μ-Calorimeters for Spatial X-ray Astronomy

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Outline

- Ultra quick Overview of X-ray Astrophysics
- Ultra short Astro X-ray detectors History
- Calorimetry Principle
- XRISM
- New-Athena
- Conclusion

Overview of X-ray Astrophysics

Numerous (nearly all) astrophysical objects emit in the soft X-ray band (100 eV to 15 keV).

→ X-ray emissions come mainly from heated gases (1-100 MK) or Synchrotron (Power Law Spectrum) in compact objects.

→ X-rays sources : The Sun, Stars, compact objects (Black Hole Neutron Stars, Binaries), Supernovae, Galaxies Clusters, even Planets & Comets !!!

New-Athena science case

Overview of X-ray Astrophysics at "high" Spectral resolution in Imagery

- Ascertain the nature of the primary source of high-energy radiation in stellar-mass and supermassive accreting black holes (**Active Galactic Nuclei, AGN**), and its connection with accretion and ejection mechanisms close to the event horizon.
- Determine the mechanism(s) regulating the **cosmological co-evolution of accreting black holes and their host galaxies**.
- Measure the space density of the AGN that dominate the supermassive black hole growth, reaching combinations of luminosity and obscuration hitherto unexplored.
- Constrain the **kinematics of hot gas and metals in massive halos** (galaxy clusters and groups).
- Map the properties of the most common **baryonic reservoirs in the Universe**, and probe their evolution and connection to the cosmic web.
- Constrain **supernova explosion mechanisms** by determining the **3-dimensional kinematics**, ionisation state and abundances in young remnants probing the physics of the enrichment and heating of our Galaxy's interstellar medium.
- Provide novel and unprecedented constraints on the **equation of the state of neutron stars** exploring the behaviour of matter under extreme conditions of density and magnetic fields.

Astro X-ray detectors History in 1 Slide!

- Gaz Counter (Rocket 1961)
- Solid State Spectrometer (HEAO-2 1978)
- CCDs (ASCA 1993, Chandra, XMM 2000)

} Ionisation

- µCalorimeters

(XRISM 2023 … New-ATHENA 2037)

Calorimetry

Ionisation : Spectral resolution limited by Fano Factor (i.e. a fraction of the incoming X-ray energy is lost in heat thus not converted in electrons).
In Silicon, δE~120eV @ 6 keV

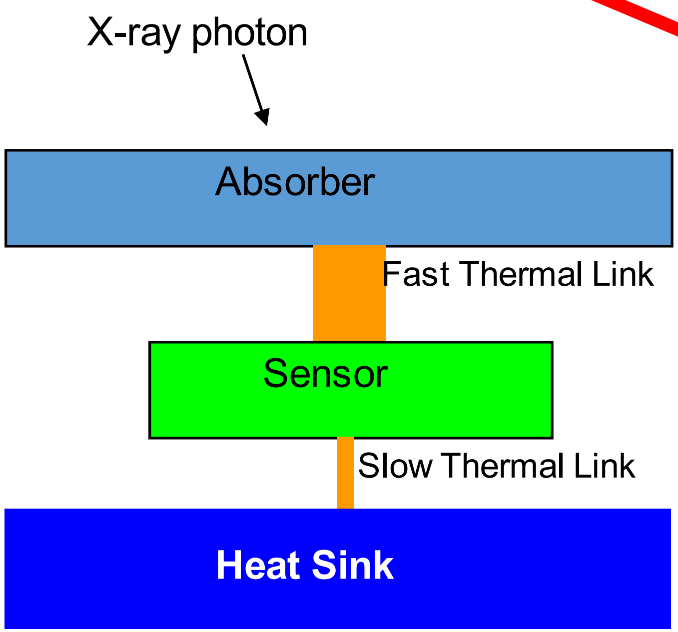
Calorimetry : Since Heat is inescapable when converting X-rays in « readable signal » then wait until all energy of the incoming photon is transform into heat and read the heat !

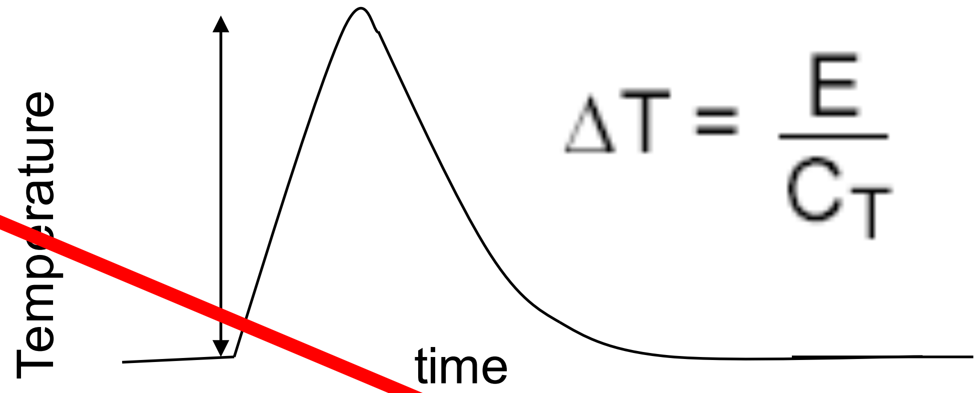
Remember : The atmosphere is completely opaque to X-rays ⇒ Astro X-rays need Satellite

μ-Calorimetry Principle for Astro X-rays

In Astro X-rays (100eV-15keV) , photons flux are very low & Large area mirrors are very difficult to build
As a matter of fact one can consider that **photon arrive mostly one by one** ....
This, in turn, is a very good thing, as it makes it **possible to build spectro-imagers with time resolution** !

