Low Temperature Detectors: Principles and Applications in Astrophysics

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Outline

• Introduction: What can be measured with LTDs?
• Detailed example: Thermal equilibrium detectors in comparison to silicon detectors
• First Showcase: IXO – International X-Ray Laboratory
• Further LTD examples
• Planck/Herschel

Credits:
A large number of slides is taken from a presentation held by Gene Hilton (NIST) at LTD 13
Introduction: What can LTDs measure?

• **Photons:**
  - Mass Spectrometry (M \sim 1 - 10^6 \text{ u}, E \sim 1 - 10 \text{ keV})
  - Heavy Ion Physics (\textsuperscript{4}He – \textsuperscript{238}U, E \sim 0.1 – 400 \text{ MeV/u})
  - α particles (E \sim 1 – 10 \text{ MeV})
  - β particles

• **(Conventional) Matter**

• **Other**
  - Neutrinos
  - Dark Matter (WIMPs)
  - Primordial gravity waves (indirectly)
Introduction: What can LTDs measure?

- **Photons:**
  - (Conventional) Matter
    - Mass Spectrometry \((M \sim 1 - 10^6 \text{ u}, E \sim 1 - 10 \text{ keV})\)
    - Heavy Ion Physics \(^4\text{He} - ^{238}\text{U}, E \sim 0.1 - 400 \text{ MeV/u}\)
  - \(\alpha\) particles \((E \sim 1 - 10 \text{ MeV})\)
  - \(\beta\) particles

- **Other**
  - Neutrinos \(C.\text{Pies, M. Schmidt}\)
  - Dark Matter (WIMPs) \(M.\text{Kiveni, L.Pattavina}\)
  - Primordial gravity waves (indirectly)
Introduction: What are they?

All sorts of things – 12 orders of magnitude

• Monolithic (simple) W TES detector
  • Volume ~ $2 \times 10^{-16}$ m$^3$
  • Mass ~ 3 pg

• Composite dark matter detector (charge and thermal signals)
  • Volume ~ $4 \times 10^{-5}$ m$^3$
  • Mass ~ 200 g/subunit
Introduction: Coherent vs Direct Detection

**Coherent Detection**
- Signal proportional to received field strength
- Amplitude and phase measured
- Used at low frequencies $\leq 2$ THz
- Easier to obtain very high spectral resolution in the infrared
- But: limited in sensitivity for low fluxes (due to quantum limit)

**Direct Detection**
- Signal proportional to intensity of absorbed signal
- Used at higher energies
- Usable at low fluxes

![Energy vs Wavelength Diagram](image-url)
How do LTDs work?

**Charge-like excitations (non-equilibrium)**
- Superconducting Tunnel Junction – STJ
- Microwave Kinetic Inductance Detector MKID
- Charge collection in large crystals

**Thermal excitations (equilibrium)**
- Semiconductor thermistor
- Transition-edge sensor (TES)
- Metallic magnetic calorimeter (MMC)
- Superfluid $^3$He bolometer

**Other and combinations**
- Athermal phonons
- Evaporation or excitation in a superfluid
- Superheated superconducting granules
  - SSPD/nanowire
- Charge and thermal
- Scintillation and thermal
• Photons:

X-ray
Semiconductor ionization detector
Semiconductor ionization detector

x-ray photon $E_0$
Semiconductor ionization detector

- Photon creates initial photoelectrons.
• Photon creates initial photoelectrons.
• Photoelectron sheds energy creating electron hole-pairs (secondaries) and high-energy phonons.
Semiconductor ionization detector

- Photon creates initial photoelectrons.
- Photoelectron sheds energy creating electron hole-pairs (secondaries) and high-energy phonons.
- Applied field separates e-h pairs. Photoelectron and phonons continue to down-convert.
Semiconductor ionization detector

- Photon creates initial photoelectrons.
- Photoelectron sheds energy creating electron hole-pairs (secondaries) and high-energy phonons.
- Applied field separates e-h pairs. Photoelectron and phonons continue to down-convert.
- Energy ends up in e-h pairs and thermal phonons.
Semiconductor ionization detector

