Low Mass Dark Matter Search in CRESST

Dark Pollica Workshop 2022

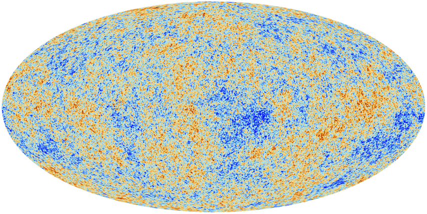
Dominik Fuchs

June 15, 2022

Outline

Evidence for Dark Matter

on different scales



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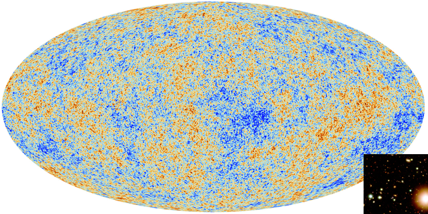

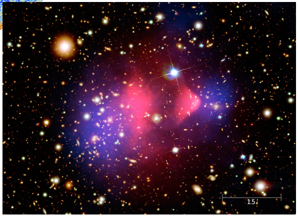

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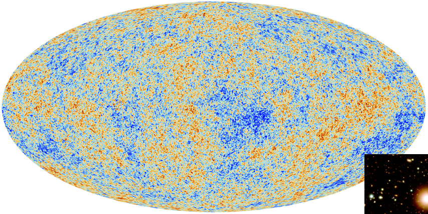
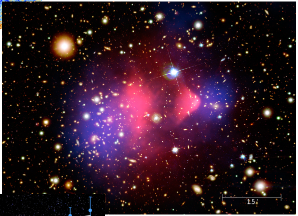
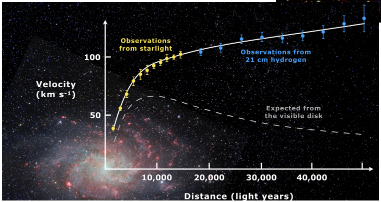
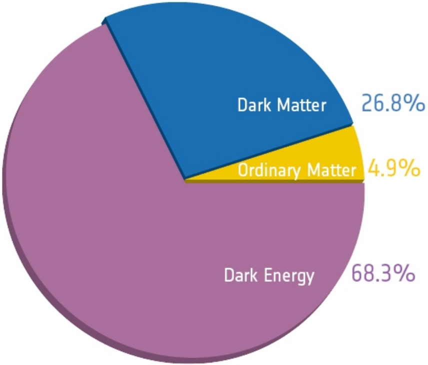






Dark Matter

Introducing Dark Matter and Dark Energy can explain observed phenomena on all scales...



Source: European Space Agency

...But leaves the questions:

What are they?

What we know so far...

- **Content in our Universe:** CMB power spectrum

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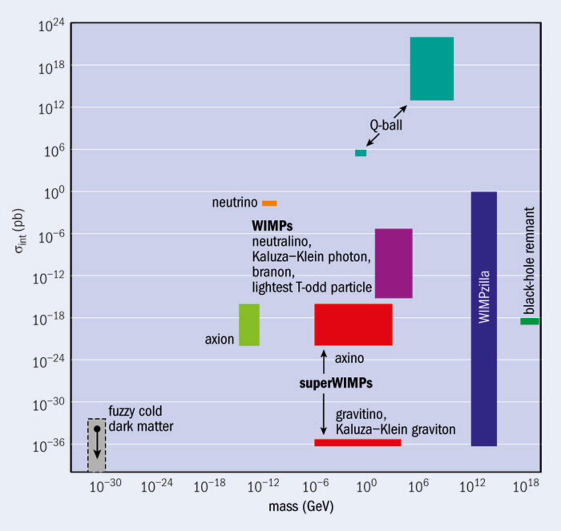
- **Any other interaction must be on some sub-weak scale**

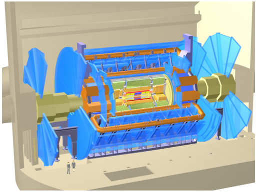
No particle in standard model fulfills all of these properties!

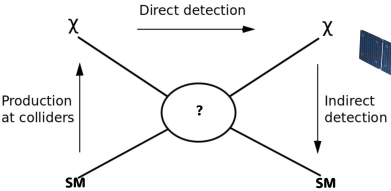
Some Particle Candidates

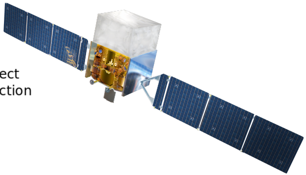


Source: Physicsworld

Different Detection channels







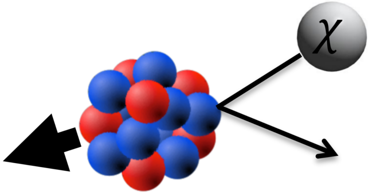
Outline

Basic Idea

Dark matter particles scatter off nuclei leading to a recoil of the nucleus

Most standard scattering scenario:

- elastic
- coherent ($\sim$A^2)
- spin-independent



Dark Matter Halo Model

- Spherical halo of DM around center of Milky Way

Standard assumptions:

- DM particles thermalized $\rightarrow$ Maxwellian velocity distribution
- solar velocity: 220 km/s
- galactic escape velocity: 544 km/s
- Local DM density: $\rho_{\mathrm{DM}} = 0.3\,\mathrm{GeV/cm^3}$

Expected Recoil Spectrum

Recoil Rate

$$\frac{dR}{dE_R} \propto \frac{\rho_\chi}{2m_\chi \mu_N^2} \cdot \sigma_0 \cdot F^2(E_R) \cdot \int_{v_{min}(E_R)}^{v_{esc}} d^3v \frac{f(\vec{v})}{v}$$

