Cryogenic Semiconductor Detectors for Dark Matter searches

Enectalí Figueroa-Feliciano
Northwestern
Cryogenic Semiconductor Detectors for Dark Matter searches

Enectalí Figueroa-Feliciano
Northwestern
Outline

- Cryogenic Crystal Detector Basics
- Applications
  - Dark Matter: Direct Detection
  - Dark Matter: Indirect Detection
  - Neutrino Physics
Cryogenic Crystal Detectors are used in...

- Astrophysics
  - mm to gamma-ray energies
- Particle Physics
  - Dark Matter Detectors
  - Neutrino Physics
- Materials-analysis
- Others!
Why Use Cryogenic Detectors?

Cryogenic microcalorimeters can provide a unique combination of energy sensitivity, low thresholds, and efficiency.
Cryogenic Crystal Detectors

The Phonon Channel

Thermometer

Absorber

Weak Thermal Link

Refrigerator
10–40 mK

Temperature

Time
Cryogenic Crystal Detectors

The Phonon Channel

Thermometer

Absorber

Weak Thermal Link

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10–40 mK

Temperature

Time
Cryogenic Crystal Detectors

The Phonon Channel

Thermometer

Absorber

Weak Thermal Link

Refrigerator

10–40 mK

The height of the pulse is proportional to the energy deposited

Temperature

Time
• Refrigerator temperature has to be close to absolute zero

• Thermometer is a Superconducting Transition-Edge Sensor (TES)

• Readout is done with Superconducting Quantum Interference Devices (SQUIDs)
Dark Matter: Direct Detection
Dark Matter Detection Channels
Dark Matter Detection Channels

Dark Matter Mass

feV, peV, neV, μeV, meV, eV, keV, MeV, GeV, TeV, PeV
Dark Matter Detection Channels

ALPs  Axions  Sterile \nu's  WIMPs

\text{feV}  \text{peV}  \text{neV}  \mu\text{eV}  \text{meV}  \text{eV}  \text{keV}  \text{MeV}  \text{GeV}  \text{TeV}  \text{PeV}

Dark Matter Mass
Dark Matter Detection Channels

Hidden Sector Particles

ALPs  Axions  Sterile $\nu$'s  WIMPs

Dark Matter Mass

feV  peV  neV  $\mu$eV  meV  eV  keV  MeV  GeV  TeV  PeV
Dark Matter Detection Channels

Hidden Sector Particles

ALPs
Axions
Sterile $\nu$’s
WIMPs

Dark Matter Mass

feV peV neV $\mu$eV meV eV keV MeV GeV TeV PeV

Nuclear Recoils
Dark Matter Detection Channels

Hidden Sector Particles

ALPs        Axions        Sterile V’s        WIMPs

\begin{array}{llllllllllll}
\text{feV} & \text{peV} & \text{neV} & \mu\text{eV} & \text{meV} & \text{eV} & \text{keV} & \text{MeV} & \text{GeV} & \text{TeV} & \text{PeV} \\
10^{-46} & 10^{-40} & 10^{-34} & 10^{-28} & 10^{-22} & 10^{-16} & 10^{-10} & 10^{-4} & 10^2 & 10^5 & 10^5 \\
\end{array}

Dark Matter Mass

Max Recoil Energy in Silicon [eV]

Nuclear Recoils
Dark Matter Detection Channels

Hidden Sector Particles

ALPs | Axions | Sterile V’s | WIMPs

<table>
<thead>
<tr>
<th>feV</th>
<th>peV</th>
<th>neV</th>
<th>μeV</th>
<th>meV</th>
<th>eV</th>
<th>keV</th>
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<td>$10^{-4}$</td>
<td>$10^2$</td>
<td>$10^5$</td>
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</tr>
</tbody>
</table>

Max Recoil Energy in Silicon [eV]

| $10^{26}$ | $10^{23}$ | $10^{20}$ | $10^{17}$ | $10^{14}$ | $10^{11}$ | $10^8$ | $10^5$ | $10^2$ | $10^{-1}$ | $10^{-4}$ |

