X-IFU

X-ray Integral Field Unit

THE X-RAY INTEGRAL FIELD UNIT (X-IFU) FOR THE ATHENA OBSERVATORY

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ON BEHALF OF THE X-IFU CONSORTIUM

OUTLINE

contents

- X-IFU science - illustrative examples
- X-IFU performance requirements
- X-IFU design and challenges

Schedule

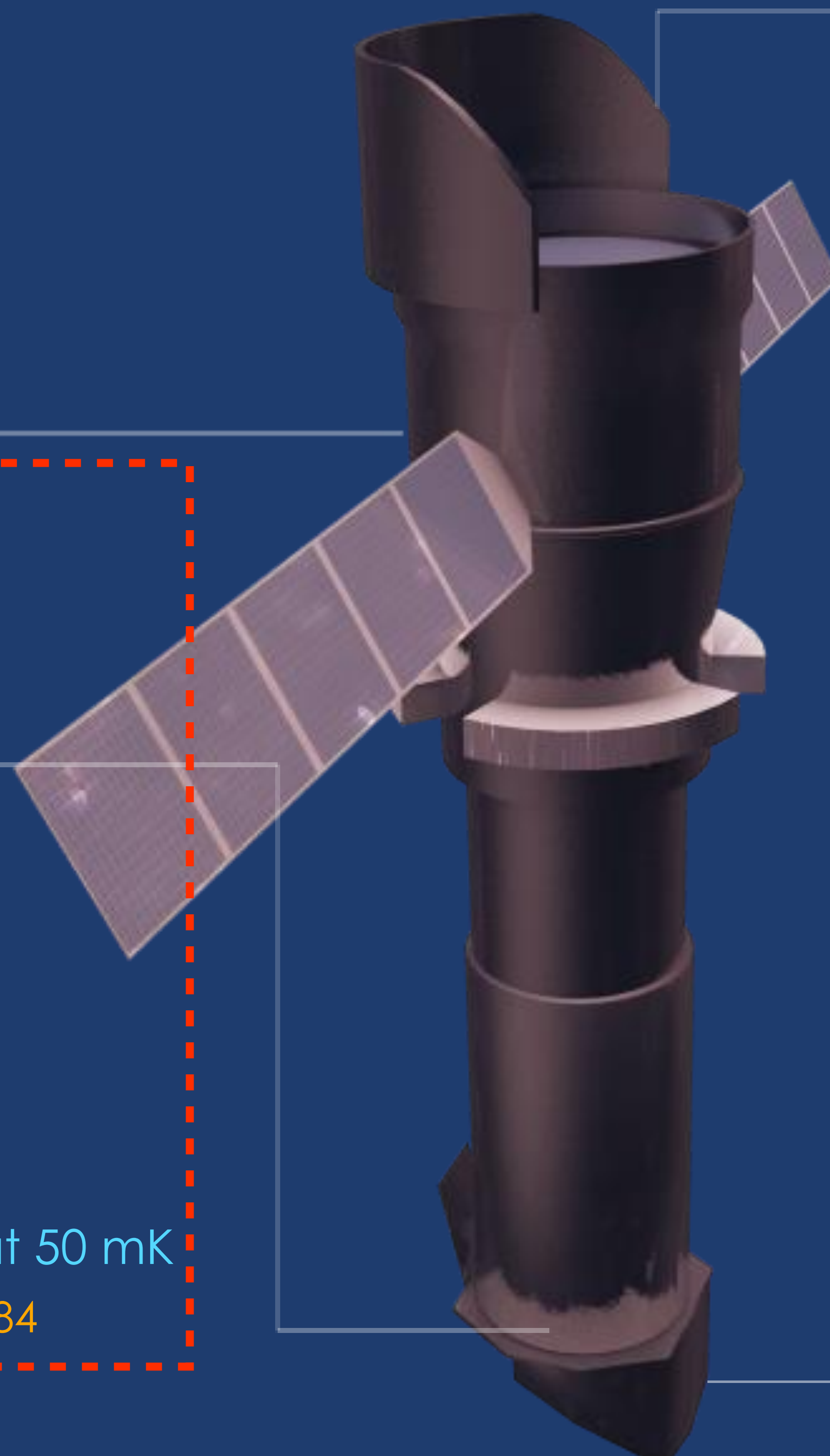
- Instrument selection (AO) 2016
- Mission adoption 2020
- Launch 2028

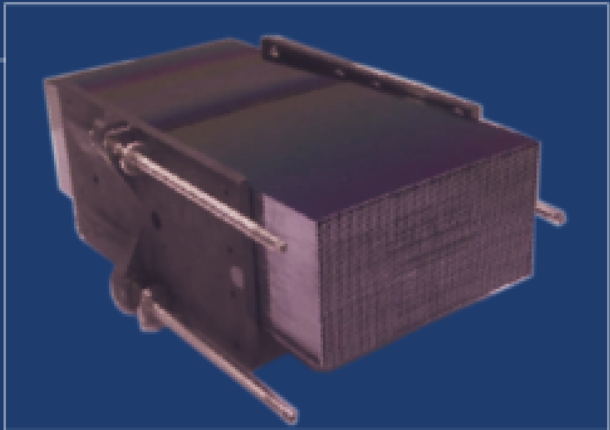
THE X-IFU FOR ATHENA - OUR NEXT LARGE ESA MISSION

X-IFU
X-ray Integral Field Unit

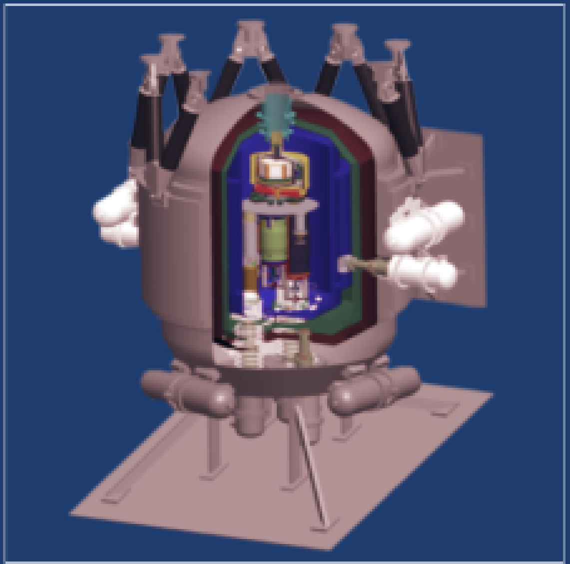
Nandra et al. 2013 arXiv1306.2307

Ariane VI class launcher
Satellite mass ~ 5500 kg
Power ~5600 W
Focal length: 12 m
Lifetime: 5 years (10 years)

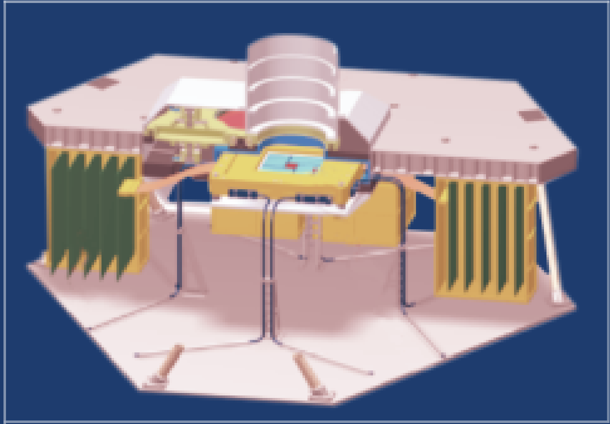




Silicon Pore Optics:
Effective area: $2m^2$ @ 1 keV
PSF (HEW): 5''
Willingale et al. 2013 arXiv1308.6785



X-ray Integral Field Unit:
⊗E: 2.5 eV
Field of view: 5 arcmin
Large array of TES cooled at 50 mK
Barret et al. 2013 arXiv:1308.6784



Wide Field Imager:
⊗E: 125 eV
Field of view: 40' x 40'
Rau et al. 2013 arXiv1307.1709

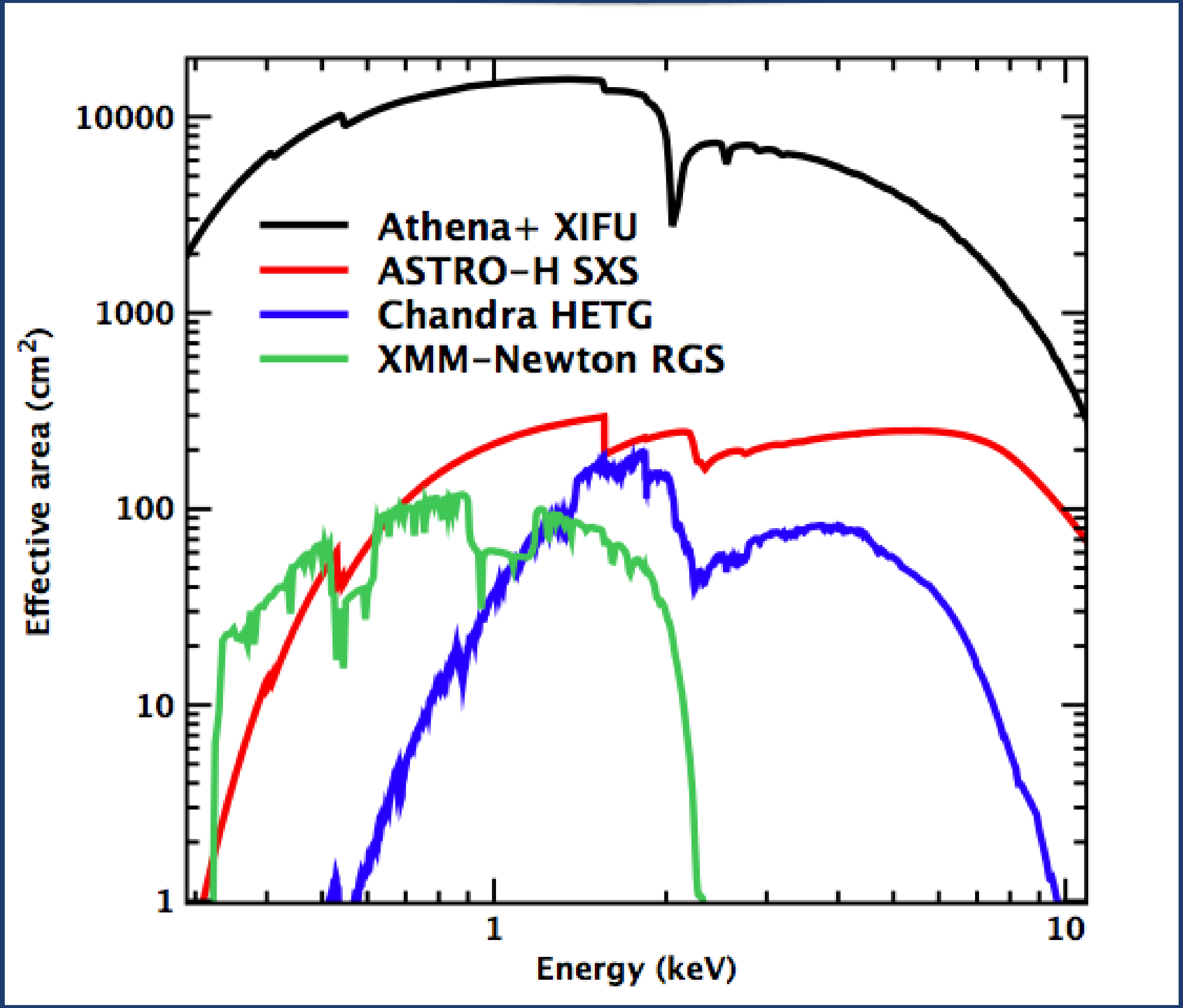
THE HOT AND ENERGETIC UNIVERSE AND THE X-IFU