- Photon creates initial photoelectrons.
- Photoelectron shed energy creating electron hole-pairs (secondaries) and high-energy phonons.
- Applied field separates e-h pairs. Photoelectron and phonons continue to down-convert.
- Energy ends up in e-h pairs and thermal phonons.
### Signal:

For Si: $E_{\text{gap}} \approx 1.15 \text{ eV}$

Number of e-h created: $N \neq E_0 / E_{\text{gap}}$

Instead, $N = E_0 / \varepsilon$

For Si: $\varepsilon \approx 3.65 \text{ eV / e-h pair (X-ray energies)}$

$N \approx 1600 \text{ e}^- @ 6 \text{ keV}$

### Energy resolution:

Determined by statistics of down-conversion

Because the generation of e-h pairs is not statistically independent, $\delta N < N^{1/2}$

$\delta N = (f N)^{1/2}$

For Si: $f \approx 0.12$ (the Fano factor)

$\delta E = 2.355 (f \varepsilon E_0)^{1/2} \approx 120 \text{ eV FWHM @ 6 keV}$

(FWHM = Full Width Half Maximum)

- Signal unaffected by thermal noise ($E_{\text{gap}} / k_B T > 50$).
- Only $\varepsilon / E_{\text{gap}} (=30 \%)$ of input energy goes into quantized excitations – rest ends up as heat.
- Fundamental noise/resolution limit caused by measuring a relatively small number of quantized excitations.
- All the details are hiding in $\varepsilon$ and $f$. 
Energy resolution

Measured at -80°C with a 384x384 pnCCD

Combined spectrum of 150 000 pixels!
Calorimetry

\[ \text{x-ray photon } E_0 \]

\[ \text{Weak thermal link } G \]

\[ \text{Thermal bath at } T_0 \]
Calorimetry

- Photon creates initial photoelectrons.
Photon creates initial photoelectrons.

Photoelectron shed energy creating electron hole-pairs (secondaries) and high-energy phonons.
Calorimetry

- Photon creates initial photoelectrons.
- Photoelectron shed energy creating electron hole-pairs (secondaries) and high-energy phonons.
- Photoelectrons and phonons continue to down-convert. e-h pairs start recombining.
Calorimetry

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- Photoelectrons and phonons continue to down-convert. e-h pairs start recombining.
- e-h pairs recombine and create phonons. All energy ends up in thermal excitations.
Calorimetry

- Photon creates initial photoelectrons.
- Photoelectron shed energy creating electron hole-pairs (secondaries) and high-energy phonons.
- Photoelectrons and phonons continue to down-convert. e-h pairs start recombining.
- e-h pairs recombine and create a phonon. All energy ends up in thermal excitations.

If you can wait, thermodynamics takes over and details of the down-conversion are less important. The second law can be your friend!

Number of corresponding excitations much larger \( \rightarrow \delta N/N \) gets smaller
**Equilibrium thermal detectors**

**Signal and noise**

**Signal:**
\[ \Delta T = \frac{E_0}{C} \]
\[ \Delta T \text{ decays with a time constant } C/G \]

**Noise:**
(if T could be measured perfectly):
\[ N \text{ total excitations with mean energy } k_B T \]
\[ N \sim C T/k_B T ; \delta N = N^{1/2} \]
\[ \delta E_{\text{RMS}} = \delta N k_B T = (k_B T^2 C)^{1/2} \]

**Thermodynamic Fluctuation Noise –**
Random fluctuations in energy due to transport across the weak link
This is **not** the energy resolution

- Low temperatures → better energy sensitivity.
Energy Fluctuation is not Energy Resolution

Time Domain

(a) Signal only

(b) Signal + TFN

Frequency Domain

Still assuming temperature readout is perfect!

\[ \Delta E = \left( \frac{2\pi f_c}{\Delta f} \right)^2 \sqrt{k_B T^2 C} ; \quad f_c = \frac{G}{2\pi C} \]
Temperature readout: resistive thermometers

