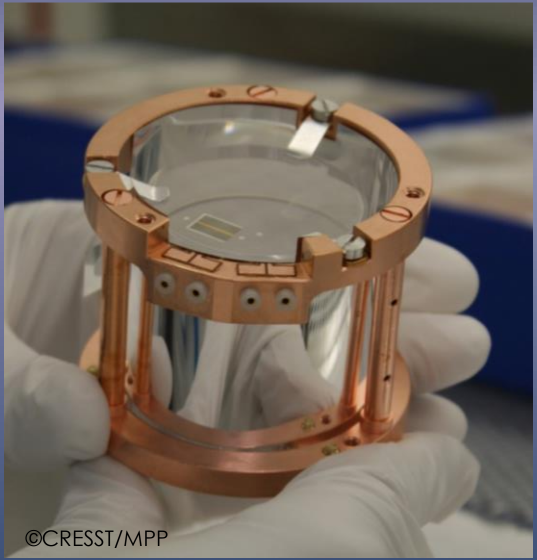
CRESST-II results

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



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

World leading experiment below 1.7 GeV/c^2

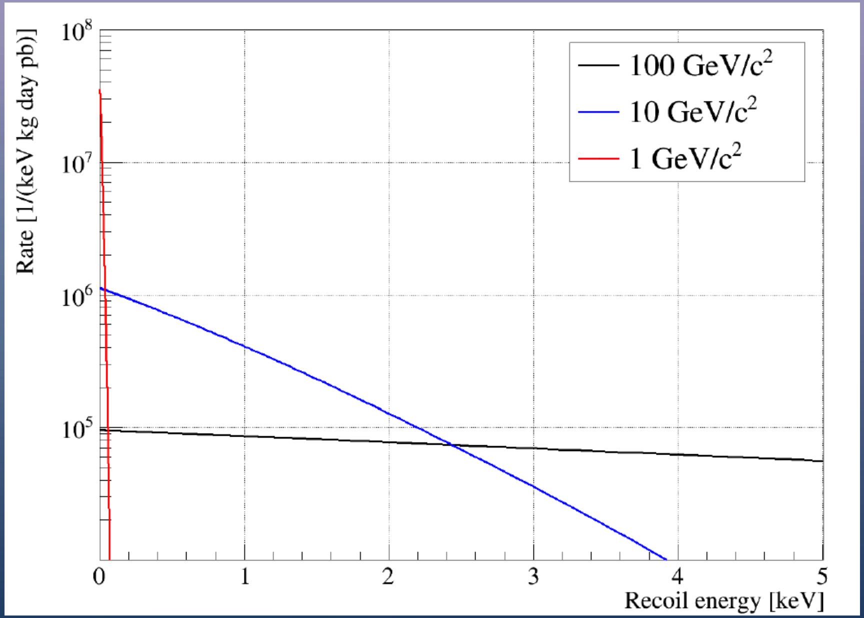


Hunting light dark matter requires a low threshold!

Low threshold detectors

Exploring new parameter space below 0.5 GeV/c^2

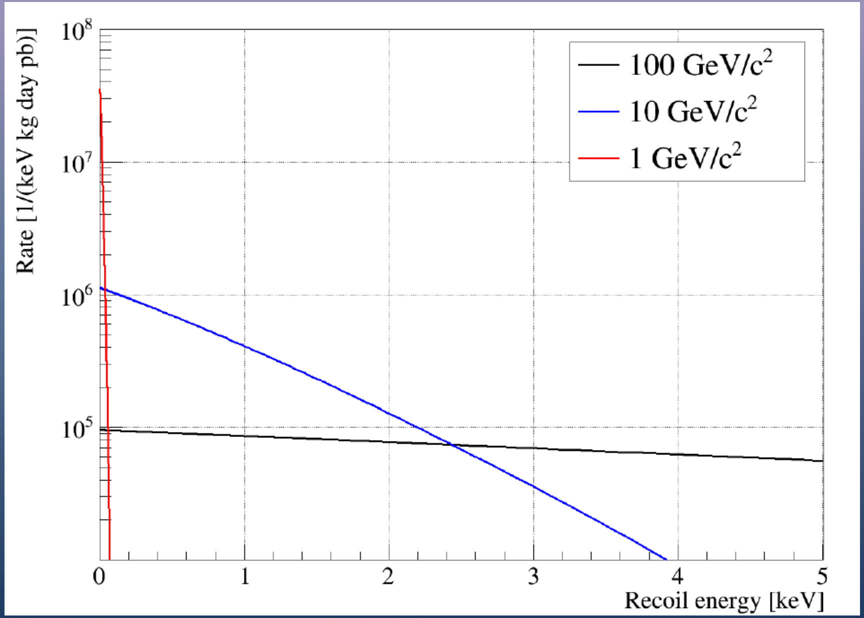
Dark matter recoil spectrum: $CaWO_4$ target , ideal detector