X-IFU
X-ray Integral Field Unit

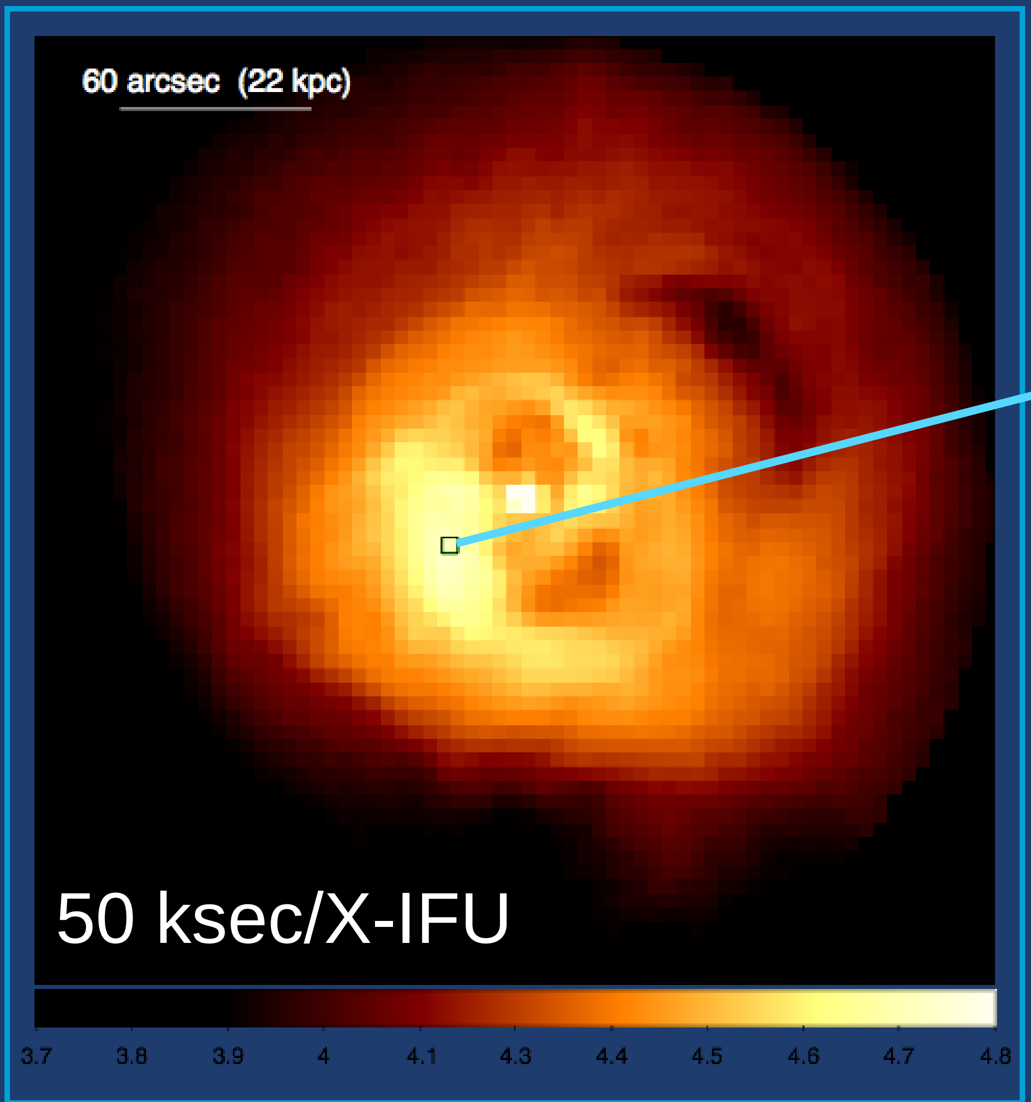
- The Hot and Energetic Universe (HEU) science theme poses two key astrophysical questions (Nandra et al. 2013, 2014):
  - How does ordinary matter assemble into the large-scale structures we see today?
  - How do black holes grow and shape the Universe?
- To address the HEU theme, the X-IFU must provide breakthrough capabilities for:
  - Mapping in 3D the hot cosmic gas to measure motions and turbulence: e.g. to study matter assembly in clusters, AGN feedback on galaxy and cluster scales, …
  - Detecting weak lines to characterise metals in clusters, the missing baryons in the WHIM, features from progenitors in distant GRBs, …
  - Characterizing hot cosmic plasmas, using line ratios (e.g., line multiplets), AGN reverberation and spins, AGN outflows, massive stellar outflows, Solar wind charge exchange, …