Thermistor: Resistance = R(T)

- Adds Johnson noise to the thermometer signal
- To measure R, a bias voltage or current must be applied
  - More precise measurement of R at higher bias, but also more heating
- The thermometer sensitivity is defined as:

\[
\alpha = \frac{d \log R}{d \log T} = \frac{R}{T} \frac{dR}{dT}
\]

- Bias heating causes temperature to change, changing resistance \( \rightarrow \) Feedback!
- Usually, a negative thermal feedback is desired:
  - If \( \alpha > 0 \): voltage bias (\( P = U^2/R \))
  - If \( \alpha < 0 \): current bias (\( P = R I^2 \))
With some more noise and additional time constants…

\[
\Delta E = \left( \frac{2\pi f_c}{\Delta f} \right)^{\frac{1}{2}} \sqrt{k_B T^2 C} \quad ; \quad f_c = \frac{G}{2\pi C}
\]

Reality even more complex, but usually good approximation:

\[
\Delta E_{RMS} \sim \sqrt{\frac{k_B T_0^2 C_0}{\alpha}}
\]
Resistive thermometers – two types

Doped Semiconductors

- \( \alpha \) negative; \(| \alpha | < 10\)
- Resistance large
- Current bias and read voltage

Superconducting transition-edge

- \( \alpha \) positive; \(10 < \alpha < 1000\)
- Resistance small, limited dynamic range
- Voltage bias and read current
Energy resolution

- Doped semiconductors

- Transition Edge Sensors

![Graph showing energy resolution](image1.png)

**Fit Parameters**

FWHM: $1.80 \pm 0.16$ eV  
Amplitude: $234.0 \pm 8$ counts  
Counts: 3707  
$\chi^2$: 1.14
Transition-edge sensor (TES)

- Bias power raises $T_{\text{TES}}$ above $T_b$ and into transition ($\sim T_c$)
- $P_{\text{joule}} = V^2/R$
- Absorbed photon raises $T$, $R$, lowers $P_{\text{joule}}$, speeds up $\tau_{\text{TES}}$

$$\tau_{\text{TES}} \sim \frac{CT_c}{\alpha P_{\text{joule}}}$$

- Self biasing into transition
Transition-edge sensor (TES)

- TES is a resistor → Johnson noise:
  \[ I_{\text{Johnson}} \sim \sqrt{\frac{4k_B T_c}{R}} \]

- Including Johnson and TFN:
  \[ E_{\text{FWHM}} \sim 2.355 \sqrt{\frac{4k_B T_c^2 C}{\alpha}} \]

- Best ΔE for small \( T_c \), C and large \( \alpha \)
Transition-edge sensor (TES)

- TES is a resistor $\rightarrow$ Johnson noise:
  \[ I_{Johnson} \sim \sqrt{\frac{4k_B T_c}{R}} \]

- Including Johnson and TFN:
  \[ E_{FWHM} \sim 2.355 \sqrt{\frac{4k_B T_c^2 C}{\alpha}} \]

- Best $\Delta E$ for small $C$, $T_c$ and large $\alpha$
- However finite dynamic range $E_{lin} \propto \frac{C}{\alpha}$
Equilibrium thermal detectors

**Key advantages over non-equilibrium (ionization) detectors**

- No requirement for efficient charge transport
  - Impurities can often be tolerated
- Flexible choice of absorbers
  - Large volume detectors
  - Use of High-Z materials for good quantum efficiency at high energies possible
- No Fano limits

**Key disadvantages**

- Speed – detectors based on non-equilibrium can be made faster before loss of resolving power
- Size – performance in an equilibrium detector scales inversely with heat capacity $C$. Best performance in small detectors
- Temperature – very low temperature required for good performance
First Showcase: IXO

- IXO: International X-ray Observatory
- Joined mission of ESA, NASA and JAXA
- Launch planned for 2021

Scientific Goals:

- Studies of Strong Gravity
- Measuring Black Hole Spin
- Neutron Star Equation of State
- Growth of Supermassive Black Holes
- Evolution of Galaxy Clusters & Feedback
- Cosmology
- Cosmic Web of Baryons
IXO – Key Requirements