Low threshold detectors

Exploring new parameter space below 0.5 GeV/c^2

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



Challenges

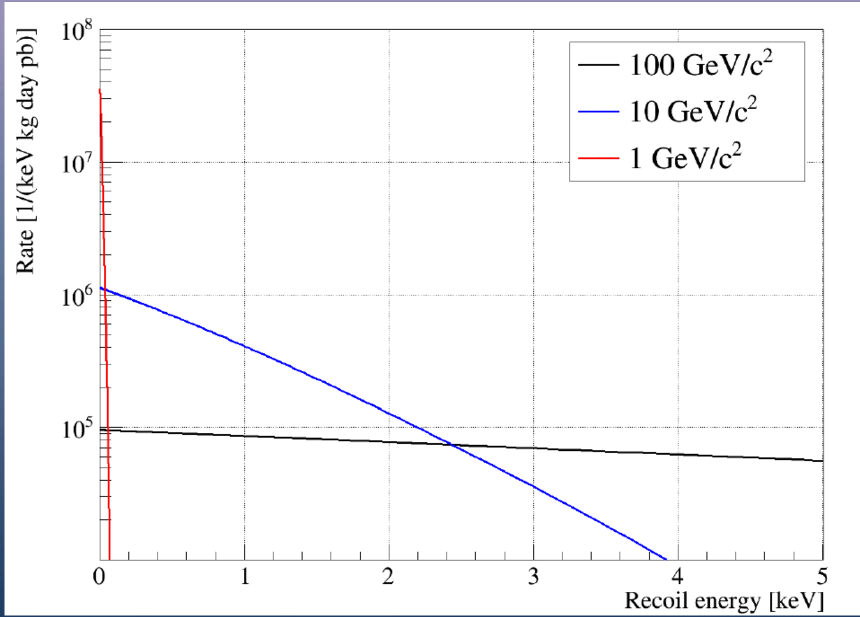
- **Small recoil energies**

  ~ sub-keV range

Low threshold detectors

Exploring new parameter space below 0.5 GeV/c^2

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



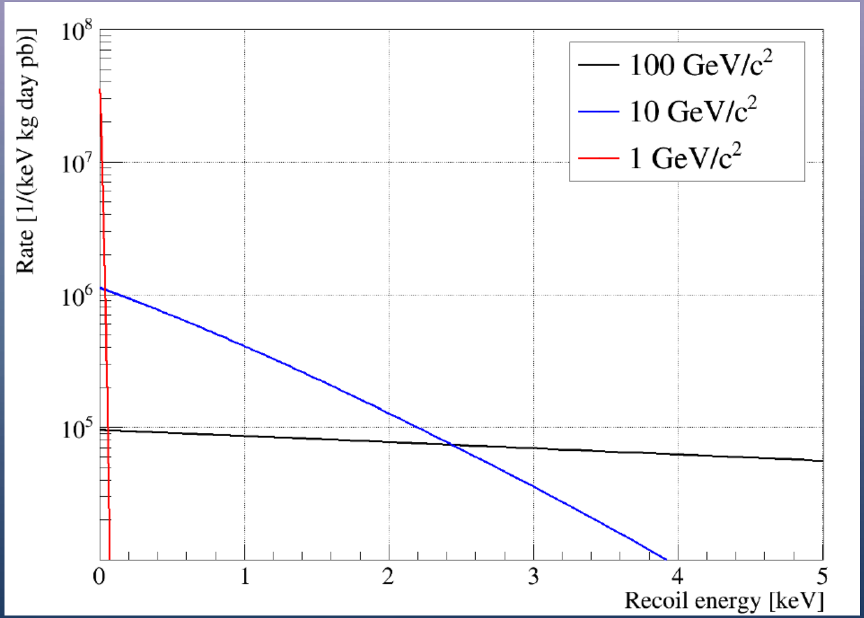
<u>Challenges</u>

- **Small recoil energies**
  ~ sub-keV range
- **Featureless spectrum**

Low threshold detectors

Exploring new parameter space below 0.5 GeV/c^2

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



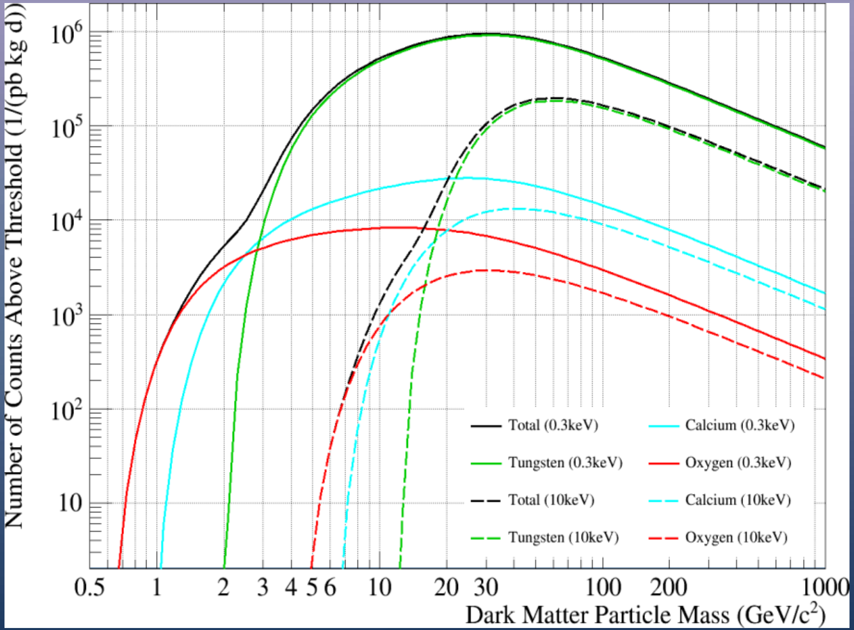
Challenges

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

Low threshold detectors

Exploring new parameter space below 0.5 GeV/c^2

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

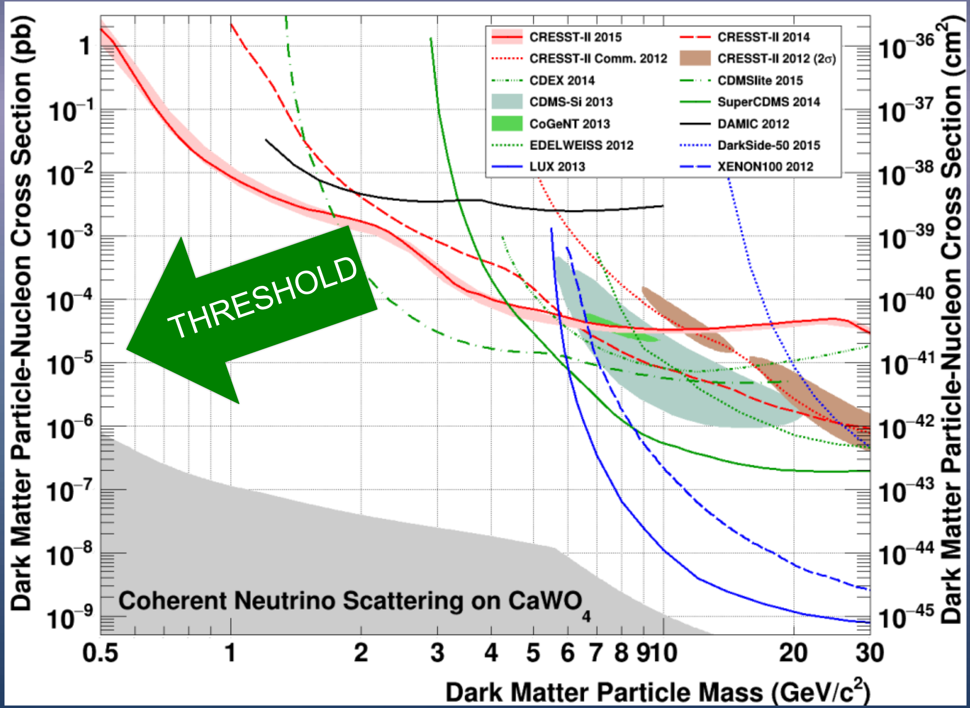


Challenges

- **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/c^2



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