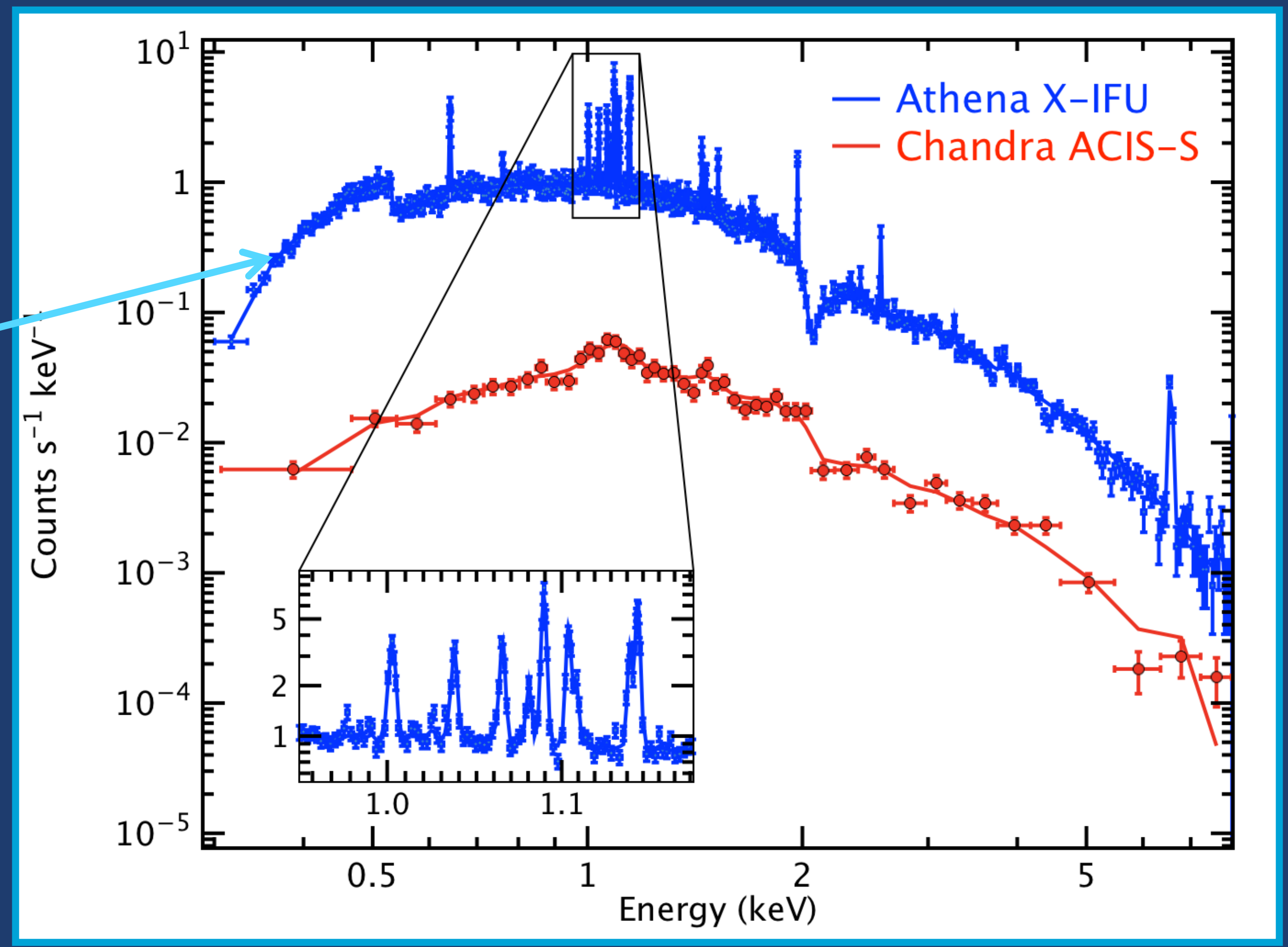
X-IFU EFFECTIVE AREA ON ATHENA

100 x Spectroscopy throughput



A TRUE X-RAY INTEGRAL FIELD UNIT



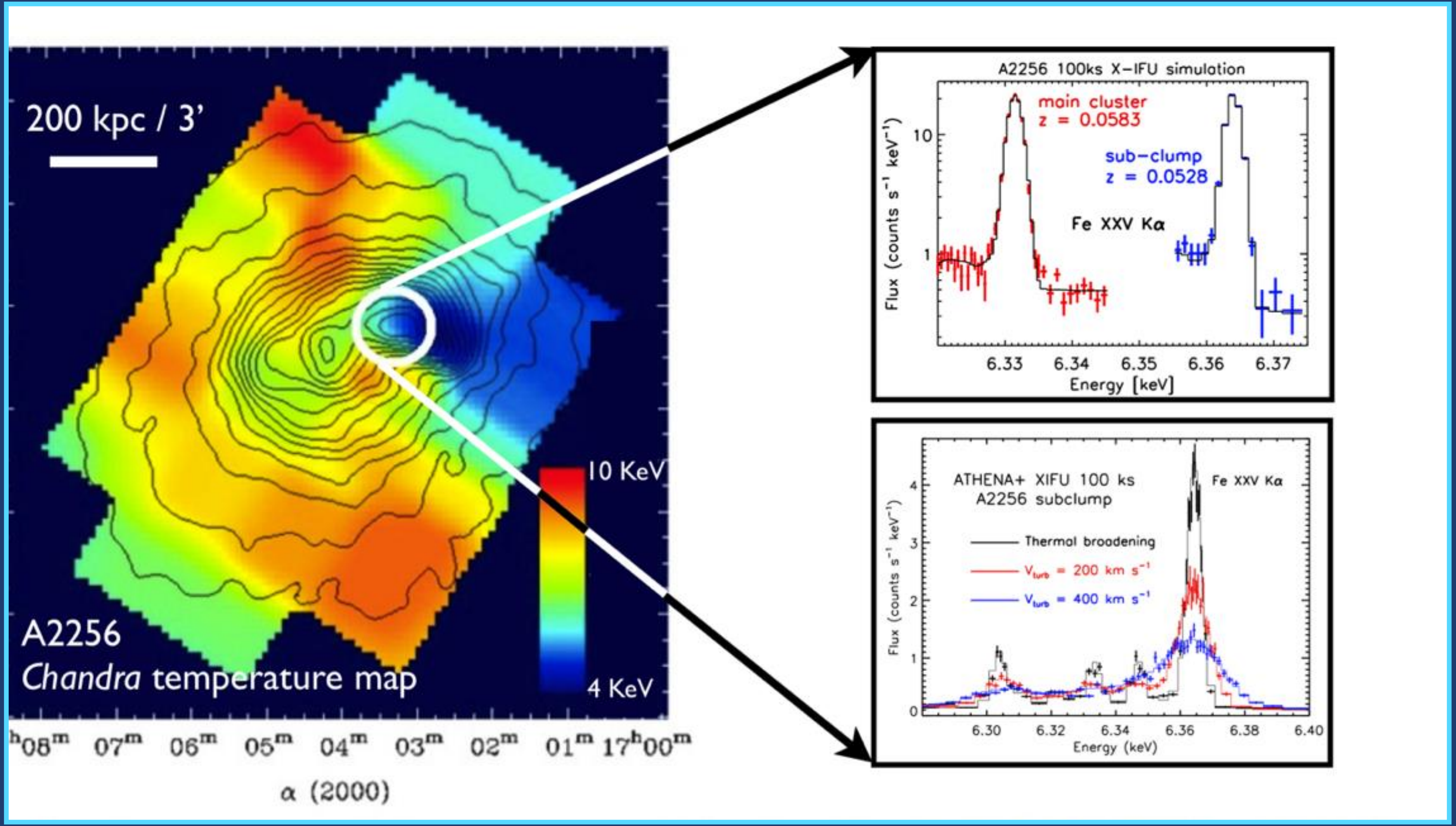


X-IFU simulated image of Perseus and extracted 5"×5" spectrum, compared with the existing Chandra ACIS spectrum. The inset shows the region around the iron L complex. *Croston, Sanders, Heinz, et al., 2013arXiv1306.2323*

Will tell us how jets from AGN dissipate their mechanical energy in the intracluster medium, and how this affects the hot gas distribution

BARYON EVOLUTION IN DARK MATTER POTENTIALS

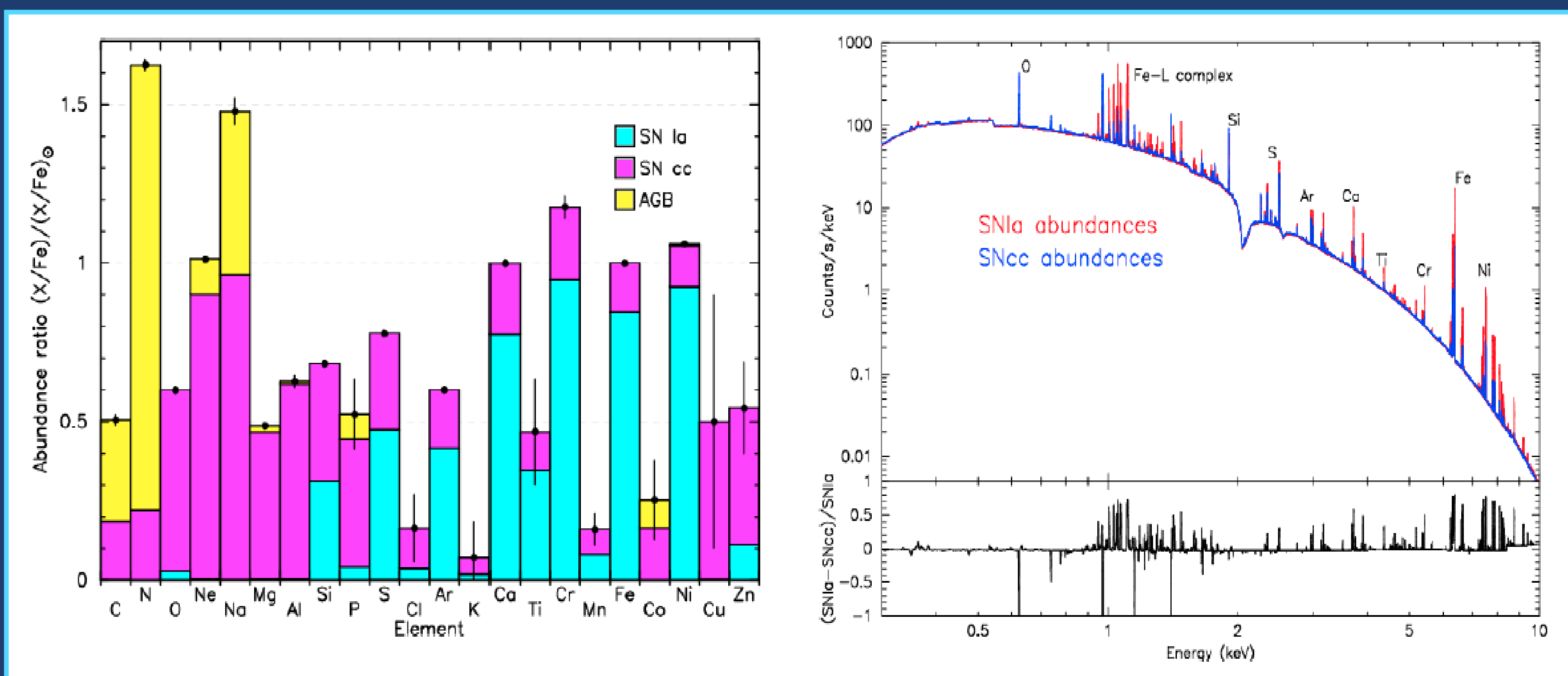
- Key issue: Understand how baryons assemble and evolve in the largest dark matter potential wells of groups and clusters
  - Key measurement: Measure the gas bulk motions and turbulence through high spectral resolution spatially resolved spectroscopy



Right) Bulk motion and turbulent broadening of the Iron K line centered on the sub-clump accreting onto the main body, opening the way to understand how structures assemble and how much energy is stored in gas motion and turbulence. Coupled with lensing observations, this will show how gas reacts to an evolving dark matter potential. *Ettori, Pratt, de Plaa, et al., 2013arXiv1306.2322*

CHEMICAL ENRICHMENT

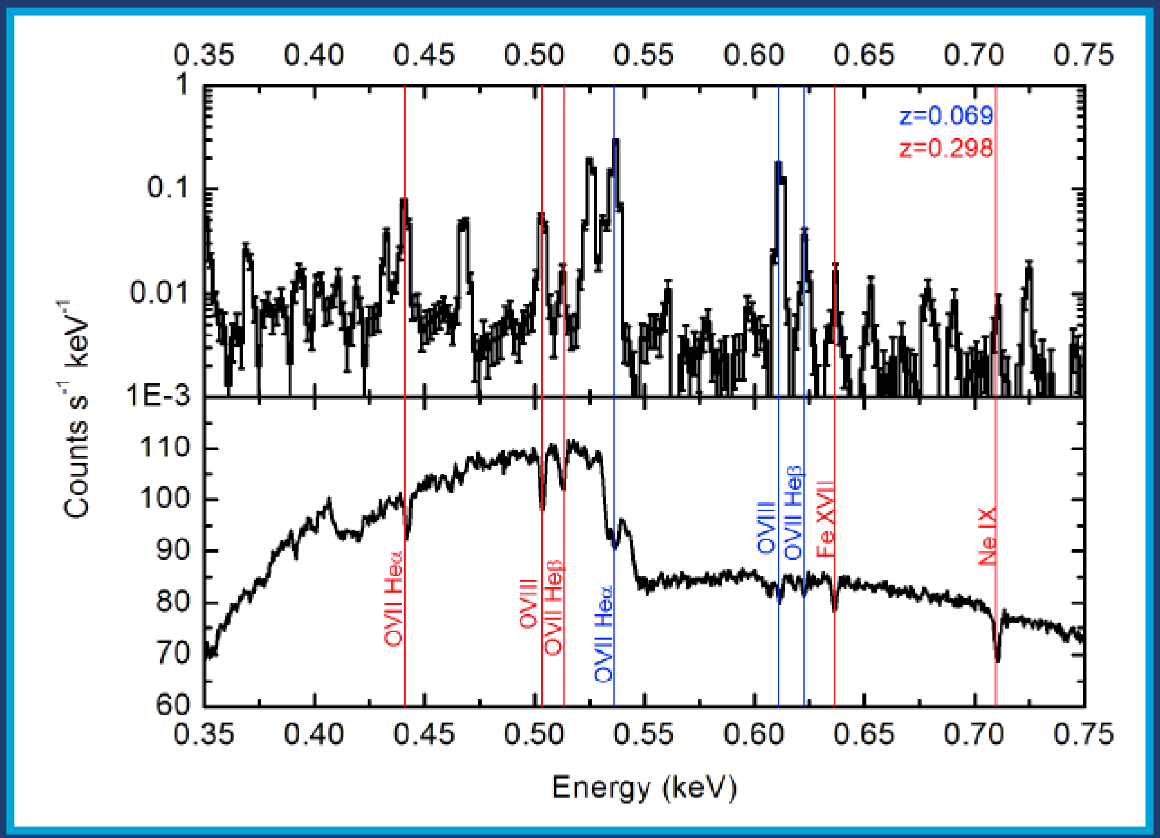
- Key issue: Determine when largest hot gas reservoirs in galaxy clusters were chemically enriched and by which processes.
  - Key measurement: Measure abundances of heavy elements from O to Fe in clusters at different redshifts. Invert the abundances using yields from various SN types and AGB stars to constrain the IMF. Determine where metals are produced in nearby clusters.