Since **Heat is inescapable when converting X-rays in « readable signal »** then
Wait until all energy of the incoming photon is transformed into heat and **read the heat !**



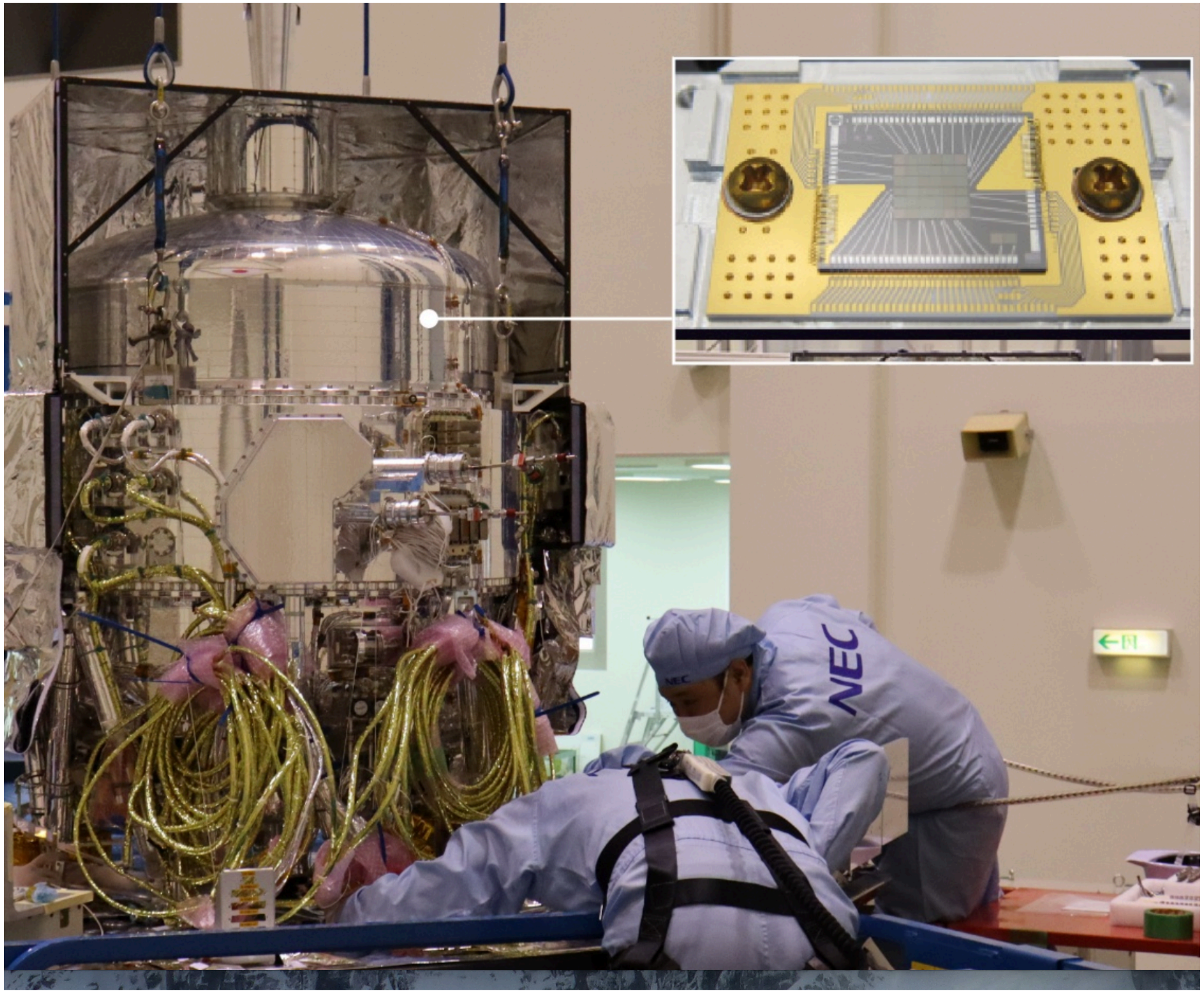


Need to measure few μK around 100mK @ 10 kHz!

