Direct Dark Matter Search
with the CRESST III-Experiment &
brief summary from other Dark Matter Experiments

Jochen Schieck
Institute of High Energy Physics (HEPHY) of the Austrian Academy of Sciences
and
Institute of Atomic and Subatomic Physics, TU Wien

for the CRESST collaboration
Outline

• brief introduction to direct detection of dark matter

• low mass dark matter - status and results of CRESST III

• search for Dark Matter with several GeV/c²
  - liquid noble gas experiments - Xenon1T

• potential dark matter signals
  - directions towards a deeper understanding - COSINUS

• towards even lighter dark matter particles - DANAE
Unraveling the Particle Character of Dark Matter

- clear evidence for dark matter on different scales
- observation of dark matter based on gravitational pull only
- undiscovered new particles well motivated candidate for dark matter
- mass region below the WIMP mass scale ("low mass dark matter") recently gained a lot of theoretical interest

Physics Reports 555 (2015) 1–60

**SIMP Dark Matter**

The SIMP paradigm is presented in Fig. 1. A schematic description of the SIMP paradigm. The dark sector consists of DM which annihilates via a 3→2 annihilation mechanism, relevant if DM is charged under a symmetry, leads to DM in the keV mass region below the WIMP mass. The couplings to the visible sector for it to remain in thermal equilibrium is given by the temperature of the photon bath. Consequently, the scattering with the SM bath enables the DM to cool off significantly altering structure formation [1, 2]. In contrast, while the couplings to the visible sector predict measurable consequences.

**Strongly Interacting Dark Matter**

Strongly interacting dark matter—expected mass scale ~ 100 MeV/c^2

**Physical Review Letters 113 (2014) 171301**

- **DM**
- **SM**

\[ 3 \rightarrow 2 \]

\[ \alpha_{\text{eff}} \]
The Dark Matter Landscape - Detector Challenge

- different mass regions require different detector technologies
- low mass dark matter requires **low detection threshold**
- detection of larger dark matter masses depend on exposure

![Graph showing dark matter particle mass vs. detection cross section and log scale of dark matter-nucleon scattering rate.]

- **low mass dark matter**
- **WIMP**
- Coherent Neutrino Scattering on CaWO_4
- detection threshold
- exposure
The CRESST Experiment
The CRESST Collaboration

About 40-50 scientists from 6 institutions and 4 countries
CRESST - Detection Principle I

simultaneous read-out of two signals

- **phonon channel**: particle independent measurement of total deposited energy

- **(scintillation) light**: different response for signal and background events for background rejection ("quenching")
Signal-Background Separation

- simultaneous readout of light and phonon channel allows background reduction
- less scintillation light from dark matter-nucleus scattering
  - clear separation between signal and background at large Energy
- significant overlap of bands at low energies (= **low mass dark matter**)
CRESST - Detection Principle II

- experiment operated at cryogenic temperature (<10 mK)

- nuclear recoil will deposit energy in the crystal leading to a temperature rise proportional to energy

$$\Delta T \propto \frac{\Delta Q}{c \cdot m}$$

- detection of small energy depositions requires very small heat capacity $c$

- detection of temperature rise with superconductor operated at the phase transition from normal to superconducting

$$c \propto \left(\frac{T}{\theta_D}\right)^3$$

$\theta_D$: Debye temperature
Crystal Intrinsic Background

- experimental sensitivity limited by background
- CRESST dominated by crystal-intrinsic radioactive contaminations
- in-house production of CaWO$_4$ crystals improves radio purity significantly

\[ \begin{align*}
\text{counts} / (\text{kg keV d}) \\
\text{~3.5 counts} / (\text{kg keV d})
\end{align*} \]
Background Simulation of CRESST Data

- understanding of background crucial
- Geant4 based simulation to estimate intrinsic background
- use measured α-activity as input for Geant4 to determine intrinsic β/γ radiation

**Figure 6.** Histogram of the events in the ROI (black line) recorded with TUM40 in CRESST-II Phase 2. The red line indicates the sum of all identified background sources with the dominant peaks from cosmogenic activation (2.6 keV, 10.7 keV, 11.3 keV) and the Cu X-ray line (8.0 keV). Inset: decomposition of the background based on MC simulation (see text). The contributions of external gamma radiation (green), external betas (gray) and intrinsic beta/gamma radiation from natural decay chains (blue) are shown. The sum of these components (plus gamma peaks) are shown in red.

