Low temperature dark matter detectors

Federica Petricca
MPP Munich
Compelling evidence for dark matter on various cosmological scales
THE DARK MATTER PROBLEM

One model fits all the observations...

...but raises some fundamental questions:
What is dark matter?
What is dark energy?

Source: © European Space Agency / Planck
AFTER >80 YEARS...

• **Non-baryonic**
  Height of acoustic peaks in the CMB
  Power spectrum of density fluctuations
  Primordial nucleosynthesis

• **Cold (non-relativistic)**
  Structure formation

• **Interacts via gravity and (maybe) some sub-weak scale force**

• **STILL HERE!**
  Stable (or extremely long-lived)
Progress in ruling out parameter space resulted in a broadening of efforts

Experimental community struggling to gain sensitivity in a broad mass range with complementary approaches
II. SCIENCE CASE FOR A PROGRAM OF SMALL EXPERIMENTS

Given the wide range of possible dark matter candidates, it is useful to focus the search for dark matter by putting it in the context of what is known about our cosmological history and the interactions of the Standard Model, by posing questions like: What is the (particle physics) origin of the dark matter particles’ mass? What is the (cosmological) origin of the abundance of dark matter seen today? How do dark matter particles interact, both with one another and with the constituents of familiar matter? And what other observable consequences might we expect from this physics, in addition to the existence of dark matter?

Might existing observations or theoretical puzzles be closely tied to the physics of dark matter? These questions have many possible answers — indeed, this is one reason why...
FIG. 1: Mass ranges for dark matter and mediator particle candidates, experimental anomalies, and search techniques described in this document. All mass ranges are merely representative; for details, see the text. The QCD axion mass upper bound is set by supernova constraints, and may be significantly raised by astrophysical uncertainties. Axion-like dark matter may also have lower masses than depicted. Ultralight Dark Matter and Hidden Sector Dark Matter are broad frameworks. Mass ranges corresponding to various production mechanisms within each framework are shown and are discussed in Sec. II. The Beryllium-8, muon (\(g-2\)), and small-scale structure anomalies are described in VII. The search techniques of Coherent Field Searches, Direct Detection, and Accelerators are described in Secs. V, IV, and VI, respectively, and Nuclear and Atomic Physics and Microlensing searches are described in Sec. VII.
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WE LIVE IN A DARK MATTER HALO

Halo model:
• Velocity distribution
• Earth’s velocity around the Sun
• Sun’s velocity around the center of the Galaxy
• Local dark matter density

From Cosmology: Dark matter and dark energy
Robert Caldwell & Mire K famousowski
Nature 458, 587-590 (2 April 2009)
doi:10.1038/nsr2009-5
Basic idea
Dark matter is made of particles
which interact with Standard Model particles

Most common scenario
Dark matter particles scatter off nuclei:
• elastically
• coherently: \( \sim A^2 \)
• (spin-independent)

\[
\frac{dR}{dE_r} \propto \frac{\rho_0}{m_\chi \mu^2} \sigma_0 F^2(E_r)
\]

\[
v_{\text{esc}} \int d^3v \frac{f(\tilde{v})}{\nu} \]

\[
v_{\text{min}}(E_r) = \sqrt{\frac{E_r m_N}{2 \mu^2}}
\]
DIFFERENTIAL INTERACTION RATE

\[ \frac{dR}{dE_R} \propto \frac{\rho_0}{m_\chi \mu^2} \sigma_0 F^2(E_R) \]

\[ \nu_{\text{esc}} \int d^3 \nu \frac{f(\bar{\nu})}{\nu} \]

\[ \nu_{\text{min}}(E_R) = \sqrt{\frac{E_R m_N}{2 \mu^2}} \]

Low temperature dark matter detectors

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Credit: ESO/L. Calçada
At large dark matter masses, sensitivity is dominated by exposure - **target mass**

At light dark matter masses, sensitivity is dominated by performances - **energy threshold**
At large dark matter masses sensitivity is dominated by exposure
- **target mass**

At light dark matter masses sensitivity is dominated by performances
- **energy threshold**
EXPERIMENTAL CHALLENGES