Left) Abundance ratios predicted from different contributions of SN types and AGB stars. Right) X-ray spectrum of a typical 3 keV cluster at z=0.05 showing the products of two different types of SN: 1a and CC. *Ettori, Pratt, de Plaa, et al., 2013arXiv1306.2322*

REVEALING THE MISSING BARYONS

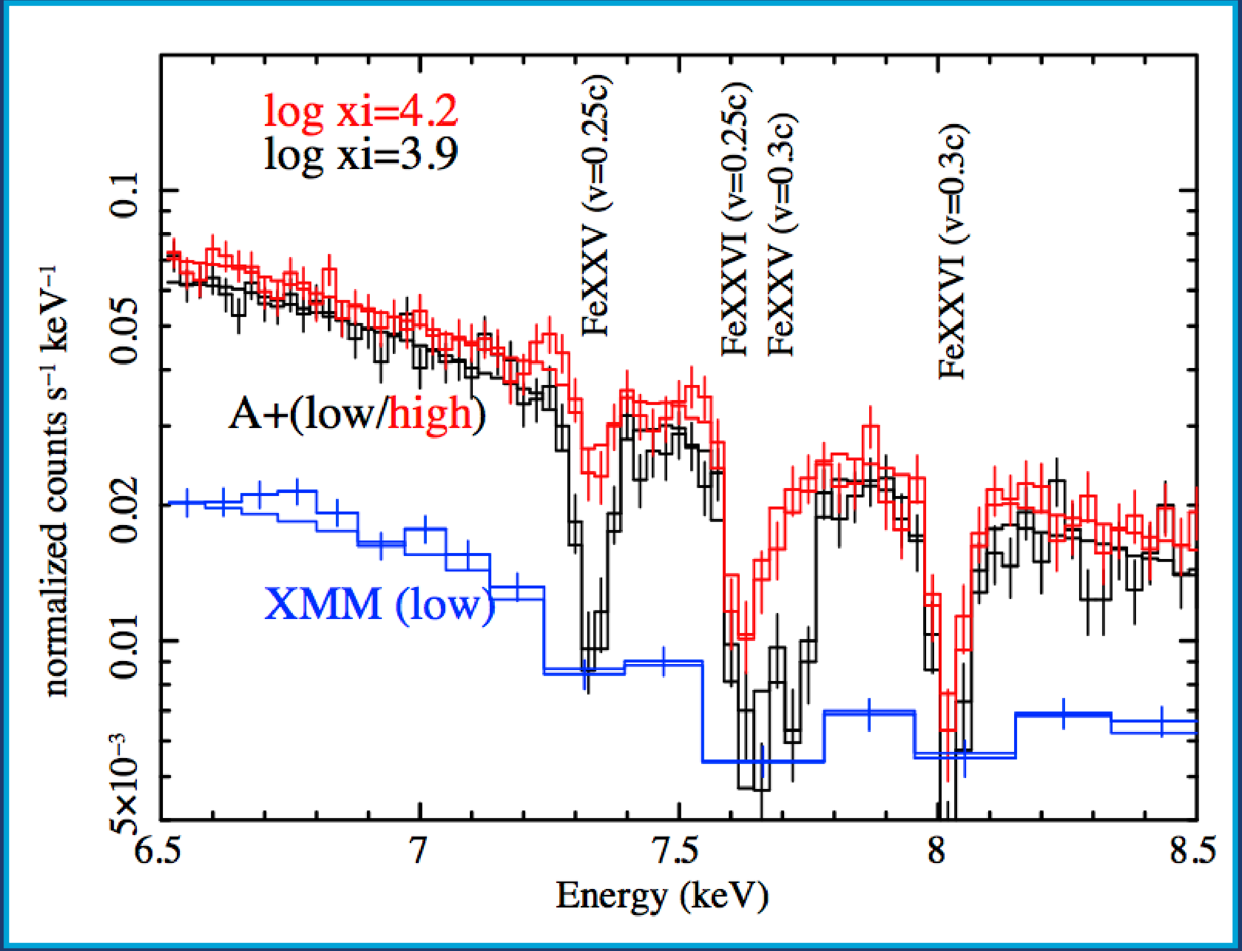
- Key issue: As a probe of structure formation and metal enrichment theory, find the missing baryons at low redshifts (z<1), determine their physical state and composition.
  - Key measurement: X-ray spectra of bright background sources to detect weak absorption lines of highly ionized species (C, N, O, Ne, and Fe) to measure their chemical composition, density, size, temperature, ionization and turbulence and emission line spectroscopy of dense WHIM regions



Simulated emission (top) and absorption (bottom) line spectra for two filaments at two different redshifts. The absorption spectrum is produced by illumination of the filaments by a strong background source (quasar or bright GRB afterglow). *Kaastra, Finoguenov, Nicastro, et al., 2013arXiv1306.2324*

Energetics of AGN feedback

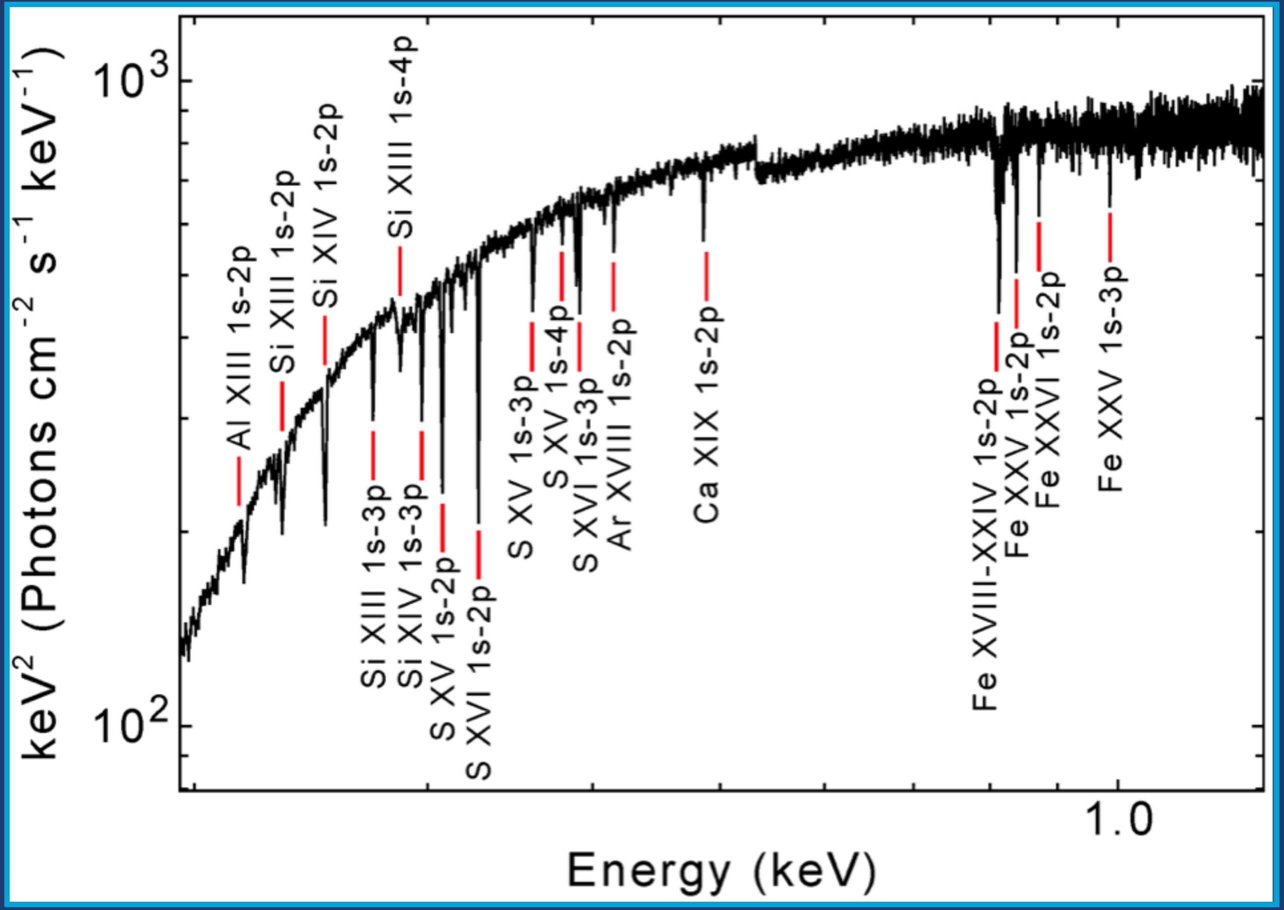
- Key issue: Understand how accretion disks around black holes launch winds and outflows and determine how much mechanical energy is carried away
  - Key measurement: X-IFU spectra to fully characterize the ejecta, by measuring ionization state, density, temperature, abundances, velocities and geometry of absorption and emission features produced by the winds and outflows



X-IFU simulated spectra of ultra-fast outflows with two different velocities, and comparison with an XMM-Newton like X-ray spectrum. *Cappi, Done, Behar, et al., 2013arXiv1306.2330*

PROBING THE FIRST GENERATION OF STARS

- Key issue: Trace the first generation of stars to understand cosmic re-ionization, the formation of the first seed black holes, and the dissemination of the first metals.
  - Key measurement: Measure metal abundance patterns for a variety of ions (e.g., S, Si, Fe) in high-z gamma-ray burst X-ray afterglows as a way to distinguish between progenitors.



