TES-based light detectors for the CRESST direct dark matter search

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Phonon-light technique

- Simultaneous detection of a **phonon signal** from a scintillating crystal and a **light signal** in a separate cryogenic detector allows **event-by-event particle identification**
- Important technique in dark matter searches to suppress environmental backgrounds
- **Quenching** of the light signal is due to different ionization densities in the scintillating crystal
- **Light yield** (LY, ratio between light energy and energy in the main absorber) distinguishes
  - electron/gamma interactions: LY = 1 by definition
  - alpha interactions: LY $\approx$ 0.2
  - nuclear recoils: LY $\approx$ 11% (O), 6% (Ca), 4% (W)

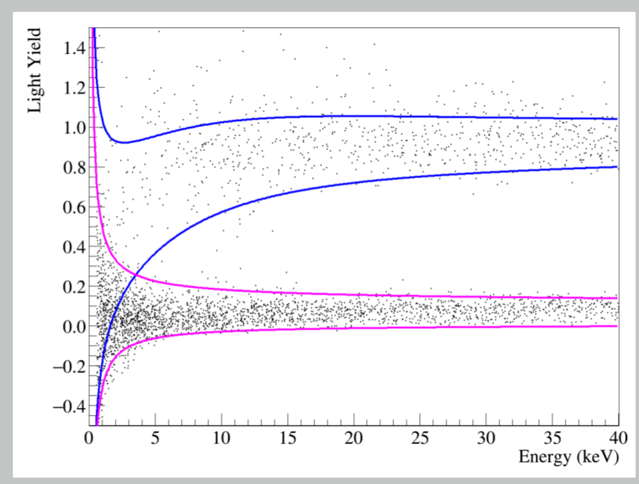

Figure 1: Light-yield vs. energy: event-by-event background discrimination between electron recoils (blue band) and nuclear recoils (pink band) [1].

Light channel design

- Scintillating $CaWO_4$ target crystal
  $\Rightarrow$ light output 20-30 ph/keV
- Silicon-on-sapphire (SOS) light absorber
  $\Rightarrow$ sapphire as excellent cryodetector, 1 μm silicon for light absorption
- Absorption efficiency $\sim$ 85% in the relevant wavelength range
- Scintillating/reflecting foil
  $\Rightarrow$ increasing light collection to $\sim$ 30 %
- Collected light energy typically 2% of the energy measured in the main absorber

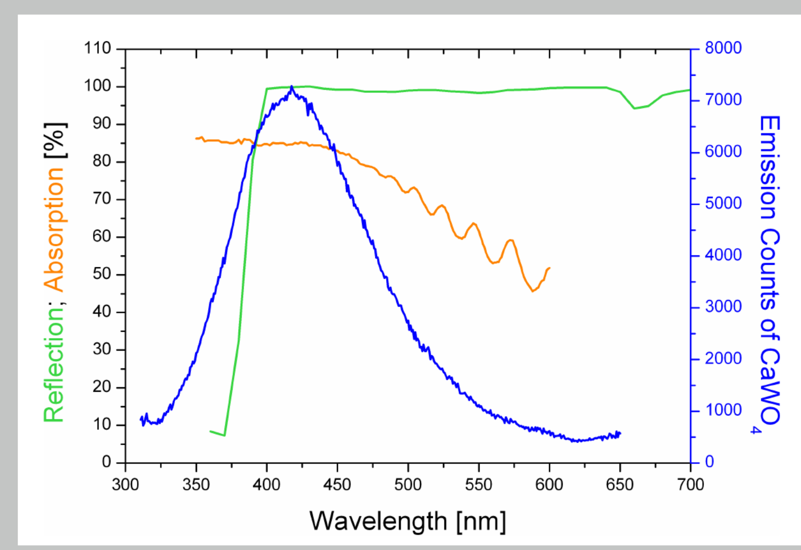

Figure 2: $CaWO_4$ emission (blue), SOS absorption (orange), foil reflectivity (green) [2]