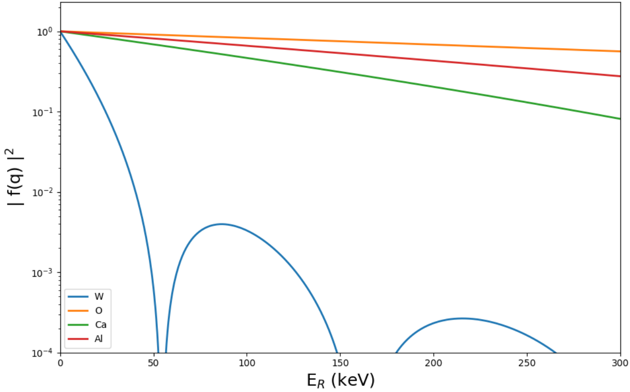
- $v_{min} = \sqrt{\frac{E_R m_N}{2\mu_N^2}}$
- Dark Matter Mass and interaction Cross section
- Dark Matter Halo Model
- Nuclear form factor

Cross Section

- Cross Section at zero momentum transfer σ_0:
  $\sigma \propto \sigma_0 \cdot F^2(E_R)$

Nuclear Form Factor

Accounts for distribution of nucleons inside the nucleus



Important for high recoil energies and heavy targets

Cross Section

- Cross Section at zero momentum transfer σ_0:
  $\sigma \propto \sigma_0 \cdot F^2(E_R)$

- Material independent dark matter - nucleon (n) cross section, normalized to one nucleon $\sigma_{\chi n}$:
  $\sigma_0 \propto \sigma_{\chi n} \cdot \frac{\mu_N^2}{\mu_n^2} \cdot A^2$

Cross Section II

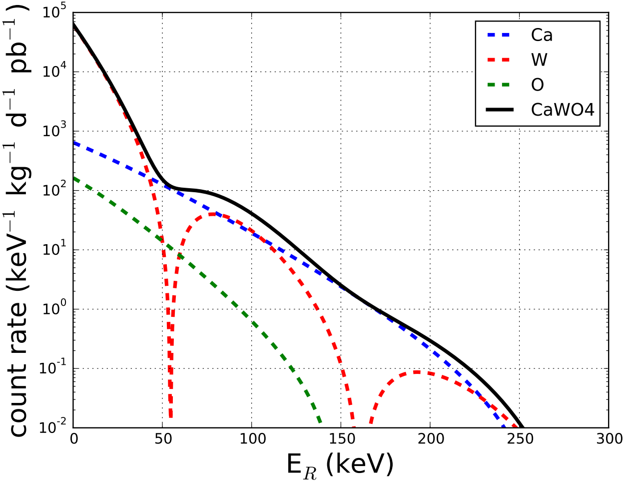
More general

- Spin independent:
  $$\sigma_0^{SI} \propto \sigma_{\chi n} \cdot \frac{\mu_N^2}{\mu_n^2} \cdot [Z \cdot f^p + (A - Z) \cdot f^n]^2$$
  f^p and f^n: contributions of protons and neutrons to total coupling strength

- Spin dependent:
  $$\sigma_0^{SD} \propto \mu_N^2 \cdot \frac{J_N + 1}{J_N} \cdot [a_p \cdot \langle S^p \rangle + a_n \cdot \langle S^n \rangle]^2$$
  a_p and a_n: effective couplings to protons and neutrons
  $\langle S^p \rangle$ and $\langle S^n \rangle$: expectation values of n and p spins within the nucleus

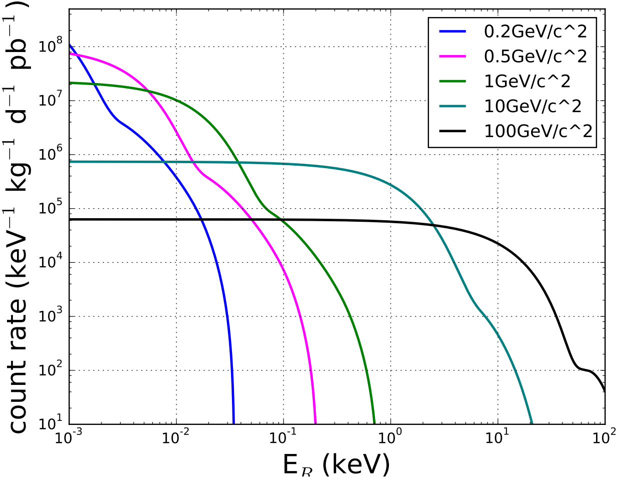
Expected Recoil Spectrum

$m_\chi = 100$ GeV



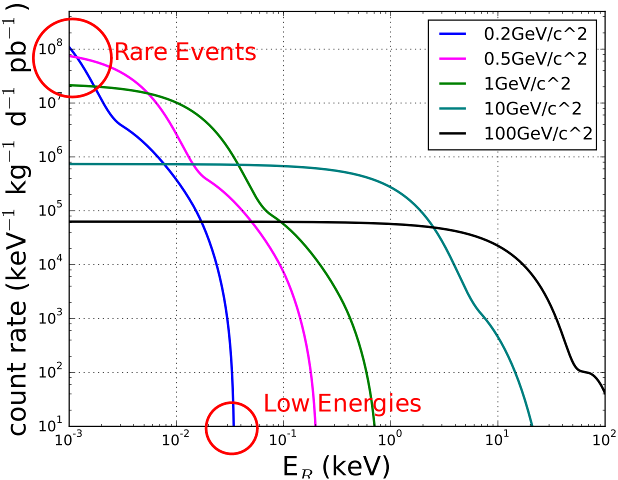
Expected Recoil Spectrum

$m_\chi = 0.2$ - 100 GeV



Expected Recoil Spectrum

Experimental Challenges



Minimizing Background

- Cosmic radiation
- Long-lived natural radioisotopes
- Anthropogenic radio activity
- Neutron background
- Neutrino background