Dark Matter Particle Density per Liter

Nuclear Recoils
Dark Matter Detection Channels

Hidden Sector Particles

ALPs  Axions  Sterile V’s  WIMPs

- Dark Matter Mass
  - feV  peV  neV  μeV  meV  eV  keV  MeV  GeV  TeV  PeV
  - $10^{-41}$  $10^{-35}$  $10^{-29}$  $10^{-23}$  $10^{-17}$  $10^{-11}$  $10^{-5}$  $10^{0}$  $10^{1}$  $10^{1}$  $10^{1}$

- Max Electron Recoil Energy [eV]
  - $10^{26}$  $10^{23}$  $10^{20}$  $10^{17}$  $10^{14}$  $10^{11}$  $10^{8}$  $10^{5}$  $10^{2}$  $10^{-1}$  $10^{-4}$

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Electron Recoils  Nuclear Recoils
## Dark Matter Detection Channels

### Hidden Sector Particles

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<tr>
<th>ALPs</th>
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<table>
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<tr>
<th>$\text{meV}$</th>
<th>$\text{eV}$</th>
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<td>$10^{12}$</td>
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</table>

**Dark Matter Mass**

**Max Electron Recoil Energy [eV]**

**Mean Distance Between Particles [m]**

**Dark Matter Particle Wavelength [m]**

**Electron Recoils**

**Nuclear Recoils**
### Dark Matter Detection Channels

**Hidden Sector Particles**

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**Electron Recoils**

**Nuclear Recoils**
Dark Matter Detection Channels

Hidden Sector Particles

ALPs | Axions | Sterile \( \nu \)'s | WIMPs

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Coherent/Resonant Detection | Electron Recoils | Nuclear Recoils
Nuclear Recoils

WIMPs, etc.
Interaction Rate
(events/keV/kg/day)

\[
\frac{dR}{dE_R} = \frac{\sigma_o}{m_\chi} \frac{F^2(E_R)}{m_r^2} \frac{\rho_o T(E_R)}{v_o \sqrt{\pi}}
\]
Principles of Particle Detection

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Interaction Rate
[events/keV/kg/day]
Principles of Particle Detection

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\]

\[m_r = \frac{m_\chi m_N}{m_\chi + m_N}\]

“reduced mass”
Different Energy Deposition Channels

- Phonons
  - 10 meV/ph
  - 100% energy

- Scintillation
  - ~ 1 keV/γ
  - few % energy

- Ionization
  - ~ 10 eV/e
  - 20% energy
Different Energy Deposition Channels

- **Phonons**
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Different Energy Deposition Channels

- **Phonons**: 10 meV/ph, 100% energy
- **Scintillation**: ~1 keV/γ, few % energy
- **Ionization**: ~10 eV/e, 20% energy
Different Energy Deposition Channels

- **Phonons**
  - Energy deposition: 10 meV/ph
  - Efficiency: 100%
  - Materials: CRESST I, CUORE, TeO₂, Al₂O₃, LiF

- **Scintillation**
  - Energy deposition: ~1 keV/γ
  - Efficiency: few %

- **Ionization**
  - Energy deposition: ~10 eV/e
  - Efficiency: 20%
Different Energy Deposition Channels

- **Phonons**
  - 10 meV/ph
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**Materials**:
- CRESST I
- CUORE
- TeO$_2$, Al$_2$O$_3$, LiF
- CRESST I
- CUORE
- TeO$_2$, Al$_2$O$_3$, LiF
- ANAIS
- CoGeNT
- COSME
- COUPP
- DM-TPC
- DRIFT
- IGEX
- Ge, CS$_2$, C$_3$F$_8$
Different Energy Deposition Channels

**Phonons**
- 10 meV/ph
- 100% energy

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- ~1 keV/\(\gamma\)
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- ~10 eV/e
- 20% energy

