Direct Dark Matter Search with the Experiments CRESST and EURECA

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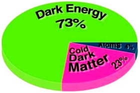
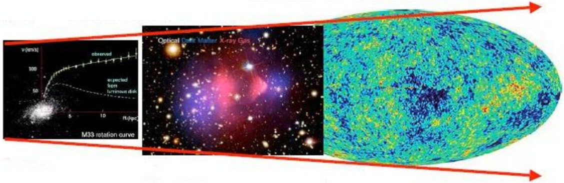
Dark Matter

current picture of the constituents of our universe:



evidence of Dark Matter can be found on all scales in the universe:



rotation curves in glaxies - colliding galaxy clusters - CMB

$\Rightarrow$ lightest supersymmetric particle (LSP) from SUSY theory delivers a well motivated non-baryonic Cold Dark Matter candidate:

e.g. the WIMP - Weakly Interacting Massive Particle

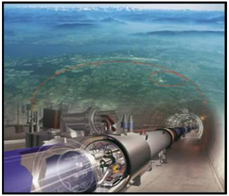
Different search approaches

gravitational, e.g. colliding galaxy clusters

indirect, e.g. MAGIC,

air-Cherenkov-telescope

direct, e.g. CRESST, cryogenic detectors



production, e.g. LHC, missing energy

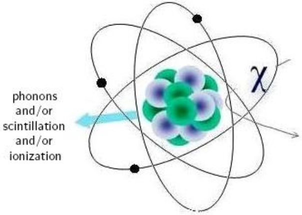
WIMP search with cryogenic detectors

direct detection of WIMPs:

- nuclear recoil in the target of a cryogenic detector
- mass: GeV-TeV
- cross section: $\sigma_\chi < 5 \cdot 10^{-7}$ pb
- local density: $\rho_\chi \sim 0.3$ GeV/cm^{-3}
- relative velocity (WIMP-earth): 270 km/s

$\Rightarrow$ energy deposited $\sim$ keV

$\Rightarrow$ scattering rate < 0.1/day/kg



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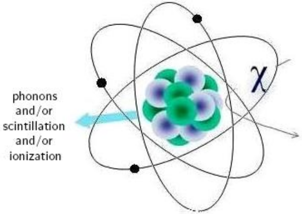


$\Rightarrow$ energy deposited $\sim$ keV

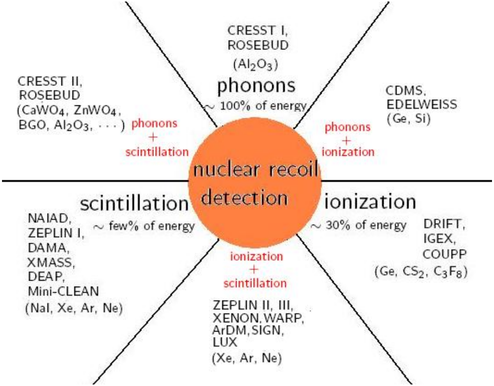
$\Rightarrow$ scattering rate < 0.1/day/kg

requirements for direct DM search experiments:

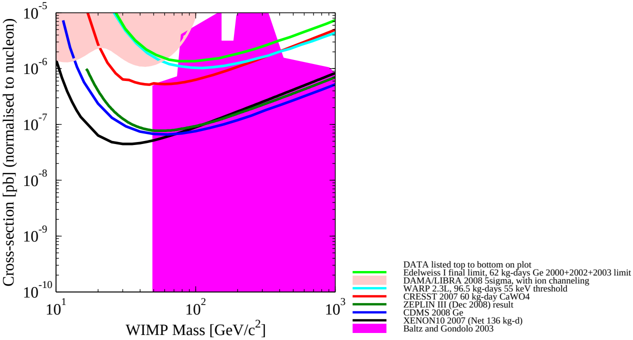
- low energy threshold of the detectors: few keV range
- low background environment: underground laboratory ($\sim$4000 m.w.e.)
- passive low background shielding (PE, Pb, Cu, H_2O)
- active low background shielding (μ-veto, flux$\sim$1m^2/h)
- highly efficient background suppression technique: discrimination of background induced by electron recoils (γ, β) and neutrons

WIMP search with cryogenic detectors

background events give a different amount of scintillation/ionization than the searched for WIMP-nuclear recoil events:



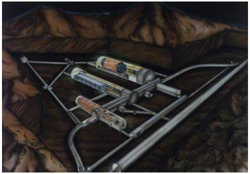
present limits on WIMP mass and interaction



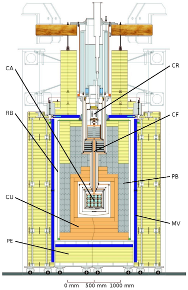
- $\sigma = 10^{-6}$pb $\Rightarrow$ ~1 event/kg/day (~0.1 now reached)
- $\sigma = 10^{-8}$pb $\Rightarrow$ ~3 events/kg/year (aim of CRESST II, 10kg)
- $\sigma = 10^{-10}$pb $\Rightarrow$ ~30 events/ton/year
  (e.g. EURECA, further $\times 100$ improvement required)

CRESST

Cryogenic Rare Event Search with Superconducting Thermometers



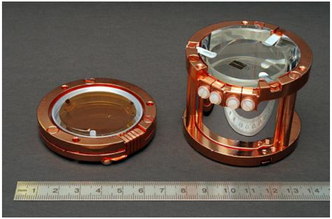
underground laboratory at Gran Sasso, Italy



installation of the CRESST experiment

collaboration: Max-Planck-Institut für Physik - University of Oxford - Technische Universität München - Laboratori Nazionali del Gran Sasso - Universität Tübingen

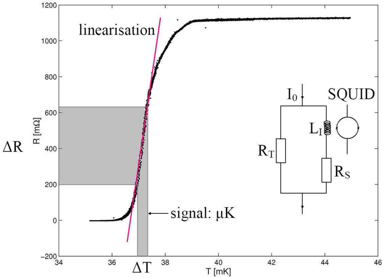
CRESST - detector design



CRESST detector module

- tungsten (W) thin films (200nm respectively 120nm) as Transition Edge Sensors (TESs)
- phonon channel $\hat{=}$ scintillating $CaWO_4$-crystal (300g, height, $\oslash$=40mm) as target with W-TES on top
- light channel $\hat{=}$ SOS (Silicon on Sapphire) crystal ($\oslash$=40mm) with W-TES on top

CRESST - detector design



TES working principle

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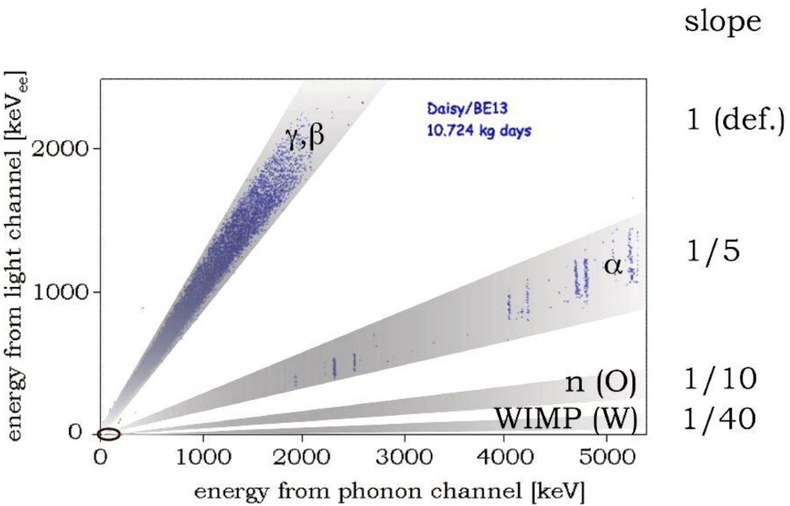
Phonon-light background suppression technique

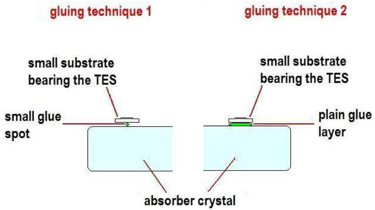


Present status of the experiment

CRESST running now with 10 detector modules taking data

modifications:

- patch of a leakage in the neutron shield
- introduction of redesigned holding clamps of the absorber crystals
- 3 detector modules built according to the so-called composite detector design, i.e.:
  - production of the TES on a separate crystal substrate
  - gluing the TES onto the large absorber crystal