The astronomers want
- High spectral resolution
- High angular resolution
- High time resolution
- Large field of view
- Polarization information
- High quantum efficiency up to 40 keV
- Long lifetime

The satellite designers want
- Low mass
- Low power requirements
- Radiation hardness

→ There currently does not exist an all-in-one device that provides all this
## IXO – Key Requirements

<table>
<thead>
<tr>
<th>Science Topic</th>
<th>Typical Target</th>
<th># of Pts</th>
<th>Src Size</th>
<th>Typical Flux</th>
<th>Analysis</th>
<th>S/N required</th>
<th>Obs Time</th>
<th>Abs Ast arc-sec</th>
<th>FOV arc-sec</th>
<th>Band-pass keV</th>
<th>PSF HPD arcsec</th>
<th>1.25 keV</th>
<th>6 keV</th>
<th>30 keV</th>
<th>FWHM(eV) @ E (keV)</th>
<th>Energy Res Rqmt</th>
<th>Rel Timing</th>
<th>Instrum</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strong Gravity</strong></td>
<td>MCG-6-30-15</td>
<td>20</td>
<td>point</td>
<td>5×10⁻¹¹</td>
<td>spectra</td>
<td>10</td>
<td>8</td>
<td>N/A</td>
<td>N/A</td>
<td>1-40</td>
<td>N/A</td>
<td>1.5</td>
<td>0.65</td>
<td>0.015</td>
<td>2.5</td>
<td>6</td>
<td>N/A</td>
<td>XMS (WFI/HXI)</td>
</tr>
<tr>
<td><strong>SMBH Spin Survey</strong></td>
<td>NGC 4051</td>
<td>200</td>
<td>point</td>
<td>10⁻¹²</td>
<td>spectra</td>
<td>5-10/bin</td>
<td>10</td>
<td>N/A</td>
<td>N/A</td>
<td>1-40</td>
<td>N/A</td>
<td>1</td>
<td>0.65</td>
<td>0.015</td>
<td>1000</td>
<td>30</td>
<td>N/A</td>
<td>WFI/HXI (XMS)</td>
</tr>
<tr>
<td><strong>Neutron Star EoS</strong></td>
<td>MCG-6-30-15</td>
<td>10</td>
<td>point</td>
<td>5×10⁻¹¹</td>
<td>polarization</td>
<td>1% MDP</td>
<td>10</td>
<td>N/A</td>
<td>N/A</td>
<td>2-10</td>
<td>N/A</td>
<td>2.5</td>
<td>0.5</td>
<td>N/A</td>
<td>1200</td>
<td>6</td>
<td>N/A</td>
<td>XPOL</td>
</tr>
<tr>
<td><strong>Growth of SMBH</strong></td>
<td>4U1636-536</td>
<td>15</td>
<td>point</td>
<td>10⁻⁸</td>
<td>spectra</td>
<td>20/bin</td>
<td>5.5</td>
<td>N/A</td>
<td>N/A</td>
<td>0.3-10</td>
<td>N/A</td>
<td>3</td>
<td>0.6</td>
<td>N/A</td>
<td>150 0.3-6</td>
<td>10</td>
<td>N/A</td>
<td>HTRS</td>
</tr>
<tr>
<td><strong>Clusters / Feedback</strong></td>
<td>CDF-S</td>
<td>38</td>
<td>point</td>
<td>3×10⁻¹⁷</td>
<td>imaging spectra</td>
<td>5 at flux limit</td>
<td>10 1 18 dia</td>
<td>0.3-2</td>
<td>5</td>
<td>3</td>
<td>0.65</td>
<td>0.015</td>
<td>150 1</td>
<td>N/A</td>
<td>WFI/HXI (XMS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cosmology</strong></td>
<td>z=0.1-2 cluster</td>
<td>250</td>
<td>2-18</td>
<td>10⁻¹³</td>
<td>imaging spectra</td>
<td>50 at flux limit</td>
<td>14 2×2 3.40</td>
<td>5</td>
<td>3</td>
<td>0.65</td>
<td>0.015</td>
<td>2.5 6</td>
<td>N/A</td>
<td>XMS (WFI/HXI)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Cosmic Web of Baryons</strong></td>
<td>z=1-2 cluster</td>
<td>1000</td>
<td>3</td>
<td>5×10⁻¹⁴</td>
<td>image, spectra</td>
<td>2000 cts/obj</td>
<td>15 10 5×5 0.3-7</td>
<td>10 1 0.1</td>
<td>N/A</td>
<td>N/A</td>
<td>10 6</td>
<td>N/A</td>
<td>XMS (WFI/HXI)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>QSO B1426+428</td>
<td>30</td>
<td>point</td>
<td>10⁻¹¹</td>
<td>spectra</td>
<td>12/bin</td>
<td>15</td>
<td>N/A</td>
<td>N/A</td>
<td>0.3-1</td>
<td>5</td>
<td>N/A N/A</td>
<td>N/A 0.1 0.3</td>
<td>N/A</td>
<td>XGS (XMS)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

