High resolution X-ray spectroscopy with the X-IFU instrument from Athena

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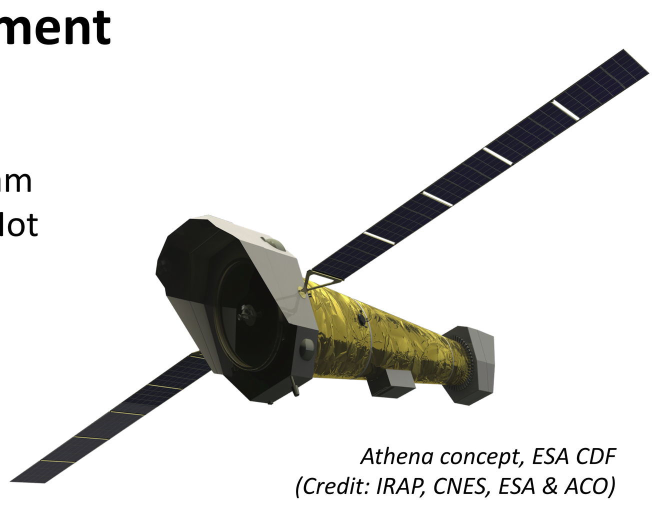
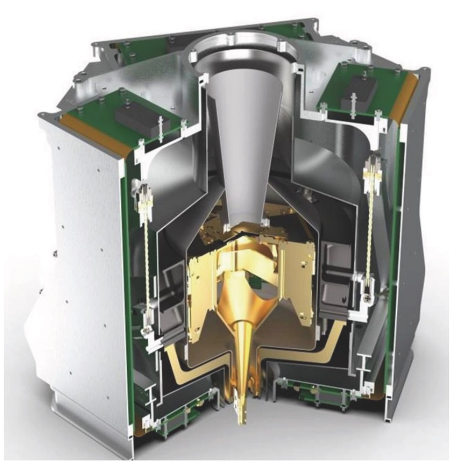
1 The Athena Mission & X-IFU instrument

- **Athena** = Advanced Telescope for High-Energy Astrophysics
  ↳ L-class mission part of ESA 2015-2025 Cosmic Vision program
  ↳ X-ray observatory to implement the science theme of the Hot and Energetic Universe
  - How does ordinary matter assemble into the large scale structures that we see today?
  - How do black holes grow and shape the Universe?
- Launch schedule early 2030s, to L1 orbit
  Baseline duration : 4 years, + 4 years extension
- This telescope of a focal length 12 m will have 2 instruments:
  - WFI = Wide Field Imager
  - **XIFU** = X-ray Integral Field Unit [1]

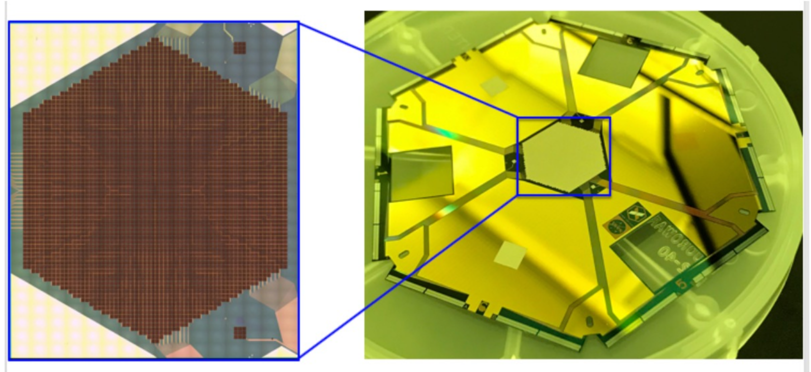


Athena concept, ESA CDF (Credit: IRAP, CNES, ESA & ACO)

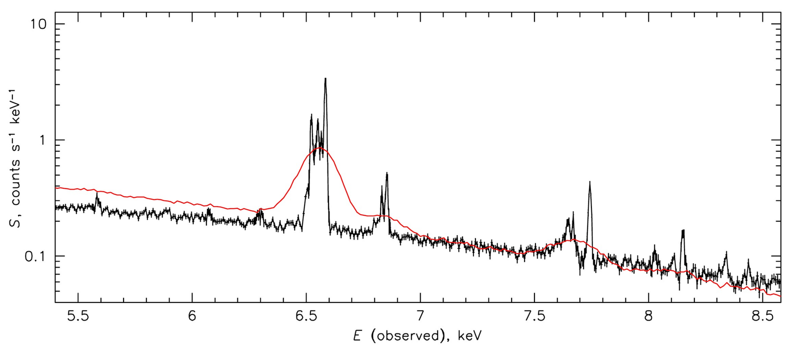


X-IFU Focal Plane Assembly (Credit : SRON)