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

Smaller crystals:
250g → 24g

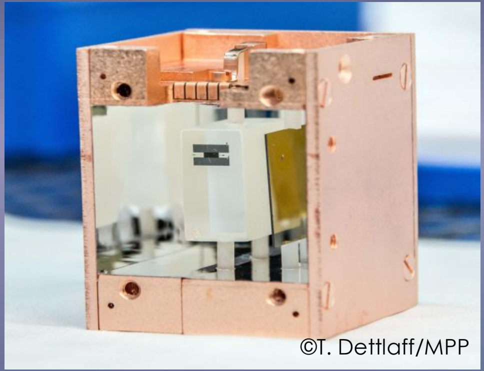
Threshold goal:
300eV → 100eV

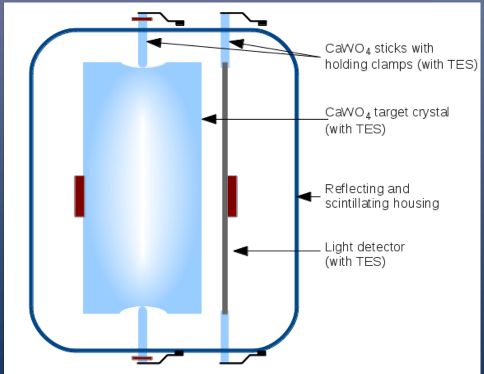
CRESST-III low-threshold detector

Exploring new parameter space below 0.5 GeV/c^2

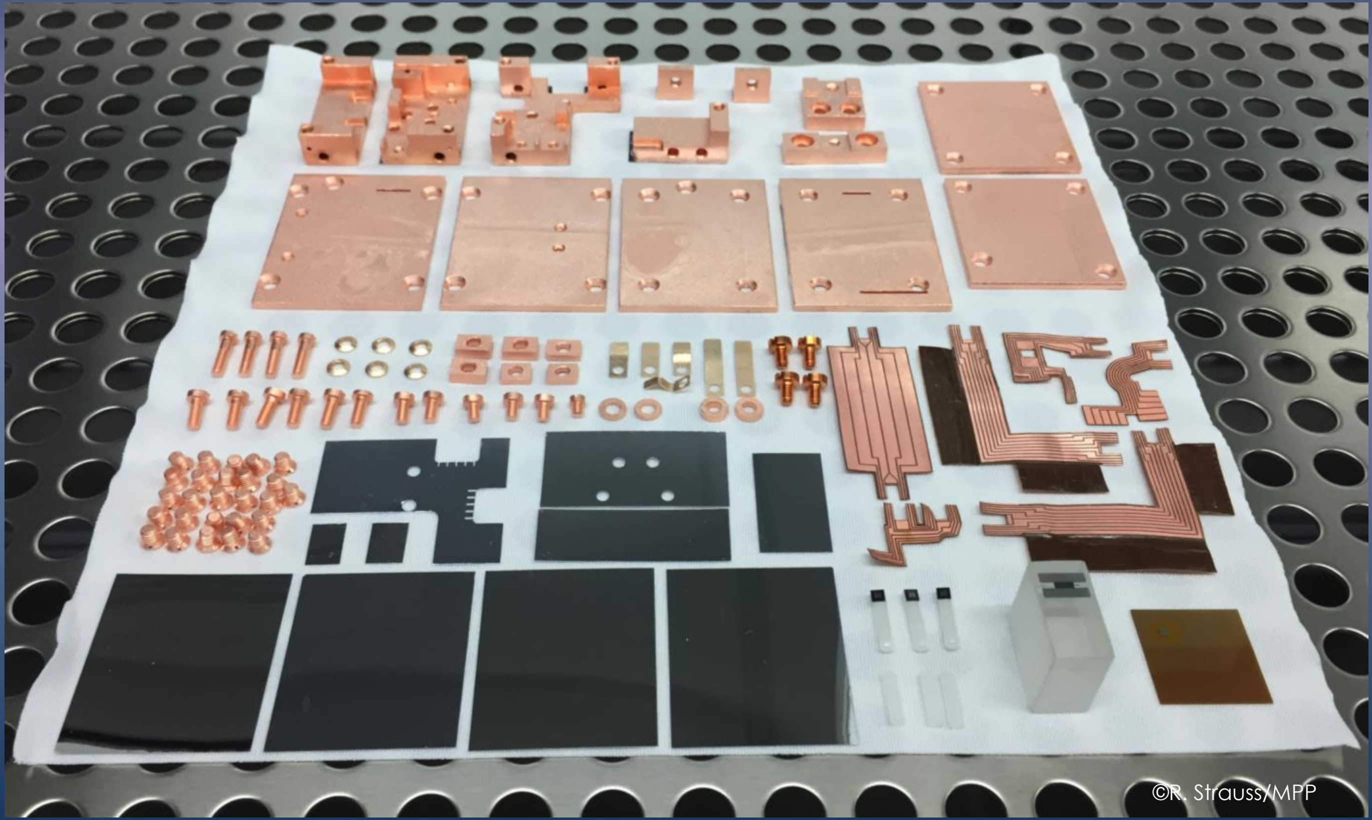
CRESST-III detector dimensions scaling down	**(CRESST-II)**
• $(20\times20\times10)$ mm^3	$(40\times40\times40)$
• Mass ~ 24 g	(~300)
• Threshold goal ~ 100 eV	(~300)
• Self grown crystals ~ 3 counts/(keV kg day)	(~8.5)
• Fully scintillating housing	no
• Instrumented sticks	no

→ Surface related background vetoing

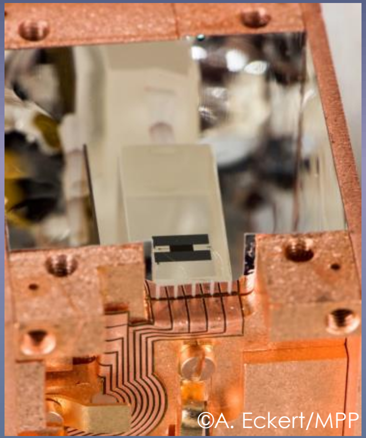


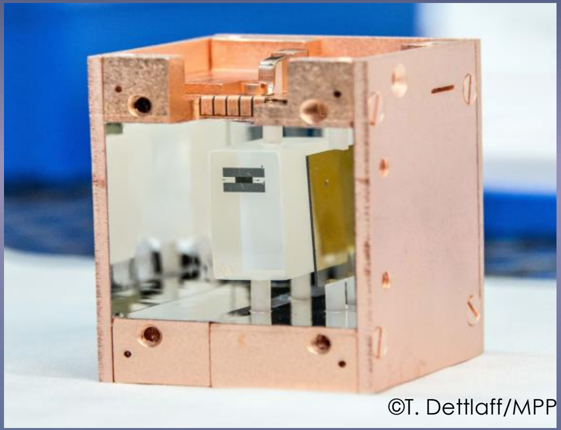


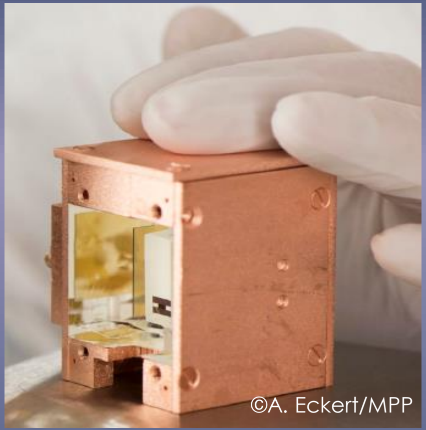
CRESST-III Phase 1

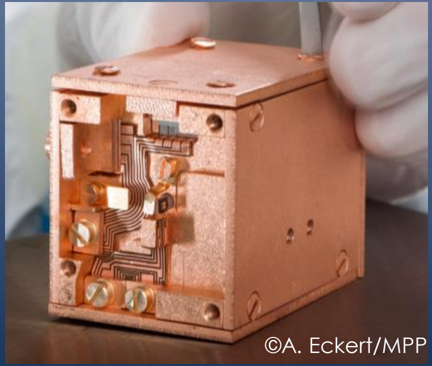


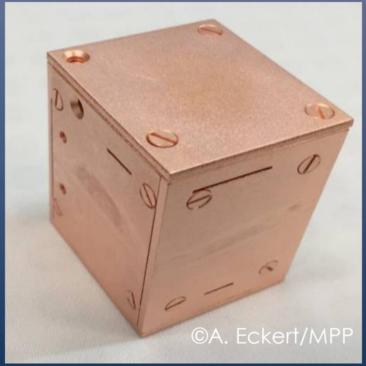
CRESST-III Phase 1

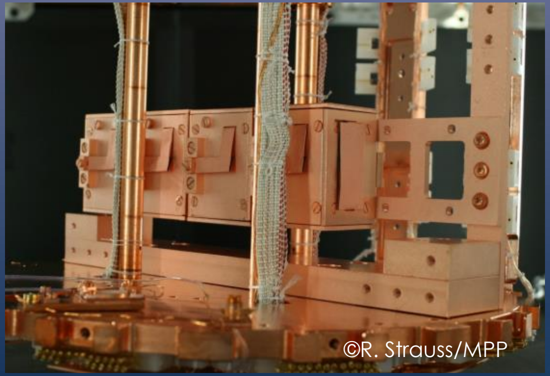












Data taking started July 2016

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
Resolution:	σ = 4.6 eV @ 0 eV