For all of the intended observation, you can cut back on some of the requirements.
IXO - Instruments

5 instruments:

- XMS – X-Ray Microcalorimeter Spectrometer
- WFI/HXI – Wide Field Imager/ Hard X-ray Imager
- XGS – X-ray Grating Spectrometer
- HTRS – High Time Resolution Spectrometer
- XPOL – The X-ray Polarimeter

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Bandpass</th>
<th>PSF (HPD)</th>
<th>FOV</th>
<th>Energy Resolution</th>
<th>Science Driver</th>
</tr>
</thead>
<tbody>
<tr>
<td>XMS</td>
<td>0.3–12</td>
<td>5</td>
<td>2 x 2, 5 x 5</td>
<td>2.5@6</td>
<td>Galaxy Clusters</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10@6</td>
<td></td>
<td></td>
</tr>
<tr>
<td>WFI/HXI</td>
<td>0.1–15</td>
<td>5</td>
<td>18 diameter</td>
<td>150@6</td>
<td>SMBH survey</td>
</tr>
<tr>
<td>HXI</td>
<td>0.3–1.0</td>
<td>5</td>
<td>N/A</td>
<td>1000@30</td>
<td>SMBH Spin</td>
</tr>
<tr>
<td>XGS</td>
<td>0.3–10</td>
<td>N/A</td>
<td>N/A</td>
<td>E/ΔE = 3000</td>
<td>Cosmic Web</td>
</tr>
<tr>
<td>HTRS</td>
<td>0.3–10</td>
<td></td>
<td>N/A</td>
<td>150@6</td>
<td>NS EoS</td>
</tr>
<tr>
<td>XPOL</td>
<td>2.0–10.0</td>
<td>6</td>
<td>2.5 x 2.5</td>
<td>1200@6</td>
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FOV = Field of View
PSF = Point Spread Function

Timeresolution
Polarisation
### IXO – Key Difference WFI/HXI and XMS

<table>
<thead>
<tr>
<th>Detector</th>
<th>XMS - Core</th>
<th>XMS - Outer</th>
<th>Widefield Imager</th>
<th>Hard X-Ray Imager</th>
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<tr>
<td>Bandpass</td>
<td>0.3 – 12 keV</td>
<td>0.3 – 12 keV</td>
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<td>10 – 40 keV</td>
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<tr>
<td>Point Spread Function</td>
<td>5 arcsec</td>
<td>5 arcsec</td>
<td>5 arcsec</td>
<td>30 arcsec</td>
</tr>
<tr>
<td>Field of View</td>
<td>2 x 2 arcmin</td>
<td>5 x 5 arcmin</td>
<td>18 arcmin diameter</td>
<td>8 x 8 arcmin</td>
</tr>
<tr>
<td># Pixels</td>
<td>40 x 40 = 1600</td>
<td>56 x 56 – inner = 2304</td>
<td>1024 x 1024 = 10^6</td>
<td></td>
</tr>
<tr>
<td>FWHM</td>
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<td>1000 @ 30 keV</td>
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<tr>
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<td>TES - Microcalorimeter</td>
<td>Si - DepFET</td>
<td>Cd-Te strip detector</td>
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![Diagram of IXO components](image)
# IXO – Key Difference WFI/HXI and XMS