The individual 1-error bands are depicted in the corresponding colour. The identified backgrounds explain \( \sim 70\% \) of the observed events.

**Conclusions and outlook**

TUM40 operated in the new detector housing has reached unprecedented background levels. Using CaWO\(_4\) sticks to hold the target crystal, a fully-scintillating inner detector housing is realized and backgrounds from surface-alpha decays are rejected with high efficiency. A phonon trigger threshold of \( \sim 0.60 \) keV and a resolution of \( \frac{\text{keV}}{0.090 \pm 0.010} \) keV (at 2.60 keV) are reached with TUM40. By using a CaWO\(_4\) crystal produced at the TUM, the intrinsic background rate was reduced to the lowest level reported for CRESST CaWO\(_4\) detectors: on average 3.51 \( \pm 0.09 \) beta/gamma events per kg keV day in the ROI (1-40 keV) and a total alpha activity from natural decay chains of \( A_{\text{tot},\beta} \sim 3.08 \pm 0.04 \) mBq/kg. In this paper, a detailed alpha analysis was performed which allowed to derive the activities of all decaying isotopes of the natural decay chains. Based on these results, a GEANT4 MC simulation was set up to investigate the contribution of intrinsic beta/gamma backgrounds in the ROI for dark matter search (1-40 keV). An activity of \( \sim 494 \mu\text{Bq/kg} \) was found which corresponds to \( \sim 30\% \) of the total event rate. The MC simulation also shows the contribution of events originating from external gamma radiation. An activity of 62.2 \( \mu\text{Bq/kg} \) (\( \sim 4\% \) of total) is...
CRESST - Status before Summer 2017
Final Result of CRESST II

- energy threshold at 307 eV for nuclear recoil resolution 62 eV (at zero energy)
- background level ~ 8.5 counts / (keV·kg·d)
- best sensitivity for dark matter particles between 0.7* and 1.7 GeV/c²

*July 2017: NEWS-G arxiv:1706.04934
CRESST III
CRESST III - expected sensitivity

- expect to reach $\sigma_{\chi-n} \sim 10^{-40}$ cm$^2$ for 1 GeV/c$^2$ dark matter particles
- detector R&D program for improved radio purity ongoing
- to increase exposure upgrade of read out system planned

CRESST III projections

- $E_{th} = 100$ eV
- $\sigma_{\chi-n}$ projections for different exposures (50 kg-days small, 25 kg-days small)

CRESST III - expected sensitivity

- $\sigma_{\chi-n}$ for 1 GeV/c$^2$ dark matter particles

Detector R&D program for improved radio purity ongoing

Exposure upgrade of read out system planned

arXiv 1503.08065
CRESST III - expected sensitivity

- expect to reach $\sigma_{X-n} \sim 10^{-40}$ cm$^2$ for 1 GeV/c$^2$ dark matter particles
- detector R&D program for improved radio purity ongoing
- to increase exposure upgrade of read out system planned

arXiv 1503.08065
CRESST-III - low threshold detectors

- layout optimised for low-mass dark matter
- cuboid crystal (20 · 20 · 10) mm³ ~ 24g
- self-grown crystal with ~ 3 counts / (keV · kg · d)
- full scintillating housing and instrumented sticks

\[ \Delta T \propto \frac{\Delta Q}{c \cdot m} \]
CRESST-III  low threshold detectors

• operation started in July 2016

• high statistics $\gamma$- and neutron calibration

• 20% of data used as training set
CRESST-III Optimum filter

- implementation of the Gatti-Manfredi filter
- optimum filter maximizes signal-to-noise ratio
- typical improvement about factor 2-3
- new DAQ for CRESST-III with continuous data sampling, threshold set after optimum filter
CRESST-III Energy threshold

- ten detectors installed
- six of ten detectors can be operated
- four detectors have technical problems (no transition or noise)

- 4 out of 5 detectors exceed design goal of 100 eV threshold
Analysis of Detector A

- analysed data: 10/2016-01/2018
- non-blind data: 20% randomly selected
- detector mass: 24 g
- exposure: 5.7 kg·d
- exposure after cuts: ~3.7 kg·d
- threshold: 30.1 eV; $\gtrsim 60\%$ survival probability

- data selection design on non-blinded data set
- cuts to guaranty correct reconstruction of amplitude

30.1 eV: Threshold

Survival probability vs. Simulated Energy (keV)
Detector A - Unblinding and Analysis optimised for 30 eV Threshold