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

Objective

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

Unbiased (blind) analysis

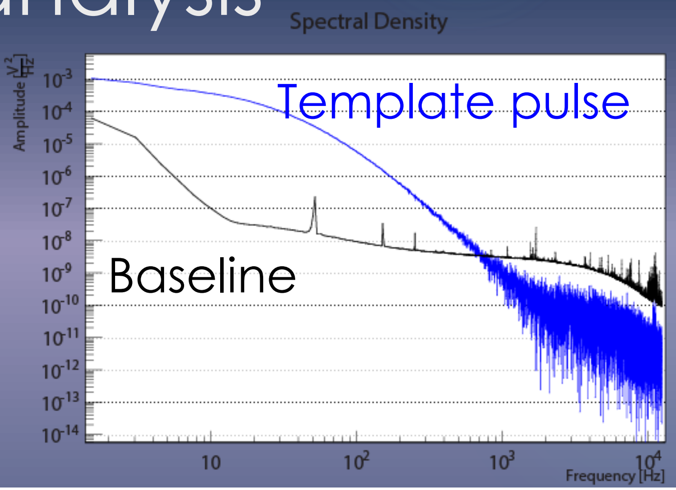
1. Design cuts on non-blind training set (≦20% of DM data)
2. Apply without change to blind DM data set

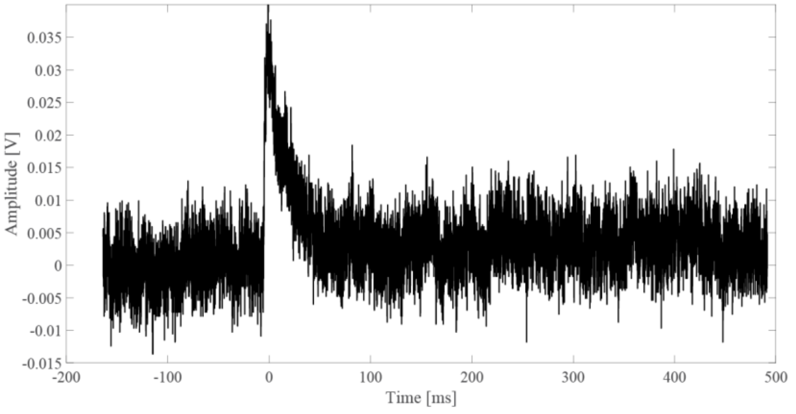
Rate:	noise condition (14% of measuring time)
Stability:	Detector(s) not in operating point (3% of measuring time)
Data quality:	Non-standard pulse shapes (e.g. i-Stick events and pileup)
Coincidences:	with μ-veto (7.6% of measuring time), i-Sticks and other detector modules

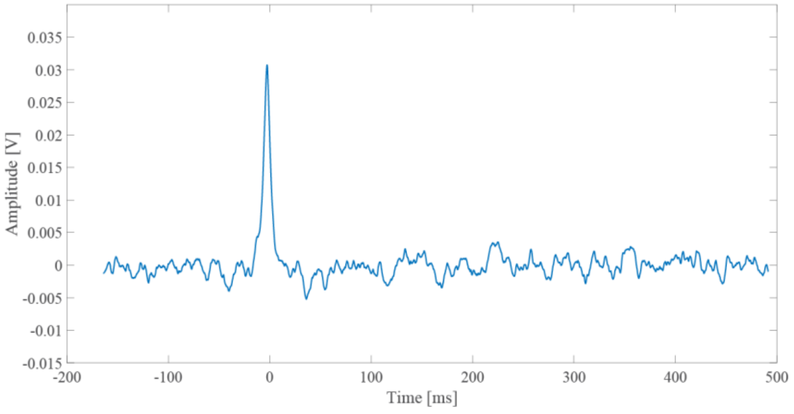
Det A – Full dataset analysis

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

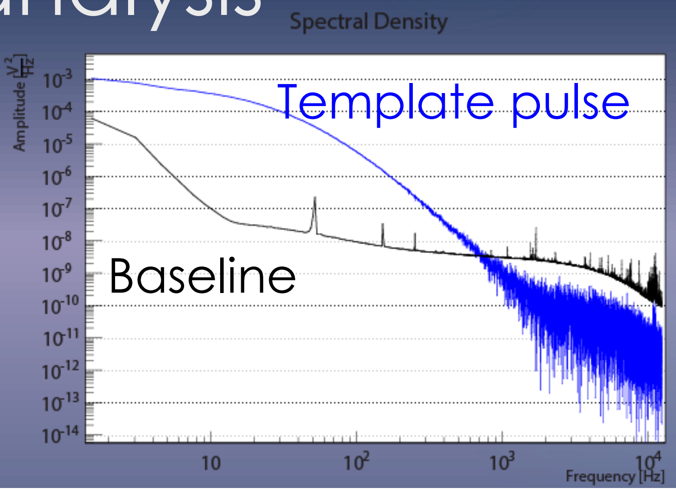






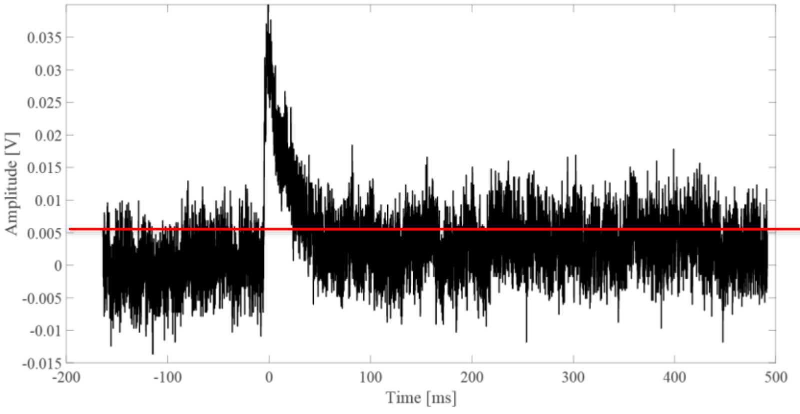
Det A – Full dataset analysis

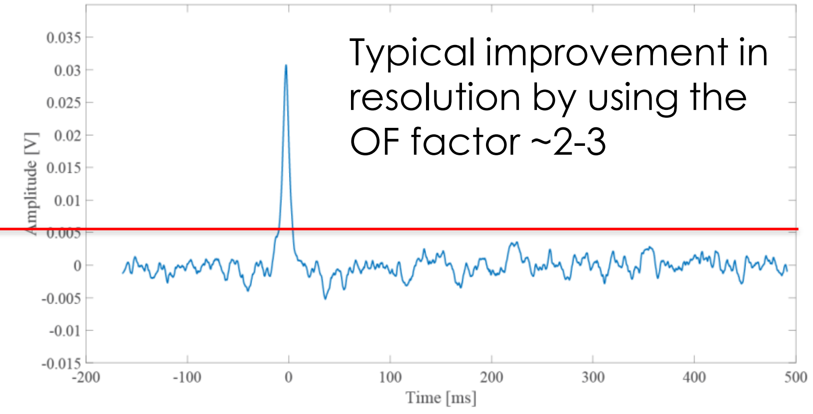
Pulse height evaluation



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

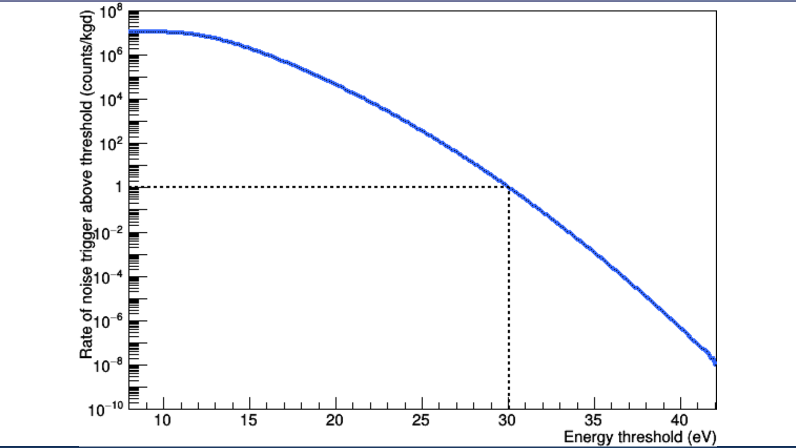
Det A – Full dataset analysis

Optimum filter for threshold analysis

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

Detector A
30.1 eV threshold

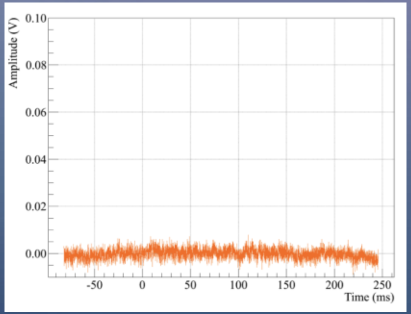
- Analytical description of amplitude distribution in empty baselines
- Threshold optimised based on noise triggers in a given exposure
- Allowed 1 noise trigger per kg day surviving selection criteria