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![Graph showing energy versus flux](image1)

![Image of IXO/WFI 1Msec with 18 arcmin]
XMS – Multiplexing scheme

Time domain multiplexing

- Switch on one row after the other
- Switch fast enough to still have a good sample frequency for each of the rows
Multiplexing is possible and does provide promising results

but upscaling from 16 to ~4000 pixels not easy. Possible problems:

- crosstalk (electrical, thermal)
- inhomogeneity
- required cooling power increases
- increased number of rows decreases sample frequency
- yield
- ...?
IXO – WFI Readout scheme

Why is it possible to have a much higher Pixel number?

- Integrating Detector → No need to measure a pulse shape, 1 sample per cycle sufficient
- Only the pixels read out at the moment (1/512 at a time) dissipate heat
- Operation at ~210K:
  - Use of high speed ASICs dissipating ~20 W in focal plane
  - no active cooling required
- Use of ASIC allows parallel amplification of pixel with subsequent serial MUXing
  → only 1 ADC for 128 columns (=65k pixels!) sufficient
  → very high speed possible (1 frame/ms with 1MPixel /frame)
IXO – The cost

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<thead>
<tr>
<th>Instrument</th>
<th>XMS</th>
<th>WFI/HXI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>263 kg</td>
<td>65 + 24 kg</td>
</tr>
<tr>
<td>Power</td>
<td>649 W</td>
<td>222 + 46 W</td>
</tr>
<tr>
<td>Number of ADC channels</td>
<td>68</td>
<td>32 + 18</td>
</tr>
<tr>
<td>Telemetry</td>
<td>25.6 kbps</td>
<td>55 kbps</td>
</tr>
<tr>
<td>Money</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

**XMS - Details**

<table>
<thead>
<tr>
<th>Item</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cryostat Assembly</td>
<td>87</td>
</tr>
<tr>
<td>Dewar Bipod Assembly</td>
<td>9</td>
</tr>
<tr>
<td>Cryocooler</td>
<td>32</td>
</tr>
<tr>
<td>XMS Thermal Subsystem</td>
<td>19</td>
</tr>
<tr>
<td>XMS Electronic Boxes</td>
<td>109</td>
</tr>
</tbody>
</table>

Comparison:

- Flight Mirror Assembly (the optics): 1731 kg, 1504 W!
- Total satellite mass: 4374 kg, 3675 W
Different types of LTD

Charge-like excitations (non-equilibrium)
- Superconducting Tunnel Junction – STJ
- Microwave Kinetic Inductance Detector MKID
- Charge collection in large crystals

Thermal excitations (equilibrium)
- Semiconductor thermistor
- Transition-edge sensor (TES)
- Metallic magnetic calorimeter (MMC)

Other and combinations
- Athermal phonons
- Evaporation or excitation in a superfluid
- Superheated superconducting granules
  → SSPD/nanowire
- Charge and thermal
- Scintillation and thermal
Metallic Magnetic Calorimeter

Thermometer is temperature dependent magnetization of paramagnetic ions

- Paramagnetic Sensor
- Changes Magnetization with temperature
- Readout by SQUID

SQUID flux signal:

$$\delta \Phi_{sq} \propto \delta M$$

- No heat dissipation by sensor readout → Easier to go to large arrays
- 2.7 eV FWHM @ 6 keV already achieved, sub-eV resolution possible
- Possibility to directly connect to a metallic heat bath

→ See talk by C. Pies!
Microwave kinetic inductance detectors - MKIDs

- Incoming photons/ heat break up Cooper pairs and create quasiparticles
- Addition of quasiparticles $\delta n_{qp}$ shifts the surface inductance $L_S$:

$$\frac{\delta L_S}{L_S} \approx \delta n_{qp} N_0 \Delta$$
Microwave kinetic inductance detectors - MKIDs

