High Impedance Transition Edge Sensor (TES) and associated cryo-electronics

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Contexte Astrophysique

How to perform high spectral resolution images of spatially spread astrophysical objects ?

→ CCD spectro-imaging in the soft X ray band (100 eV-10 keV) of celestial objects such as :

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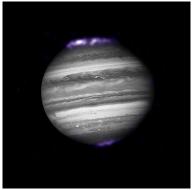

Jupiter and its two X ray aurorae

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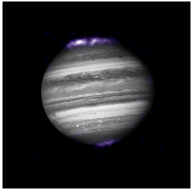

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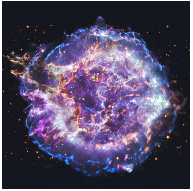

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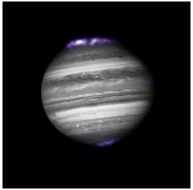

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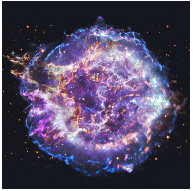

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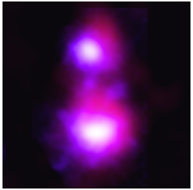

Elstir & Vinteuil (in visible and X ray), two merging dwarf galaxies

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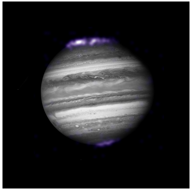

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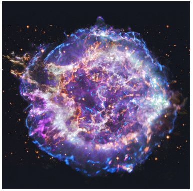

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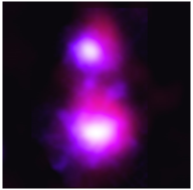

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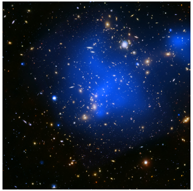

Abell 2744, X ray emitting galaxy cluster (composite)

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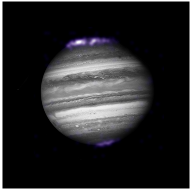
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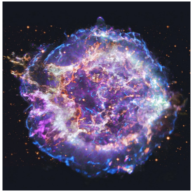
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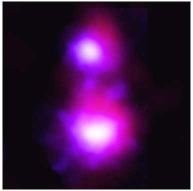
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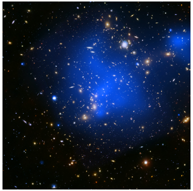
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The CCD technology for X-ray spectro-imaging has been used in Chandra (NASA) and XMM (ESA) telescopes with excellent results but not in spectroscopy.

Contexte Astrophysique

How to perform high spectral resolution images of spatially spread astrophysical objects ?

→ **Microcalorimeters reach much high spectral resolution than CCDs.**

- Very high spectral resolution in every pixel.
- CCD $\approx$ 100 eV
- TES $\approx$ 2.5 eV

Working principle : measure of temperature rise caused by the X-ray absorption with a thermometer (an electric temperature-sensitive resistor).

$$\boxed{\Delta T = \frac{\Delta E}{C} \text{ and } < \Delta E^2 >= k_B T^2 C} \tag{1}$$

$\Longrightarrow$ Decreasing the thermal capacity increases the signal amplitude and decreases noise.

$\Longrightarrow$ The dR/dT slope is a very important factor for technology choice.

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Two types of microcalorimeters based on two different thermometer technologies

- SiP :B doped silicon thermistor, high impedance ≈ $10\ M\Omega - 1\ G\Omega$,
- Superconducting transition : TES, very low impedance ≈ $10\ m\Omega$.

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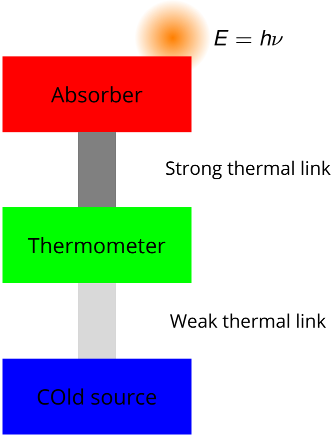
Two types of microcalorimeters based on two different thermometer technologies

- SiP :B doped silicon thermistor, high impedance $\approx 10\ M\Omega - 1\ G\Omega$,
- Superconducting transition : TES, very low impedance $\approx 10\ m\Omega$.

We develop a third technology : the high impedance TES

Microcalorimeter’s working principle



A photon with energy $E = h\nu$ hits the absorber. Its temperature rises.