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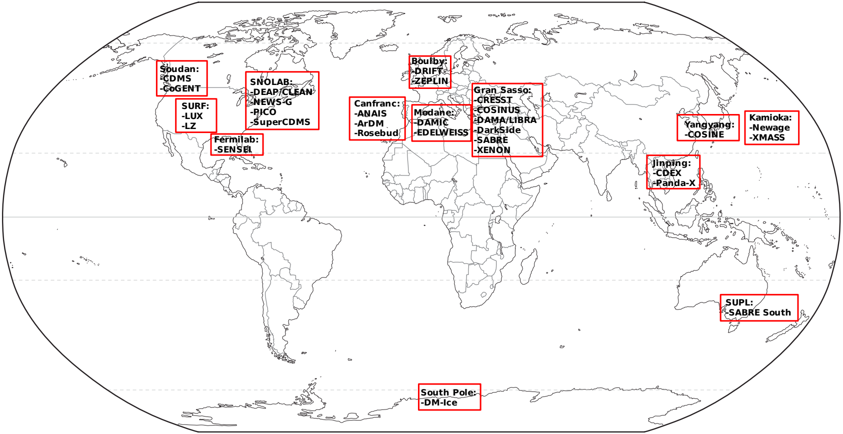
- Underground site
- Shielding/vetoing
- Radon mitigation
- Purity of materials
- Material handling
- Event-by-event discrimination

Worldwide efforts for the last decades ...

a selection of dark matter direct detection experiments



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Outline

CRESST
Cryogenic **Rare Event Search**
with Superconducting Thermometers

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

TUM
TECHNISCHE
UNIVERSITÄT
MÜNCHEN

UNIVERSITAS COMENIANA BRATISLAVENSIS · MCMXIX ·

MAX PLANCK INSTITUTE
FOR PHYSICS

EBERHARD KARLS
UNIVERSITÄT
TÜBINGEN

HEPHY
INSTITUTE OF HIGH ENERGY PHYSICS

TU WIEN
TECHNISCHE
UNIVERSITÄT
WIEN

UNIVERSITY OF
OXFORD

The CRESST Experiment

Cryogenic **R**are **E**vent **S**earch with **S**uperconducting **T**hermometers

- $\sim$ 3600 m.w.e. deep
- μs: $\sim 3 \cdot 10^{-8}$ /(s cm^2)
- γs: ~ 0.73 /(s cm^2)
- neutrons: $4 \cdot 10^{-6}$ n/(s cm^2)

CRESST goal: direct detection of dark matter particles via their scattering off target nuclei in cryogenic detectors, operated at $\sim$15 mK

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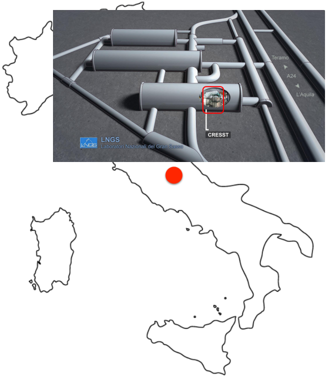

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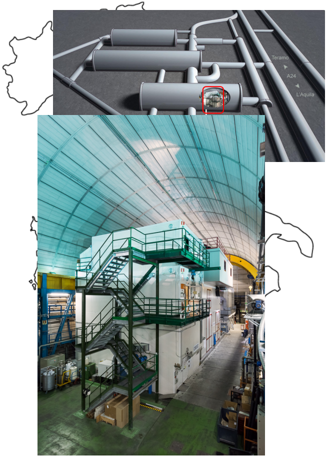

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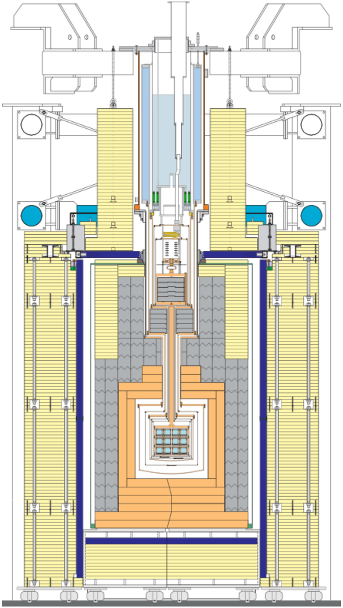
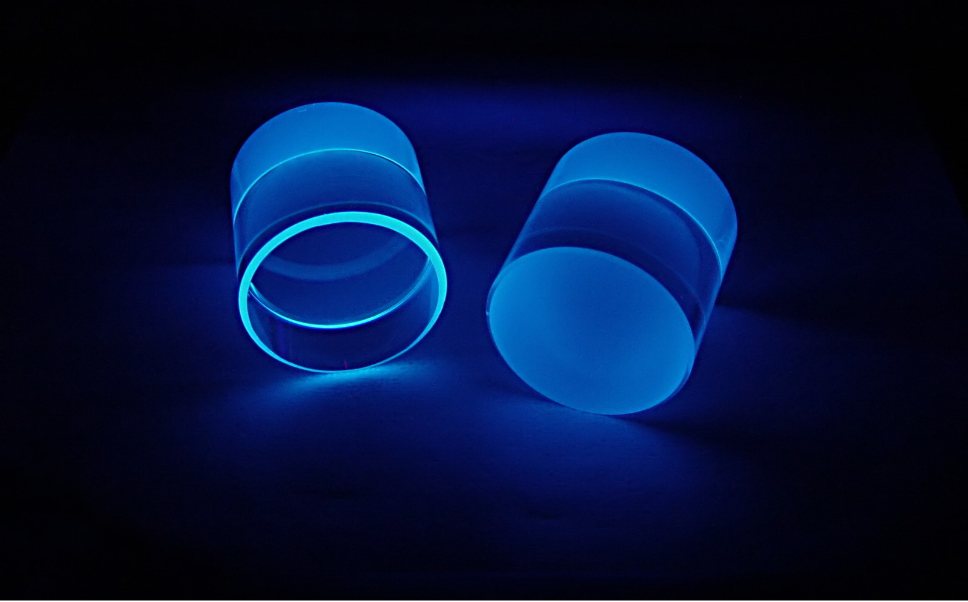
CRESST Setup

Shielding:

- polyethylene (10t)
- muon veto system
- lead (24t)
- copper (10t)