- X-IFU : based on a **TES microcalorimeter array** of ~3k pixels
  ↳ providing spectral data over the soft X-ray energy band (0.2-12 keV) with unprecedented energy resolution
  ↳ key performance parameters : - 2.5 eV up to 7 keV
  - FoV ~ 5'
  - pixel size ~ 5"
- Detector array + cold front-end electronics integrated in the Focal Plane Assembly (providing magnetic and EMI shielding)
- Instrument built by international consortium of 11 European countries + USA + Japan, led by IRAP and CNES



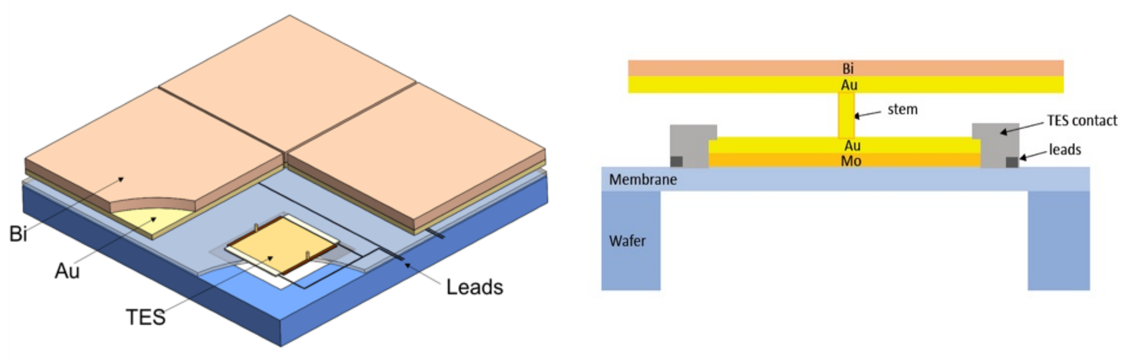
Prototype TES microcalorimeter array (left) and its supporting wafer (right) (Credit : NASA GSFC)



Comparison of CCD data (Suzaku, black) and semiconductor microcal. data (Hitomi, red) (Credit : Hitomi Collaboration)

2 From TES development…

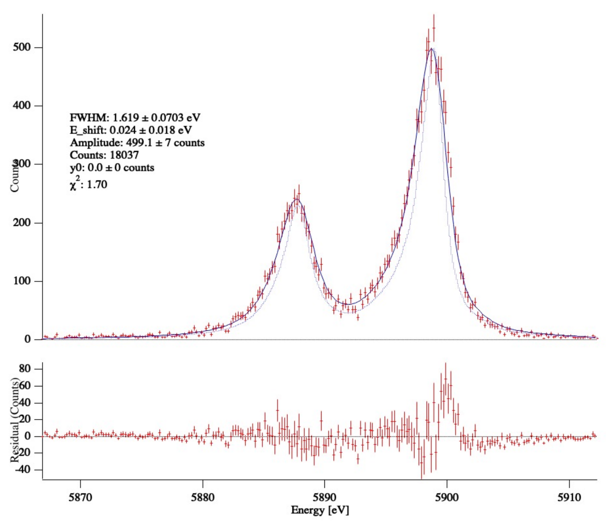
- TES (Transition Edge Sensors) detectors under development at Goddard [2]
  ↳ tests on-going to fine tune the pixel design and reach desired parameters for X-IFU
  ↳ tests on-going to reach TRL5/6 (including lifetime and radiation testing)
- General pixel design correspond to ~5-6 µm thick and ~275 µm wide Au/Bi absorbers, attached to Au/Mo TESs tuned to hit Tc ~ 90 mK [3]



Scheme of TES detector seen from above (left) and from the side (right)

TES testing

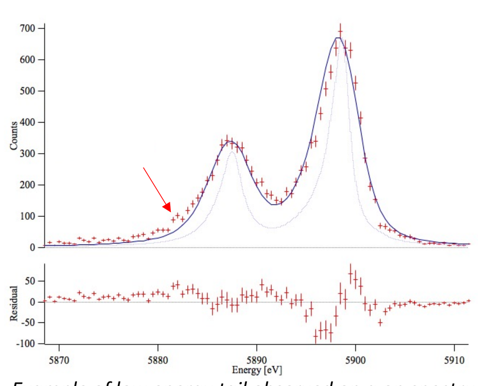
- TES chips with various pixel designed are tested, including :
  - different TES sizes/aspect ratios (e.g., 50x40, 60x30, etc)
  - different oxide layer recipes (e.g. Si oxide, Al oxide, etc)
  ⇒ provides parameters such as Tc, heat capacity, thermal conductance, energy resolution, etc, which are keys to optimize detector performance