- extensive studies on training set (~20%)
Detector A - Background and Acceptance Region

- background in the energy range above 1 keV identical to previous CRESST results
- increased sensitivity towards lower recoil energies opens unexplored background regions
  - strong raise of counts below 0.2 keV
  - further studies needed
- separation of signal and background using light yield

background rate 1-40 keV: ~3.5 counts / (keV·kg·d) identical to previous CRESST result (Eur.Phys.J. C74 (2014) no.12, 3184)

Note: different binning and exposure

Light Yield

region of interest (ROI)

50% O recoils

99.5% W recoils
Detector A - Energy Spectrum

- region of interest between 30 eV and 16 keV
- 445 events between 30 eV and 16 keV in RoI
- set limit with Yellin’s optimal interval method; using standard astrophysical assumptions

M-shell (2.6 keV) and L-shell (10.7 keV & 11.3 keV)

$^{179}$Ta electron capture
Detector A - Dark Matter Exclusion Limit

reach extended down to 160 MeV/c²

sensitivity at 500 MeV/c² improved by factor 10

deeper understanding of background required

CRESST-II
307 eV and 52 kg·d
Search for Dark Matter with masses at serval GeV/c$^2$
Dark Matter Searches with Liquid Nobel Gases

- Dark Matter experiments based on Xenon lead the limit in the high mass ($m_X \approx 5$ GeV)

- Simultaneous read out of
  
  (a) Scintillation (S1)
  
  (b) Ionisation (S2)
Latest result from Xenon1T

- separation of electron and nuclear recoil events in the S1 / S2 plane
- total exposure of 1 t x yr
- profile likelihood analysis returns no excess of events above the expected background
Result from Xenon1T

- set limit in the cross-section vs mass plane
- observed sensitivity consistent within the 2σ expectation
- best limit in the above 6 GeV/c²

![Graph showing WIMP-nucleon cross-section vs mass](image)

4.1x10^{-47} cm² @30 GeV
Annual modulation of Signal
Dark Matter searches by Annual Modulation

- small interaction rate of dark matter expected
- excellent knowledge of background required to identify dark matter signal
- movement of earth in dark matter wind leads to annual modulation of dark matter signal
  - size of modulation amplitude can reach up to 7%
Annual Modulation of Dark Matter Interaction Rate

- DAMA/LIBRA experiment searches for dark matter via annual modulation of signal rate
- operation of radiopure NaI(Tl)-crystals and detection of scintillation light from dark matter - nucleus scattering
- residual signal shows clear sign for an annual modulation of interaction rate in the energy region of 1-6 keVee (new - previously 2-6 keVee)

Figure 2: Experimental residual rate of the single-hit scintillation events measured by DAMA/LIBRA–phase2 in the (1–3), (1–6) keV energy intervals as a function of time. The time scale is maintained the same of the previous DAMA paper for consistency. The data points present the experimental errors as vertical bars and the associated time bin width as horizontal bars. The superimposed curves are the cosinusoidal functional forms $A \cos(\omega(t - t_0))$ with a period $\frac{2\pi}{\omega} = 1$ year, phase $t_0 = 152.5$ day (June 2nd), and modulation amplitudes, $A$, equal to the central values obtained by best fit on the data points of the entire DAMA/LIBRA–phase2. The dashed vertical lines correspond to the maximum expected for the DM signal (June 2nd), while the dotted vertical lines correspond to the minimum.

Fig. 2 shows the time behaviour of the experimental residual rates of the single-hit scintillation events in the (1–3), and (1–6) keV energy intervals for the DAMA/LIBRA–phase2 period. The residual rates are calculated from the measured rate of the single-hit events after subtracting the constant part, as described in Refs. [2, 3, 4, 5, 14, 15]. The null modulation hypothesis is rejected at very high C.L. by $\chi^2$ test: $\chi^2$/d.o.f. 6

arXiv:1805.10486
Interpretation of Annual Modulation as Dark Matter

- **interpretation** of annual modulation as dark matter scattering (previous 2-6 keVee results)

- **preferred mass and cross-section area excluded by other dark matter experiments**

- **latest results 1-6 keVee cannot be explained with WIMP spin-independent interaction**

\[
m_X \approx 50 \text{ GeV} \ ; \ \sigma_X n \approx 7 \times 10^{-6} \text{ pb} \\
m_X \approx 6-10 \text{ GeV} \ ; \ \sigma_X n \approx 10^{-3} \text{ pb}
\]
Annual Modulation - what do we know?