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  - production of the TES on a separate crystal substrate
  - gluing the TES onto the large absorber crystal
  - $\rightarrow$ simplified TES production process
  - $\rightarrow$ TESs can be pre-tested concerning their superconducting transition
  - $\rightarrow$ usage of small substrates for the deposition: produce several TESs in one step
  - $\rightarrow$ heating cycles of the absorber crystals that could lead to a degradation of the light output are avoided
  - $\rightarrow$ other crystal materials can be used more easily: e.g. one $ZnWO_4$ detector in the present CRESST run
  - $\rightarrow$ mass production is feasible

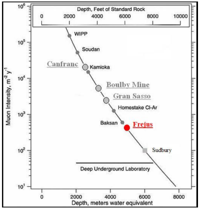
EURECA

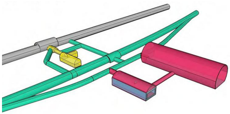
European Underground Rare Event Calorimeter Array

- future European ton-scale experiment
- started March 2005; including CRESST, EDELWEISS, ROSEBUD with additional groups joining
- aim: explore scalar cross sections in the 10^{-9} to 10^{-10}pb region with a target mass of up to one ton
- aligned with European Roadmap Recommendations: multiple target materials (Ge, $CaWO_4$, $ZnWO_4$ etc.) and multiple techniques (phonon-light, phonon-ionization)
- from 2010: start of EURECA construction
- setup at the LSM laboratory, France
- design studies of the cryostat layout have been started

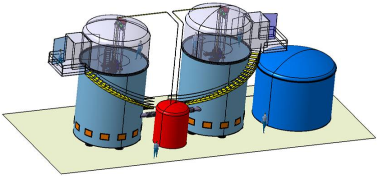
EURECA

European Underground Rare Event Calorimeter Array





existing lab (yellow) and planned extension of the lab (red)



design study of the EURECA cryostat with two separate detector volumes, each stored in one water tank

EURECA - European Underground Rare Event Calorimeter Array

requirements for a dark matter experiment like EURECA:

- target mass up to ∼1ton
  ⇒ large-scale production of detector modules
- detectors with very similar properties
  ⇒ reproducible production
- possibility to employ multi-material targets
  ⇒ introduce a detector design that allows the use of different absorber materials
- detailed understanding of the detector response
  ⇒ thermal model for the chosen detector design

⇒ Composite Detector Design

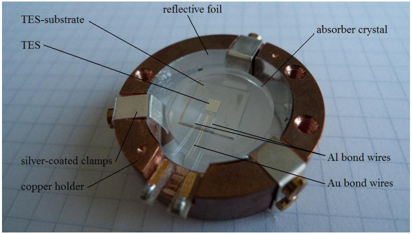
Current research topics:

- composite detector design: i.e. realization, optimization and possible mass production of composite detectors
- thermal detector model for cryogenic composite detectors
- Neganov-Luke amplified composite light detectors
- self-grown $CaWO_4$-crystals that are optimized concerning radiopurity and light output
- determination of the exact quenching factor, i.e. the light output, for neutron-induced Ca, O and W recoils

Composite Detector Design (CDD)

- realization, optimization and possible mass production of composite detectors

shadow mask for production of several TESs at the same time



example of a realized and tested composite detector

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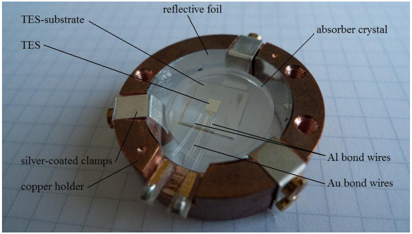


example of a realized and tested composite detector

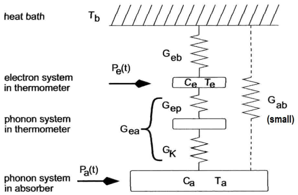
in order to optimize and tailor composite detectors to the requirements of dark matter experiments a detailed understanding of the signal evolution and detector response is required

$\Rightarrow$ thermal detector model for cryogenic composite detectors

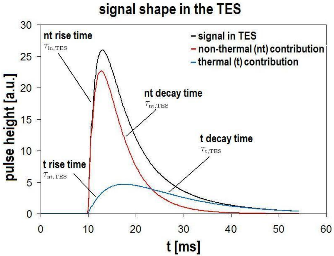
Thermal detector model for cryogenic composite detectors:

- basic thermal model

Modelling of the detector response (pulse shape) dependent on basic detector components [F.Proebst et al., J. Low Temp. Phys. **100**, 69 (1995)]



model of a cryogenic detector with the TES directly deposited on the surface in terms of its thermal components



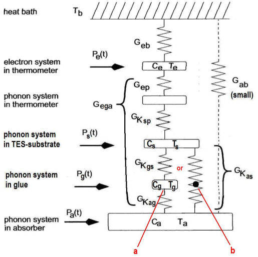
signal shape in the TES of a cryogenic detector with the TES directly deposited on the surface

non-thermal phonons and thermal phonons lead to the observed signal shape in the TES

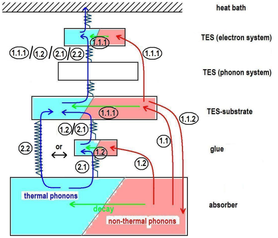
Thermal detector model for cryogenic composite detectors:

- thermal detector model for composite detectors

include glue and TES-substrate into the model: ⇒ influence of these components on the pulse shape (evolution and propagation of phonons)?



model of a composite cryogenic detector in terms of its thermal components



most relevant propagation possibilities for the non-thermal and thermal phonons

[S.Roth et al., Opt. Mat.**31** 1415 (2009)]

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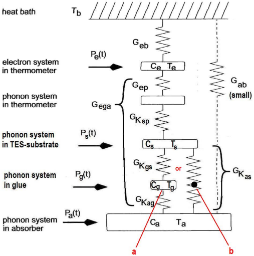

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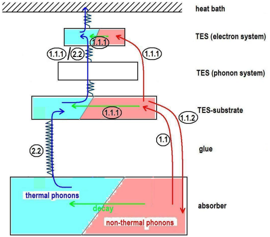


remaining non-thermal and thermal phonon propagation possibilities

[S.Roth et al., Opt. Mat.**31** 1415 (2009)]

Thermal detector model for cryogenic composite detectors:

- thermal detector model for composite detectors

what we learn from the model

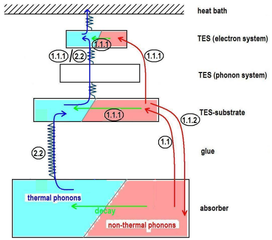
for phonon detectors:

- transparancy of the glue area for nt phonons
- TES-area should be $\geq$ glue area
- glue area *as large as possible* $\rightarrow$ however, consider light output and heat capacity

$\Rightarrow$ **built detectors with TES areas as for CRESST and glue areas of similar size**

$\rightarrow$ preliminary results of composite CRESST detectors (built in agreement with the model): exhibit comparable energy threshold and resolution as classical ones

[S.Roth et al., Opt. Mat.**31** 1415 (2009)]



remaining non-thermal and thermal phonon propagation possibilities

Neganov-Luke light detectors

- Neganov-Luke amplified composite light detectors

motivation:
only about 1% of the deposited energy is detected as light, for W nuclear recoils the light yield is even suppressed by a factor of 40!!

$\longrightarrow$ background discrimination ability of detector modules is presently limited by threshold & resolution in the light channel
$\longrightarrow$ light detector performance has to be improved
$\Rightarrow$ **Neganov-Luke amplified light detectors**
C.Isaila, PhD thesis

[C.Isaila to be published]

Neganov-Luke light detectors

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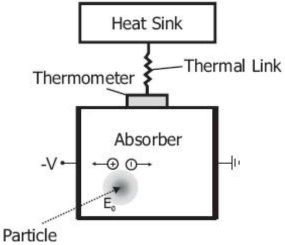

scheme of the Neganov-Luke principle

principle:
particle interaction in the absorber (semiconductor) creates free charge carriers
drifting charge carriers in an electric field generates phonons
total energy E_{tot} deposited in the absorber:

$$E_{tot} = \left(1 + \frac{eV}{\epsilon}\right) \cdot E$$

e = electron charge
E = energy of incident particle
V = applied voltage
ϵ = energy needed to create an electron-hole pair

[C.Isaila to be published]