Example of energy resolution measured at the MnKα line, on a single 60x30TES

TRL development - Lifetime study

- TES detectors must maintain their performance their whole "life"
- However, if not maintained under suitable environmental conditions, humidity, oxygen or temperature may lead to changes in the absorber properties and cause low energy tails
- Testing is on-going to evaluate exactly what those conditions might be, and define an appropriate procedure accordingly



Example of low energy tail observed on a on spectrum

TRL development - Robustness to radiations

- TES detectors must maintain their performance during the whole duration of the mission, meaning being robust to space radiation
- Simulations showed that this can be evaluated by irradiating the TES chip with a beam of protons at 64 MeV, which can/will be done at UC Davis in the fall 2021

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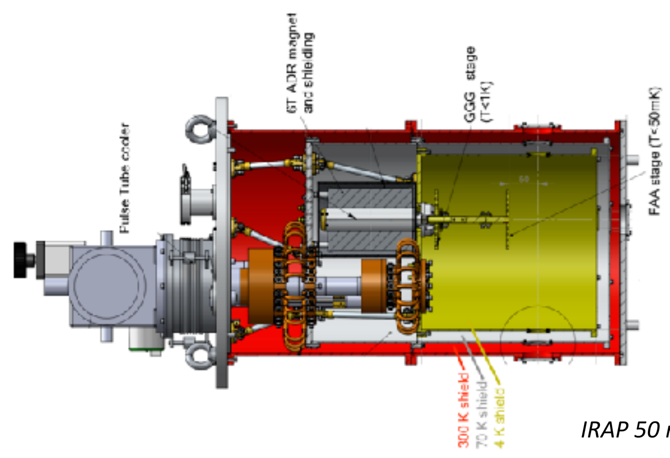
3 …to test in the full detection chain…

IRAP/CNES 50 mK test bench

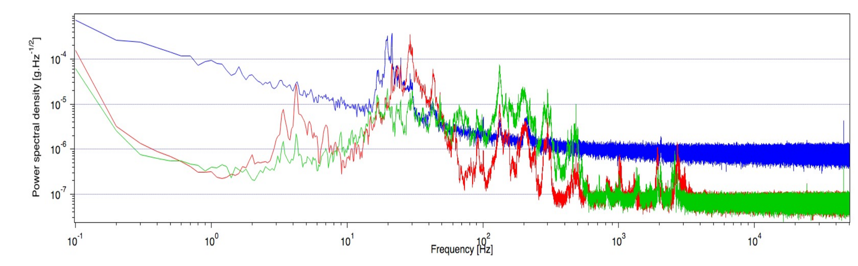
- To verify system performance : crucial to test and validate full mission-baseline detection chain
  ↳ from the TESs @ 50 mK to X-rays measured by the warm electronics (WFEE [4] + DRE [5])
  ⇒ "Elsa", cryostat owned by IRAP and CNES
- Cryostat provided by Entropy GmbH
  ↳ 2-stage PTR, to 70 K and 4 K
  ↳ 2-stage ADR, to 500 mK and 50 mK



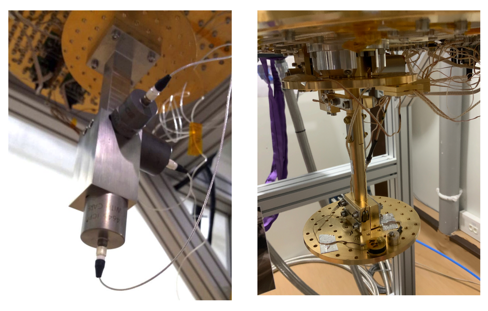
IRAP 50 mK test bench "Elsa"

Characterization

- TES detectors and SQUIDs magnetically sensitive and temperature-dependent : crucial to characterize the environment of the cryostat prior to their integration. Including :
  ↳ level of microvibrations
  ↳ thermal performance (noise, hold time)



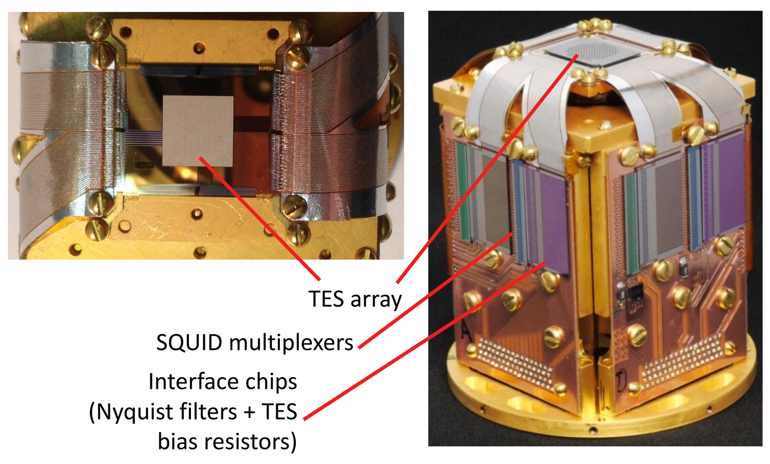
Example of PSD of the signal from the accelerometers (in blue: x-axis, red: y-axis, green: z-axis) with pulse tube off and heat switch closed