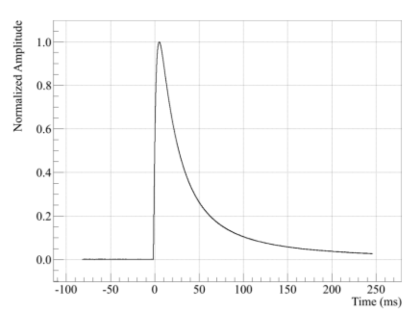
Det A – Full dataset analysis

Efficiency/signal survival probability

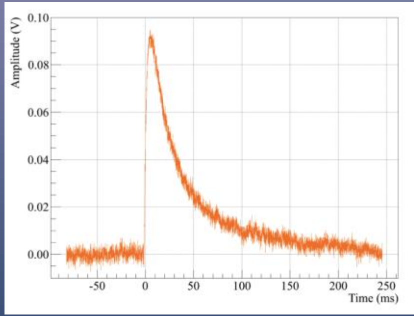
Simulated pulses of desired energies passed through analysis chain



\+



=



Empty baseline

Averaged pulse

Simulated pulse

Det A – Full dataset analysis

Efficiency/signal survival probability

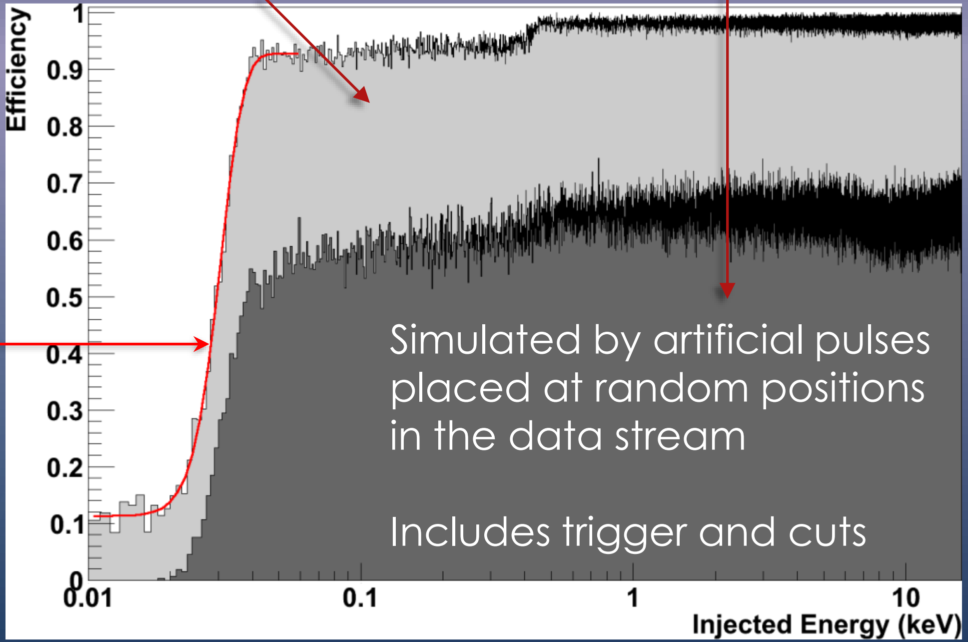
filter effect

≳60% efficiency over broad energy range

fit of the threshold with an error function

threshold fit compatible with noise analysis value 30.1 eV

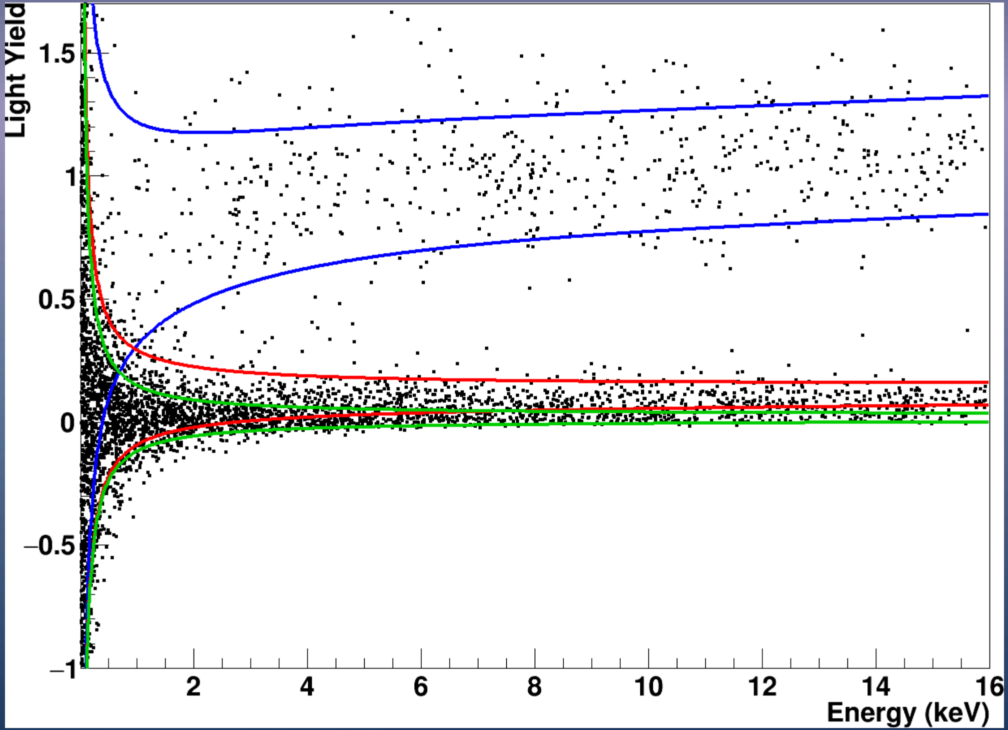
pile-up



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

Det A – Full dataset analysis

Neutron calibration - bands fit



e/γ

O

W

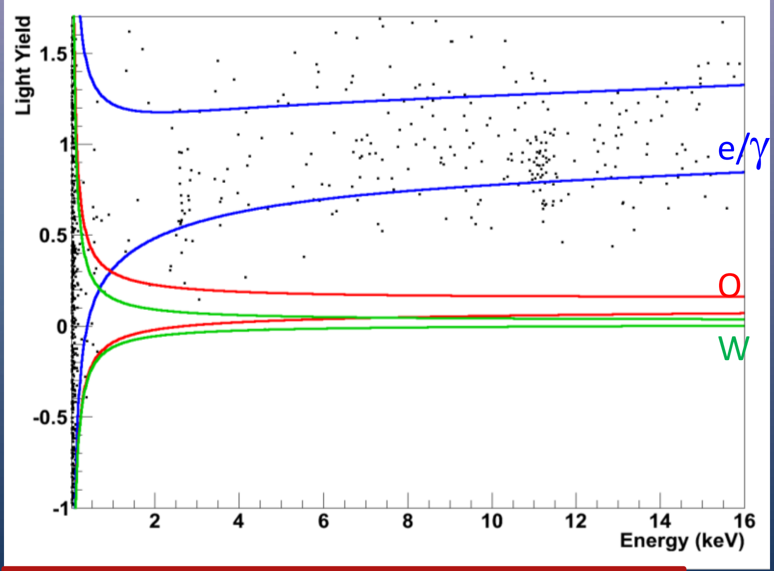
- Unbinned Maximum Likelihood fit
- Calculation using QFs from MLL neutron beam measurement