- statistically significant observation of annual modulated rate of events observed through NaI(Tl) scintillation light

- **origin of underlying process is unknown**

- observation is **consistent** with expectation from **dark matter** scattering modulated by annual changes of dark matter flux

- detailed systematic studies cannot explain annual fluctuation by background processes

- **assumptions**: quenched scintillation light, together with standard astrophysical assumption could explain signal modulation via dark matter-nucleus scattering
Independent NaI(Tl) experiments

- gain deeper understanding of DAMA/LIBRA results
  
i. repeat experiment with identical conditions
  
ii. detailed study origin of annual modulation
      (locate experiment at southern hemisphere)
  
iii. understanding underlying scattering process

- several experiments started or ongoing to understand origin of observed annual modulation
Global NaI(Tl) efforts

- KIMS/COSINE @Yangyang
- PICO-LON @Kamioka
- ANAIS @Canfranc
- SABRE @LNGS
- DAMA @LNGS
- SABRE @Kamioka
- DM-Ice @South Pole

Physics run start Sept/2016
Physics run start Aug/2017

NEW

COSINUS @LNGS

H.S.Lee at ICHEP 2018
The COSINUS Experiment - Detection Principle

detection principle similar to CRESST

- cryogenic operation of NaI-crystal
- simultaneous read-out of
  - phonon channel: particle independent measurement of deposited energy (= nuclear recoil energy)
  - (scintillation) light: different response for signal and background events for background rejection (“quenching”)

→ separation between nuclear scattering and β/γ background events
The COSINUS Experiment - Challenges

• NaI is hygroscopic → requires careful handling in glove box

• high contamination with $^{40}$K emission of $\sim 3$ keV Auger electron possible

• small signal amplitude

$$\Delta T \propto \frac{\Delta Q}{c \cdot m}$$

$c$: specific heat capacity of the crystal

$$c \propto (T / \Theta_D)^3$$

$\Theta_D$: Debye temperature

<table>
<thead>
<tr>
<th>Properties</th>
<th>NaI (pure)</th>
<th>CsI (pure)</th>
<th>CdWO$_4$</th>
<th>CaWO$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density [g/cm$^3$]</td>
<td>3.67</td>
<td>4.51</td>
<td>7.9</td>
<td>6.12</td>
</tr>
<tr>
<td>Melting point [°C]</td>
<td>661</td>
<td>894</td>
<td>1598</td>
<td>1650</td>
</tr>
<tr>
<td>Structure</td>
<td>CsCl</td>
<td>CsCl</td>
<td>Wolframite</td>
<td>Scheelite</td>
</tr>
<tr>
<td>$\lambda_{\text{max}}$ at 300 K [nm]</td>
<td>$\sim 300$</td>
<td>$\sim 315$</td>
<td>$\sim 475$</td>
<td>420-425</td>
</tr>
<tr>
<td>Hygroscopic</td>
<td>yes</td>
<td>slightly</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>$\Theta_D$ [K]</td>
<td>169</td>
<td>125</td>
<td>-</td>
<td>335</td>
</tr>
<tr>
<td>Photons per keV at 3.4 K</td>
<td>19.5 ± 1.0</td>
<td>58.9 ± 5.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mean energy of emitted photon [eV]</td>
<td>3.3</td>
<td>3.9</td>
<td>-</td>
<td>3.14</td>
</tr>
</tbody>
</table>
1st NaI Prototype and Mounting in Cryostat

Construction and operation of first detector module for cryogenic operation

- Light detector (Silicon on Saphire + TES)
- NaI phonon detector (undoped)
- Copper housing
- CdWO₄ carrier crystal
- 5 cm of Pb to shield radioactivity from the dilution unit of the cryostat
- Decoupling system to reduce microphonic noise

arXiv:1705:11028
NaI-crystal - Prototype Performance

→first successful measurement of NaI crystal as cryogenic detector
Required Sensitivity for COSINUS

- relate rate from annual modulation with total rate for dark matter-nucleus scattering → **requirement on exposure**

- need to be sensitive to a rate of **0.01 / (kg day)** in order to exclude dark matter interpretation of DAMA / LIBRA
Towards even lighter Dark Matter mass scales
Physics of the Dark Sector

• new forces / new mediators relax the theoretical lower bound on dark matter masses → sub-GeV dark matter