A simulated X-ray spectrum of a GRB afterglow at z=7, characterized by deep narrow resonant lines of Fe, Si, S, Ar, Mg, from the ionized gas in the environment of the GRB. The abundance pattern measured by Athena+ can distinguish Population III from Population II star forming regions. *Jonker, O'Brien, Amati, et al., et al., 2013arXiv1306.2336J*

X-IFU DRIVING PERFORMANCE REQUIREMENTS

X-IFU
X-ray Integral Field Unit

Parameter	Value	Main science drivers
Spectral resolution	2.5 eV (E < 7 keV)	Matter assembly in clusters - Jet energy dissipation on cluster scales - Census of warm-hot baryons - *Bulk motion of 20 km/s - Weak line sensitivity - Resolving OVII like triplet*
Field of view	5' (diameter)	Matter assembly in clusters - X-ray cooling cores - Metal production and dispersal - Jet energy dissipation in clusters - *Mapping nearby clusters out to R_{500}*
Pixel size	< 5'' (mirror PSF HEW)	Jet energy dissipation in clusters - AGN ripples in clusters - Cumulative energy deposited by radio galaxies *- Match structure size*
Background level	<5 E-3 count/s/cm^2/keV	Matter assembly in clusters - Metal production and dispersal - *low surface brightness objects*
Low-energy threshold	0.3 keV	Census of warm-hot baryons - Physical properties of the WHIM *- C V lines at 0.31 keV*

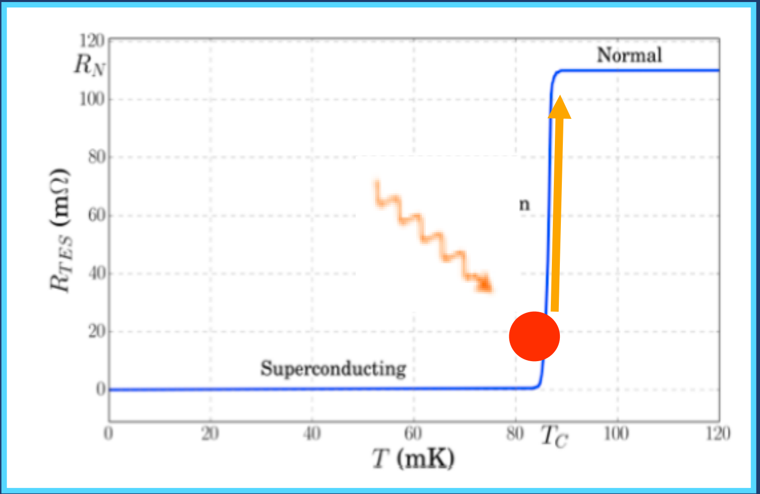
These requirements can be met by a large array of 3840 Transition Edge Sensors with absorbers of 250 µm x 250 µm actively shielded

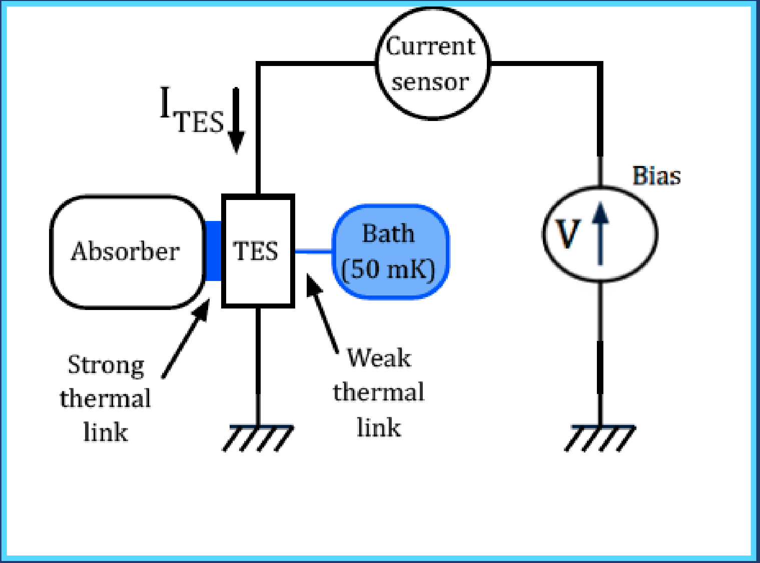
WHAT DEFINES WHAT

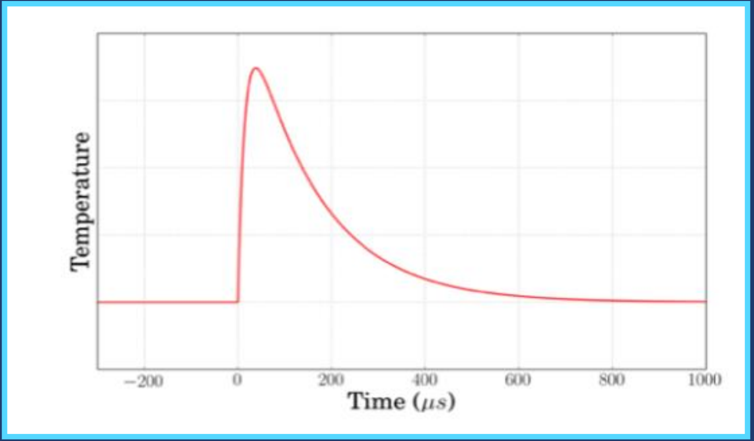
Parameter	Value	What it defines
Spectral resolution	2.5 eV (E < 7 keV)	Defines the sensor technology, the pixel size and readout scheme
Field of view	5' (diameter)	Defines the number of pixels, their size and number of electronic channels (hence heat load on the cryochain)
Quantum efficiency (of mirror effective area)	> 60 % @ 1 keV > 70 % @ 7 keV	Defines the absorber properties and the thermal optical blocking filters
Background level	<5 E-3 count/s/cm^2/keV	Defines the anti coincidence performance and the passive shielding of the detector
Count rate performance	1 mCrab (80% high-res)	Defines the time constant of the TES and the capability to grade events

TES PRINCIPLE

- The TES is a micro-calorimeter that senses the heat pulses generated by X-ray photons when they are absorbed and thermalized
  - The TES is biassed in its transition between its superconducting and normal states
  - When a photon hits the absorber, it heats up both the absorber and the TES whose resistance increases
  - Under a constant voltage bias, the change of the TES resistance leads to a change of the current passing through the TES
  - The change in temperature (or resistance) with time shows a fast rise and a slower decay



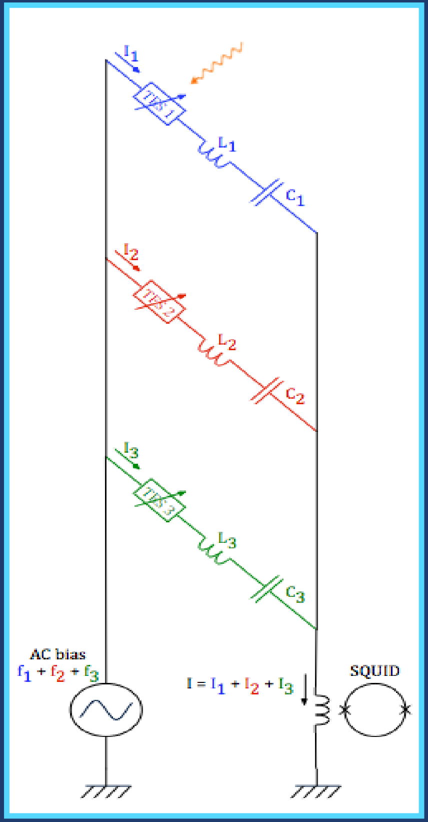


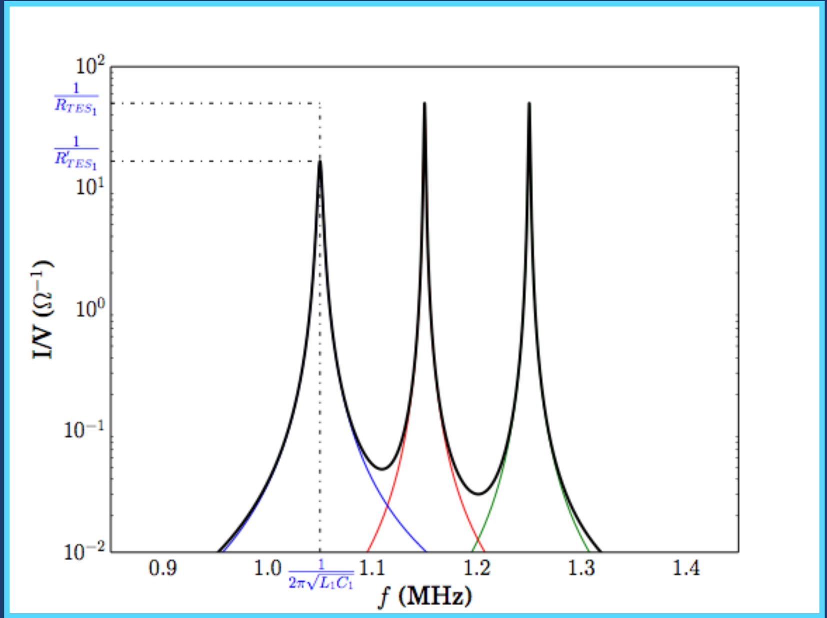


Ravera et al. (2014, SPIE)

FREQUENCY DOMAIN MULTIPLEXING - I

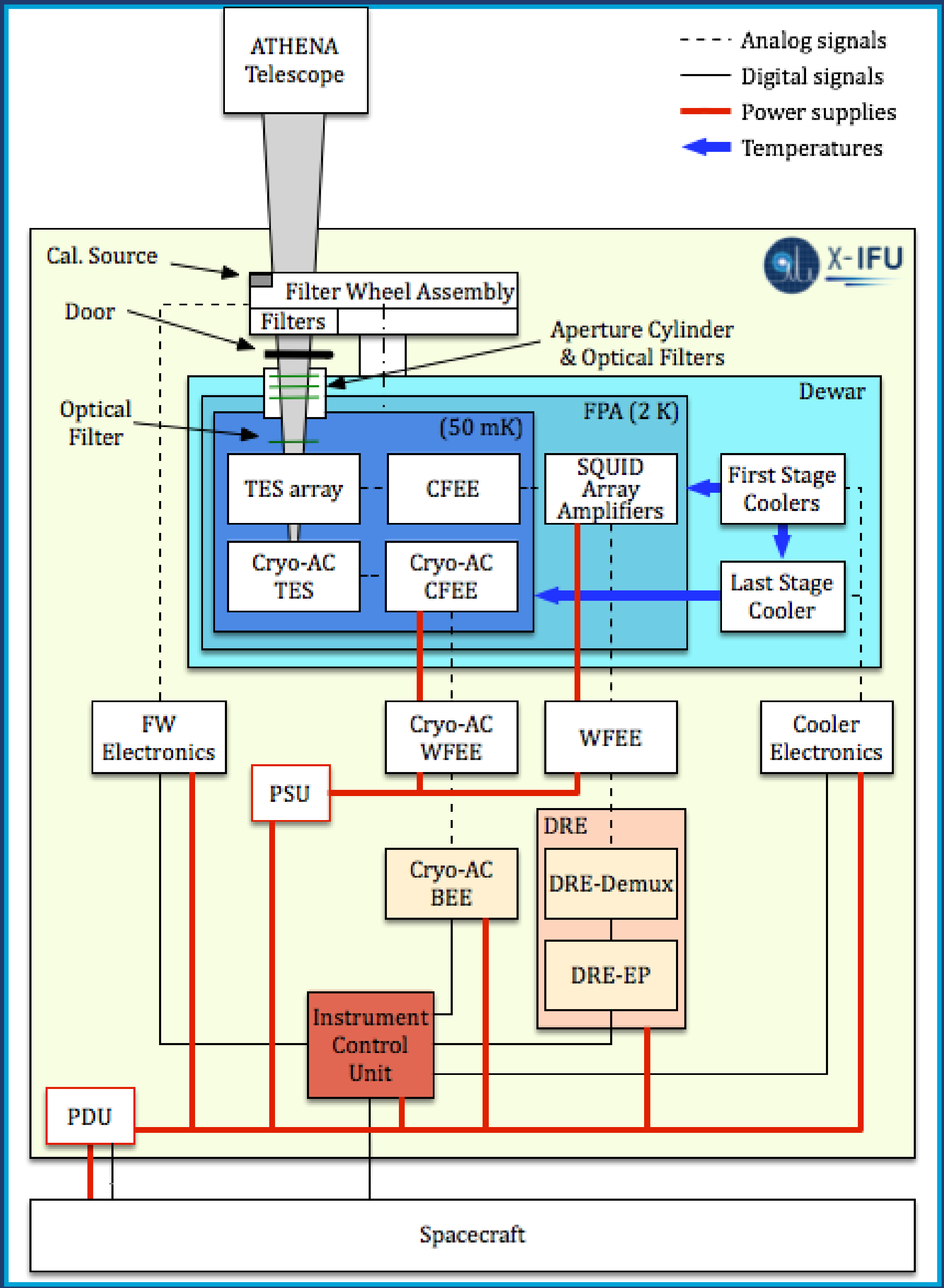
- Multiplexing enables several pixels to be readout by the same SQUID
  - each pixel is AC biased with a specific carrier frequency, each matching the resonant frequency of an R_{TES} LC circuit
  - The amplitude of the resonant frequency peak changes with the TES resistance
- With a frequency range of 1 to 5 MHz and a bandwidth separation of 100 kHz, 40 pixels can be multiplexed in a single read-out channel
- Demultiplexing and optimal filtering to determine energy of each photon in the event processor