Impact of the light channel on dark matter search

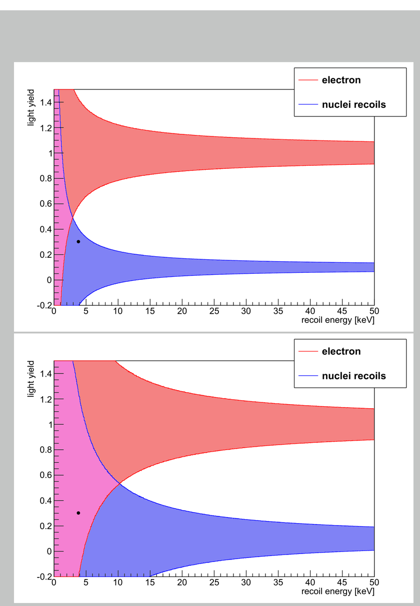

Figure 3: Bottom: the event shown can not be assigned to a band. Top: superior LD perfomance allows identifying the event as a nuclear recoil.

- Light detector resolution and light collection efficiency determine the width of the light yield-bands
- Overlap at low-energies causes "leakage" of e/γ background into dark matter search region
- For low-mass dark matter searches, leakage is unavoidable
- Light detector adds valuable information on origin of backgrounds
- Fully scintillating CRESST-III detector holder: light signal to veto external backgrounds

New developments for CRESST-III

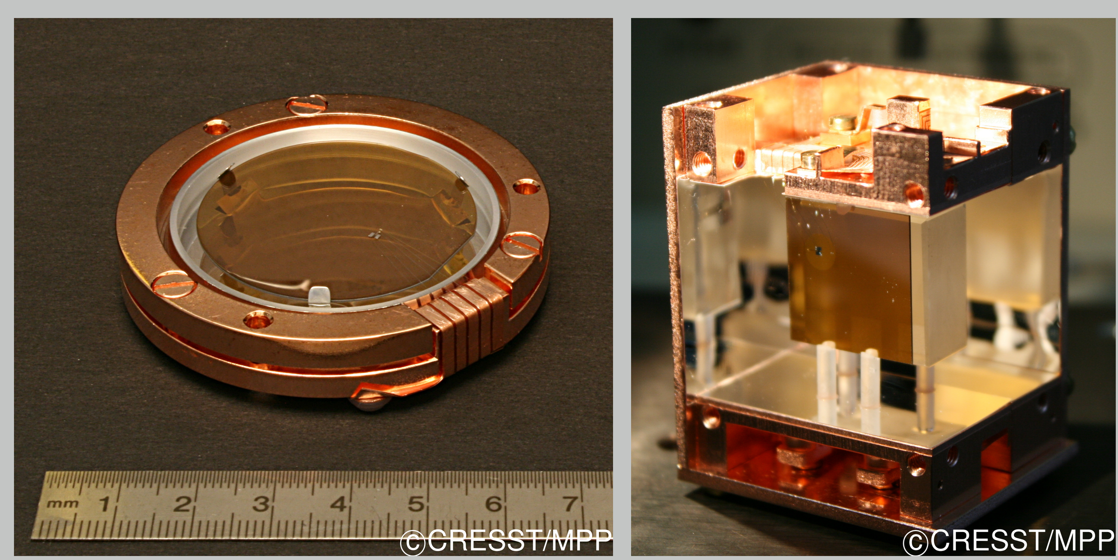

Figure 4: Left: CRESST-II light detector. Right: CRESST-III light detector.

- matched size to new phonon detectors: 20mm x 20mm x 0.4mm
- detector holding by scintillating sticks: light as veto signal

TES design of the light detector

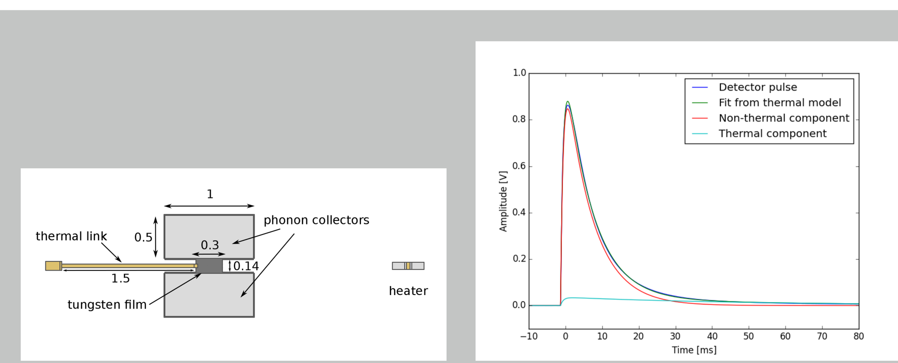

Figure 5: TES design for the CRESST light detectors. Left: layout of tungsten (grey), aluminum (silver) and gold films [3]. Right: Measured detector response overlayed with two-component thermal/non-thermal model [4].