Dark matter recoil spectrum: CaWO$_4$ target, ideal detector

Very rare current limit* $\mathcal{O}(0.01)$ counts/tonne day

Featureless spectrum

Small recoil energies
~ keV range

MINIMISING BACKGROUND

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

Low radioactivity materials for detector hardware

Water/plastic+scintillator
DIRECT DARK MATTER SEARCHES

An incomplete compilation

Dual phase noble liquids:
- XENON1T/nT
- LUX/LZ
- Panda-X
- ArDM
- DarkSide

Inorganic scintillators:
- DAMA/LIBRA
- ANAIS
- COSINE
- SABRE
- KIMS

Single phase noble liquids:
- DEAP
- XMASS

Scintillation ~1-5%

Scintillating calorimeters:
- CRESST
- COSINUS

Ionization ~10%

Semiconductors:
- CDEX
- COGENT
- DAMIC
- SENSEI

Gas:
- NEWS-G
- MIMAC
- DRIFT
- DMTPC

Superheated liquids:
- PICO

Heat/Phonons ~100%

Semiconducting calorimeters:
- SuperCDMS
- EDELWEISS

22 July 2019

Low temperature dark matter detectors
CALORIMETERS

Heat link
Thermometer
Absorber
Particle interaction

heat bath ≈ 10 mK

\[ \Delta T = \frac{\Delta E}{C} \]

- Direct measurement of the full energy deposition
- Cryogenic temperatures
Pros:
- Total energy measurement
  - Phonon signal (almost) not quenched
- Excellent energy resolution
  - Detailed study of dark matter signal
  - Detailed study of background sources
- Low threshold (sub-keV for nuclear recoils)

Cons:
- Small detectors ($O(10 \text{ to few 100g})$)
  - Small exposures
- Complex technology
**SEMICONDUCTING CALORIMETERS**

Phonon + Ionization
EDELWEISS, SuperCDMS

- **Heat:** \( \Delta T = E/C_{cal} \)

- **Ionization:** \( N_{pairs} = E/\varepsilon_{\gamma} \) or \( \varepsilon_{n} \)

**Low bias voltage (iZIP, FID):**
- Phonon and charge sensors on both sides
- Particle identification via ratio of ionization to primary phonon
- Fiducialization

**Figure 11.** Ionization yield versus recoil energy for a large statistics (> \( 3 \times 10^4 \)) of events from a neutron calibration using an AmBe source. The two red (blue) solid lines delimit the 90% C.L. nuclear (electron) recoil band. Purple dashed lines correspond to inelastic scattering of neutrons on the first (13.28 keV) or the third (68.75 keV) excited state of \( ^{73}Ge \).

The AmBe source also emits high energy \(-\)rays of 4.4 MeV which lose energy via Compton scattering, leading to the population of events distributed around \( <Q(E_r) > = 1 \). Events between...
**SEMICONDUCTING CALORIMETERS**

Phonon + Ionization  
EDELWEISS, SuperCDMS  

**Heat:** $\Delta T = E/C_{\text{cal}}$  

**Ionization:** $N_{\text{pairs}} = E/\varepsilon_{\gamma}$ or $\varepsilon_n$

**High bias voltage:**  
Charge mediated phonon amplification (Neganov-Trofimov-Luke Effect)  
- Gain in threshold  
- Dilution of background from electron recoil events  
- Reduced discrimination

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Low temperature dark matter detectors
SEMICONDUCTING CALORIMETERS

Phonon + Ionization
EDELWEISS, SuperCDMS

New SuperCDMS
SNOLAB Detectors

TES phonon channels optimized differently for the two techniques, both in channel arrangement and in patterning on the surfaces.

Fast but technologically complicated

100mm diameter, 33mm thick
Ge 1400g per detector
Si 600g per detector
**SEMICONDUCTING CALORIMETERS**

Phonon + Ionization
EDELWEISS, SuperCDMS

**EDELWEISS-III FID**

NTD phonon channels on each surface
Slow but technologically simple
70mm diameter, 40mm thick
Ge 870g per detector

**EDELWEISS high-voltage R&D program**

NbSi209: 200g Ge with TES thermal sensor

RED30: 33 g Ge Al electrodes, NTD thermal sensor
SCINTILLATING CALORIMETERS

Phonon + Light

CRESST: Scintillating crystals as target

- Target crystals operated as cryogenic calorimeters (~15mK)
- Separate cryogenic light detector to detect the scintillation light signal
SCINTILLATING CALORIMETERS

Phonon + Light
CRESST

CRESST-III
Layout optimized for low-mass dark matter
TES phonon sensor on target crystal
TES phonon sensor on light detector absorber

Absorber crystal $(20 \times 20 \times 10) \text{mm}^3$
CaWO$_4$ 24g
Light detector absorber $(20 \times 20 \times 0.4) \text{mm}^3$
Silicon-on-Sapphire