• dark matter searches based on dark matter nucleon elastic scattering

• energy deposition from recoil: $E_{NR} \approx 2\mu_{X,N}^2 \cdot v_x^2/m_N$
  → for 100 MeV $m_X \sim 1$ eV $E_{NR}^*$

* for silicon
Detection techniques for light Dark Matter

- dark matter detection using ionisation signal from Dark Matter-electron scattering
- inelastic nature of scattering and increased energy transfer possible due to lightness of electron
- detection of small ionisation signals allow to probe Dark Matter particles down to ~ 1 MeV
DEPFET detector as sub-GeV Dark Matter detector

• DEPFET: depleted field effect detector
  • charge collection in an internal gate
  • collected charge modulates current in FET

• known and applied detector concept, e.g. for Belle II
  • focus previously on energy measurement and spatial resolution

• noise performance limited by 1/f noise
DEPFET detector as sub-GeV Dark Matter detector

- 1/f noise limit can be further reduced by using repetitive non-destructive readout (RNDR)
- charge transfer between sub-pixels in a “super-pixel” allow statistically independent measurements
- effective noise can be reduced to $\sigma_{\text{eff}} \approx \sigma/\sqrt{N}$
Measured Performance of DEPFET-RNDR

- noise performance as a function of readout cycles measured and reproduced by simulation

- noise performance of $\sigma=0.21\ e^-$ achieved
Dark Matter studies using RNDR DEPFET

- common R&D project between semiconductor laboratory of Max Planck Society and HEPHY
- ongoing study with a 64x64 pixel test device
- understanding and reduction of dark current essential
- first measurements expected by early 2019

![Graph showing dark matter studies](image)
Summary and Outlook

• CRESST operates CaWO$_4$ crystals at cryogenic temperatures to search for low mass dark matter particles - threshold of 30 eV reached

• excellent sensitivity to low energy nuclear recoils provide the best sensitivity for dark matter particles $< 1.7$ GeV/c$^2$

• Xenon1T provides best limit for dark matter $> 6$ GeV/c$^2$

• (region between 1.7 and 6 GeV/c$^2$ covered by DarkSide (formerly CDMS))

• several projects underway to perform independent measurement of DAMA/LIBRA observation → COSINUS

• new detector developments to move towards MeV/c$^2$ dark matter
additional information
Results from a gram-scale cryogenic calorimeter
Results from gram-scale cryogenic calorimeter

- energy detection threshold $E_{\text{th}} \propto M^{2/3}$
- O(1g) detector is expected to reach 10 eV threshold
- cryogenic operation of detector above ground without significant shielding
- initially planned as a proof-of-principle measurement
- run-time of 0.11 g \cdot days


\begin{align*}
E_{\text{th}} &= (19.7\pm0.1)\text{eV} \\
\sigma_{\text{th}} &= (3.83\pm0.15)\text{eV}
\end{align*}

Transition Edge Sensor (TES)

size: 5x5x5 mm$^3$
weight: 0.49 g

TES for phonon readout

\(\text{Al}_2\text{O}_3 \text{ (Sapphire)}\)

randomly triggered noise traces
Results from gram-scale cryogenic calorimeter

- improve signal to noise performance by applying optimum filter
- no-data blinding → no data quality cuts applied (only stability cuts) → most conservative approach
- dark matter limit using standard astrophysical assumptions and Yellin optimal interval method
- probe elastic dark matter scattering down to 140 MeV/c^2
- see also v-cleus proposal (Eur.Phys.J. C77 (2017) 506) for application as detector for coherent v-nucleus scattering

Background rate: ~1.2×10^5 counts/(kg·keV·d)
• G-LD: no transition
• I-all: no transitions
• B- one iStick : heater broken cannot be operated
• C and D - iStick system: working, but introduces strong noise on phonon channel

6/50 TES not working (including the 5 of detector I)
• The wiring is >10 years old
• A TES is a sensitive but challenging device
FIG. 1. Upper left panel: Constraints from different observations on the fraction of PBH DM, $f_{\text{PBH}}$, as a function of the PBH mass $M_c$, assuming a monochromatic mass function. The purple region on the left is excluded by evaporations [8], the red region by femtolensing of gamma-ray bursts (FL) [40], the brown region by neutron star capture (NS) for different values of the dark matter density in the cores of globular clusters [41], the green region by white dwarf explosions (WD) [42], the blue, violet, yellow and purple regions by the microlensing results from Subaru (HSC) [43], Kepler (K) [44], EROS [45] and MACHO (M) [46], respectively. The dark blue, orange, red and green regions on the right are excluded by Planck data [36], survival of stars in Segue I (Seg I) [47] and Eridanus II (Eri II) [48], and the distribution of wide binaries (WB) [49], respectively. The black dashed and solid lines show, respectively, the combined constraint with and without the constraints depicted by the colored dashed lines.