Detector Modules



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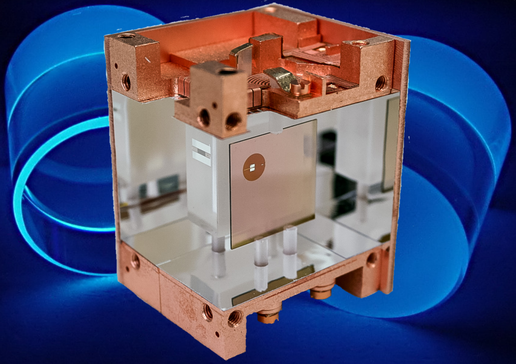
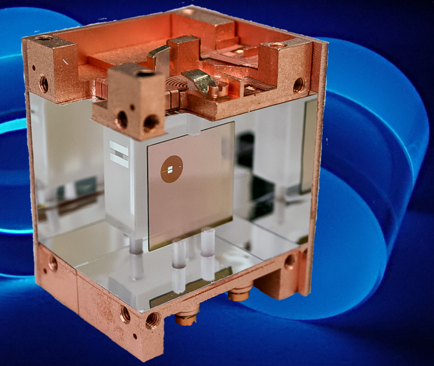


Detector Modules

Crystals:

- scintillating $(20x20x10)mm^3$ target crystals
- different materials ($CaWO_4$, $LiAlO_2$, Al_2O_3, Si)
- W-TES sensor
- $E_{thr} \leq 100eV$ (nuclear recoils)



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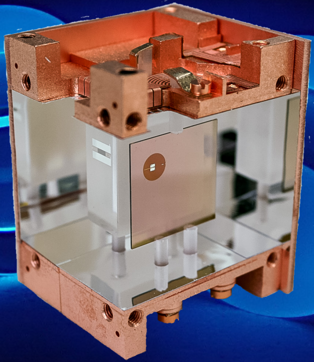
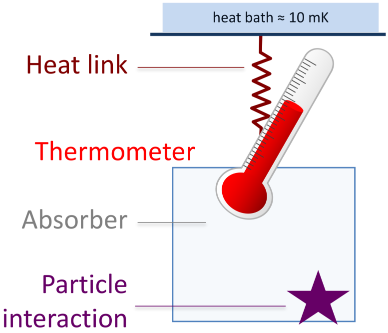
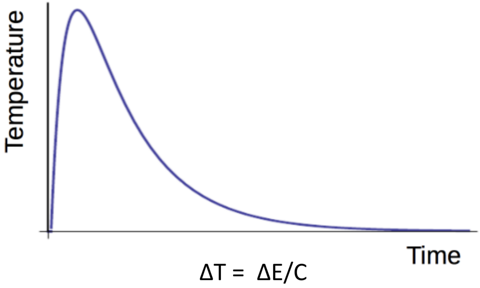


Particle discrimination:

- Light detector
- Light Yield characteristic of type of recoil

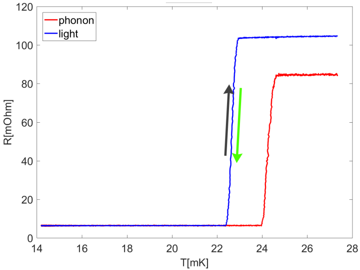
Cryogenic Calorimeter

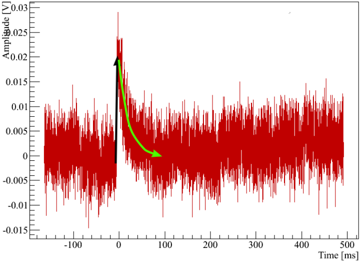




Signal

- Nuclear Recoil heats up crystal $\mathcal{O}(\mu K)$
- Change of resistance in bias current $\mathcal{O}(m\Omega)$
- SQUID readout and signal amplification $\mathcal{O}(mV)$



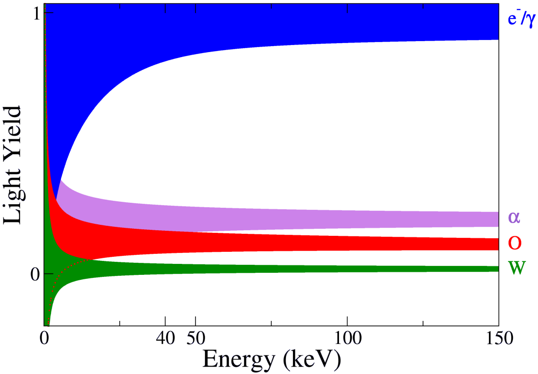


Event Discrimination

$$\text{Light Yield} = \frac{\text{Light signal}}{\text{Phonon signal}}$$

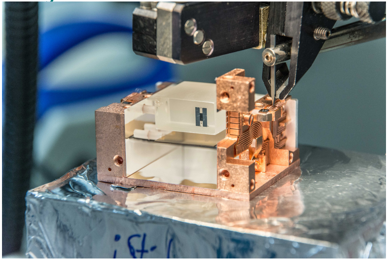
Characteristic of event type

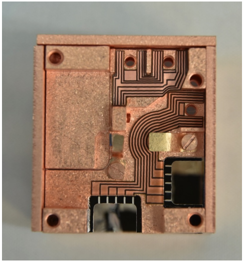
Discrimination between potential signal events (**nuclear recoils**) and dominant radioactive background (**electron recoils**)

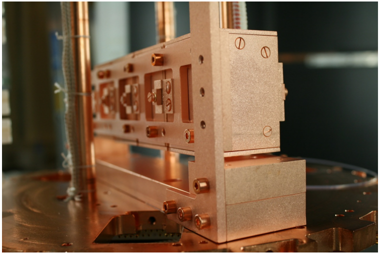


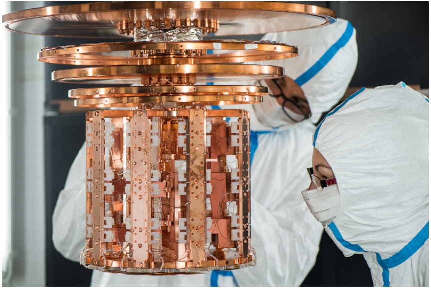
CRESST-III First Run

May 2016 to Feb 2018









Status of CRESST-III

Currently taking data since fall 2020

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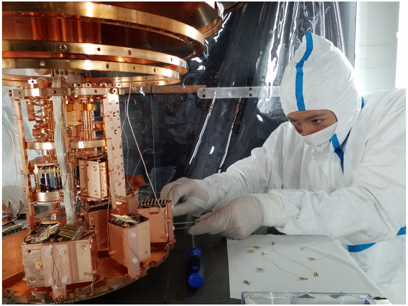