- Signal generation: photon interaction creates a population of non-thermal phonons
- Calorimetric TES: thermometer relaxation (5-9 ms) slower than non-thermal phonon lifetime (0.3-0.8 ms)
- Stabilized at operating temperatures of 17-23 mK

Resolution within CRESST modules

- Standard calibration: 122 keV γ from ^{57}Co in the main absorber $\Rightarrow$ electron-equivalent (keV_{ee}) scale for the light detector
- depends on scintillation efficiency of the crystal, light collection of the module and light detector resolution
- most relevant for dark matter search, can be measured from width of the bands in the light yield plot
- 1-σ resolution at zero energy: 246 eV_{ee} (TUM-40)
- at higher energies: dominated by photon Poisson fluctuations

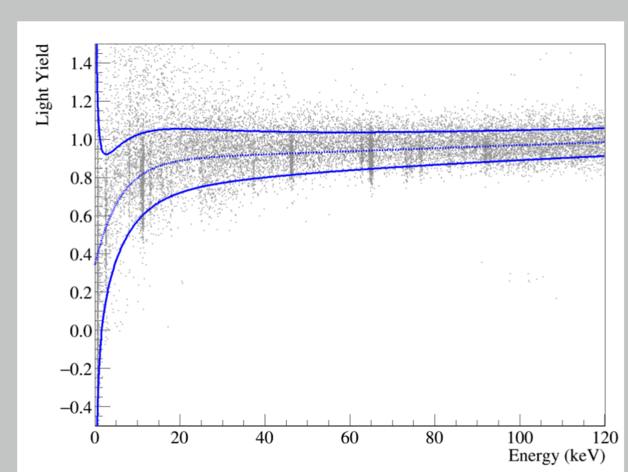

Figure 6: Light-yield plot of detector TUM-40 [1]

Performance as individual detectors

- CRESST-II Phase 2: several LDs equipped with ^{55}Fe sources
- 5.9/6.5 keV γ (^{55}Mn K_α/K_β) directly deposited
  $\Rightarrow$ establishes independent energy scale
- 1-σ resolution at zero energy (determined from baseline noise) between 4.1 eV and 6.7 eV achieved
- resolution degrades with higher energy (known effect in sapphire [5]): 45 eV at 6 keV

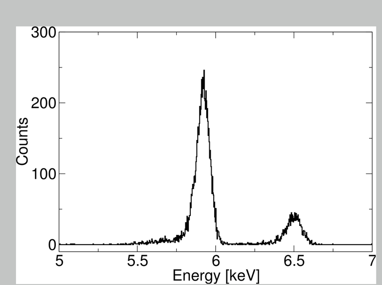

Figure 7: ^{55}Mn K_α/K_β lines observed in light detector *Leon*

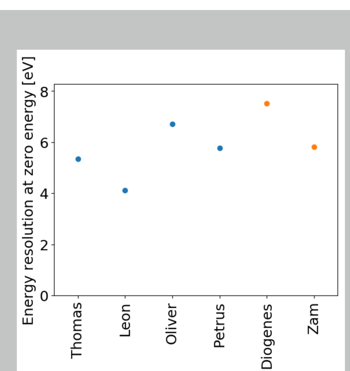

Figure 8: Calibrated light detector performances: standard LD (blue), beaker (orange).

Beaker light detectors

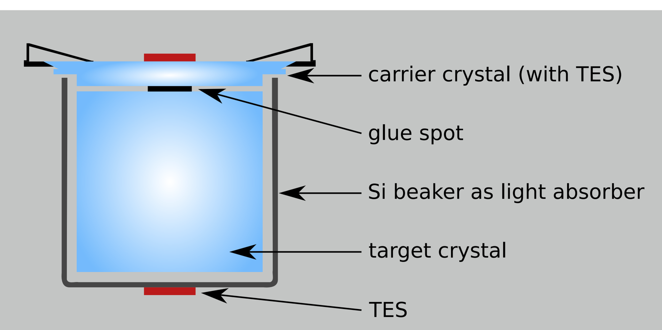

Figure 9: CRESST-module with beaker light detector: holding scheme including glued TES-carrier to complete 4π-veto.