Other panels: Same as the upper left panel but for a lognormal PBH mass function with $a = 2$ (upper right) and for a power-law PBH mass function with $a = 1$ (lower left) and $a = 1$ (lower right).

The Cosmic Microwave Background (CMB) anisotropy constraints on PBH accretion are subject to uncertainties in the accretion process and its effect on the thermal history of the universe at early times. To account for this, we show the bounds for both collisional ionisation (solid dark blue line) and photoionisation (dotted dark blue line) [36]. Recently, another sort of accretion limit has been obtained in the mass range from a few to $10^7 M_\odot$ on the grounds that PBH accretion from the interstellar medium should result in a significant population of X-ray sources [53]. Indeed, several earlier papers have considered such a limit [54, 55]. However, all these limits are very dependent on the accretion scenario and are therefore not shown.

Lensing is the only phenomenon which has been claimed to provide positive evidence for PBHs. For example, the results of the MACHO project – searching for microlensing of stars in the Magellanic clouds – originally suggested halo DM in the form of $10^{-5} M_\odot$ objects [56] and these could plausibly be PBHs formed at the quark-hadron phase transition at $10^{15}s$. However, the DM fraction was later reduced to 20% [57]. The interpretation of the MACHO results – and also the EROS and OGLE results – is very sensitive to the properties of the Milky Way's dark matter halo.
Search for Dark Photons
Dark Photons as Dark Matter Candidates

- Dark Matter candidate through U’(1) Standard Model allowed extension → Dark Photon

- coupling to the Standard Model U(1) symmetry via kinetic mixing term $\kappa$

  \[ \mathcal{L} = \mathcal{L}_{\text{SM}} - \frac{1}{4} V_{\mu\nu}^2 - \frac{\kappa}{2} F_{\mu\nu} V^{\mu\nu} + \frac{m V^2}{2} V_\mu V^\mu \]

- relic abundance of dark photons from inflationary perturbations can account for Dark Matter relic density

  \[ \Omega_V \approx 0.3 \sqrt{\frac{m_V}{1 \text{ keV}}} \left( \frac{H_{\text{inf}}}{10^{12} \text{ GeV}} \right)^2 \]

- possible parameter space for kinematic mixing term $\kappa$ experimentally not excluded

arXiv:1504.02102

$H_{\text{inf}}$: Hubble scale at inflation
Detection Principle of Dark Photons

- dark photons couple with $e\kappa$ to charged particles

- ‘photoelectric effect’ leads to deposition of total energy in the crystal

- total absorption - no elastic scattering!

- expected cross-section for Dark Photons: $\sigma_V(E_V=m_V)\nu_V=\kappa^2\sigma_Y(\omega=m_V)c$

- expected rate per $\approx \rho_{DM}/m_Vc^2 \cdot \kappa^2\sigma_Y(\omega=m_V)c$
Detection of Dark Photons with CRESST

- data collected with the Lise detector
  - \( E_{\text{thr}} \approx 300 \text{ eV} \)
- signal expected in the electron band
- search for mono-energetic peak at dark photon mass
  - focus on dark photons with \( m_V < 2 \text{ keV} \)
Detection of Dark Photons with CRESST

- empirical background model with several components
  - constant electron recoil background
  - excess-light events (electrons originating from outside detector module → light from scintillating foil)
  - Dark Photon signal with assuming detector resolution (~60 eV to ~100 eV)

---

**Fig. 3.**

- Top panel: Fit results for the phonon energies. In addition to the measured data, the stacked contributions of all different interactions are shown. The fixed mean of the signal peak was set to 0.4 keV. The drop in the models below 2 keV is related to the decreasing signal-survival probability.

- Bottom panel: The residuals are depicted as solid black line. In addition, the statistical uncertainties (central 90% region) of the fitted model are shown as green-shaded region.

- The recently started (July 2016) Phase 1 of CRESST-III has the potential to further improve this limit. The limits for dark-photon masses between 0.3 and 0.7 keV/c are shown. Our result improves the existing constraints from astronomy, the XENON and DAMIC experiments.

- In addition, existing limits (90% confidence level) for dark-photon mixing is shown in Fig. 6 as a function of dark-photon energy.