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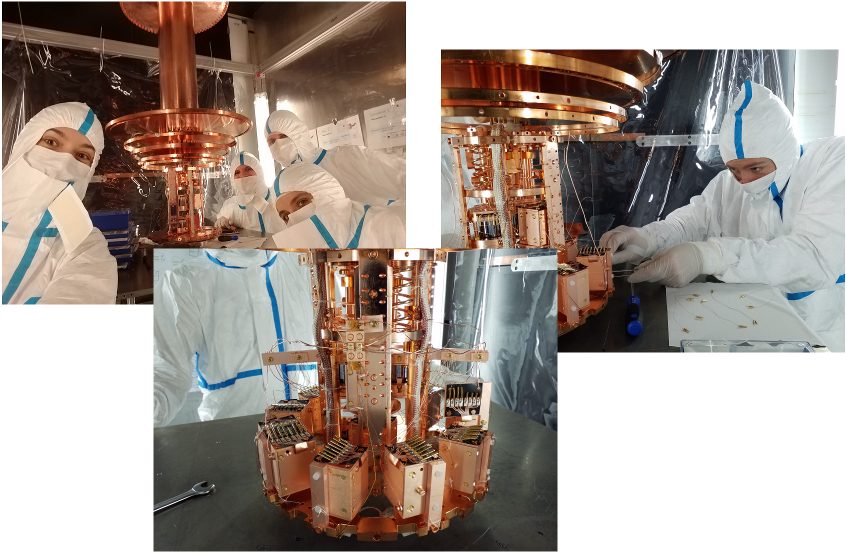
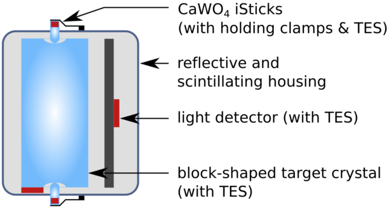


Detector A

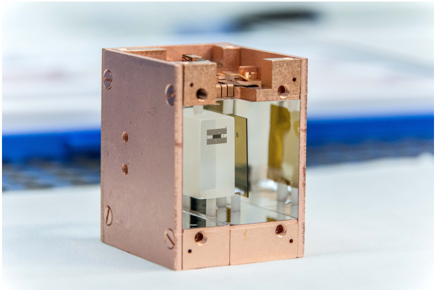
Lowest threshold in first run of CRESST-III



- Data taking: 10/2016 - 01/2018
- Geometry: (20 x 20 x 10) mm^3
- Veto surface-related background

Phys. Rev.D100(2019) 10 102002

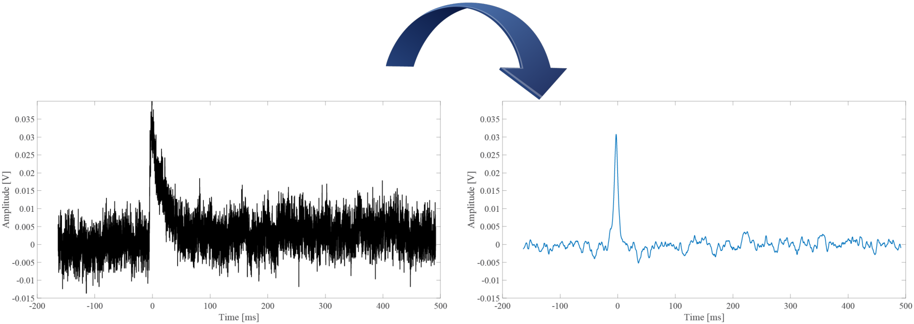
- Self grown
- Mass: 23.6 g
- Gross exposure: 5.689 kgd
- Nuclear recoil threshold: 30.1 eV



Outline

Continuous DAQ + Optimum Filter

- Dead-time free DAQ: detector output is continuously recorded
- Maximize Signal-to-Noise ratio in frequency space



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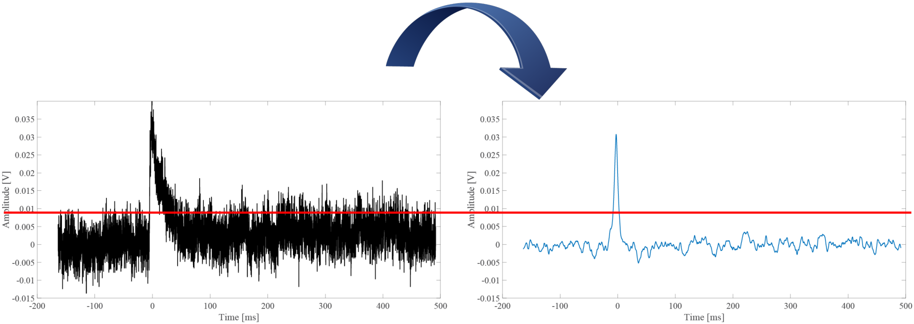