**Materials**
- TeO\(_2\), Al\(_2\)O\(_3\), LiF
- Ge, CS\(_2\), C\(_3\)F\(_8\)

**Experiments**
- CLEAN
- DAMA
- DEAP
- NAIAD
- ZEPLIN I
- XMASS
- Xe, Ar, Ne
- NaI(Tl)

- ANAIS
- CoGeNT
- COSME
- COUPP
- DM-TPC
- DRIFT
- IGEX

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Different Energy Deposition Channels

Phonons
- 10 meV/ph
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Ionization
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- 20% energy

Scintillation
- ~ 1 keV/γ
- few % energy

CDMS
- EDELWEISS
  - Ge, Si

ANAIS
- CoGeNT
- COSME
- COUPP
- DM-TPC
- DRIFT
- IGEX
  - Ge, CS₂, C₃F₈

CRESST I
- CUORE
  - TeO₂, Al₂O₃, LiF

CLEAN
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Different Energy Deposition Channels

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  - 20% energy

**Materials and Technologies**

- **Phonons**
  - CRESST I
  - CUORE
  - TeO$_2$, Al$_2$O$_3$, LiF

- **Scintillation**
  - ArDM
  - DarkSide
  - LUX
  - WArP
  - XENON
  - ZEPLIN II, III
  - Xe, Ar, Ne

- **Ionization**
  - CDMS
  - EDELWEISS
  - Ge, Si

- **Clean**
  - CLEAN
  - DAMA
  - DEAP
  - NAIAD
  - ZEPLIN I
  - XMASS
  - Xe, Ar, Ne
  - NaI(Tl)

- **CoGeNT**
  - CDMS
  - EDELWEISS
  - Ge, Si

- **LUX**
  - ArDM
  - DarkSide
  - LUX
  - WArP
  - XENON
  - ZEPLIN II, III
  - Xe, Ar, Ne

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Different Energy Deposition Channels

**Phonons**
10 meV/ph
100% energy

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**Ionization**
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20% energy

**CRESST I**
**CUORE**
TeO₂, Al₂O₃, LiF

**CRESST ROSEBUD**
CaWO₄, BGO,
ZnWO₄, Al₂O₃ ...

**CDMS EDELWEISS**
Ge, Si

**ArDM DarkSide**
**LUX**
**WArP**
**XENON**
**ZEPLIN II, III**
Xe, Ar, Ne

**ANAIS CoGeNT**
**COSME**
**COUPP**
**DM-TPC**
**DRIFT**
**IGEX**
Ge, CS₂, C₃F₈

**CLEAN DAMA DEAP NAIAD ZEPLIN I XMASS Xe, Ar, Ne NaI(Tl)**

**CLEAN DAMA DEAP NAIAD ZEPLIN I XMASS Xe, Ar, Ne NaI(Tl)**
Other ways of attaining Particle Identification

• Pulse-Shape Discrimination
  • e.g., scintillation timing (DEAP/CLEAN, DarkSide, etc…)

• Nuclear-recoil-only trigger mechanism
  • (a la COUPP, PICASSO, PICO…)

• Self-Shielding (XMASS)

• Others…
To Neutrinos, and Beyond!

F. Ruppin, J. Billard, EFF, L. Strigari: 1408.3581
To Neutrinos, and Beyond!

![Graph showing WIMP mass versus nucleon cross section.](image)

F. Ruppin, J. Billard, EFF, L. Strigari: 1408.3581

- Neutrino Background
- DAMIC
- CRESST-II
- CDMS-II
- SuperCDMS
- CDMS-Lite
- LUX 2015
- XENON100
- DarkSide-50
- DAMA-EDLWESS
- WIMP-nucleon cross section [pb]
To Neutrinos, and Beyond!

WIMP–nucleon cross section [cm$^2$]

WIMP–nucleon cross section [pb]

WIMP Mass [GeV/$c^2$]

Neutrino Background

F. Ruppin, J. Billard, EFF, L. Strigari: 1408.3581
Cryogenic Crystal Detectors: Looking for Low-mass WIMPs

Phonons
- 10 meV/ph
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CRESST I
CUORE
TeO$_2$, Al$_2$O$_3$, LiF

CRESST ROSEBUD
CaWO$_4$, BGO, ZnWO$_4$, Al$_2$O$_3$, ...