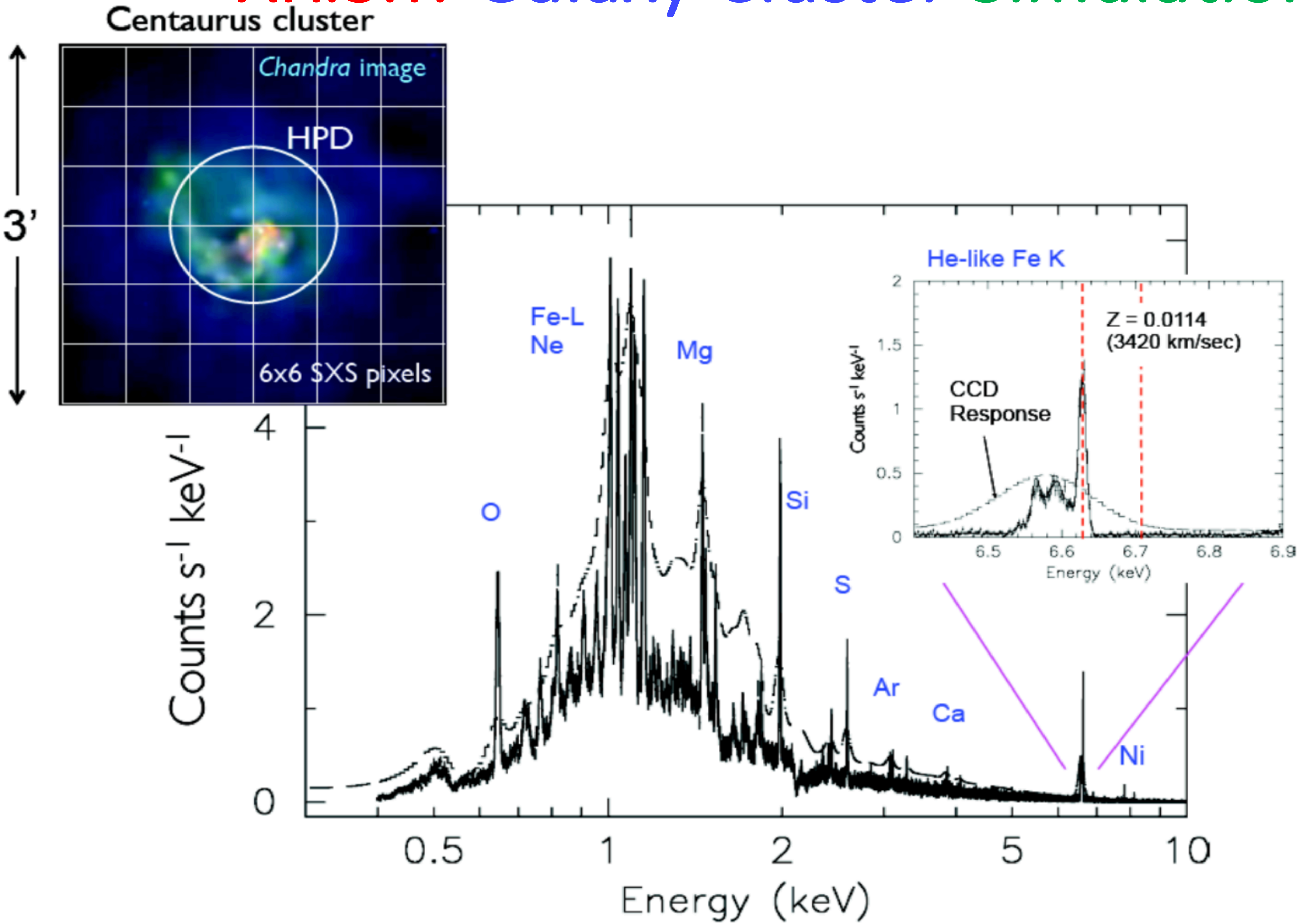
N.B. must be operated much below 1K,
~50-100 mK to **drastically reduce**
thermodynamic fluctuations & heat capacities.

XRISM (µCal with "standard JFET Electronics")