Neganov-Luke light detectors

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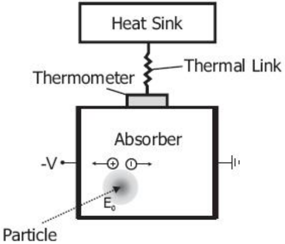
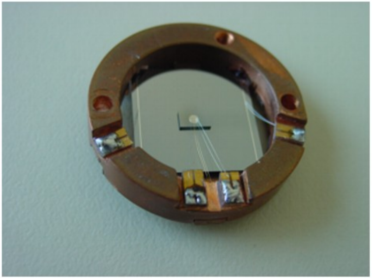


scheme of the Neganov-Luke principle

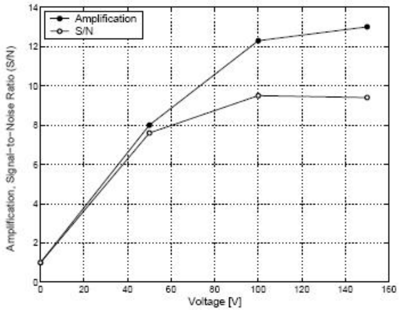


composite NL light detector (C. Isaila)

[C.Isaila to be published]

Neganov-Luke light detectors

- Neganov-Luke amplified composite light detectors



$\Rightarrow$ **improvement of the signal-to-noise ratio by a factor of 10!**

[C.Isaila to be published]

Conclusions

- CRESST presently running with 10 detector modules taking data
- EURECA design study starting
- detailed understanding of composite detectors
- consequences for future detector designs (EURECA)
- composite detector design successfully introduced in CRESST: best ($\sim$2 keV) discrimination threshold achieved with a $CaWO_4$ composite detector
- Neganov-Luke amplified light detectors: improvement of the signal-to-noise ratio by a factor of 10

The Commissioning Run

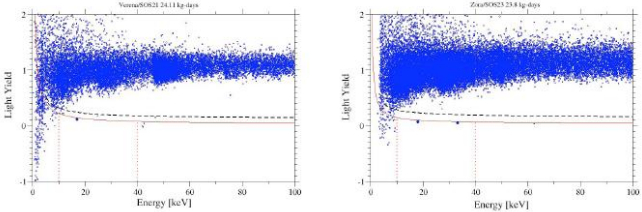
installation of:

- a detector carousel that can accommodate 33 detector modules
- a neutron shield
- a muon veto
- calibration source lift

after the run was finished:

- neutron calibration was carried out, supporting the principle of using the light yield to identify the recoiling nucleus

The Commissioning Run

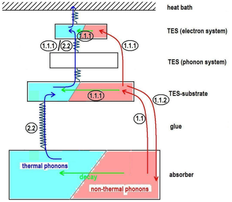


⇒ data taken between nov.2006-oct.2007 with two detector modules is used for the Dark Matter analysis:

- total exposure of 47.9 kg days
- three events remain in the tungsten recoil acceptance region corresponding to a rate of 0.063 per kg-day
- the origin of these events still not clarified: remaining neutrons (weak spot in the neutron shield or non-operational modules), cracks, incomplete coverage of the detector surrounding with scintillating material (surface-α decays with "escaped" α)
- reached sensitivity: $\sigma = 4.8 \cdot 10^{-7}$pb for M_{WIMP} ~50 GeV

Thermal Detector Model for Cryogenic Composite Detectors

on the basis of the pulse shape analysis of three different composite detectors (different absorber sizes and glue areas) ⇒ **identification of dominant contributions to the signal in the TES**



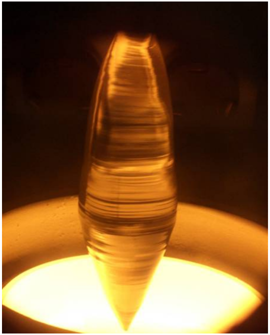
remaining non-thermal and thermal phonon propagation possibilities

main conclusions:

- **in every detector:**
  non-thermal contribution along path 1.1 → 1.1.1 (results in one decay time $\tau_{\mathrm{nt,as}}$) **and** glue is transparent for nt phonons
- **depending on the effective TES-to-glue-area ratio:**
  thermal contribution along path 2.2 from thermalisation in the absorber (results in a second decay time $\tau_{\mathrm{t,as}}$)

Self-grown $CaWO_4$-crystals

self-grown $CaWO_4$ single-crystals



Czochralski-system