CDMS EDELWEISS
Ge, Si

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**SuperCDMS SNOLAB**

<table>
<thead>
<tr>
<th>CDMS II</th>
<th>SuperCDMS Soudan</th>
<th>SuperCDMS SNOLAB</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.6 kg Ge (19 x 240 g)</td>
<td>9.0 kg Ge (15 x 600g)</td>
<td>Funded G2 Experiment</td>
</tr>
<tr>
<td>1.2 kg Si (11 x 106g)</td>
<td>3” Diameter</td>
<td>Data Taking in 2020</td>
</tr>
<tr>
<td>3” Diameter</td>
<td>2.5 cm Thick</td>
<td>30 kg Ge (22 x 1.4 kg)</td>
</tr>
<tr>
<td>1 cm Thick</td>
<td>2 charge + 2 charge</td>
<td>5 kg Si (8 x 0.6 kg)</td>
</tr>
<tr>
<td></td>
<td>4 phonon + 4 phonon</td>
<td>4” Diameter</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3.3 cm Thick</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 charge + 2 charge</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6 phonon + 6 phonon</td>
</tr>
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- 2 charge + 4 phonon
- 2 charge + 2 charge
- 4 phonon + 4 phonon
- 2 charge + 2 charge
- 6 phonon + 6 phonon
SuperCDMS SNOLAB @ the Ladder Lab

- Passive Shielding or Active neutron shield (under consideration) to achieve 0.1 /kg/keV/day background rate on Ge Towers. Much cleaner cryostat than CDMS II @ Soudan
SuperCDMS Detectors: iZIPs

- Ge (1.4 kg per detector)
- Si (0.6 kg per detector)
- 4” Diameter
- 3.3 cm Thick
- 2 charge + 2 charge
- 6 phonon + 6 phonon
SuperCDMS Soudan iZIPs

8 phonon channels +
4 charge sensors =
Lots of information per event!

“interwoven” phonon and charge on each side!
Getting Energy to the Athermal Phonon Sensors

Phonon TES rails
Charge electrode

Bias+
Al
Al
Al
Al
Bias-

Al Collection Fin

Quasiparticles transport energy to the TES
Trapping region

Cooper pairs
Hot TES electrons

Athermal phonon

Hot TES electrons

R

T

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SuperCDMS High-Voltage Operation

CDMSlite: CDMS low ionization threshold experiment
SuperCDMS High-Voltage Operation

E field

prompt phonons

h+

e−
SuperCDMS High-Voltage Operation
SuperCDMS High-Voltage Operation

Phonon energy = \( E_{\text{recoil}} + E_{\text{Luke}} \)

= \( E_{\text{recoil}} + n_{\text{eh}} e^- \Delta V \)
Phonon sensors measure amount of charge produced:
Phonon-based charge amplification!

\[
\text{Phonon energy} = E_{\text{recoil}} + E_{\text{Luke}} \\
= E_{\text{recoil}} + n_{eh} e^- \Delta V
\]
SuperCDMS SNOLAB HV Detector Design

Soudan: asymmetric vs. symmetric bias

+70V, 0V bias

+35V, -35V bias

maximize phonon radial position reconstruction information

Symmetric HV bias at +/- 50V to maximize fiducial volume

Uniform coverage phonon sensors to maximize energy collection

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Better Phonon Sensitivity with Lower $T_c$!
- CRESST: phonon + light
- Current Experiment: CRESST Phase 2 ongoing
- New CRESST Phase III detectors focused on low-mass WIMPs

**CRESST**

Light detector (with TES)
Reflective and scintillating housing
Target crystal

Heat Bath

TES
Thermal coupling
CRESST

- New CRESST Phase III detectors focused on low-mass WIMPs
- Design Goal: Threshold of 100 eV. How? Smaller Crystals!
- Going from 250g in CRESST II to 24g in CRESST III
• EDELWEISS: phonon + charge

• 36 x 800 g detectors installed in cryostat; results later this year

• New runs with better sensitivity to light WIMPS using High Voltage operation coming soon.
To the Neutrino Background… and Beyond!