Resonant circuit with variable inductance

- Ignoring surface resistance, addition of quasiparticles $\delta n_{qp}$ shifts the surface inductance $L_S$

$$\frac{\delta L_S}{L_S} \approx \delta n_{qp} N_0 \Delta$$
Microwave kinetic inductance detectors - MKIDs

Resonant circuit with variable inductance

- Ignoring surface resistance, addition of quasiparticles $\delta n_{qp}$ shifts the surface inductance $L_S$
  \[ \frac{\delta L_S}{L_S} \approx \frac{\delta n_{qp}}{N_0 \Delta} \]

- Frequency shifts by
  \[ \left| \frac{\delta f}{f_0} \right| \approx \alpha \delta L_S / 2L_S ; \quad \alpha = L_S / L_{total} \]
Microwave kinetic inductance detectors - MKIDs

- Ignoring surface resistance, addition of quasiparticles $\delta n_{qp}$ shifts the surface inductance $L_S$

$$\frac{\delta L_S}{L_S} \approx \delta n_{qp} N_0 \Delta$$

- Frequency shifts by

$$\left| \frac{\delta f}{f_0} \right| \approx \alpha \frac{\delta L_S}{2 L_S} ; \quad \alpha = \frac{L_S}{L_{total}}$$

- Typically operated with phase sensitive readout
Microwave kinetic inductance detectors – MKIDs
Why is this so interesting

You can fine tune the resonance frequency by the geometry

→ You can put many high Q resonators on one feed line

→ All signals read out with one cryogenic HEMT amplifier and one coaxial line

→ Easy Multiplexing
Microwave kinetic inductance detectors – MKIDs
Why is this so interesting
Comparison of Low-Temperature X-ray detectors
What can LTDs measure?

- **Photons:**
  - Far Infrared
    - Planck, Herschel
Planck, Herschel - Overview

Medium Sized ESA missions, in Space since May 2009

Planck

- High angular resolution measurement of the CMB
- Frequency range: 30 GHz to 857 GHz
- A total of 52 NTD-Ge bolometers

Herschel

- Study intergalactic space, star forming regions → cold objects
- Frequency range: 480 GHz to 5.5 THz
- A total of 300 NTD-Ge bolometers
### Differences of X-ray and Infrared detectors

<table>
<thead>
<tr>
<th>X-Rays</th>
<th>Infrared</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Measure single, high energetic photons</td>
<td>• Measure a steady photon flux</td>
</tr>
<tr>
<td>• Signal gives information on energy of the</td>
<td>• Signal gives information on incoming power</td>
</tr>
<tr>
<td>incoming photon</td>
<td>• Thermal radiation by optics/ surrounding</td>
</tr>
<tr>
<td></td>
<td>structure can be a limiting factor</td>
</tr>
<tr>
<td>• Figure of merit: Energy resolution</td>
<td>• Figure of merit: Noise Equivalent Power</td>
</tr>
</tbody>
</table>

**Equivalent Noise Power:**

r.m.s. power required at input at a given frequency to produce an output voltage equal to the r.m.s. noise voltage in a unit bandwidth at that frequency

Units: $\text{W/Hz}^{1/2}$
Absorber: Spiderweb / Grid:
- Small heat capacity
- Large exposure surface
- Small Surface for high energetic particles

Achieved NEP: \(\sim 10^{-17} \text{ W/Hz}^{1/2}\)
Planck – first results

The Planck one-year all-sky survey

(c) ESA, HFI and LFI consortia, July 2010
Conclusion

- Low temperature detectors have very interesting properties for applications in astrophysics
- There are already some cryostats in space, producing excellent scientific results
- But there is still much space for improvement

Moore's law for LTDs?
Planck Instruments

Low Frequency Instrument (LFI)
- 22 tuned radio receivers (coherent detection)
- Three different frequency channels (30, 44, 70 Ghz) with bandwidth $\Delta v/v=0.2$
- Based on devices called HEMT (High Electron Mobility Transistors)
- Working at 20 K → too hot for this conference to talk about