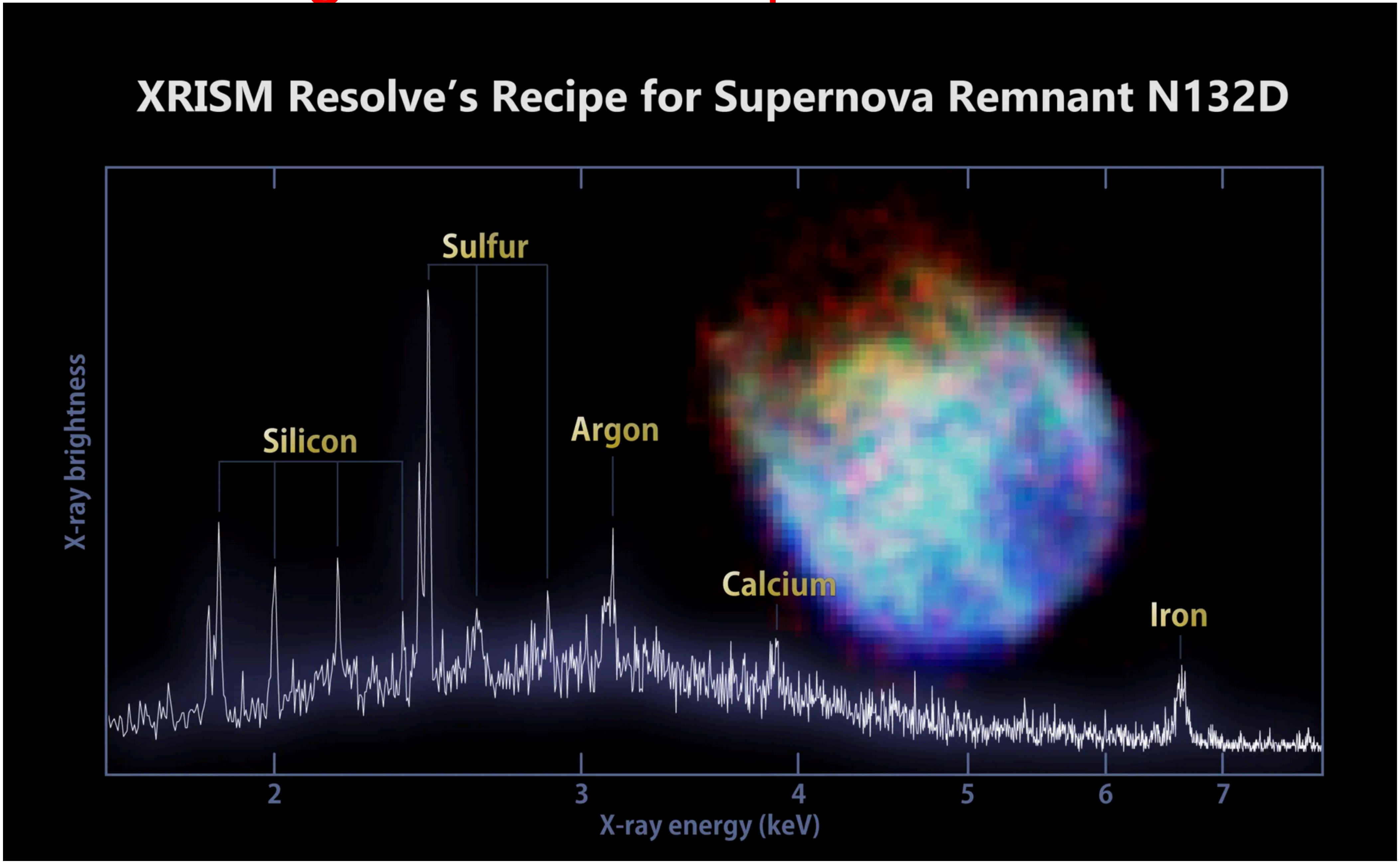
- **Sept 7, 2023 : Launch**
- **Jan 5, 2024 : First Light !**
- **Spectral Res: δE ~7eV !!!**
- 6x6 pixels
- Ion implanted Sensors
- 8µm HgTe Absorbers
- 36 JFET @110K



