Data Analysis in CRESST

IMPRS Colloquium February 2021

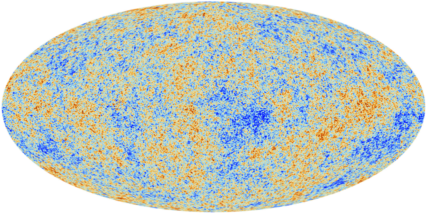
Dominik Fuchs

Technical University of Munich
Max Planck Institute for Physics

February 25, 2021

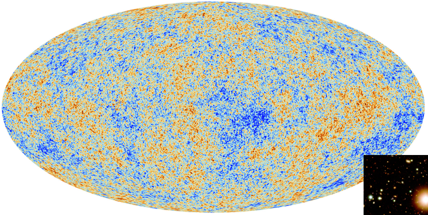
Outline

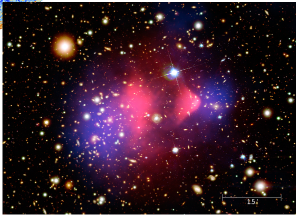
Evidence for Dark Matter



CMB Image:ESA

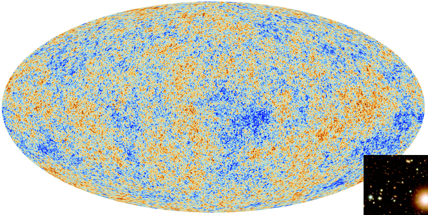
Evidence for Dark Matter

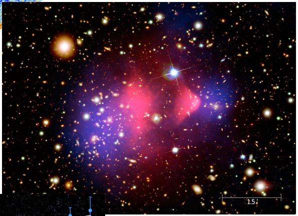


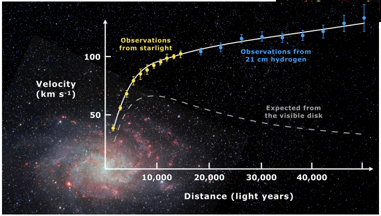


CMB Image:ESA

Evidence for Dark Matter







WIMPs

Weakly **I**nteracting **M**assive **P**articles

- Interactions with SM particles only on the weak scale or below
- Stable on cosmological time scale
- Lee-Weinberg-bound excludes WIMP masses below $\sim$ 2-3 GeV/c^2
- Sub-GeV masses: light dark matter
- **A**symmetric **D**ark **M**atter models are not bound to the Lee-Weinberg limit

Dark Matter Halo Model

- Spherical halo of DM around center of Milky Way
- DM particles thermalized $\rightarrow$ Maxwellian velocity distribution
- Local DM density: $\rho_{\mathrm{DM}} = 0.3\,\mathrm{GeV/cm^3}$
- Rotation of Milky Way $\rightarrow$ WIMP Wind

Outline

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

The CRESST Experiment

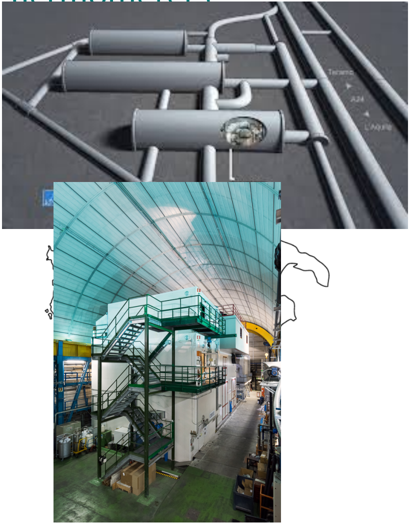
Cryogenic **R**are **E**vent **S**earch with **S**uperconducting **T**hermometers