WIMP–nucleon cross section [cm$^2$] vs. WIMP Mass [GeV/$c^2$]

- CDMSlite II
- CRESST II
- Ge-iZIP
- CRESST 50kgd
- CRESST 1000kgd
- LUX 2015

WIMP–nucleon cross section [pb]
Electron Recoils
How do we look for DM with electron recoils?

- Pretty much all experiments that look for nuclear recoils also see electron recoils!

- Single electron sensitivity expected in both liquid noble and crystal experiments.

- The main issues are threshold, fiducialization, dark currents, and lowering backgrounds.

- Using materials with a band gap or even quasiparticles in superconductors can drastically reduce the threshold!

![Graph showing freeze-in, DM with ultralight dark photon](image)

arXiv: 1509.01598
X-ray Astrophysics
Requirements

- High Energy Resolution
- High Quantum Efficiency
- High Count Rate
- Close-packing of pixels
- Large Arrays (megapixels desired)
Anatomy of an X-ray TES

Side View

Top View

150 \mu m
Anatomy of an X-ray TES
Anatomy of an X-ray TES

Side View

Top View

TES

Superconducting leads

150 µm
Anatomy of an X-ray TES

Si wafer: in good thermal contact with refrigerator

Top View

150 µm

Superconducting leads

Side View
Anatomy of an X-ray TES

Side View

- TES
- Superconducting leads
- 1 μm silicon nitride membrane is the weak thermal link (G)
- Si wafer: in good thermal contact with refrigerator
- Top View
- 150 μm
Anatomy of an X-ray TES

Si wafer: in good thermal contact with refrigerator

1 μm silicon nitride membrane is the weak thermal link (G)

Superconducting leads

Side View

Top View

150 μm
Anatomy of an X-ray TES

A 300-nm-thick TES has low x-ray stopping efficiency:

- 58% @ 1.5 keV
- 22% @ 6 keV

Si wafer: in good thermal contact with refrigerator

1 μm silicon nitride membrane is the weak thermal link (G)

150 μm
Anatomy of an X-ray TES

Si wafer: in good thermal contact with refrigerator

1 μm silicon nitride membrane is the weak thermal link (G)

150 μm

Superconducting leads

Side View

Top View
X-ray TESs

Side View

Top View

Mushroom Absorber

TES

150 µm

250 µm
Transition-edge sensor arrays

- NASA Goddard Space Flight Center TES Arrays
  - Mo/Au Bilayer, target $T_C \sim 90$ mK, suspended on SiN (~ 1 $\mu$m).
  - Au/Bi electroplated absorbers, microstrip wiring, Cu backside layer for heat sinking.
  - Prototype 32x32 array (250 $\mu$m pitch) will be used for initial Athena technology demonstrations.

Fully wired 32x32 array (8x8 mm$^2$) with 64 pixels connected to bond pads on each side
Transition-edge sensor arrays

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Fully wired 32x32 array (8x8 mm\(^2\)) with 64 pixels connected to bond pads on each side

Combined spectrum from 26 pixels simultaneously read out (multiplexed)
Dark Matter: Indirect Detection
Sterile Neutrinos

- Sterile neutrinos are a natural way of giving the known neutrino species mass. IF sterile neutrinos exist, and one of them has a mass between a few keV and 100 keV, it could constitute some or all of the dark matter.

- Sterile neutrinos may decay to a photon and active neutrino via loop-suppressed processes.

\[
\Gamma = \frac{9\alpha G_F^2 m_s^5 \sin^2 2\theta}{1024\pi^4} \\
= (1.38 \times 10^{-29} \text{ s}^{-1}) \left( \frac{\sin^2 2\theta}{10^{-7}} \right) \left( \frac{m_s}{1 \text{ keV}} \right)^5
\]
MW Sterile Neutrino Signal - FOV is important!