Continuous DAQ + Optimum Filter

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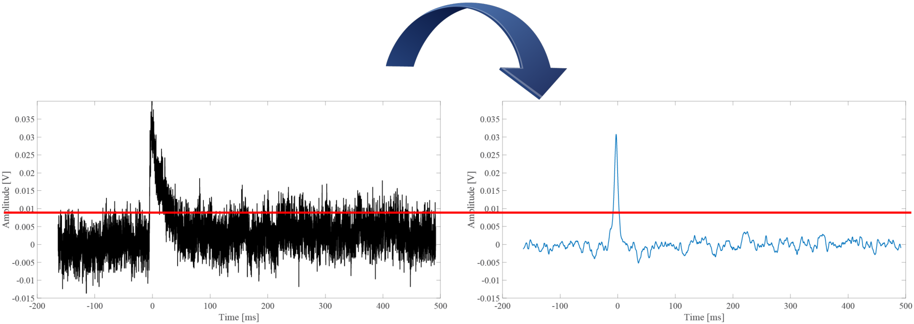
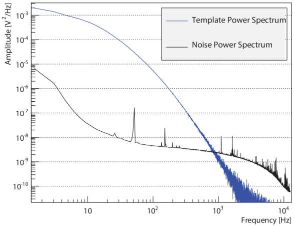
- Define threshold by choosing accepted number of noise triggers
- Select Events above threshold

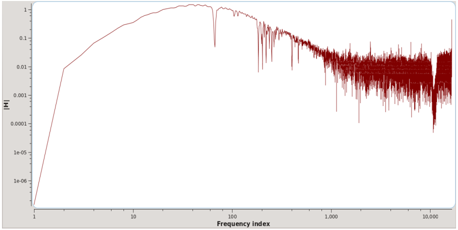


Optimum Filter

- Filter kernel $H(\omega)$: maximize Signal-to-Noise ratio in frequency space:

$$H(\omega) = K \frac{\widehat{s}^*(\omega)}{N(\omega)} e^{-i\omega\tau_M}$$





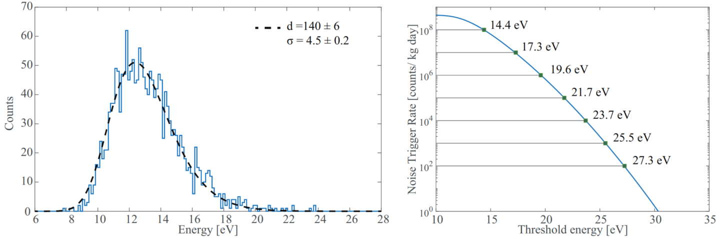
- Convolute real pulse with filter kernel:

$$y_F(t) = \frac{A}{\sqrt{2\pi}} \int_{-\infty}^{\infty} H(\omega)\widehat{s}(\omega)e^{i\omega t}\,\mathrm{d}\omega$$

Threshold determination

- Analytical description of amplitude distribution of filtered empty baselines
- Define threshold choosing accepted number of noise triggers per kgd

$$NTR(x_{thr}) = \frac{1}{t_{win} \cdot m_{det}} \cdot \int_{x_{thr}}^{\infty} P_d(x_{max})$$



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

Data cleaning and Blinding scheme

Design cuts to clean triggered events:

- Cuts defined on $\simeq 20\%$ of data set (excluded for dark matter analysis)
- Apply cuts without changes to remaining dark matter data set

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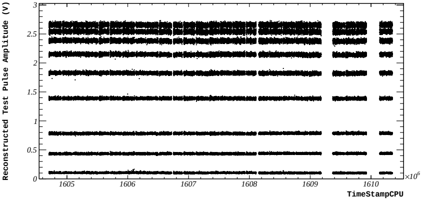
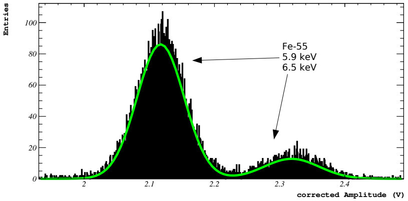
- Stability cut: time periods in which detectors are not in their operating points
- Data quality cuts: Non-standard pulse shapes (e.g. pileup, electronic artifacts, ...)
- Cut coincidences with μ-veto or other detector modules

Energy Calibration

- Calibration source with known energy
- Regular heater pulses injected → time dependence of detector response
- Correct reconstructed Amplitudes by detector response
- Convert spectrum of amplitudes from volt to energy

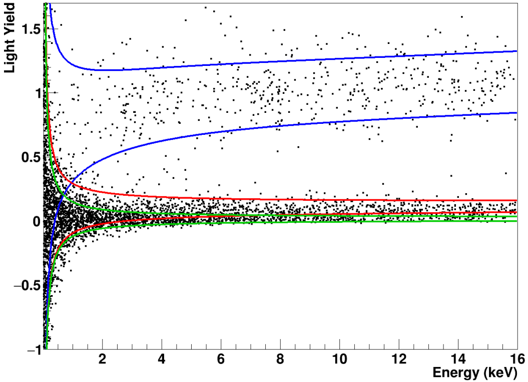




Neutron Calibration

Light Yield: $LY = E_L/E_{Ph}$

Band Fits QF



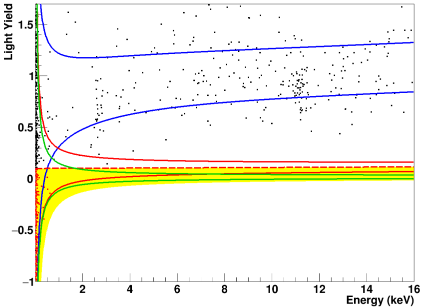
e/γ events

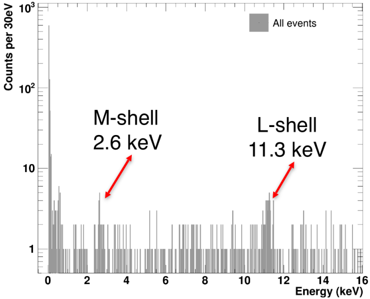
Oxygen nuclear recoils

Tungsten nuclear recoils

Light Yield Plot + ROI

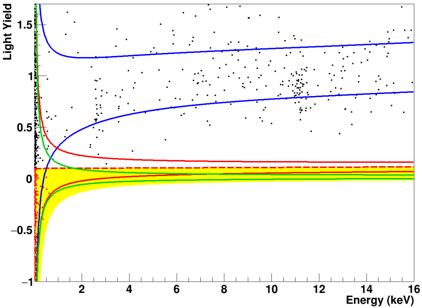
Cosmogenic activation lines: $^{179}\text{Ta} + e^- \rightarrow {}^{179}\text{Hf} + \nu_e$