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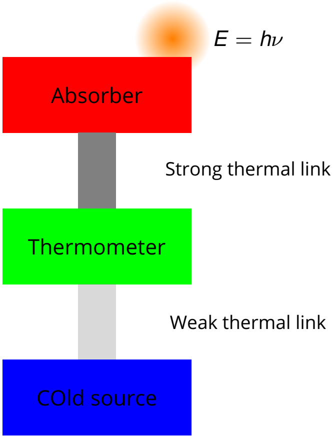

$E = h\nu$

Absorber

Strong thermal link

Thermometer

Weak thermal link

COld source

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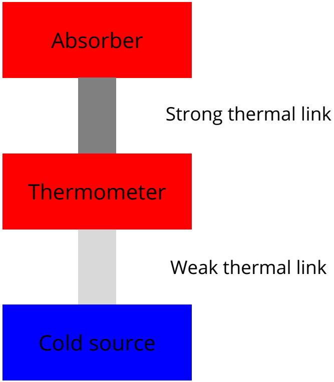

Absorber

Strong thermal link

Thermometer

Weak thermal link

Cold source

The thermometer temperature rises swiftly but the heat is not transferred to the cold source thanks to the weak (slow) link.

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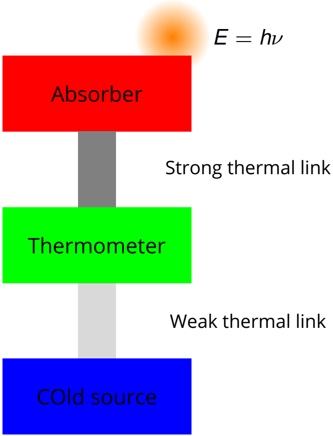

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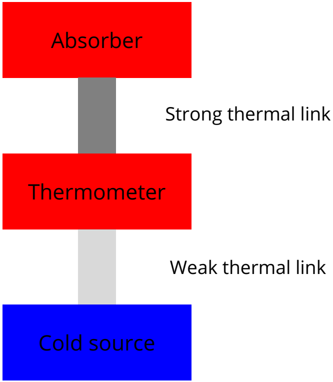

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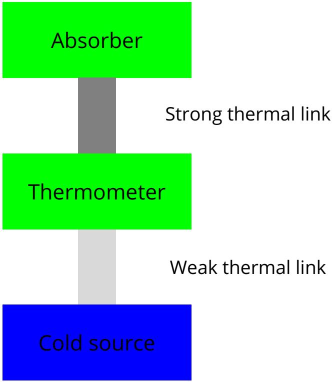
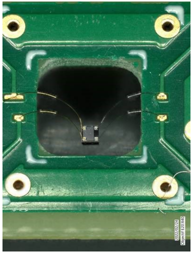


The heat is then evacuated by the weak thermal link towards the cold source. The detector is in its equilibrium state anew.

Practical realisation of calorimeters



Bonding-suspended 500 μm pixel.

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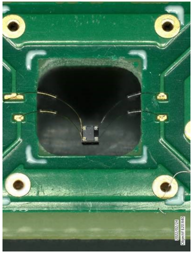

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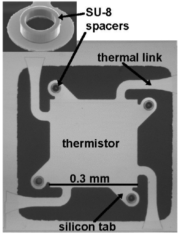

Suzaku XRS pixel with its for Si bridges.

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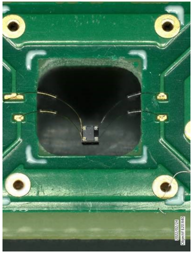

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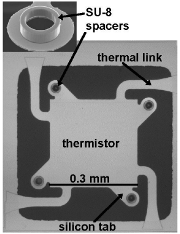

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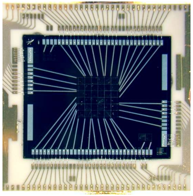

The 36 pixels focal plane of Suzaku XRS

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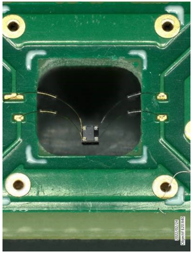

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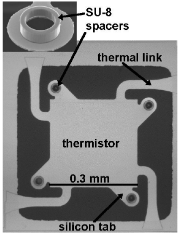

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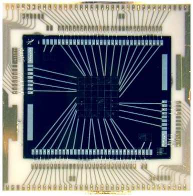

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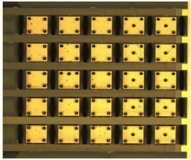

SRON's Athena pixels with absorbers.