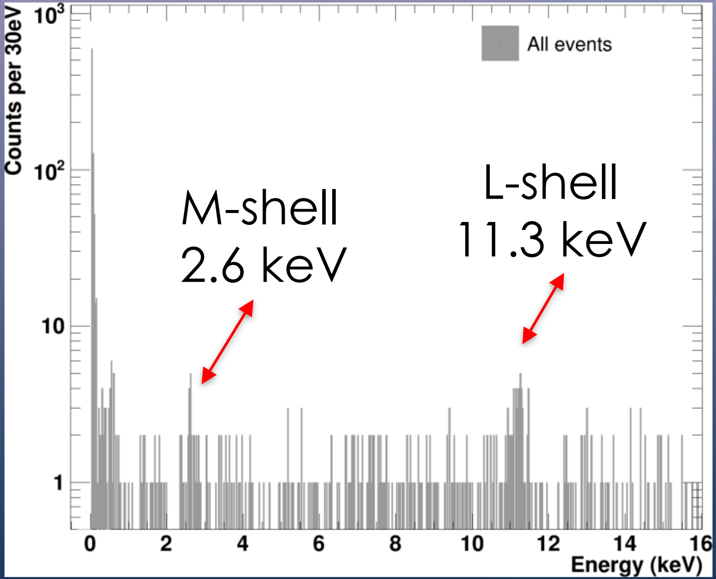
Det A – Full dataset analysis

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)



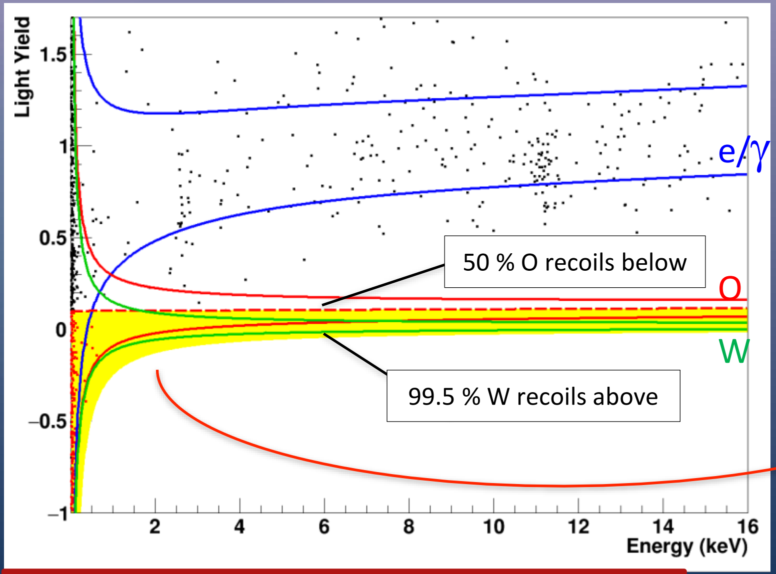


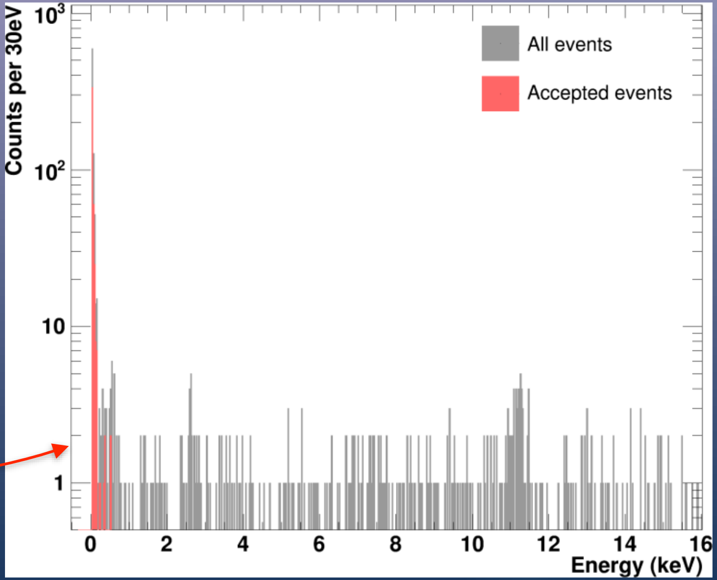
A. H. Abdelhameed et al., PDR **100**:102002 (2019)

Det A – Full dataset analysis

Dark Matter data - acceptance region

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



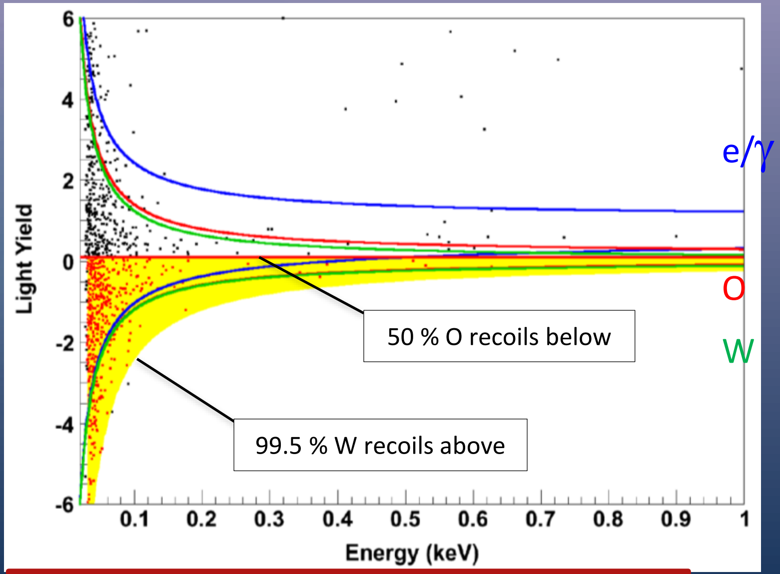


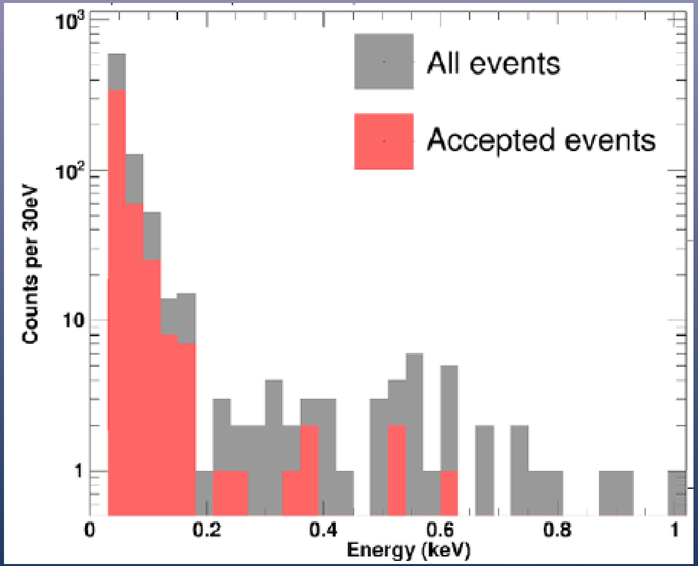
A. H. Abdelhameed et al., PDR **100**:102002 (2019)