---

**Fig. 5.**

- The marginalized posterior PDF for the signal rate can be obtained as S = 0.4 keV as an example. This upper 90% limit for the corresponding quantile of P is depicted.

- An upper limit for the signal rate can be obtained as S = 0.4 keV as an example. This upper 90% limit for the corresponding quantile of P is depicted.
Detection of Dark Photons with CRESST

- deposited energy corresponds directly to the Dark Photon mass
- performance determined by background and detector resolution

best limit for Dark Photons between 300 and 800 eV
v-cleus

arXiv:1704.04320
FIG. 8. MC simulation of the expected energy deposit in case of a -background similar to the remaining one in the Dortmund Low Background facility [29]. The histograms show the energy deposits in the target for three cases: without any veto (black), in case of a passive outer veto (blue), and in case of an active outer veto (red) with a threshold of 1 keV. The inset zoom to the first 10 keV. Clearly a background reduction of O(10^3) at lowest energies is reasonable.

an active CaWO_4 outer veto, the neutron background is reduced by a factor of \( \sim 10 \), independent of the recoil energy (studied in the energy range from 10 eV to 300 keV). By a clever combination of passive shielding elements like borated polyethylene, and active shielding elements like instrumented plastic or liquid scintillators, and LiF crystals, neutron background levels can be further reduced. This concerns shielding systems placed outside the cryogenic setup surrounding the cryostat at all sides. In addition we provide two technologies to further reduce and reject this potentially harmful background: 1) the outer cryogenic veto system described above and 2) the active background discrimination by the multi-target approach. The latter might be a powerful tool to reduce ultimate backgrounds, particularly neutrons. This is described in more detail in section III. Nevertheless, we conclude that a dedicated MC simulation using measured muon spectra in combination with a calorimeter measurement at the experimental site are necessary. This is beyond the scope of this work and will be subject of a future publication.

G. Production and scalability

A disadvantage of cryogenic detectors when compared to e.g., scintillation detectors has always been the difficulty to scale up the experiments in size. The new detector concept presented here overcomes most of these problems. In principle, the detector has been designed such, that the number of production steps of the individual detector components are independent of the number of target calorimeters involved. The target calorimeters are produced from wafers with a thickness of 5 mm and variable diameters (CaWO_4 up to 60 mm, Al_2O_3 up to 200 mm, and Si up to 300 mm). With well-established techniques of the semiconductor industry, as e.g. photolithography, thin-film evaporation, etching or sputtering, the TES sensors are being simultaneously equipped on each target calorimeter, and the wafer is cut only afterwards into the individual (5x5x5) mm^3 crystals. The same up-scaling is possible for the inner veto (section II E) which acts as a detector holder. It is entirely produced by the above-mentioned methods. The cutting of the wafers is done by means of a laser or other automated methods. The cabling for a large amount of TES sensors are implemented by photolithography in combination with sputtering on the inner veto wafers as done for the 3x3 array. Further, it has been shown (e.g. in [30]) that large amounts of SQUIDs can be realized by SQUID multiplexing.

For the first phase of the experiment, we focus on the production of 3x3 arrays with moderate requirements of size and channel numbers which is foreseen as sufficient for a discovery of CNNS (see below). In a second step, the technology mentioned above enables experiments up to the kg-scale with energy thresholds of O(10 eV); an exposure allowing precision measurements of the CNNS cross-section and interesting BSM physics. Fig. 9 shows a technical drawing of a future calorimeter array of 225 crystals which correspond, using Al_2O_3, to a total mass of \( \sim 110 \) g.
FIG. 11. Count rates on CaWO$_4$ (red) and Al$_2$O$_3$ (green) expected from a benchmark nuclear power plant of 4 GW for the experimental sites considered. The black dotted lines indicate different background levels (extrapolation to lower energies) measured in different experimental sites. From top to bottom: a) the Stanford shallow underground facility [33], b) the low-background setup at the ARC in Seibersdorf [34], c) the Dortmund low-background facility [29] and d) the Heidelberg shallow laboratory [35]. The full black line (e) shows the expected (simulated) background level using the outer and inner veto of the fiducial-volume cryogenic detector. The grey band indicates the uncertainty of the background level with a lower limit at the intrinsic background level of CaWO$_4$ crystals measured at LNGS [28]. Reactor-correlated backgrounds are considered as negligible at the considered distances from core.