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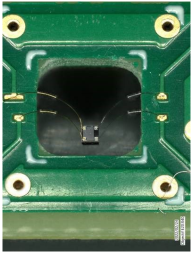
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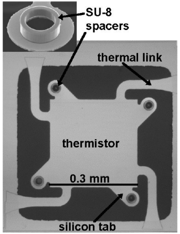

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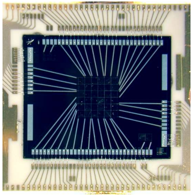
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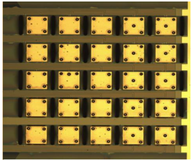
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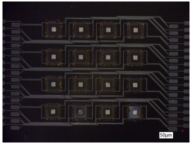


Our 16 pixels NbSi matrices developped by
S. Marnieros & C. Oriol, IJCLab

TES, doped Silicon thermistor and high impedance TES

Low impedance TES :

- ✓ High sensitivity
- ✓ Excellent spectral resolution (~ 2 eV @ 250 μm for Athena)
- ✗ Very low impedance (around 20 mΩ)

↓

- ✗ SQUID readout

↓

- ✗ Limiting power dissipation at the coldest stage

Doped Silicon :

- ✗ Lower sensitivity
- ✗ High spectral resolution ($\sim$5 eV)
- ✓ High impedance (around 10-100 MΩ)

↓

- ✓ Classical electronics readout and multiplexing

↓

- ✓ Dissipation placed at 4 K

High impedance TES :

- ✓ High sensitivity
- ✓ High spectral resolution (~ 5 eV @ 500 μm)
- ✓ High impedance (around 1 MΩ)

↓

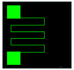
- ✓ Classical electronics readout

↓

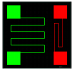
- ✓ Dissipation at 4 K
- ✗ High decoupling of phonon and electrons temperatures

High impedance TESs are very promising for X-ray astrophysics since we can place much more pixels on the focal plane due to a lower power consumption at 50 mK.

HRTES biasing : the active electro-thermal feedback



Goal : stabilise the thermometer in the transition + reduce the decoupling



Classical method :

- Principle : thermometer voltage biasin

  ↓

  The Joule heating decreases when T rises

  ↓

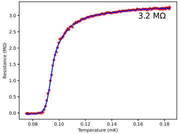
  Passive stabilising thermal feedback

- Pros :
  - Simplicity.
- Cons :
  - Requires a high biasing current (high voltage drop)

$\Longrightarrow$ Strong electron-phonon decoupling

$\Longrightarrow$ Sensitivity/resolution loss.

$$\boxed{P_J = \frac{U^2}{R} = RI^2}$$



Innovative method :

- Principle : very weak current biasing

  ↓

  The Joule heating in a heater stabilises the thermometer temperature

  ↓

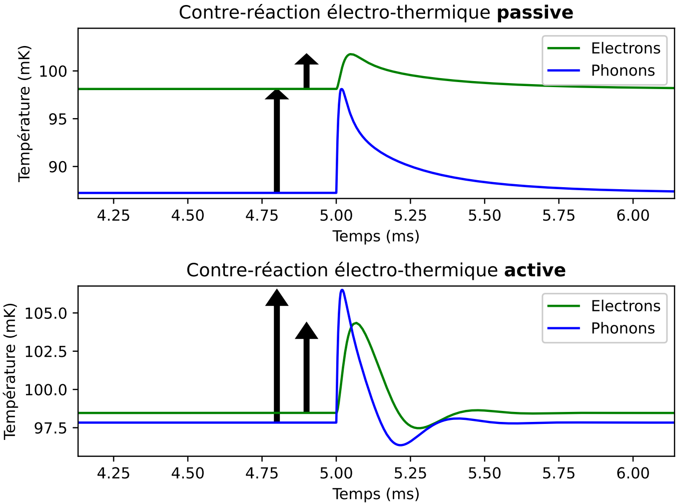
  The heater Joule heating decreases when the thermometer temperature increases

  ↓

  Active electro-thermal feedback

- Pros :
  - Very low electron-phonon decoupling.
  - Thermometer temperature kept constant (R_{th}, C_{th}) fixed.
- Cons :
  - Requires a feedback signal.
  - More wires between 4 K and 50 mK.

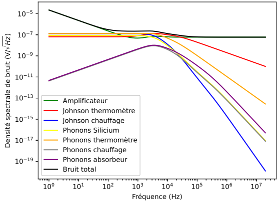
HRTES biasing : the active electro-thermal feedback



Study of the detector noises and spectral resolution optimisation

Modelling of our detectors provides the frequency response (small signal linearisation) and noise spectral density. We thus can determine the theoretical energy resolution.

- Johnson noises : every resistors : thermometer, heater, charge.
- Thermal noises : electron-phonon decoupling, thermal links.
- Amplifier noise

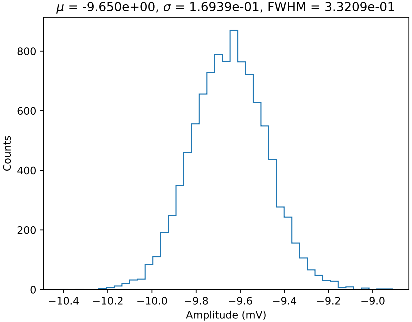


Theoretical expected resolution : 5.6 eV

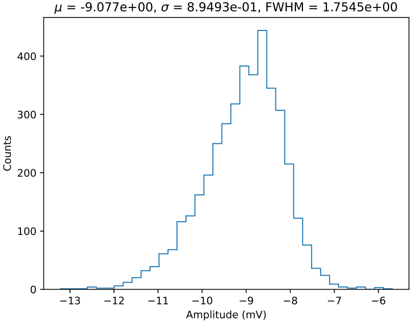
The detector's optimisation consists in tweaking the multiple available parameters : thermal link to the cold source, normal resistance of the TES, heater resistance, transition temperature, cold source temperature, amplifier noise, etc.