High Frequency Instrument (HFI)
- 52 NTD-Ge bolometers, partly polarisation sensitive
- Six frequency bands (100 to 857 GHz) $\Delta v/v=0.33$
- Operated at 100 mK
- Only 4 to 8 pixels for each bandwidth
  → Photon flux much higher than in X-ray case, hence acceptable scan rate for stable signals
  → Not appropriate for observing time-evolution of extended objects
MMC calorimeter signal

\[ \delta \Phi_{sq} = f(r, h) \left( \frac{\partial M}{\partial T} \right) \frac{1}{C_{tot} E_0} \]
Magnetization and Heat Capacity

$$\delta \Phi_{sq} \propto \frac{\partial M}{\partial T} \frac{1}{C_{tot}} E_0$$
• Final design not yet decided

• Baseline:
  • 5-stage CADR (Continuous Adiabatic Demagnetization Refrigerator) to cool from 5 K to 50 mK
  • \(^4\)He Joule Thompson provides 5 K interface to CADR stage
  • 3-stage pulse tube cooler to cool radiation shields
XMS – Simulated Performance

metal-enriched hot gas outflowing from a starburst galaxy

detailed measurement of turbulence in intracluster medium
What can LTDs measure?

- **Photons:**
  - (Conventional) Matter
    - Mass Spectrometry \((M \sim 1 - 10^6 \text{ u}, E \sim 1 - 10 \text{ keV})\)
    - Heavy Ion Physics \((^4\text{He} - ^{238}\text{U}, E \sim 0.1 - 400 \text{ MeV/u})\)
    - \(\alpha\) particles \((E \sim 1 - 10 \text{ MeV})\)
    - \(\beta\) particles
  - Other
    - Neutrinos
    - Dark Matter (WIMPs) \(\rightarrow\) Edelweiss, ULTIMA
    - Primordial gravity waves (indirectly)
Neutron Transmutation Doping

Recipe for a thermistor:

1. Stick Ge in front of neutron flux
   - $^{32}\text{Ge}^{70} + n = ^{32}\text{Ge}^{71} - \text{K-capture (11.4 d)} \rightarrow ^{31}\text{Ga}^{71}$ (acceptor)
   - $^{32}\text{Ge}^{74} + n = ^{32}\text{Ge}^{75} - \beta^- \text{ (82 m)} \rightarrow ^{33}\text{As}^{75}$ (donor)
   - $^{32}\text{Ge}^{76} + n = ^{32}\text{Ge}^{77} - \text{(12 h)} \rightarrow ^{33}\text{As}^{77} - \text{(39 h)} \rightarrow ^{34}\text{Se}^{77}$ (donor)

2. Wait

3. Anneal

4. Dice

Extremely precise doping!
Readout: Using The DC Squid

If operated correctly: \( V \propto \Phi \)

• Now couple TES current to Squid using a pickup coil: \( \Phi \propto I_{TES} \rightleftharpoons V_{Squid} \propto I_{TES} \)

• Advantage: Low heat dissipation of Squid allows operation at same temperature as TES
  → Current amplification close to sensor, reduced readout noise
Why not use smaller gap semiconductors?

- They are widely used.
- Particularly important in the near-mid IR.
- Many small gap material are tricky (no multi-billion dollar industry helping out).
- $\varepsilon$ doesn\'t always cooperate.

R.C. Alig, S. Bloom

PRL 35 p1522 (1975)
• Try to minimise $T_c$, based on available cryogenics

• Choose absorber to stop photons, and required collection area, while keeping $C$ low

• Design $\alpha$ for desired $E_{\text{lin}} \propto \frac{C}{\alpha}$

  as $E_{\text{FWHM}} \approx 2.355 \sqrt{\frac{4k_B T_c^2 C}{\alpha}}$

  Tradeoff between dynamic range and energy resolution: $E_{\text{FWHM}} \propto \sqrt{E_{\text{lin}}}$

• Choose $G$ to pick $\tau_{\text{TES}}$