Accelerometers (left) and Thermometers (right) positioned in Elsa

Detection chain integration

- System validation to be carried out first using non-flight electronics from NIST [6] and GSFC
  ↳ 1024-pixel TES array
  ↳ cold TDM readout
  ↳ warm electronic chain
- Preparation for integration on-going
- Following first tests and performance verification, warm chain will be replaced by the DRE and WFEE



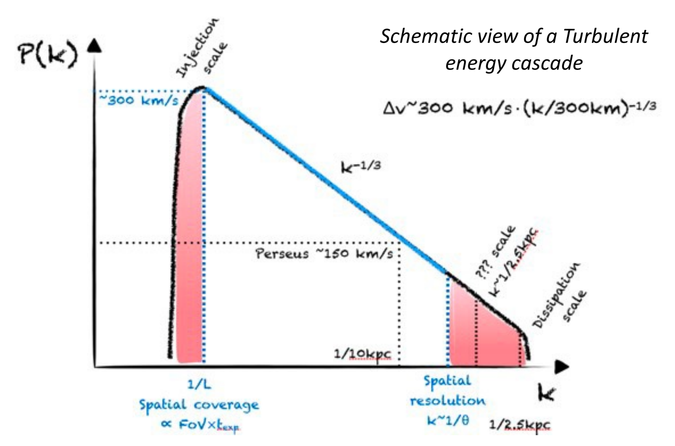
NIST 8x32 MUX readout, with GSFC 32x32 array (Credit: NASA GSFC)

4 …and a science case study

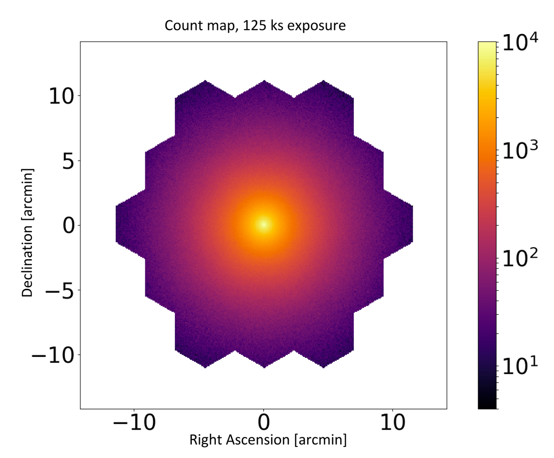
Turbulence and bulk motions in galaxy clusters

- Galaxy clusters are the most massive gravitationally-bound objects in the Universe
  ↳ mine of information to understand the chemical enrichment process, the formation of large-scale structures, estimate critical cosmological constrains, etc
- Often assumed in hydrostatic equilibrium, but strong hints part of the gas pressure provided by turbulence
  ↳ induced by accretion, merger events, AGN activity, etc
  ↳ transfers kinetic energy injected on large scales to small scale where it is dissipated
- Characterizing bulk and turbulent motions in the intra-cluster medium is key to better understand the assembly of massive halos
  ↳ Simplest model can be characterized by parameters :
  - injection scale
  - dissipation scale
  - slope
  - normalization

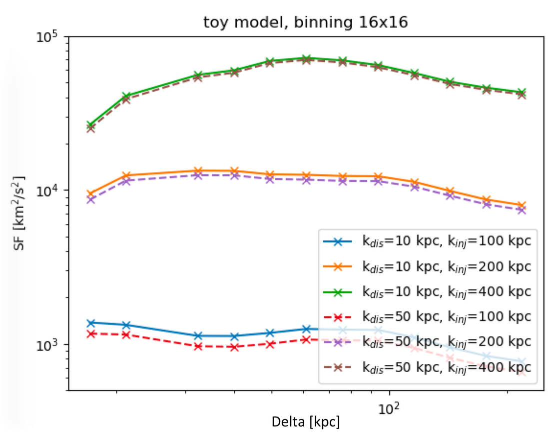
  ↳ can be studied via line diagnostics [7] :
  - line centroid shift
  - line broadening
  - structure function (SF)



- On-going study : mock X-IFU observation of a toy model galaxy cluster representative of non-cool core galaxies at z=0.1 + the simplest model for turbulence (i.e, Kolmogorov spectrum)
- reconstruct SF and assess through a MCMC analysis the ability of X-IFU to recover the turbulence parameters
- define the optimum strategy of observations toward that end for future X-IFU observation



Example of X-IFU simulation for 19 pointings



SFs for our toy model for various injection and dissipation scales

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