We use the highest background level reported as a conservative upper limit for the sensitivity studies. Even more conservative, we do not consider the additional background-rejection capability of the inner and outer cryogenic veto. As shown in chapter II E and II F by a dedicated MC study, the cryogenic fiducial-volume detector reduces surface, gamma and neutron backgrounds by factors of $\sim 10^3$ and $\sim 10$, respectively, in the target volume. In the following, the (flat) background rate of 200 counts/[kg keV day] is referred to as the benchmark. In case of CaWO$_4$ the CNNS signal is 2 orders of magnitude above the conservative benchmark background whereas in case of Al$_2$O$_3$ the signal-to-background ratio is much smaller (factor of 1-5), see Fig. 11. The multi-target approach, therefore, is a powerful tool to actively discriminate neutrino-induced signals from backgrounds. In particular, it allows to identify possible ultimate exponentially shaped, signal-like backgrounds.

3. Experimental site and discovery potential

An extensive likelihood study is performed to investigate the discovery potential of CNNS with the proposed small-scale experiment. We consider one CaWO$_4$ (total mass: 6.84 g) and one Al$_2$O$_3$ (total mass: 4.41 g) calorimeter array inside the inner and outer active cryogenic veto (see Fig. 7). The benchmark background level is assumed and, conservatively, the rejection capability of the surface veto is not used for the background estimation. Three different thresholds are studied (5, 10 and 20 eV) which, however, have only a minor impact on the discovery potential. We define three scenarios:

- **Near case:** A distance of 15 m from the reactor core - a site within the reactor containment. Highest count rates are expected, but there are tough requirements for the shielding against correlated backgrounds. The access is restricted and strict safety regulations have to be considered.
FIG. 12. Artist view of a typical nuclear power plant with possible experimental sites (red boxes) for the 3 different scenarios (see text).

- **Medium case**: A distance of 40 m from the reactor core - outside the containment and the reactor building. Possibly a shallow site in an adjoining building or a dedicated site with an artificial overburden. Easier access and a better infrastructure.

- **Far case**: A distance of 100 m from the reactor core - far away from the critical reactor components, possibly outside the entire power-plant area. Straightforward access and plenty of possible sites.

For each case, spectra are randomly generated for a large number of varying exposures. The results of this MC simulation are studied with a likelihood ratio analysis. In every MC experiment, one spectrum each is generated for the CaWO$_4$ and Al$_2$O$_3$ arrays. The unbinned likelihood of a model's parameters is calculated as a product over the individual likelihoods for each event in both spectra and the Poisson likelihood for observing this total event number (Extended Maximum Likelihood method). The single event likelihood is proportional to the sum of the signal and background rates for the given parameter values. Two very simple models are considered: the free model has two parameters, namely the level of the flat background and the strength of the CNNS signal relative to the standard model expectation. In the null model, the CNNS signal strength is held at zero. The maximum likelihood of each model at the best fit parameter values is denoted $L_{\text{free}}$ and $L_{\text{null}}$ respectively. Since the two models are nested with one additional parameter in the free model, the likelihood ratio test statistic $W = 2 \log L_{\text{free}} / L_{\text{null}}$ follows a $\chi^2$-distribution with one degree of freedom (by Wilks' theorem). The square root of the test statistic therefore follows a standard normal distribution, so that the statistical significance in $W$ of the claim of a CNNS signal with nonzero cross-section in addition to the assumed flat background is directly given by $p_W$ for each pair of spectra.

**FIG. 13** shows the resulting discovery potential of the 3 scenarios. The MC data (data points) using an energy threshold of 10 eV are fitted by square-root functions (full lines). Changing the threshold to 5 and 20 eV has only a minor influence on the discovery potential (square-root fits shown as dashed and dash-dotted lines respectively). The individual MC results for 5 and 20 eV threshold are not shown for clarity. All three scenarios show a very promising potential for the discovery of CNNS - in the near case within $\sim 1$ day, in the medium case within $< 2$ weeks and in the far case within $\sim 4$ months of measuring time.

Background studies including dedicated measurements on the individual sites and detailed MC simulations are required to find the most suitable site. At the medium and far sites, expected backgrounds are rather straightforward, while for the near site a proper understanding of the possibly remaining reactor-correlated backgrounds is needed. The near site, however, would - despite a rapid discovery of CNNS - allow a precision measurement (statistical error on a percent level) of the cross-section predicted by the Standard Model within a measuring time of one year. Impressively, this can be performed by a detector with a total target mass of $\sim 10$ g, given the necessary control of systematics.