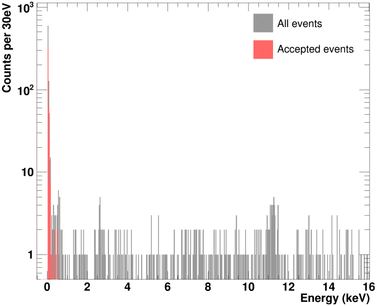




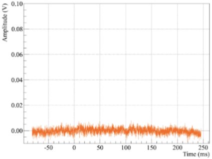
Light Yield Plot + ROI

Region of Interest: From mean of oxygen band down to 99.5% lower boundary of Tungsten band



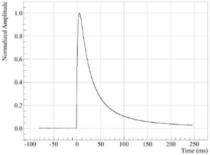


Efficiency



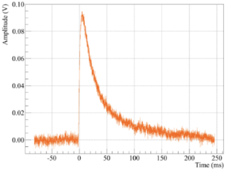
Empty baseline

+

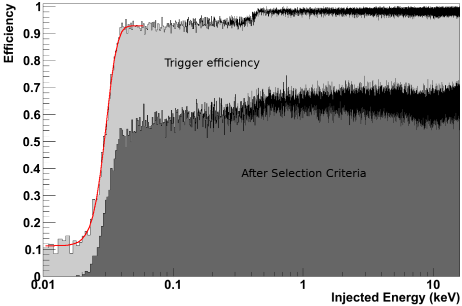


Averaged pulse

=



Simulated pulse



Limit Calculation

Two approaches:

Likelihood method:

Yellin method:

Limit Calculation

Two approaches:

Likelihood method:

+ More stringent limits
+ Make use of knowledge of background
+ Positive Analysis possible

- Need model of background

Yellin method:

Limit Calculation

Two approaches:

Likelihood method:

+ More stringent limits
+ Make use of knowledge of background
+ Positive Analysis possible

- Need model of background

Yellin method:

+ More conservative
+ No information about background needed

- Cannot include information about background
- Only limit calculation

Likelihood based method

For defined range of dark matter masses:

Likelihood ratio

$$\lambda(\sigma_\chi) = \frac{\mathcal{L}(\sigma_\chi = \mathsf{fixed}, \hat{\hat{\Theta}})}{\mathcal{L}(\hat{\sigma}_\chi, \hat{\Theta})}$$

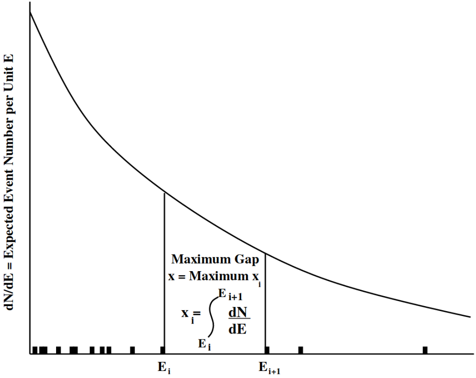
Test statistic

$$q_{\sigma_\chi} = \begin{cases} -2 \cdot \ln(\lambda(\sigma_\chi)) & , \hat{\sigma}_\chi > 0 \\ 0 & , \hat{\sigma}_\chi < 0 \end{cases}$$

Find fixed cross section σ_χ such that the significance of the test statistic excludes the observed data to the desired confidence level

Yellin maximum gap method

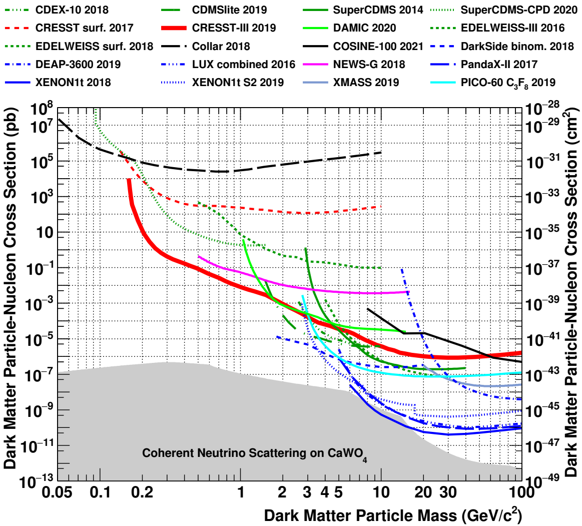
$$x_i(\sigma, m_\chi) \equiv \int_{E_i}^{E_{i+1}} \frac{d\Gamma(\sigma, m_\chi)}{dE} dE$$



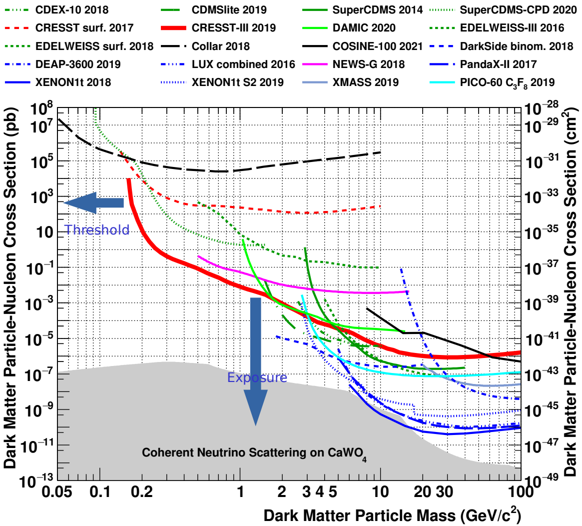
S. Yellin, "Finding an upper limit in the presence of an unknown background"

- Calculate spectra for different masses
- Use maximum gap between two events to determine limits on cross-section
- For each mass calculate cross-section which excludes observed data with certain confidence level
- Extend to Yellin optimum interval method

Dark Matter Limits



Dark Matter Limits

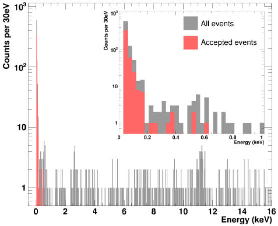


Outline

Low Energy Excess (LEE)