- $\sim$ 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

The CRESST Experiment

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



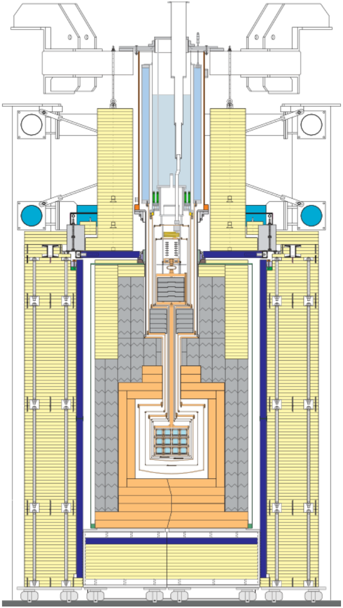
- $\sim$ 3600 m.w.e. deep
- μs: $\sim 3 \cdot 10^{-8}$ /(s cm^2)
- γs: ~ 0.73 /(s cm^2)
- neutrons: $4 \cdot 10^{-6}$ n/(s cm^2)

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

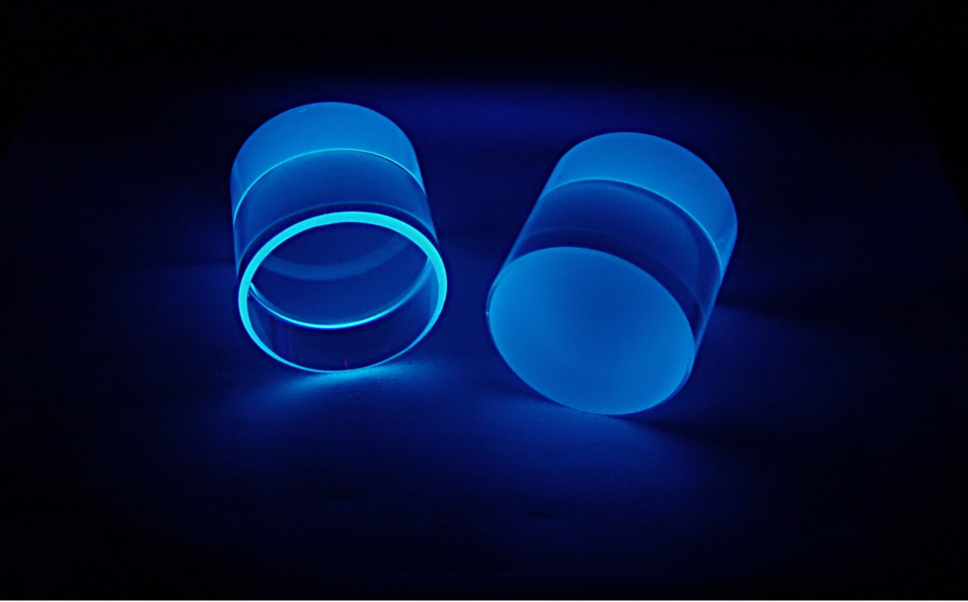
CRESST Setup

Shielding:

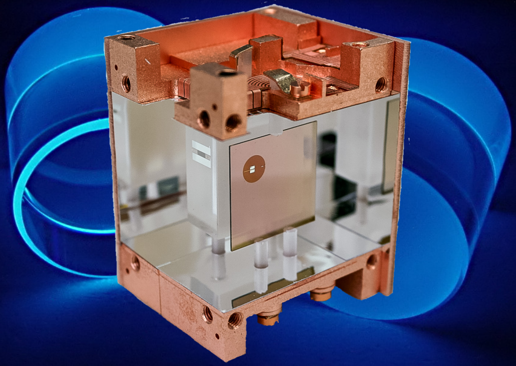
- polyethylene
- muon veto system
- lead
- copper
- polyethylene



Detector Modules



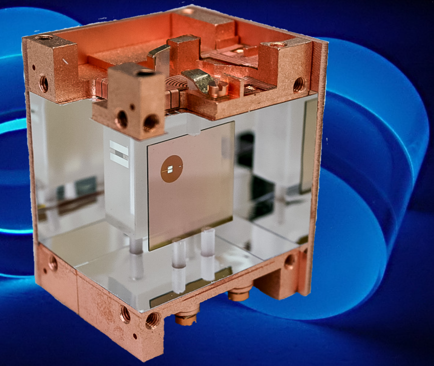
Detector Modules



Detector Modules

Crystals:

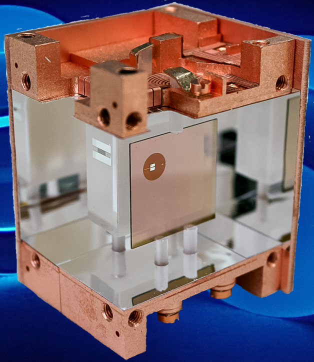
- scintillating $\sim$24g target crystals
- different materials ($CaWO_4$, $LiAlO_2$, Al_2O_3, Si)
- W-TES sensor
- $E_{thr} \leq$ 100eV (nuclear recoils)



Detector Modules

Crystals:

- scintillating ~24g target crystals
- different materials ($CaWO_4$, $LiAlO_2$, Al_2O_3, Si)
- W-TES sensor
- $E_{thr} \leq 100eV$ (nuclear recoils)

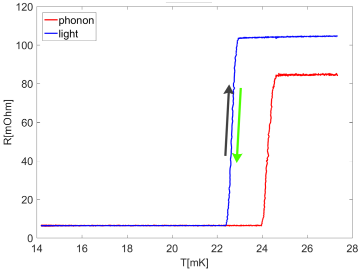


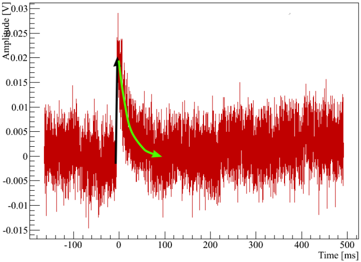
Particle discrimination:

- Light detector
- Light Yield characteristic of type of recoil

Signal

- Nuclear Recoil heats up crystal $\mathcal{O}$(mK)
- Change of resistance in bias current → SQUID readout

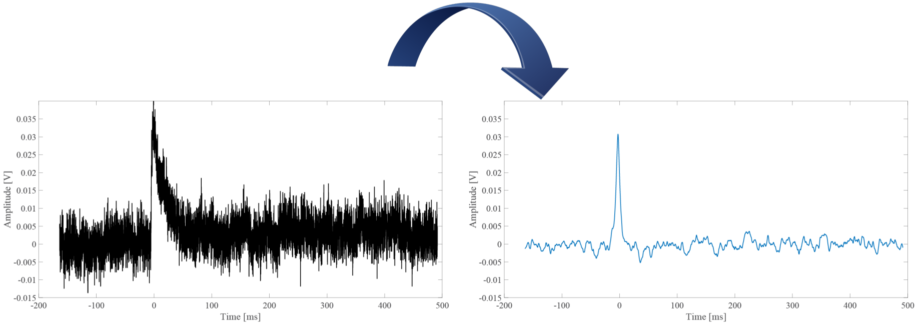




Outline

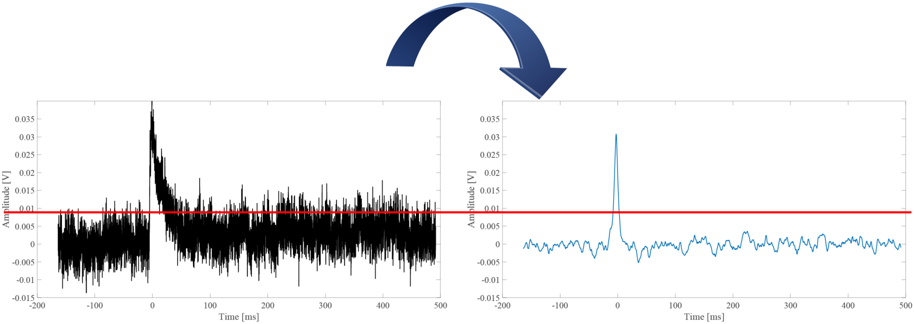
Optimum Filter

- Dead-time free DAQ: detector output is continuously recorded
- Maximize Signal-to-Noise ratio in frequency space (Pulse and Noise Power Spectra)