XRISM Galaxy Cluster Simulation



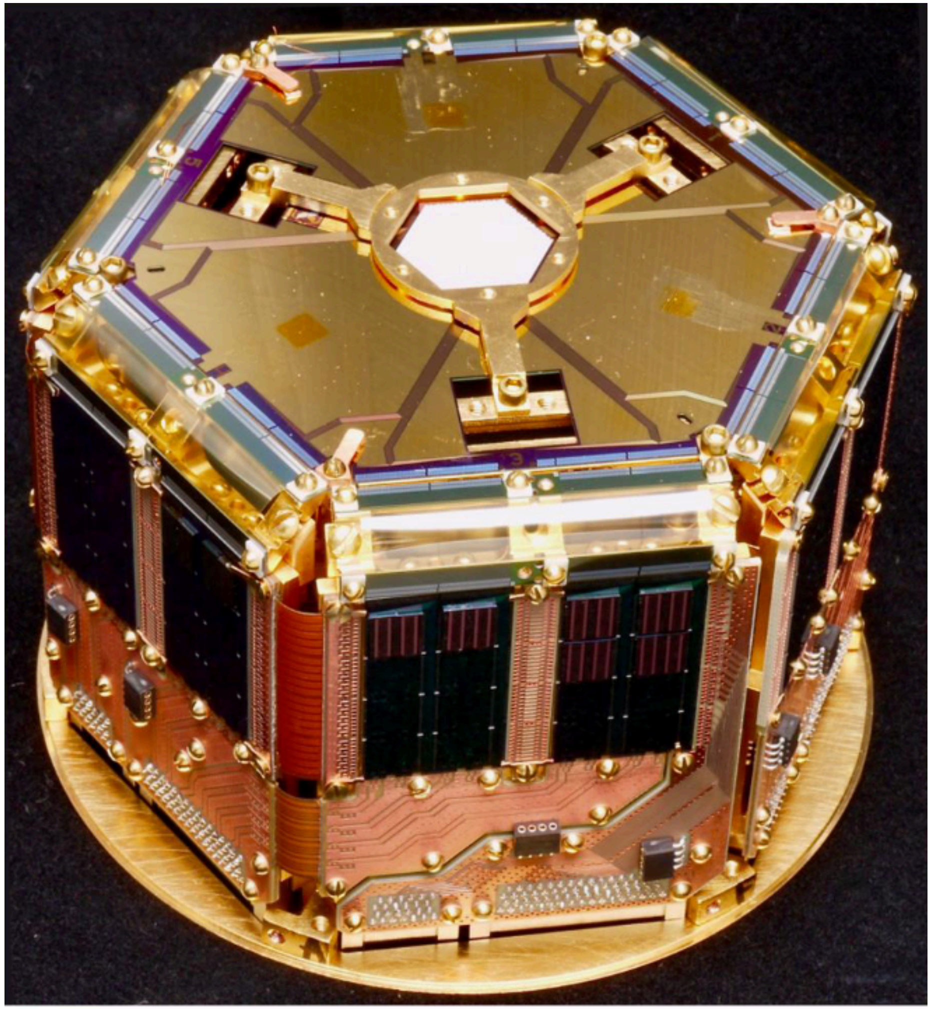
First Light on N132D Supernovae Remnant



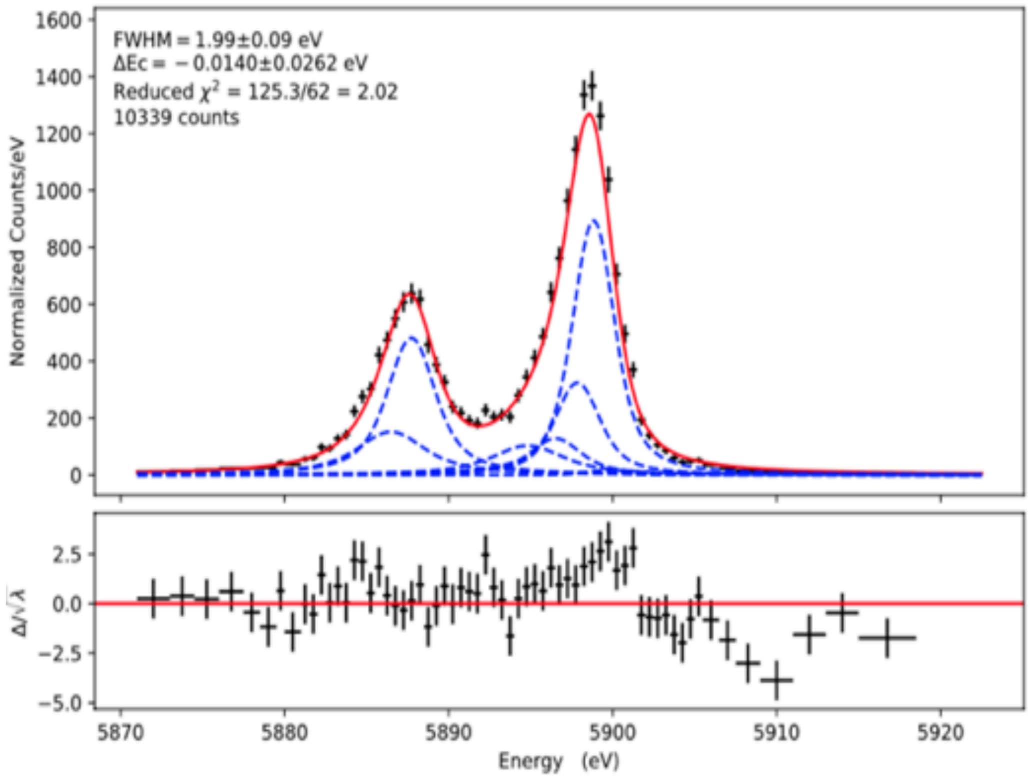
SXS Works ! δE=5eV

New-Athena (TES with Squids)

~3500 TES+ SQUIDs, MUX TDM, **δE~2eV**, Launch Date ~2037 !!!