Ravera et al., den Hartog et al. (2014, SPIE)

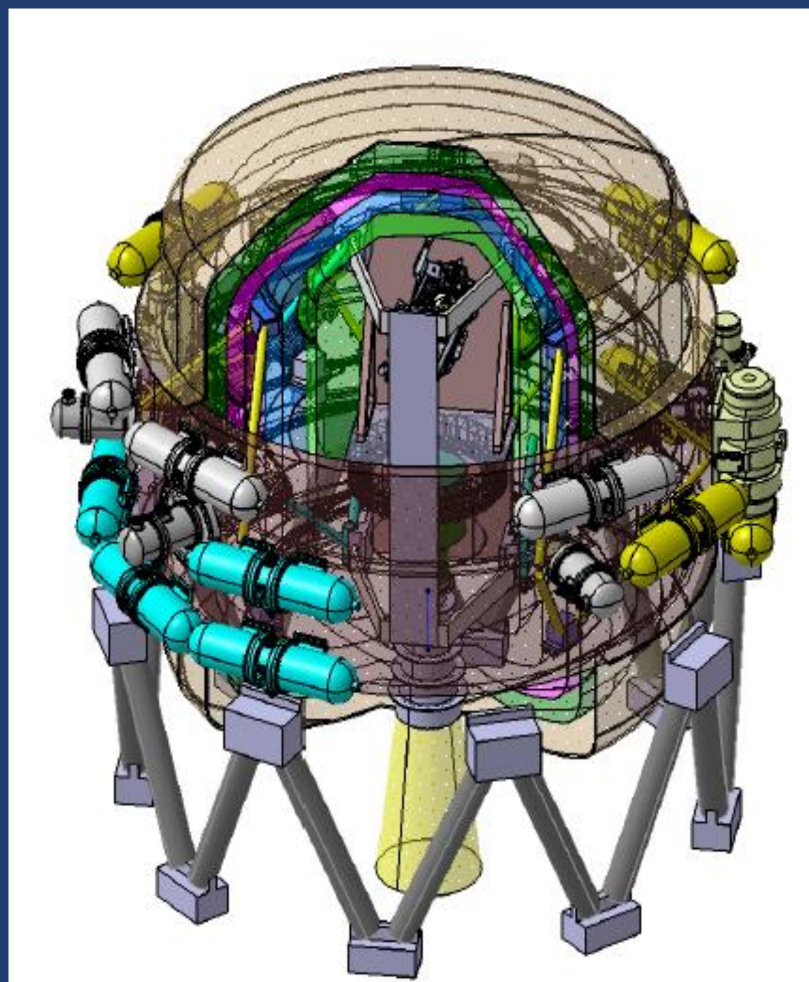
X-IFU IMPLEMENTATION - FUNCTIONAL DIAGRAM

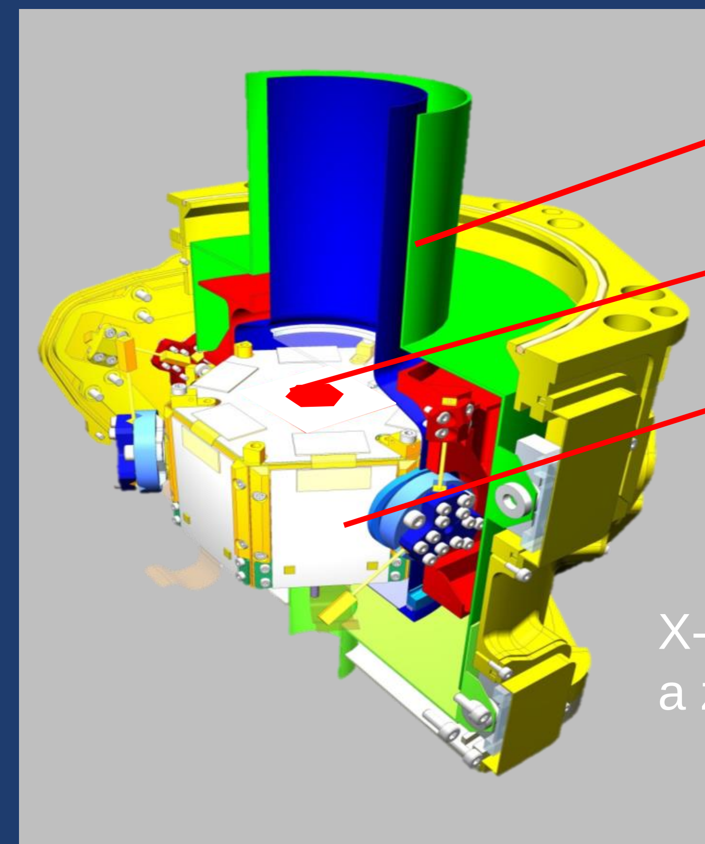


- Filter wheel & calibration source
- Aperture with thermal/optical blocking filters
- Multi-stage mechanical coolers :, 2- stage Sterling cooler, 4He JT cooler (to 4K) , and Pulse Tube and 3HeJT (to 2K) and Sorption ADR (2 K to 50 mK)
- Large array of Cu-Bi absorbers and Ti-Au TES
- Cryogenic active anticoincidence
- 2 stage SQUID readout + LNAs (in the WFEE)
- Frequency Domain Multiplexing in the DRE (96 channels of 40 pixels)
- Digital pulse shape analysis in the event processor to recover energy, time, grade

Gottardi et al., Fabrega et al., Barbera et al., Macculi et al., den Hartog et al., Ravera et al. (2014, SPIE)

MECHANICAL DESIGN AND BUDGETS





X-IFU dewar, cooling chain and a zoom on focal plane assembly

Current best estimates (no system margin)

FOCAL PLANE ASSEMBLY MASS	6 KG
CRYOGENIC CHAIN MASS & POWER	320 KG/900 W
MASS AND POWER OF ELECTRONICS	180 KG/300 W
X-IFU MASS AND POWER BUDGET	506 KG/1.2 KW

Den Herder et al. (2012), Barret et al. (2013), van Weers et al., Ravera et al., Branco et al., Duband et al. (2014, SPIE)

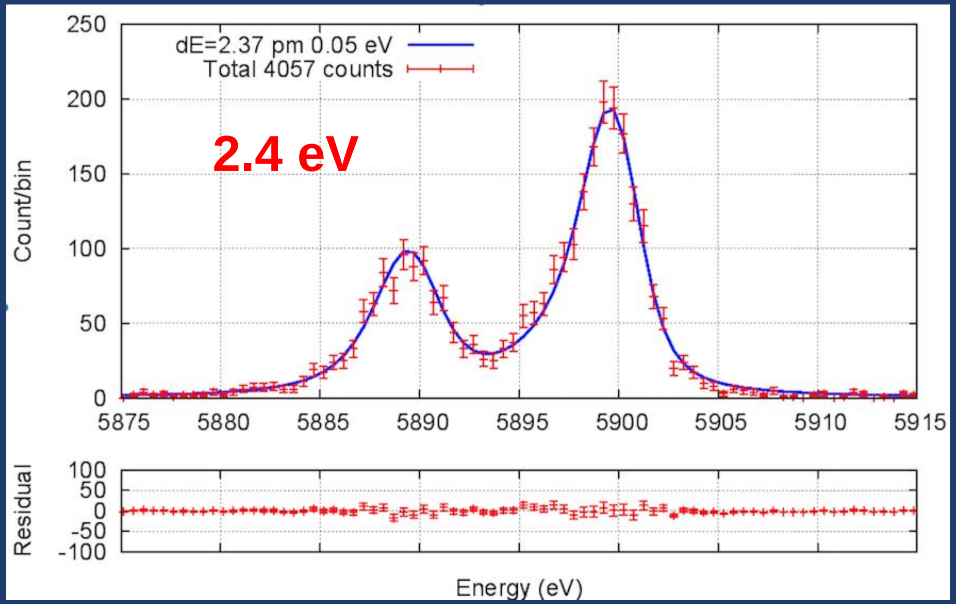
INSTRUMENTAL CHALLENGES

- Spectral resolution
- Count rate capability (1 mCrab -> 10 mCrab)
- Background
- Cooling down to 50 mK

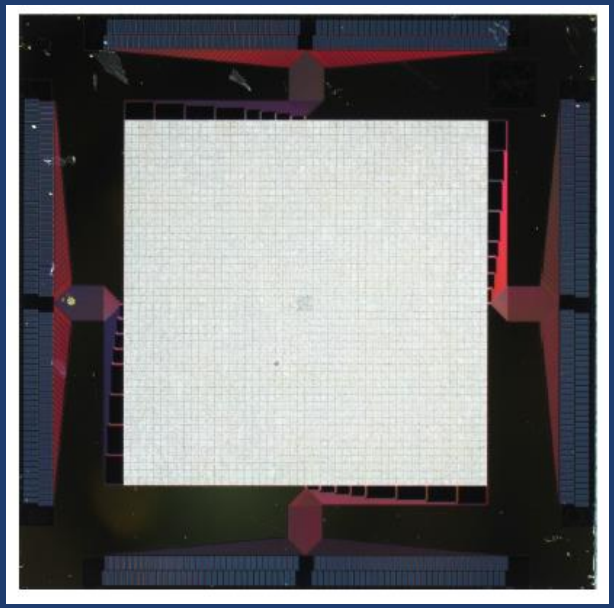
X-IFU SPECTRAL RESOLUTION

- Basic performance demonstrated:
  - pixels with < 2.5 eV resolution
  - read-out with Frequency Domain multiplexing (2 pixels)
- Challenge to realize this over full detector chain with optimized flight electronics (power, radiation tollerant etc)