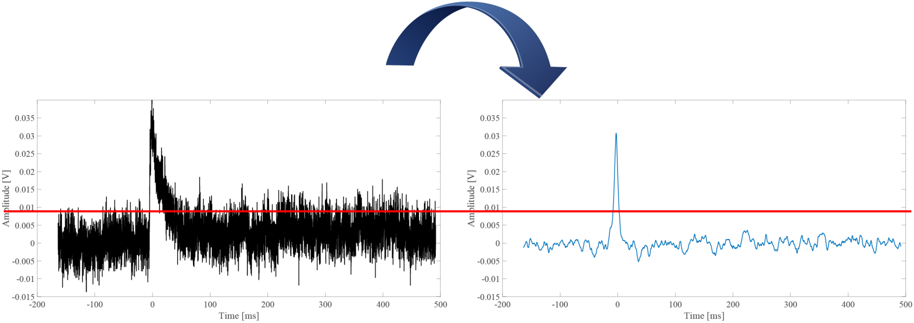
Optimum Filter

- Dead-time free DAQ: detector output is continuously recorded
- Maximize Signal-to-Noise ratio in frequency space (Pulse and Noise Power Spectra)
- Define threshold by choosing accepted number of noise triggers



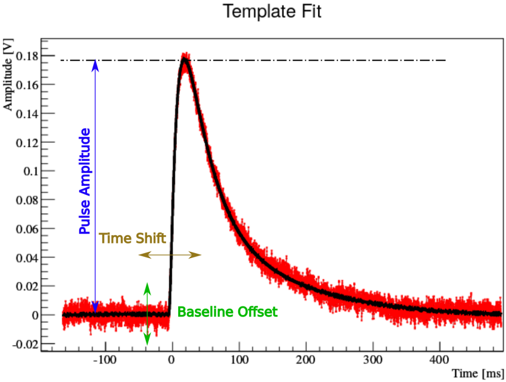
Optimum Filter

- Dead-time free DAQ: detector output is continuously recorded
- Maximize Signal-to-Noise ratio in frequency space (Pulse and Noise Power Spectra)
- Define threshold by choosing accepted number of noise triggers
- Save Events above threshold



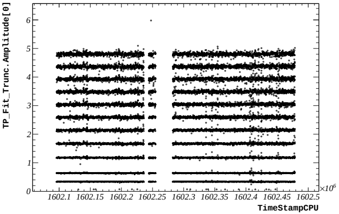
Template Fits

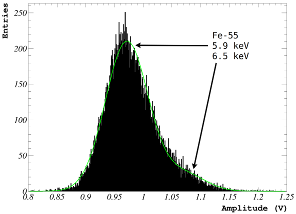
- Clean triggered events from artifacts (pile-ups, electronic disturbances, etc.)
- Fit model to cleaned List
- Spectrum of Amplitudes (V)