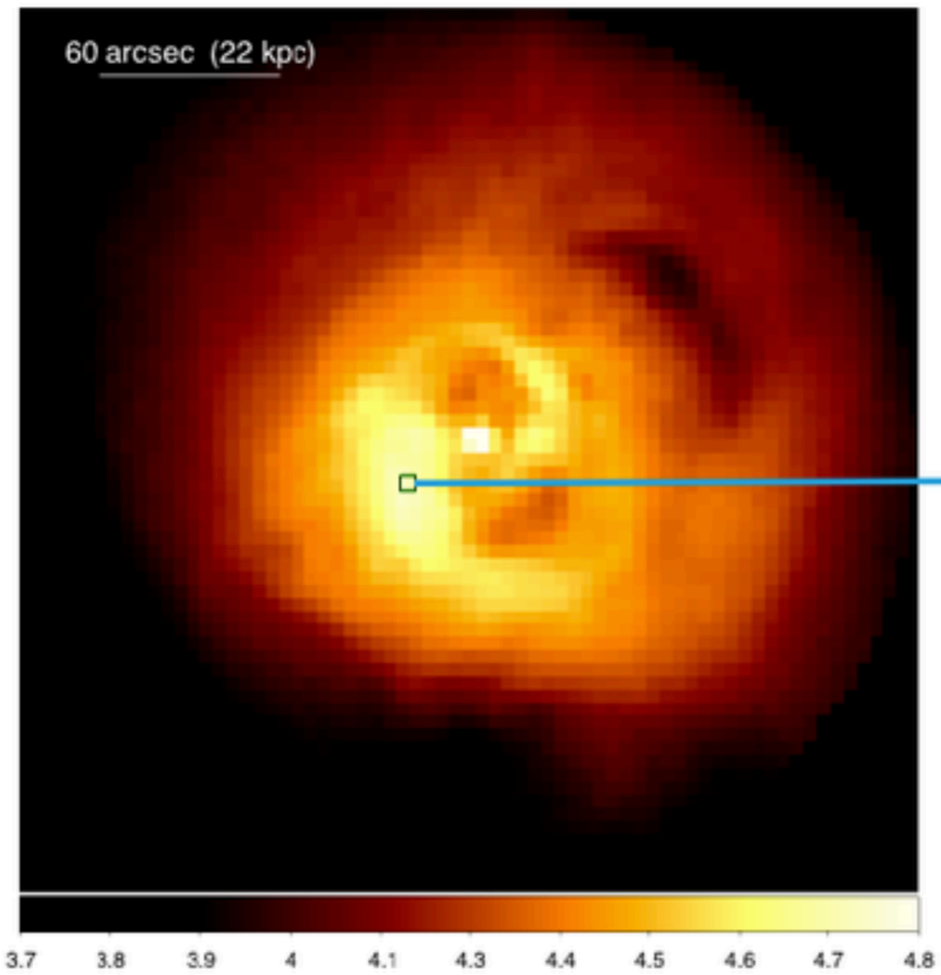


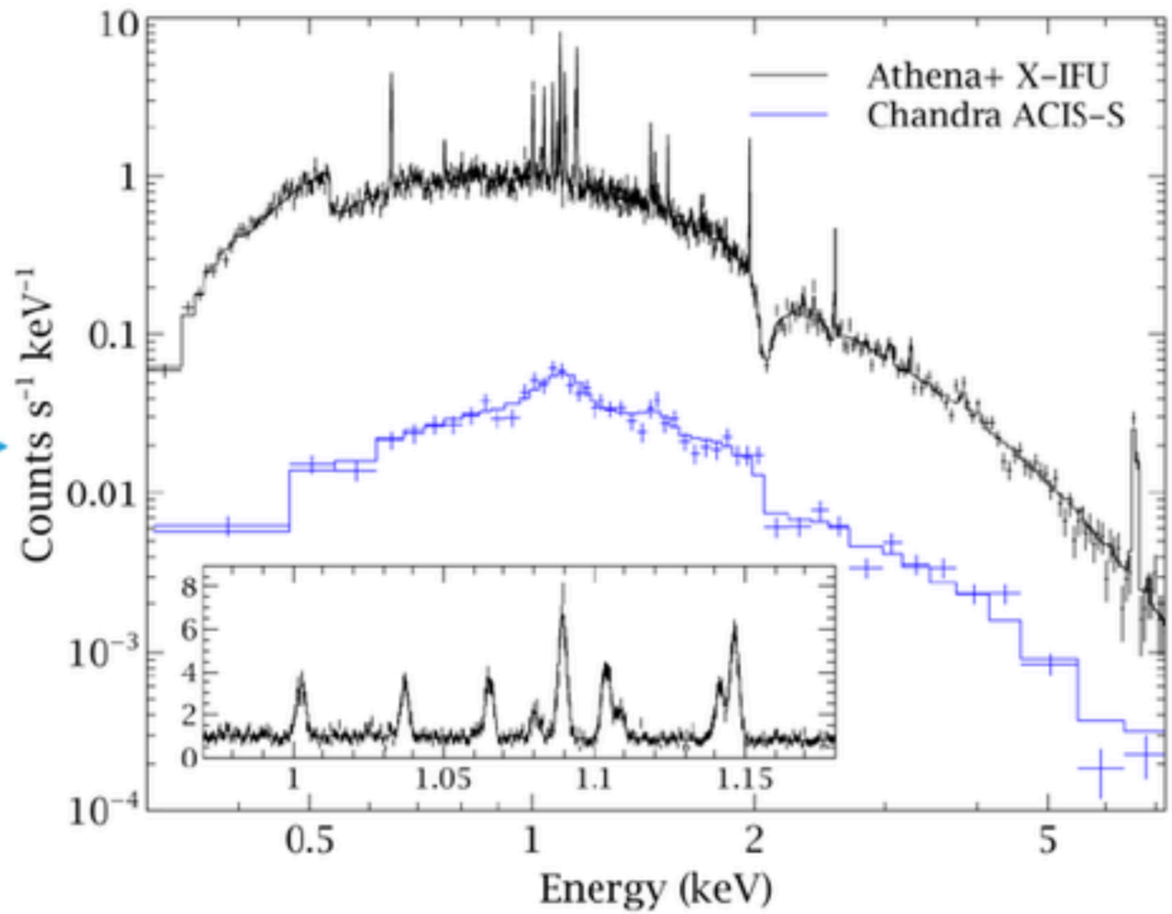
Focal Plan Array



^{55}Fe Spectrum @ 2eV resolution

Comparison Chandra CCDs vs simulated Athena X-IFU





Future ….

Mission (Instrument)	F.o.V. arc min	Angular Resolution arc sec	Number of Pixels	Energy (eV)	dE (eV)	Eff. Area (m^2) @ 1 keV
Athena (XIFU)	5	5	~3800	0.2–8 keV	2–2.5 eV	1.4
HUBS	60	~60	~3600	0.2–2	0.8–2	~0.05
Super DIOS	>30	0–15	~30,000	0.2–2	<2 eV	>0.1
Lynx (LXM)	1–5	0.5–1	~100,000	0.2–7	0.3–3	0.2–2
CWE	60	5	~1 M	0.1–3	0.3	10

To overcome dissipation, Lynx foresee a squid linked to several absorbers "Hydra" approach

General Remarks

- Thanks to their exquisite spectral resolution, **μ-Calorimeters in Astro X-Rays are THE newcomers** and promise **huge amount of new physics to come.**
- **XRISM is now flying with 5eV resolution !** …

  ATHENA should be Next @ 2eV (but not before 2037 !!!)

- The present bottleneck is the **Cooling power of Spatial CryoCooler** :

  1-2μW@50mK for New-ATHENA !

- Cryo-Electronics are power consuming and need to be very nearby the very weak signal … And Astronomers ask for more and more pixels, better spectral resolution & more sensitivity….

⇒ Very strong needs to optimize Thermal budgets at the lowest temperature for spatial cryogenic μ-Calorimeters …