- Parallel line of development: silicon beakers surrounding the main absorber
- Excellent detector properties: baseline noise of 5.8 eV reached in CRESST-II Phase 2
- Enhanced light collection to $\sim$ 80%

Figure 10: Polished silicon beaker (height 40mm, diameter 40mm, thickness 0.4mm) milled from single crystal material.

- Light detector acts additionally as veto against external backgrounds
- Superior rejection of backgrounds from surface contaminations (back-to-back topology)

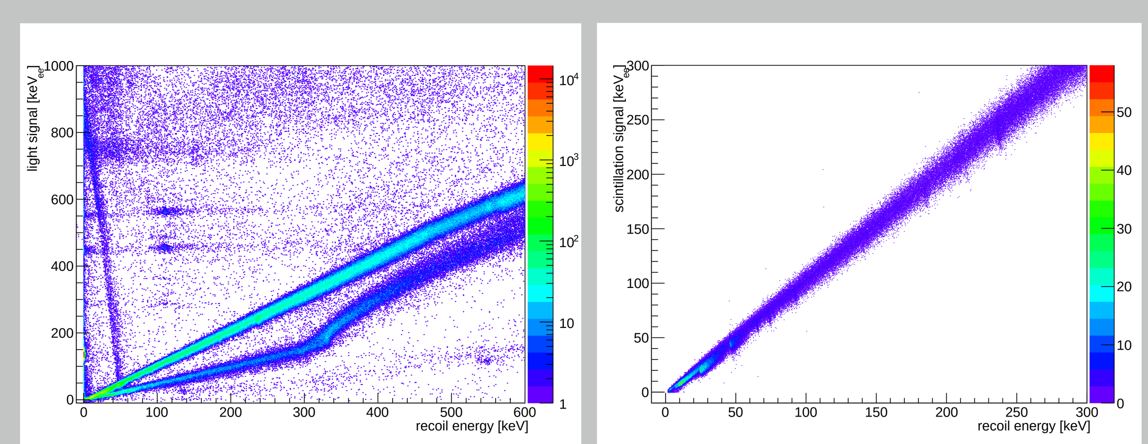

Figure 11: Pulse shape discrimination allows efficient rejection of penetrating external backgrounds and surface contaminations. Left: event population in the phonon-light plane before pulse shape cuts. Right: after pulse shape cuts.

Early view on CRESST-III performance

- Smaller $CaWO_4$ crystal, more compact module: Monte Carlo study and prototype measurement suggest total light yield improved to 2.5%
- Smaller light detector: expected 2.7$\times$ improved resolution from phonon density and free path
- First CRESST-III data: light detector achieved baseline noise of 80 eV_{ee}
  $\Rightarrow$ assuming total light yield of the prototype: baseline noise in the range of 2 eV expected
- Further study and direct calibration needed

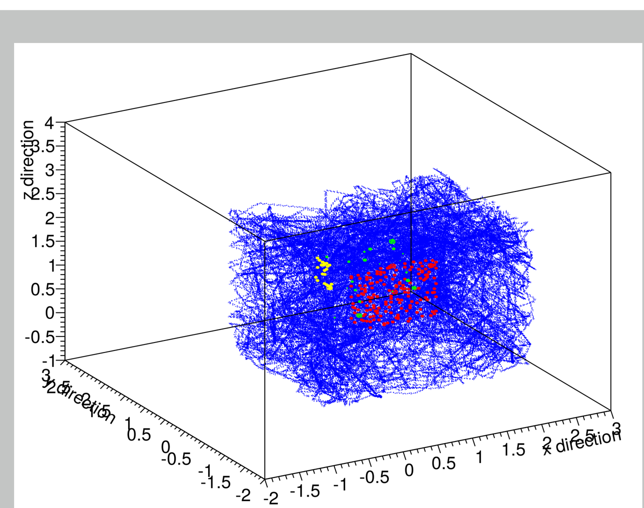

Figure 12: Monte Carlo simulation of photon propagation and collection in the CRESST-III module

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