- The signal from sterile neutrino decay would be a line at half the energy of the sterile neutrino.

- The flux goes as the number of dark matter particles in your FOV. Estimates depend on assumed MW DM profile.

\[ F = \frac{\Gamma}{m_s} \frac{1}{4\pi} \int_{F_{\text{FOV}}}^{\infty} \int_{0}^{\infty} \rho(r(\ell, \psi)) \, d\ell \, d\Omega \]

\[ r(\ell, \psi) = \sqrt{\ell^2 + d^2 - 2\ell d \cos \psi} \]
Astro-H / Hitomi

February 17—March 26 2016
The FOV limited its ability to look for the all-sky signal expected from sterile neutrino decay in the Milky Way (although it was certainly going to look!)

Extragalactic sources from galaxy clusters to dwarf spheroidals were better fits to its FOV.
Astro-H SXS Microcalorimeter Perseus Simulation

arXiv:1607.07420

- Although Hitomi did make an observation of Perseus, it was through the gate valve filter and for a short exposure, so the "effective" exposure at 3.5 keV will be only about 8% of the desired 1Ms observation.

  - Baseline Effective Area: ~200 cm$^2$
  - Gate Valve Closed Area: ~70 cm$^2$
  - Raw exposure: 230 ks

- Not sensitive enough to conclusively settle the issue!
Sounding Rocket Payloads for Sterile Neutrino Searches

arXiv:1506.05519
Sounding Rocket Payloads

• 300 seconds of on-target data above 169 km

• High resolution X-ray microcalorimeter with $\sim 1 \text{cm}^2$ area and large $\sim$steradian FOV

• Flights from White Sands Missile Range in New Mexico and Woomera Range in Australia
The XQC Rocket Payload

- Mature flight system flown 6 times between 1995 and 2014
- Si Thermistor Microcalorimeter array with 36 pixels, each with a 2mm x 2mm x 0.96μm HgTe absorber on a 14μm Si substrate
- Baseline energy resolution is 11 eV FWHM, 23 eV FWHM at 3.53 keV.
- 1 steradian FOV ~ 1900 arcmin radius
Analysis of XQC Data

- Analyzed data from 5th flight of XQC, which flew Nov 6 2011.
- 1 steradian FOV centered on Galactic coords l=165, b=-5, close to Galactic anti-center.
- About 300 seconds of on-target data were acquired at altitudes above 160 km, of which 200 s of data on 29 pixels were analyzed. After quality cuts, the effective exposure is 106 s.
- Future analysis of entire XQC data set from all flights will increase the exposure by a factor of about 5.
All-sky X-ray map from the MAXI/GSC on International Space Station
Fit to XQC Data

Diffuse X-ray Background (Hickox & Markevitch 2006)
Crab (Mori et al 2004)
Calibration Source (model from pre-flight calibration data)
Cosmic Rays (GEANT4 simulation)
X-rays hit both the HgTe absorber and its Si substrate.
XQC Analysis Results

- Not sensitive enough to rule out Boyarski’s MW detection claim... will analyze existing archival data to gain a factor of around 5 in exposure
The Micro-X Sounding Rocket

- Micro-X Science Instrument
- Black Brant IX Second Stage
- Terrier First Stage
- S19
- Telemetry
- ACS
- ORSA
- Electronics
- TES
- Microcalorimeter
- Cryostat
- Optical Bench
- X-ray Mirror
The Micro-X Sounding Rocket

- Payload under development. First flight less than a year away!

- TES Microcalorimeter array with 128 pixels, each with a 0.9mm x 0.9mm x (3μm Bi + 0.7μm Au) absorber

- Baseline energy resolution is 3-4 eV FWHM, flat out to 6-7 keV.

- 0.38 steradian FOV ~ 1200 arcmin radius, expect to increase to 1 sr in the future.