Experimental results on bonding-suspended pixels

Bonding-suspended pixels are a first validation step before the delicate fabrication of matrices. Multiple measurements have been done, one of them is the spectral resolution with heater-injected pulses and ^{55}Fe source.



Output amplitude spectrum of heater-injected pulses of 14.8 keV. $\Delta E_{FWHM} = 500\ eV$.



Output amplitude spectrum of pulses from an ^{55}Fe source. $\Delta E_{FWHM} = 1073\ eV$.

50 mK multiplexng ASIC conception

The pixel multiplexing is achieved on the focal plane to reduce the number of links with hotter stages (and thus the thermal flux). A classical CMOS technology is used (very low power consumption)

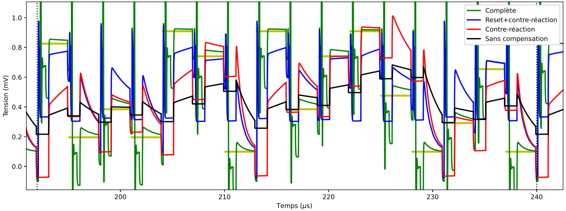
- The high impedance of our detectors allow the use of CMOS.
- The ASIC consumption must be below 1 μW.
- The high impedance coupled with the parasitic capacitance slows drastically the multiplexing

$\Longrightarrow$ Use of different capacity compensation methods :

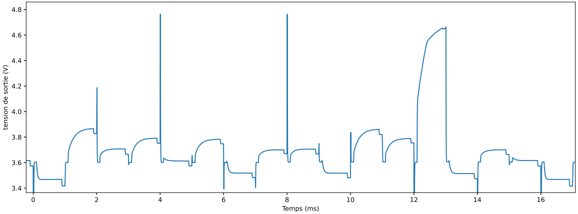
  - Simple feedback capacitor.
  - Reset voltage before reading each pixel (suppress cross-talk).
  - Loading the previous pixel state to pre-charge the input (increases speed).

The ASIC is under tests at 4 K and 1 K and every functionality is working properly.

ASIC simulations and experimental results



Effects of the different compensation methods on the output signal.

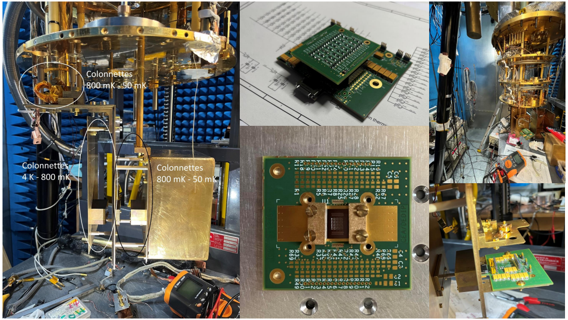


Experimental measurement of the 16 to 1 multiplexing at 1 K. (Resistors are much higher than nominal)

Experimental setup

The experimental setup is a key element to conduct reliable, reproducible and clean measurements.

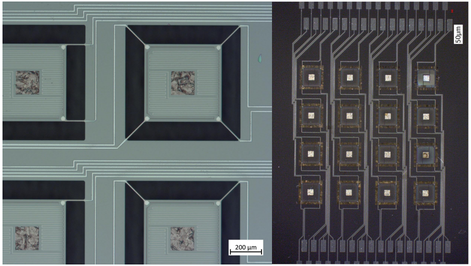
- Reliability : avoid wires and use cryogenic connectors.
- Signal integrity : get rid of floating wires, use of rigid PCBs.
- EMC shielding : Use of different boxes, harnesses
- Cohabitation of different temperatures : use of thermal insulators and conductors



HRTES NbSi matrices fabrication steps

The fabrication of pixel matrices on SOI wafers requires a series of delicate steps regarding the superconducting NbSi meanders as well as the membrane micro-machining.

- Deposition of the Nb_xSi_{1-x} by co-evaporation.
- Deposition of Aluminium (wiring and bonding pads).
- Selective etching of NbSi and Al to create the meanders and wires.
- Si etching of front face.
- Deep Si etching on back face up to the SiO_2 layer.
- SiO_2 etching (pixel liberation).



Measurements should begin asap : thermal conductances of Si bridges, heat capacity, electron-phonon decoupling, calibration pulse measurements, etc.

Merci

Merci pour votre attention !