Det A – Full dataset analysis

Dark Matter data - acceptance region

Zoom of acceptance region: 30 eV → 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

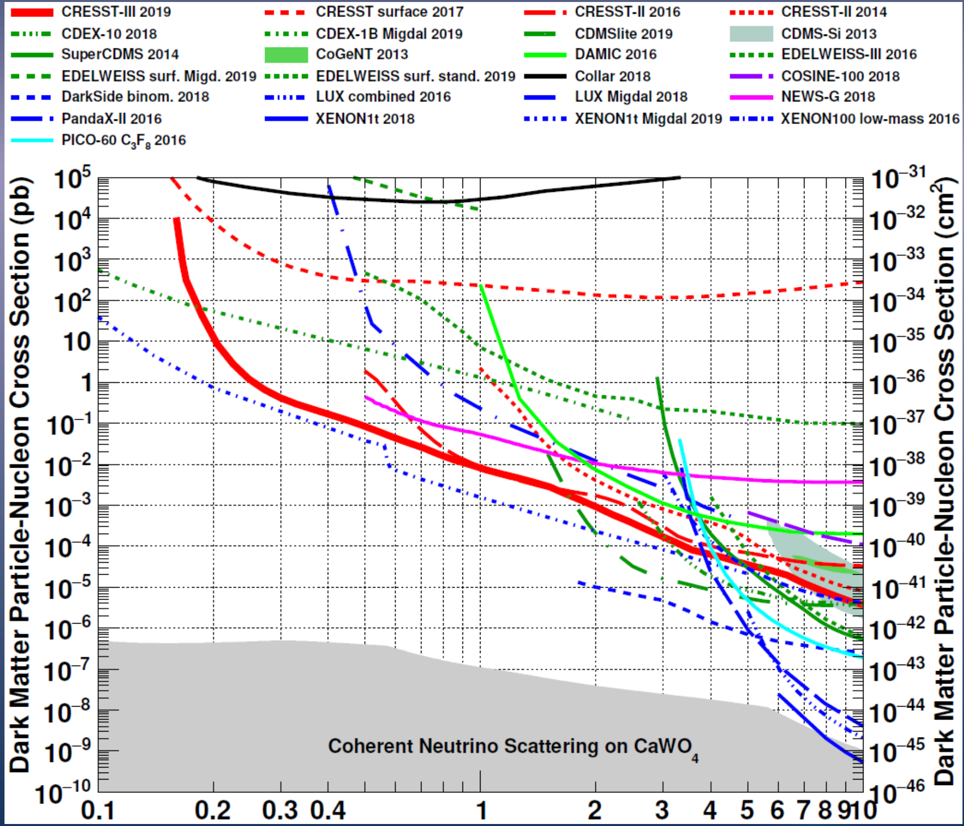
Det A – Full dataset analysis

Results

Energy spectrum of accepted events

Yellin method

Expected energy spectrum

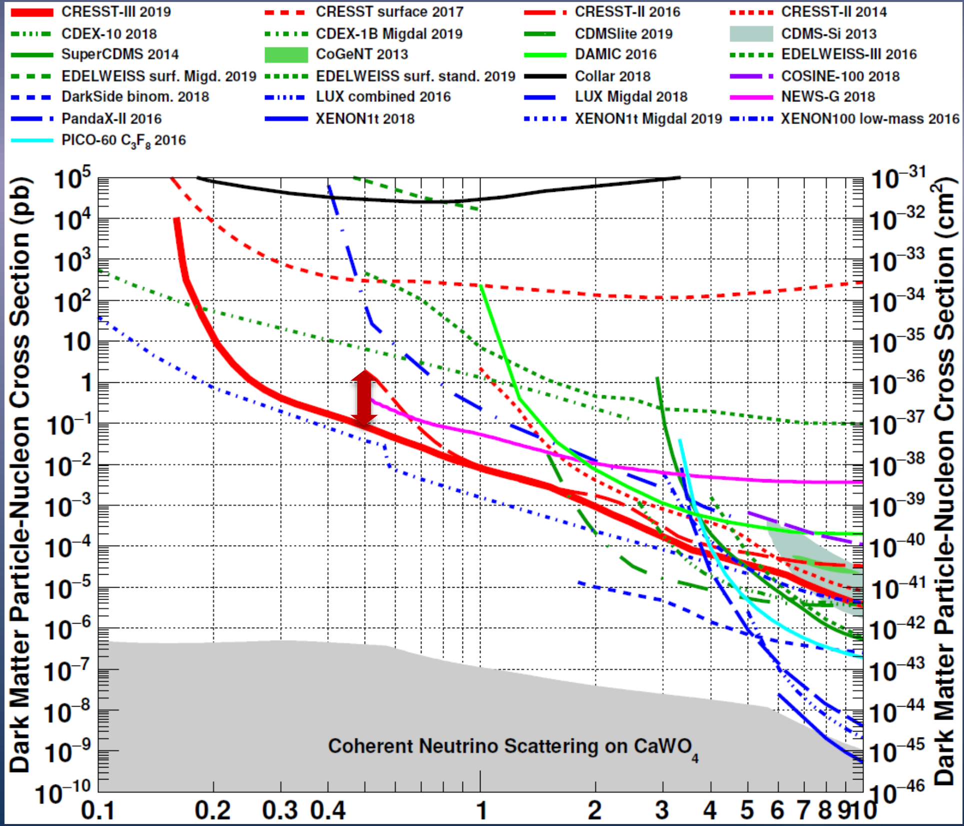


A. H. Abdelhameed et al., PDR **100**:102002 (2019)

Det A – Full dataset analysis

Results

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



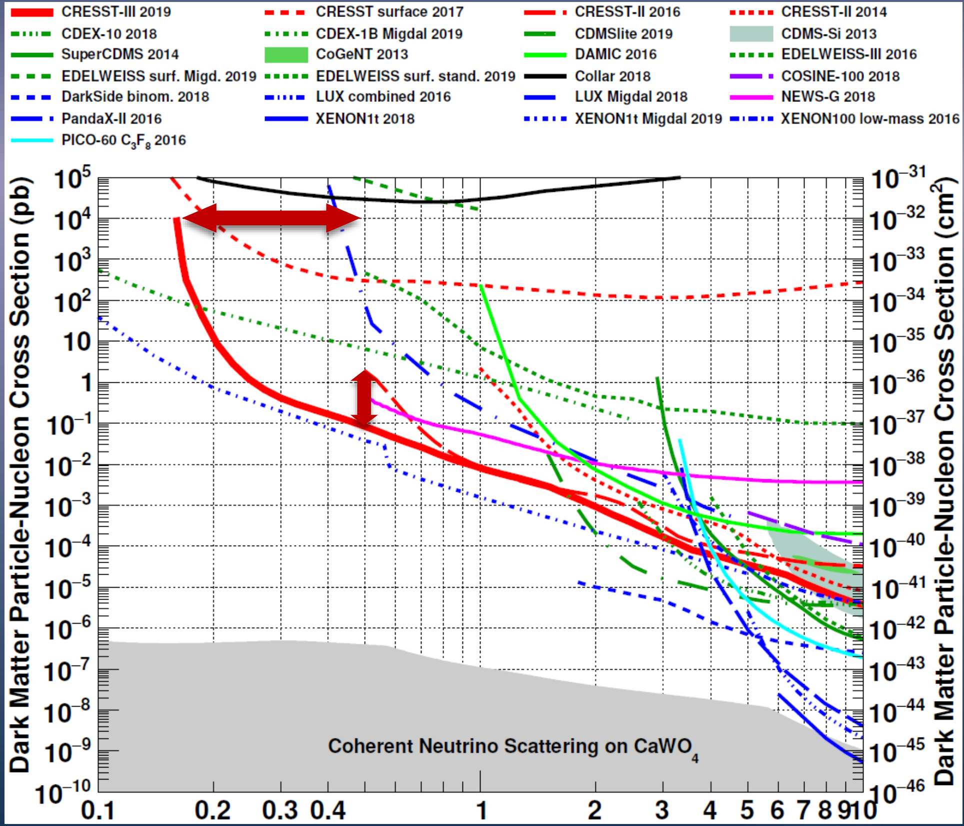
A. H. Abdelhameed et al., PDR **100**:102002 (2019)