Unexplained rise of events at energies below 200 eV

- Pulse Shape indistinguishable from particle events
- Noise trigger rate way too low to be explanation
- No clear scaling with volume or surface
- Present in different materials ($CaWO_4$, Al_2O_3)
- Decreases over time



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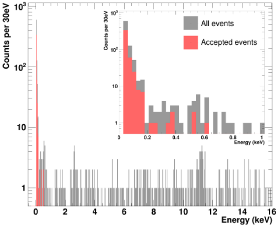

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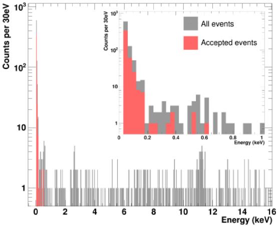

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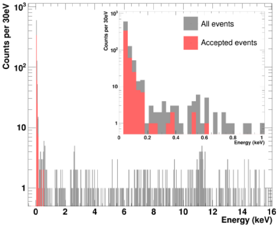

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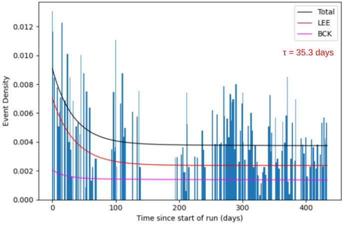
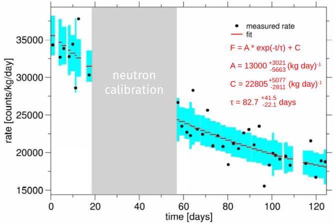




Measures taken...

Test different configurations to find source of unknown background:

- Materials ($CaWO_4$, $LiAlO_2$, Al_2O_3, Si)
- With and without scintillating foil
- With and without instrumented holding system
- Different materials of crystal holding system
- ...

Big variety of possible origins discussed:

- Stress in crystal lattice
- Stress from holders
- Scintillation light from holding structure not detected by light detector
- Low energy surface background
- ... and many others ...

$\rightarrow$ **Still open question!**

Current measurement campaign
Dedicated to LEE

- **Investigations ongoing:**
  ⇒ Currently taking data with modules designed to disentangle different hypotheses

- **Data analysis and tests in preparation:**
  ⇒ Right now doing confirmation tests and analysis cross checks

- **Common effort of community:**
  ⇒ Third edition of Excess workshop next month! **Stay tuned!**

CRESST-III Program

Upgrade of CRESST-III to read-out 288 channels
Reach tonne day exposures

Readout:
2021: Finalized prototyping and testing of

- Wiring
- SQUID readout electronics

2022-2023:

- Finalize installation inside CRESST facility at LNGS

Detector R & D:
2021-2022:

- Lower threshold
- High production rate

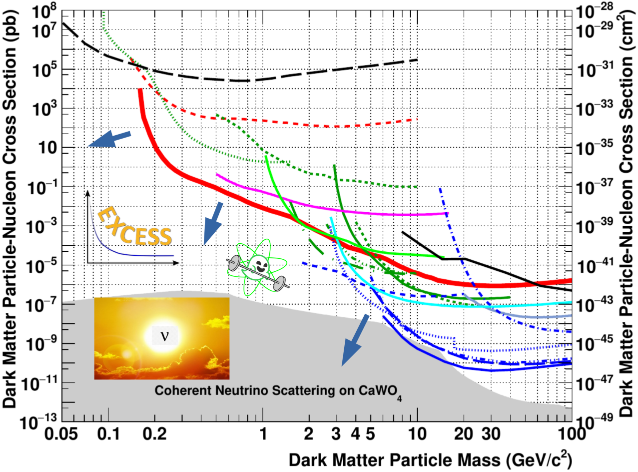
2022-2023:

- Production and testing of detectors
- Upgrade setup at LNGS

2023: Restart data taking

Probing an unexplored region

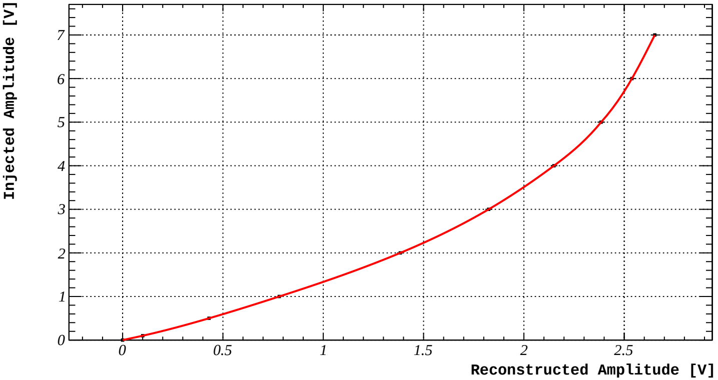
New frontiers, new challenges ...



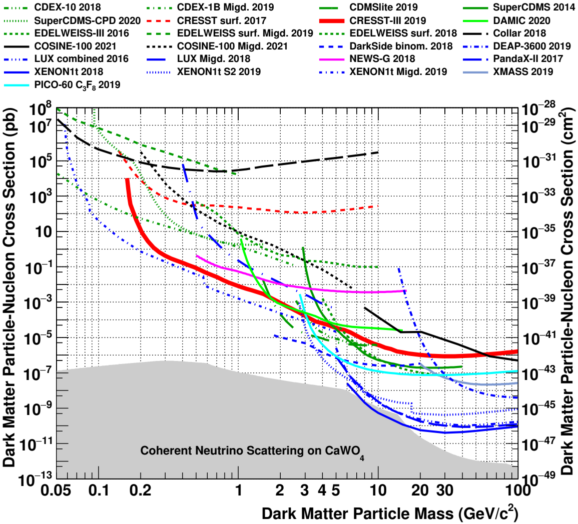
BACKUP

Transfer function

for Calibration



Limits including Migdal effect



Effect of correcting the energy scale