- For sterile neutrino searches, we will fly the payload without the mirror to obtain a large FOV and thus greater grasp:
  - With mirror, grasp = 38 cm² deg²
  - Without mirror, grasp = 1256 cm² deg²
Microcalorimeters for Micro-X

- Absorber Standoffs
- SiN$_4$ Membrane
- Perforations in membrane = Weak thermal link
- Au/Bi Absorber
- TES thermometer (yellow)
- Back-Etched Silicon Wafer
Micro-X Microcalorimeter Array

Pixel array:
12 x12 = 7.2mm / side
Micro-X Microcalorimeter Array

Pixel array:
12 x12 = 7.2mm / side
Micro-X Focal Plane
Micro-X Focal Plane
Focal Plan inside Superconducting Shield
Superconducting Shield
In-flight Calibration

Custom-designed gain calibration source provides counts above the science spectral band. Target rate is 1 count/sec/pixel.
FOV for Micro-X GC Observation

- Micro-X Field 1
- XQC
- Sco-X1
- Micro-X Field 2
- Micro-X Field 3
- Crab
Sterile Neutrino Bounds

X-ray Constraints

Boyarski et al 2006

This work: XQC

Micro-X Projection
Current Micro-X Status Report

- The payload has passed all functional tests, including vibration tests, SQUID multiplexing and ADR control.

- Micro-X is undergoing Detector Qualification Testing at NASA Goddard Space Flight Center.

- We expect a launch later this year, first dark matter observation in 2018, either from White Sands or Australia.

Currently hunting down electronics noise.

4.5 eV detectors
Hydra Concept Complex TES

Figure 4. *Left:* Schematic diagram of the Hydra concept, showing nine absorbers, each with a different thermal conductance, connected to a single TES. Each absorber is supported above the TES and solid substrate using small stem contact regions (shown as “I” shapes here). *Right:* Simulated 9-pixel Hydra noise-less pulse shapes for a photon energy of 100eV. Absorber 1 is the most strongly coupled absorber to the TES.

Hydra Fabrication

- Different combinations of Glink and Gbath to investigate energy resolution, position sensitivity and speed.

Fast $G_{link}$'s

Medium $G_{links}$'s

Slow $G_{links}$'s

Already achieved 5-6 eV across 4 pixels with 630 μs decay at 6 keV energy.
Neutrino Physics
Coherent Elastic $\nu$-Nucleus Scattering

$$\frac{d\sigma}{dT} = \frac{G_F^2}{4\pi} Q_W^2 M_A \left(1 - \frac{M_A T}{2E_\nu^2}\right) F(q^2)^2$$

- $\sigma$: Cross Section
- $T$: Recoil Energy
- $E_\nu$: Neutrino Energy
- $G_F$: Fermi Constant
- $Q_W$: Weak Charge
- $M_A$: Atomic Mass
- $F$: Form Factor

No flavor-specific terms!!!
Same rate for $\nu_e$, $\nu_\mu$, and $\nu_\tau$

Bolometric Detection of Neutrinos
Blas Cabrera, Lawrence M. Krauss, and Frank Wilczek
Department of Physics, Stanford University, Stanford, California 94305
Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 01238
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 14 December 1984)
CEvNS as a Probe

• Channel opens new doors for a variety of physics
  • Physics of supernovae (and detection)
  • Probe into the form factors of nuclei at very small $Q^2$ that are otherwise difficult to probe.
  • Sensitive to non-standard-model couplings
  • Renewed interest in nuclear proliferation monitoring
Neutrino Sources

4 sources to consider:

- The Sun + other cosmic sources
- Electron-capture sources
- Reactors
- Decay-at-rest sources
Neutrino Sources

4 sources to consider:
- The Sun + other cosmic sources
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arXiv:1402.7137
1408.3581
1409.0050
Neutrino Sources

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Neutrino Sources
• The Sun + other cosmic sources
• Electron-capture sources
• Reactors
• Decay-at-rest sources

G2 Dark Matter Experiments
(SuperCDMS SNOLAB and possibly LZ) will be able to detect the Solar $^8$B CEνNS signal!