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



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

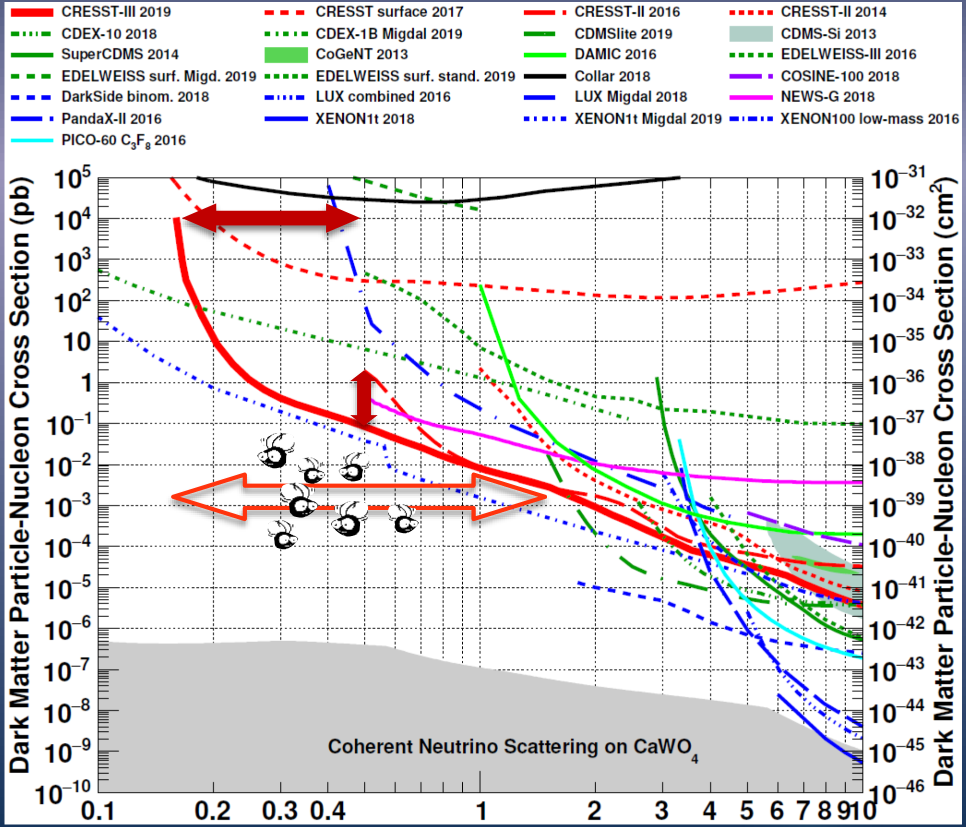
Det A – Full dataset analysis

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

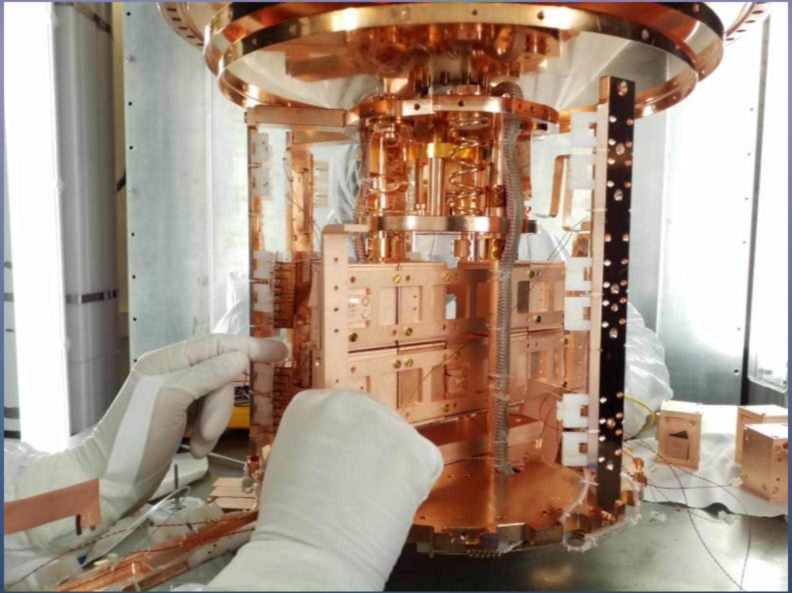


A. H. Abdelhameed et al., PDR **100**:102002 (2019)

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

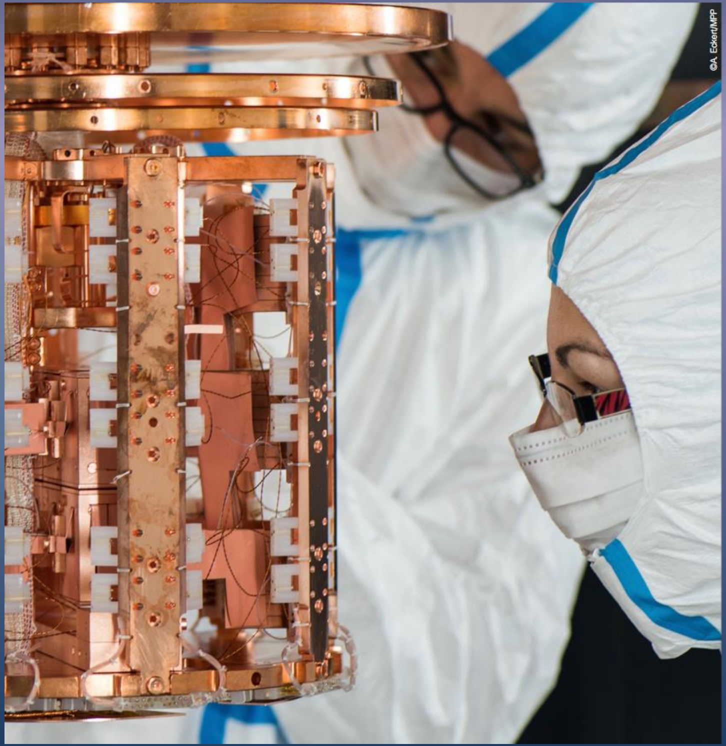
~~Conclusion~~ …this is the beginning



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

~~Conclusion~~ …this is the beginning



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

~~Conclusion~~ …this is the beginning

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

INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

TUM Technische Universität München

University of Oxford

HEPHY Institut für Hochenergiephysik

Eberhard Karls Universität Tübingen

TU Wien Technische Universität Wien Vienna University of Technology

Thanks for your attention!