How to have a FPA with large number of pixels in the tiny 50mK cooling power budget

- Two types of micro-calorimeters based on two different thermometer technologies :
- Doped semiconductor thermistors, high impedance 10 MΩ associated with JFET cold Electronics (NoMUX)
- Superconducting transition: TES, very low impedance 10 mΩ read by SQUIDs with TDM MUX

With S. Marnieros (IJCLAB) we are exploring a 3rd intermediate way: the High Resistivity (HR) TES NbSi which combine quasi standard Electronics & Very high sensitivity of TES

Quick Comparison of these 3 ways

TES	HR TES	Doped Si
✔ High Sensitivity	✔ High Sensitivity	✖ Medium Sensitivity
✔ Very Good Spectral Res.	✔ Very Good Spectral Res.	✖ Lower Spectral Res.
✖ Very Low Impedance	✔ High Impedance	✔ High Impedance
✖ SQUIDs Readout	✔ Classical Readout	✔ Classical Readout
✖ Power dissipation onto Coldest stage	✔ Dissipation onto 4K Stage	✔ Dissipation onto 4K Stage
	✖ Weak Electrons-Phonons Coupling	

HR TES looks very interesting to minimize the power consumption @ lowest temperature without degrading the spectral resolution…

Biasing of HRTES

$P_J = U^2/R = RI^2$

- Classical Method:

  Voltage Biasing $\Rightarrow P_J \searrow$ when T $\nearrow$

  Passive Electro Thermal Feedback (ETF)