Small number of events, but expect a positive CEνNS detection in the next ~5 years…
Ricochet: CE$\nu$NS with $\sim 1$ MeV neutrinos

Need Thresholds of 10’s of eV!

$\sigma/dT = \text{[cm}^2 \text{eV}_{\nu}^{-1}]$

$E_{\nu}$:
- $1\text{MeV}$
- $3\text{MeV}$
- $30\text{MeV}$

Recoil Energy [eV$_{\nu}$]

- Ge, $E_{\nu}=1\text{MeV}$
- Ar, $E_{\nu}=1\text{MeV}$
- Si, $E_{\nu}=1\text{MeV}$
- Ge, $E_{\nu}=3\text{MeV}$
- Ar, $E_{\nu}=3\text{MeV}$
- Si, $E_{\nu}=3\text{MeV}$
- Ge, $E_{\nu}=30\text{MeV}$
- Ar, $E_{\nu}=30\text{MeV}$
- Si, $E_{\nu}=30\text{MeV}$
Ricochet Source ~1 MeV neutrino sources

- Ideal mono-energetic sources have been constructed for experiments previously (SAGE, GALLEX), of order 1 MCi activity.

- Jon Link will talk about the $^{51}\text{Cr}$ program

- A Ricochet detector at SOX might also be an interesting possibility.

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<table>
<thead>
<tr>
<th>Source</th>
<th>Half-Life</th>
<th>Progeny</th>
<th>Production</th>
<th>$E_\nu$</th>
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<tbody>
<tr>
<td>$^{37}\text{Ar}$</td>
<td>35.04 days</td>
<td>$^{37}\text{Cl}$</td>
<td>$^{40}\text{Ca}(n,\alpha)^{37}\text{Ar}$</td>
<td>811 keV (90.2%), 813 keV (9.8%)</td>
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<tr>
<td>$^{51}\text{Cr}$</td>
<td>27.70 days</td>
<td>$^{51}\text{V}$</td>
<td>n capture on $^{50}\text{Cr}$</td>
<td>747 keV (81.6%), 427 keV (9%), 752 keV (8.5%)</td>
</tr>
<tr>
<td>$^{65}\text{Zn}$</td>
<td>244 days</td>
<td>$^{65}\text{Cu}$</td>
<td>n capture on $^{64}\text{Zn}$</td>
<td>1343 keV (49.3%), 227 keV (50.7%)</td>
</tr>
</tbody>
</table>

SAGE

$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$

Use of $^{37}\text{Ar}$ and $^{51}\text{Cr}$

Gallex/GNO

$^{71}\text{Ga} + \nu_e \rightarrow ^{71}\text{Ge} + e^-$

Use of $^{51}\text{Cr}$
Ricochet Phase 2: CEνNS with ~1 MeV neutrinos

- Array of 10,000 elements with $^{37}$Ar or $^{51}$Cr source just outside shield (10 cm closest distance).

- Measuring time of 300 days (for $^{37}$Ar, equivalent of 50 days signal, 250 days background).

- Background rate of 1 event/kg/day in energy region of interest

- R&D needed, would be a “smoking gun” experiment done if charged current experiments saw a signal.
Detector Design - Merge Micro-X and SuperCDMS
Ricochet Phase 2: CEvNS with ~1 MeV neutrinos

• Sensitivity study performed on 10,000 element array (500 kg Si, 200 kg Ge), $^{37}$Ar or $^{51}$Cr source.

• Assumed 300 day measuring time with background rate of 1 event/kg/day.

• Analysis on shape + rate (bulk result from shape)

• Mock signal also tested.

arXiv:1107.3512
Ricochet Phase 2: CEνNS with ~1 MeV neutrinos

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arXiv:1107.3512

Alternate Measurements

coherent scattering measurement

$\sin^2 \theta_W$ measurement

dark matter detection
```
Conclusions

• Cryogenic TES-based detectors are a powerful technology with many scientific applications.

• Astronomy, Particle Astrophysics, and Material’s Analysis are the main uses right now.

• Other uses are waiting to be pursued!