Nuclear recoil threshold of 30.1 eV
Resolution at zero energy $\sigma = 4.5 \text{eV}$
SEMICONDUCTORS vs. SCINTILLATORS

Pros:
- Ultrapure material
- Identification of surface events
  - Fiducialization

Cons:
- Limited choice of materials
- In high-voltage require model to derive energy scale of nuclear recoils

Pros:
- Total energy measurement at low threshold
- Large choice of material
  - Multi element target
- No surface effects (in selected materials)

Cons:
- Independent cryogenic light detector to detect the scintillation light signal
  - Increase number of channels
- No fiducialization
- Non-commercial materials

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Basic idea
Dark Matter Axions convert to photons in a magnetic field through the inverse Primakoff effect

Resonating cavities
The conversion rate is enhanced if the photon’s frequency corresponds to a cavity’s resonant frequency

\[ P \propto g^2 \gamma \gamma \frac{\rho a}{m_a} B_0^2 V C Q \]
AXION HALOSCOPES

Material courtesy ADMX collaboration

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Low temperature dark matter detectors

Key technologies:
- millikelvin cryogenics
- ultralow noise quantum amplifiers

Review of direct Dark Matter searches
CSN2, 8 aprile 2019, Siena

P \propto g_{a \gamma \gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C Q

PRELIMINARY

Preliminary Sensitivity from 2018 Run
We estimate sensitivity to DFSZ dark matter axions between 2.8 and 3.3 ueV
This is four times as much mass range with much more even DFSZ coverage.

3 Gaps from mode crossings in cavity.

Paper in preparation!

Dark: Maxwell-Boltzmann Lineshape, Light: N-Body Lineshape

Credit: ESO/L. Calçada
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Posters

Contribution ID : 21 Diamond Detectors for Direct Detection of Sub-GeV Dark Matter
Contribution ID : 56 SuperCDMS HV Detector R&D
Contribution ID : 71 Impact Ionization in SuperCDMS HVeV Detectors
Contribution ID : 85 Overview of SuperCDMS Experiment
Contribution ID : 86 SuperCDMS IMPACT: an Ionization Yield Calibration Program
Contribution ID : 89 Large Area TES Chip with 40meV Resolution
Contribution ID : 103 Low temperature measurement on directional dependence of phonon-scintillation signals from a zinc tungstate crystal
Contribution ID : 115 Development of TES microcalorimeters for solar axion search
Contribution ID : 121 Development of large array of Kinetic Inductance Detectors using commercial level foundry
Contribution ID : 133 Lithium-containing crystals for light dark matter search experiments in underground laboratories
Contribution ID : 145 Diamond cryogenic detector for low-mass Dark Matter searches
Contribution ID : 168 COSINUS: Cryogenic calorimeter for the direct dark matter search with NaI crystals
Contribution ID : 187 NEXUS@FNAL
Contribution ID : 191 High Voltage New Interface Studies
Contribution ID : 218 Development of low threshold detectors for light dark matter detection
Contribution ID : 220 New Approaches to Very Low-energy Calibration of Cryogenic Detectors
Contribution ID : 248 Dynamic characterization of cryogenic optical photon detectors with Ir/Pt bilayer transition edge sensors
Contribution ID : 269 Modeling low-Tc Transition-Edge Sensors Made of Multi-layer Metal Films: Thickness Dependence of Electron Transparency at Interfaces
Contribution ID : 274 Kinetic inductance detectors on CaF2 for spin-dependent dark matter search
Contribution ID : 288 The Dark Matter Radio Pathfinder
Contribution ID : 290 BULLKID - Bulky and low-threshold kinetic inductance detectors
Contribution ID : 303 Optimizing Readout for Nuclear Magnetic Resonance Axion Searches
Contribution ID : 305 Quantum Sensors for Quantum Coherent Dark Matter Detectors
Contribution ID : 312 HeRALD, a new detector concept for light dark matter direct detection
Contribution ID : 336 Development of MMC based combined photon and phonon detector for rare event searches
Contribution ID : 376 Development of Ge bolometers using NbSi transition edge sensors for the EDELWEISS and RICOCHET projects
Contribution ID : 386 Noise temperature measurements for Axion haloscope experiment at CAPP
Contribution ID : 388 Status of the SIMP project: Towards the Single Microwave Photon Detection
Contribution ID : 403 Innovative technique for large scale production of W-TES
Contribution ID : 409 Progress on a KID-Based Phonon-Mediated Dark Matter Detector
Low temperature dark matter detectors have a unique potential to explore the unknown!