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

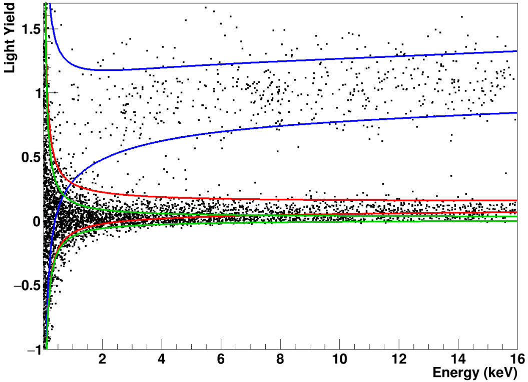




Neutron Calibration

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

Band Fits QF



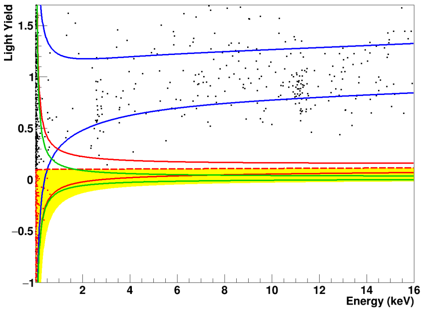
e/γ events

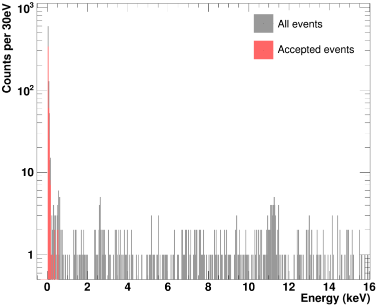
oxygen nuclear recoils

Tunsten nuclear recoils

Light Yield Plot + ROI

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





Expected Recoil Spectrum

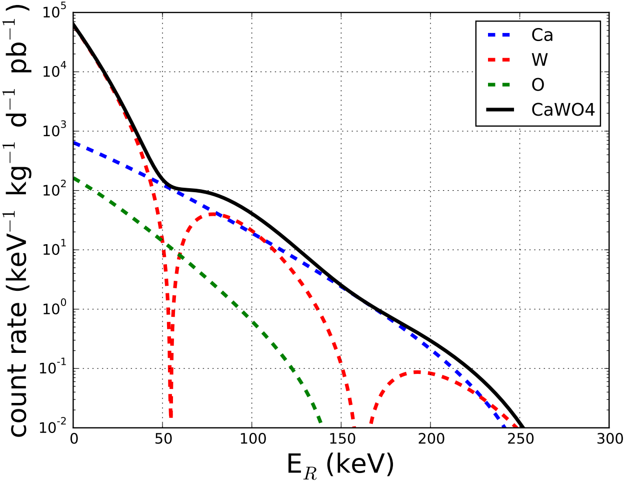
Recoil Rate

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

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

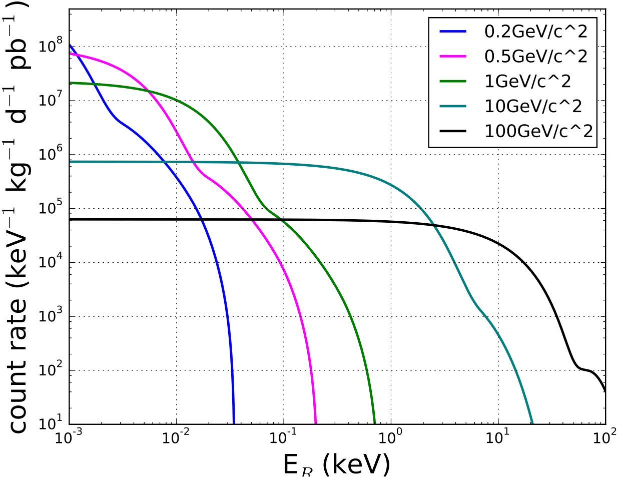
Expected Recoil Spectrum

$m_\chi = 100$ GeV

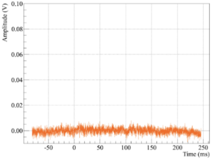


Expected Recoil Spectrum

$m_\chi = 0.2$ - 100 GeV

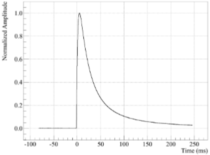


Efficiency



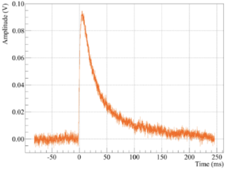
Empty baseline

+

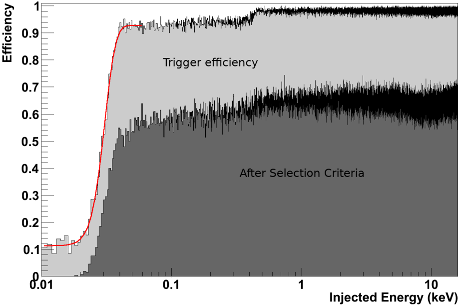


Averaged pulse

=



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

- Hard to include information about background
- Only limit calculation

Likelihood based method

For each dark matter mass:

Likelihood ratio

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

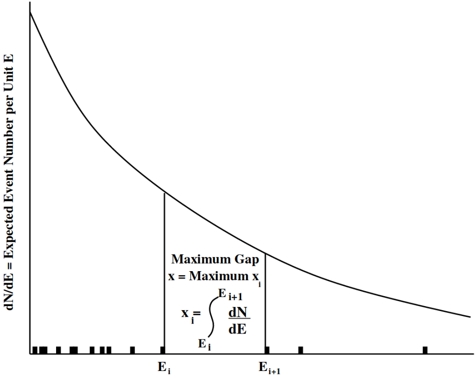
Test statistic

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

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

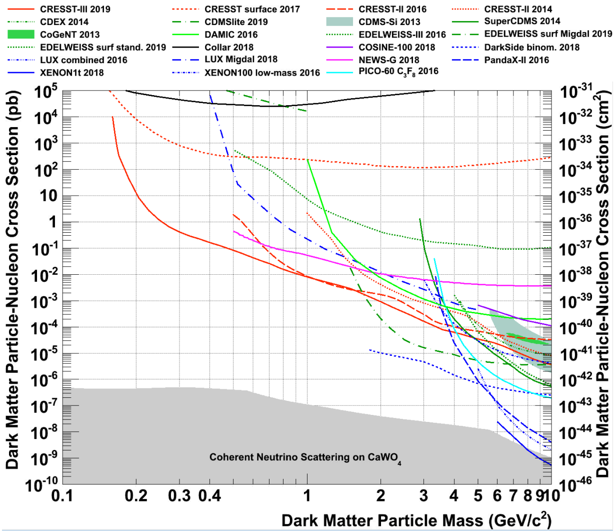
$$x_i(\sigma, m_\chi) \equiv \int_{E_i}^{E_{i+1}} \frac{d\Gamma(\sigma, m_\chi)}{dE} dE$$



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

- Simulate 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



Outline

Summary

Data Analysis in CRESST

- Filtering and triggering of continuous raw data stream
- Cleaning and fitting of triggered events
- Calibration and definition of ROI to obtain energy spectrum
- Simulations to estimate trigger and cut efficiencies
- Calculate expected energy spectra
- Likelihood analysis in case of dark matter signal
- Likelihood or Yellin method for exclusion limits

Summary

Data Analysis in CRESST

- Filtering and triggering of continuous raw data stream
- Cleaning and fitting of triggered events
- Calibration and definition of ROI to obtain energy spectrum
- Simulations to estimate trigger and cut efficiencies
- Calculate expected energy spectra
- Likelihood analysis in case of dark matter signal
- Likelihood or Yellin method for exclusion limits

Summary
Data Analysis in CRESST

- Filtering and triggering of continuous raw data stream
- Cleaning and fitting of triggered events
- Calibration and definition of ROI to obtain energy spectrum
- Simulations to estimate trigger and cut efficiencies
- Calculate expected energy spectra
- Likelihood analysis in case of dark matter signal
- Likelihood or Yellin method for exclusion limits

Summary

Data Analysis in CRESST

- Filtering and triggering of continuous raw data stream
- Cleaning and fitting of triggered events
- Calibration and definition of ROI to obtain energy spectrum
- Simulations to estimate trigger and cut efficiencies
- Calculate expected energy spectra
- Likelihood analysis in case of dark matter signal
- Likelihood or Yellin method for exclusion limits

Summary

Data Analysis in CRESST

- Filtering and triggering of continuous raw data stream
- Cleaning and fitting of triggered events
- Calibration and definition of ROI to obtain energy spectrum
- Simulations to estimate trigger and cut efficiencies
- Calculate expected energy spectra
- Likelihood analysis in case of dark matter signal
- Likelihood or Yellin method for exclusion limits

Summary

Data Analysis in CRESST

- Filtering and triggering of continuous raw data stream
- Cleaning and fitting of triggered events
- Calibration and definition of ROI to obtain energy spectrum
- Simulations to estimate trigger and cut efficiencies
- Calculate expected energy spectra
- Likelihood analysis in case of dark matter signal
- Likelihood or Yellin method for exclusion limits

Summary

Data Analysis in CRESST

- Filtering and triggering of continuous raw data stream
- Cleaning and fitting of triggered events
- Calibration and definition of ROI to obtain energy spectrum
- Simulations to estimate trigger and cut efficiencies
- Calculate expected energy spectra
- Likelihood analysis in case of dark matter signal
- Likelihood or Yellin method for exclusion limits

Summary

Data Analysis in CRESST

- Filtering and triggering of continuous raw data stream
- Cleaning and fitting of triggered events
- Calibration and definition of ROI to obtain energy spectrum
- Simulations to estimate trigger and cut efficiencies
- Calculate expected energy spectra
- Likelihood analysis in case of dark matter signal
- Likelihood or Yellin method for exclusion limits

Thank you for your attention!