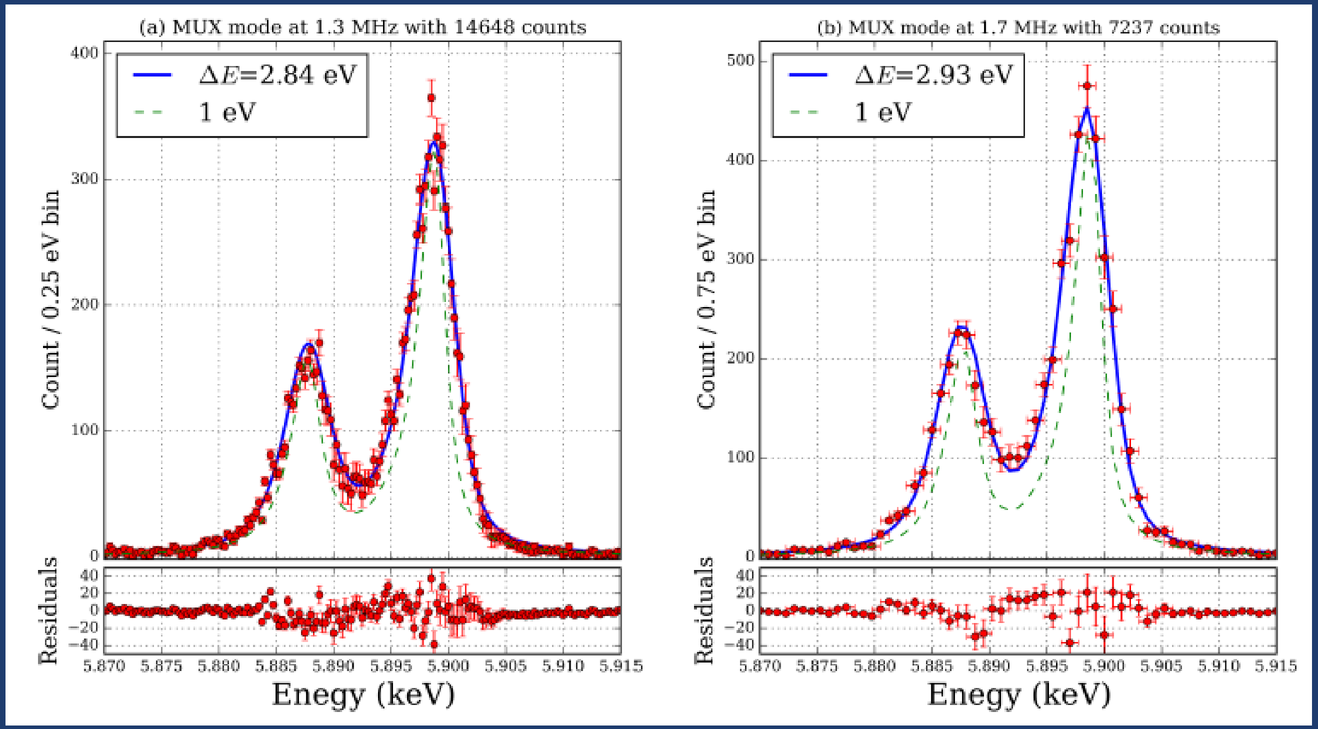
AC bias (1.7 MHz)



Prototype TES array
(32x32 array with sub-array)

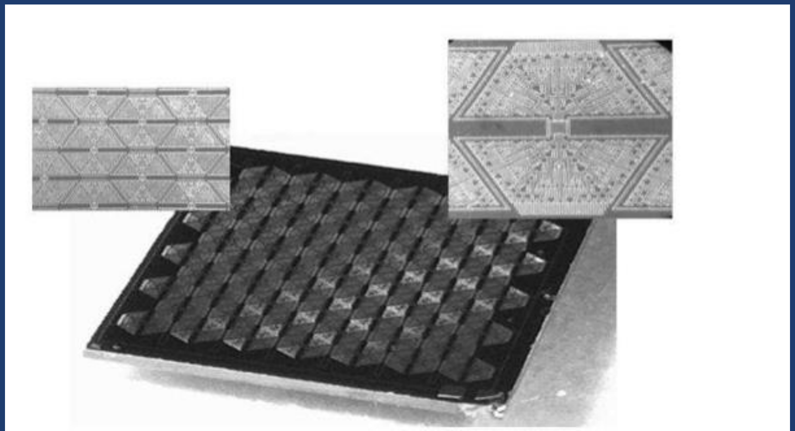


2 pixels multiplexed (1.3 and 1.7 MHz)



TES CryoAnticoincidence

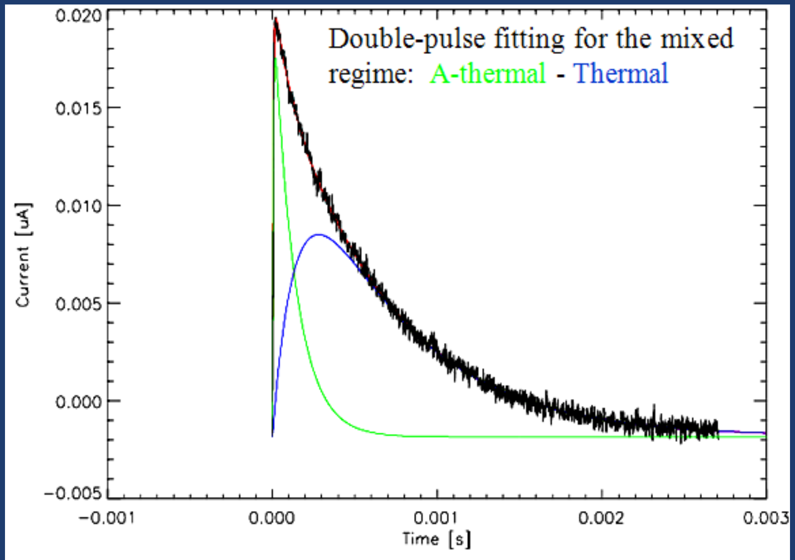
(cm^2) multi-TES pixels



- Instrument optimized (Cryo-anti coincidence detector and graded shielding near sensor
- Dependent on environment (orbit, soft protons focussed through the mirror, spacecraft structure and charged particle deflector
- Strategies to measure and predict the background

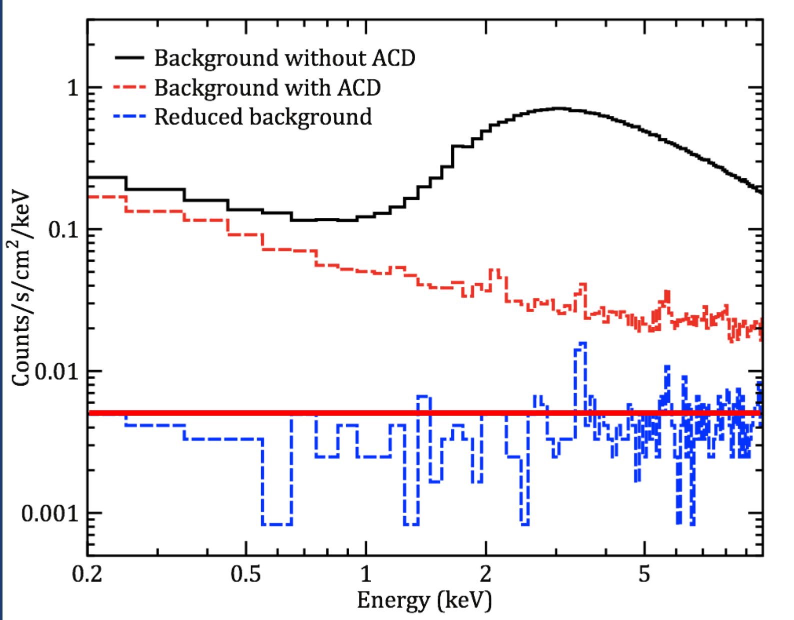
fast (rise <30 usec)

low energy threshold 20 keV



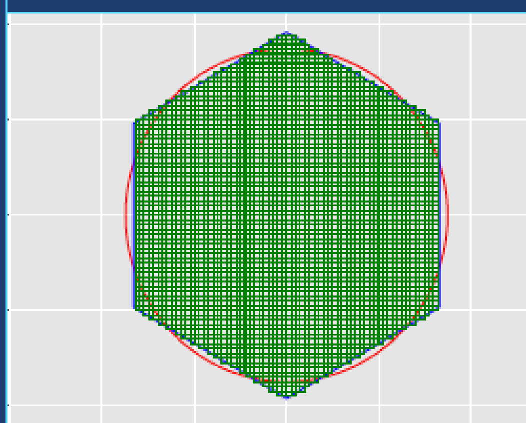
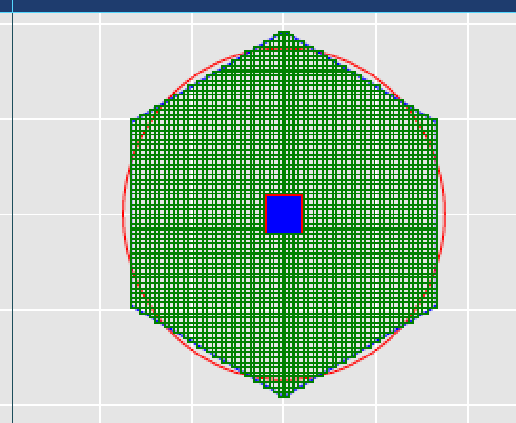
Background requirement feasible (but difficult)

Macculi et al. (2014, SPIE)