  Benefits: Simplicity

  Price to pay: High Biasing Current, Strong ETF

- Innovative approach

  Weak Current Biasing

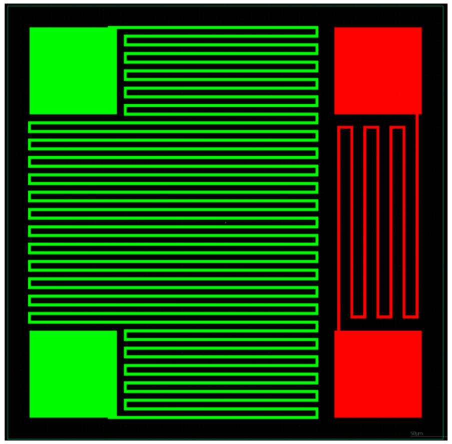
  P_J in a Heater stabilise the Sensor

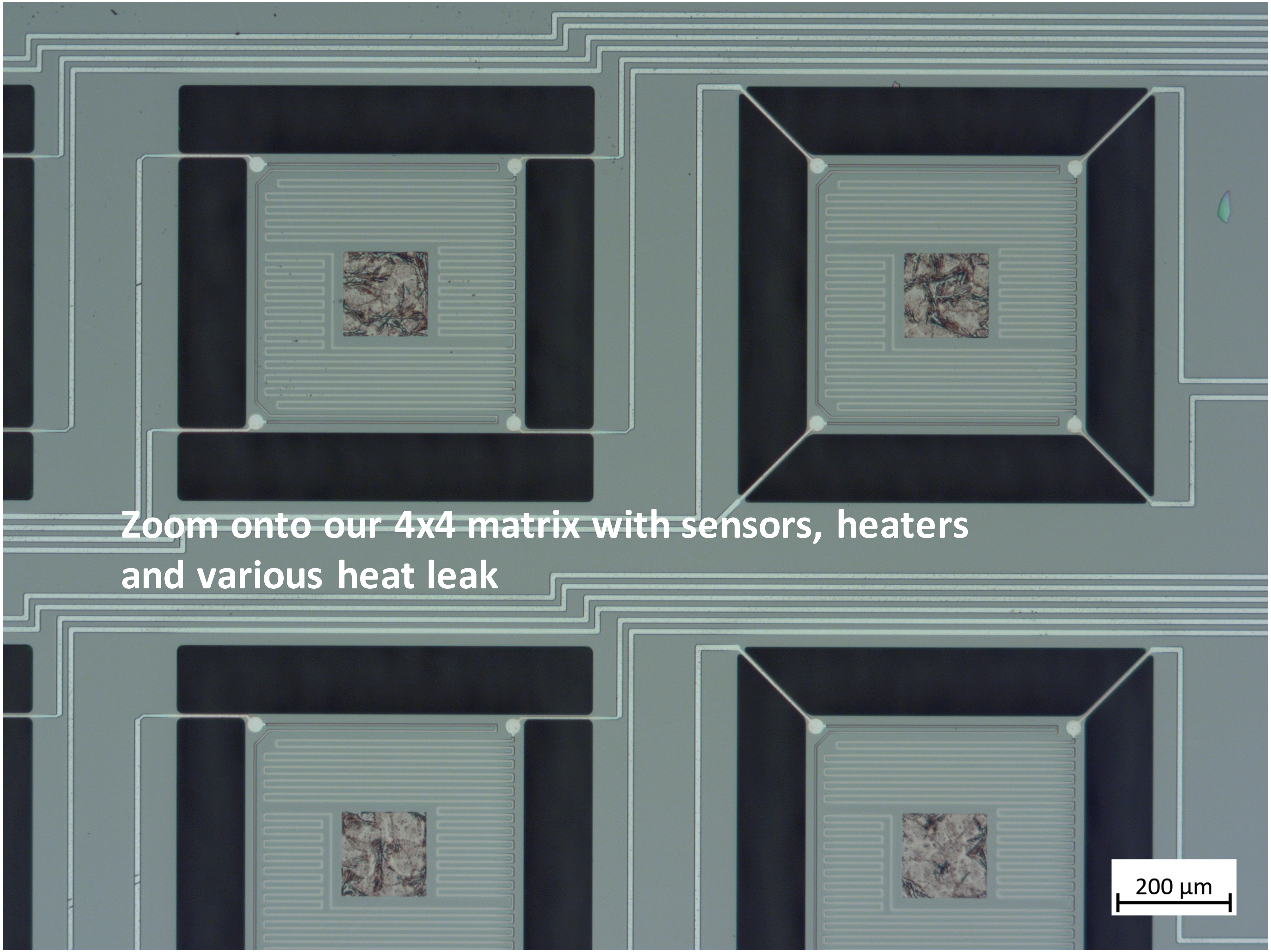
  under Active Thermal Feedback $P_J \searrow$ when T $\nearrow$

  Benefits: Very Low e^--phonon decoupling, Sensor Temp ~cste

  Price to pay: Active Feedback needed & more signals to Mux

Typical Sensor&Heater design
For a 500x500 µm pixel




Zoom onto our 4x4 matrix with sensors, heaters and various heat leak
200 µm

Where are we for the HR TES NbSi Development ?

- Realistic optimisation would lead us to 2.1 eV resolution for 500 µm pixels.
- New developments in cryogenic electronics.
- Stable and versatile HEMT-SiGe amplifier.
- Operating 50 mK CMOS multiplexing ASIC.
- High yield fabrication of 16 pixels NbSi matrices on SOI.

All developments fabricated and integrated.
Tests below 100 mK will resume as soon as possible (cf. Cryostat problems) to evaluate spectral resolution of pixel matrices & evaluate the total power consumption @ 100mK

Conclusion

- Micro-calorimeters hold great promise for X-ray astrophysics, but are very tricky to set up.
- One need to find a setup that minimises consumption at the coldest temperature in order to support the development of matrices with a very large number of pixels.
- A global system approach is essential to obtain a large field of view with very good spatial and spectral resolution within the very small thermal budget allocated by spatial cryo-coolers.