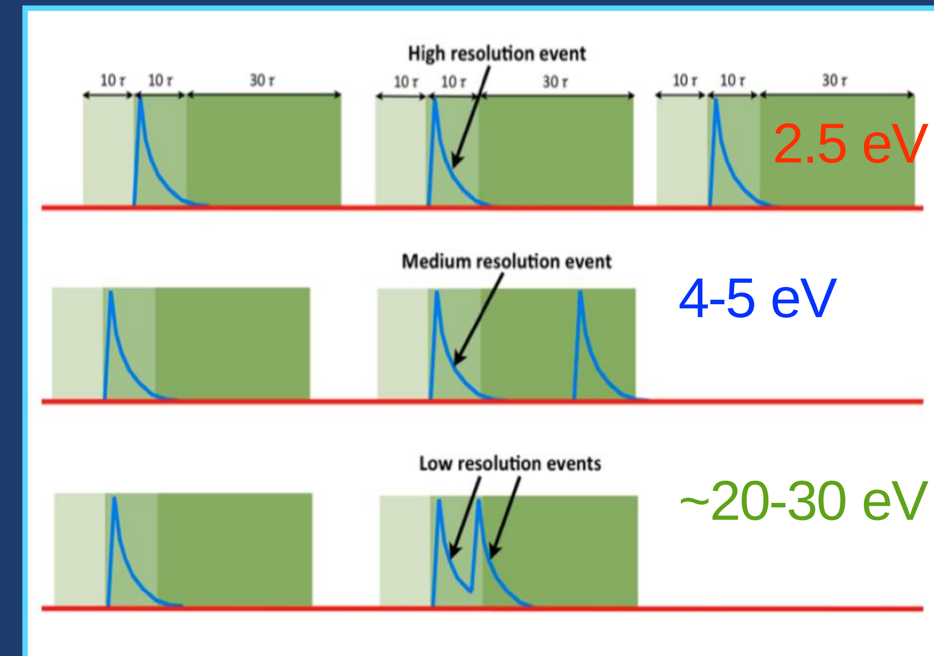
X-IFU PERFORMANCE- COUNT RATE CAPABILITY

- High countrate important for compact objects and for GRBs (used as backlight for the WHIM
- Improve from 1 mCrab to 10 mCrab with > 80% throughput for high grade events
- Introduce detector with two sectors (pixel size and countrate capability)
- Defocus may also help

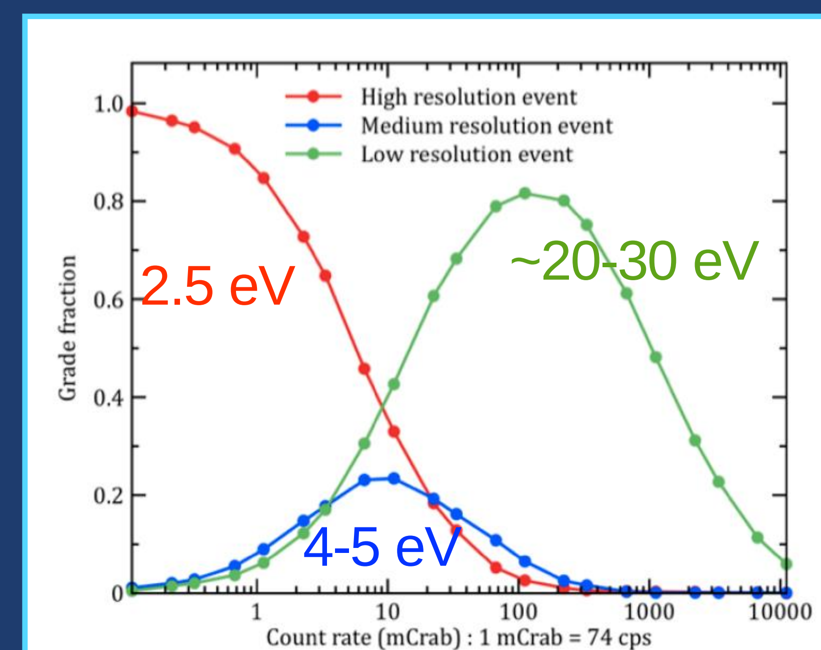
Configuration a (baseline)	Configuration b
	
Single size pixel array - 5′ (pixel of 4.2″)	Small Pixel Array (SPA) - 33″ x 33″ (1.8″)

Ravera et al. (2014, SPIE)

Event grading

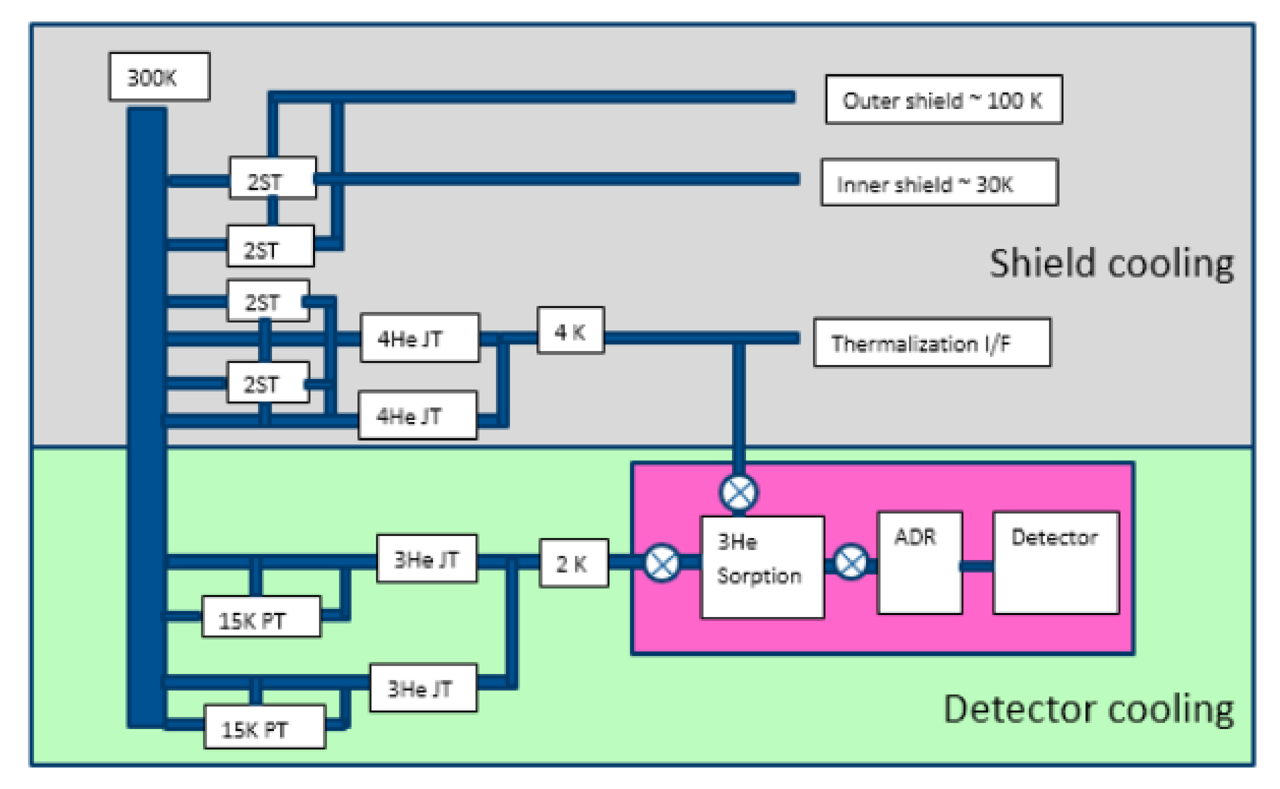


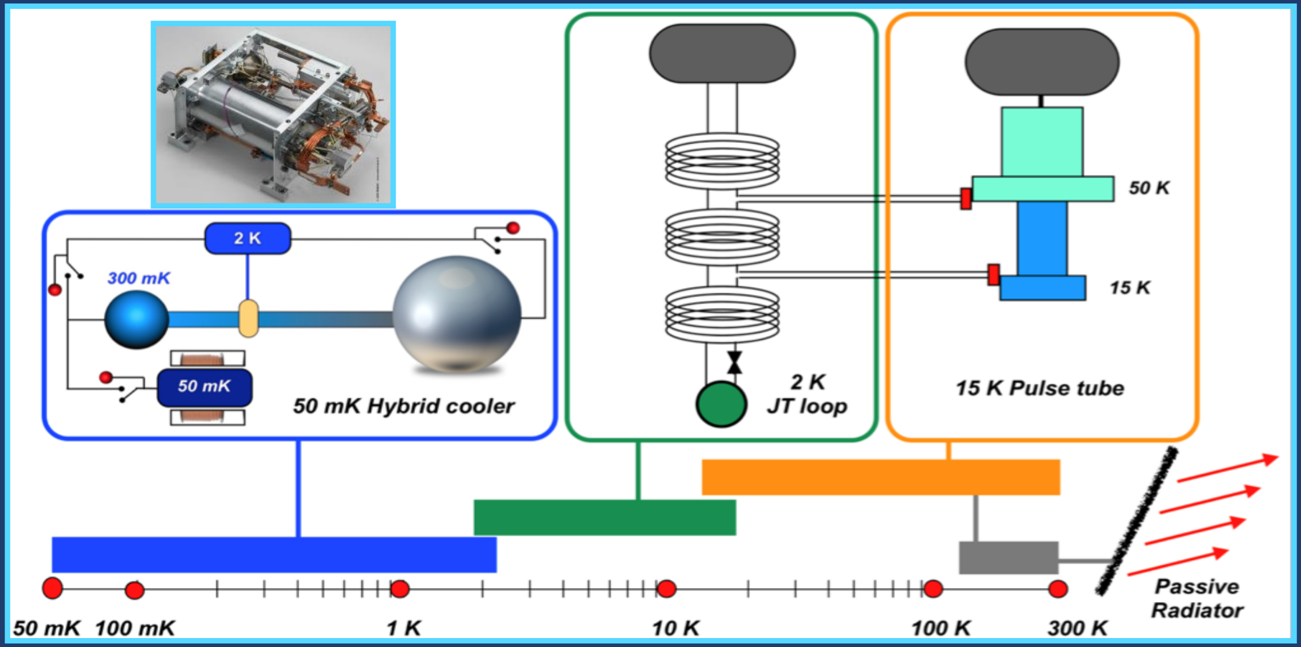
Event ratio



X-IFU COOLING CHAIN

- Multi-stage cryogen free mechanical coolers with no single-point failures to guarantee a 5 year mission lifetime
- Thermal stability of 50 mK, 300 mK, 2K environment
- Recycling time for ToOs
- Hightly transparent filters for X-rays





Duband et al., Branco et al. (2014, SPIE)

CONCLUSIONS

X-IFU
X-ray Integral Field Unit

- Athena science needs wide field imaging and spatially resolved high spectral resolution (the X-ray Integral Field Unit)

- The X-IFU will be the first X-ray Integral Field Unit, providing 2.5 eV spectral resolution combined with arcsecond spatial resolution

  - Extraordinary discovery potential for a wide range of science investigations beyond the hot and energetic Universe science theme (insterstellar dust, SNR, Stars, ….)

- The X-IFU provides high quality spectral images for a large set of sources in reasonable observing times and further optimizations are being studied together with the scientific community

A BIG ENTERPRISE

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