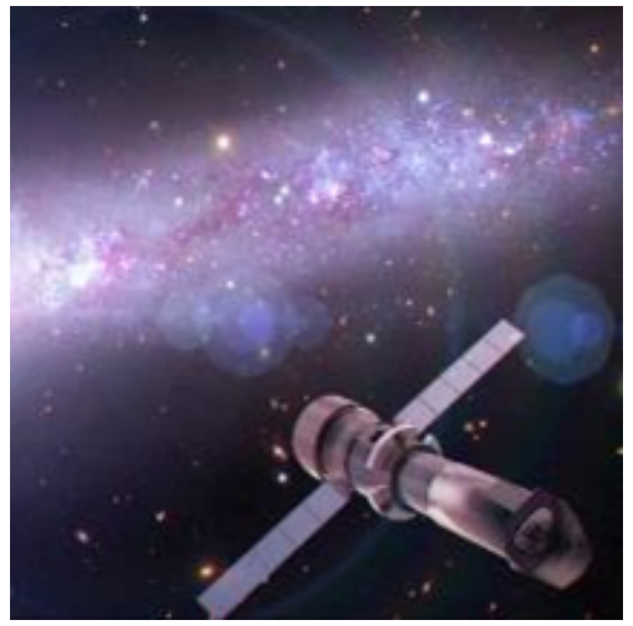
The Athena
X-ray Integral Field Unit
Calibration Plan



François Pajot (IRAP)

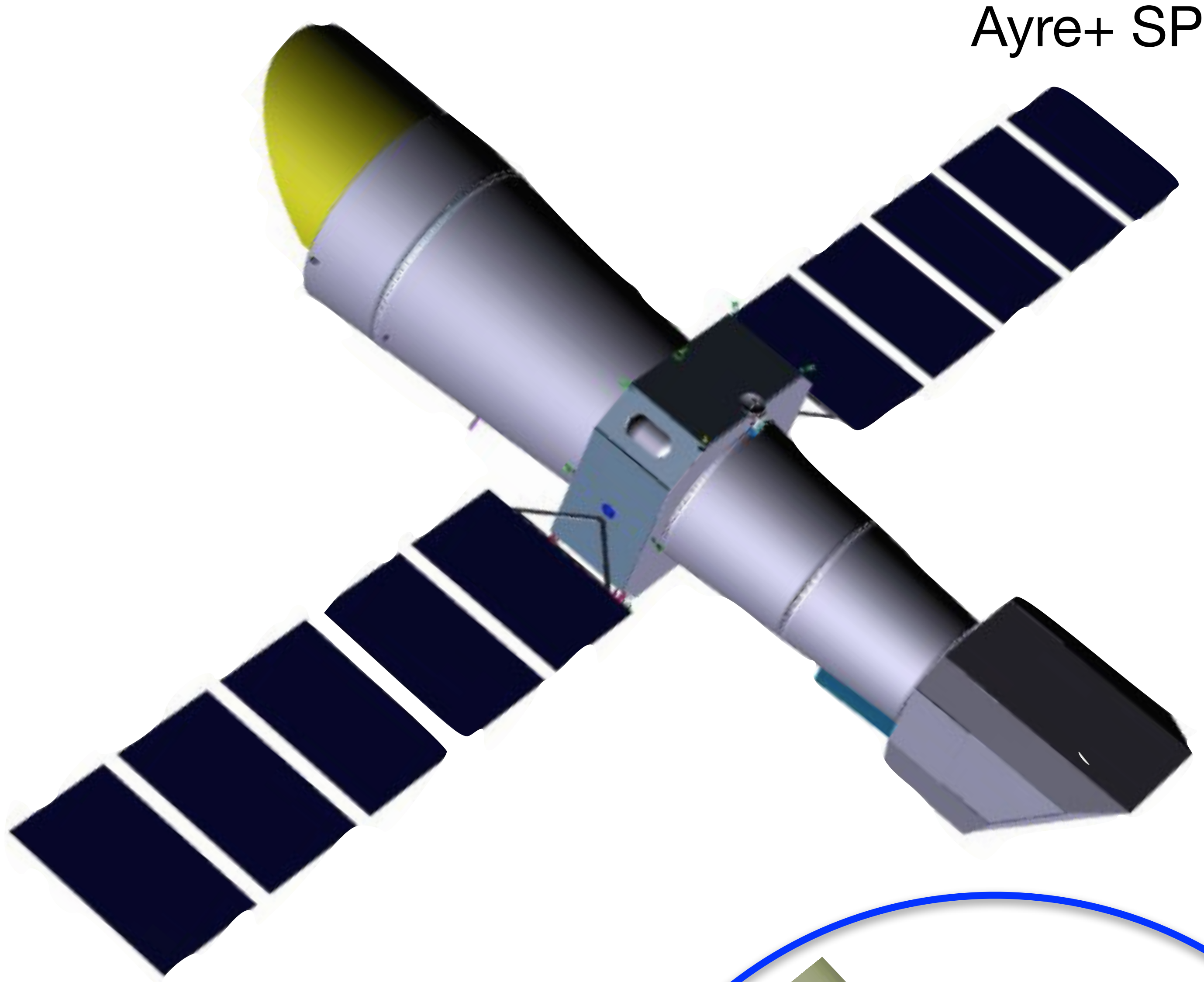
on behalf of the X-IFU Calibration Team

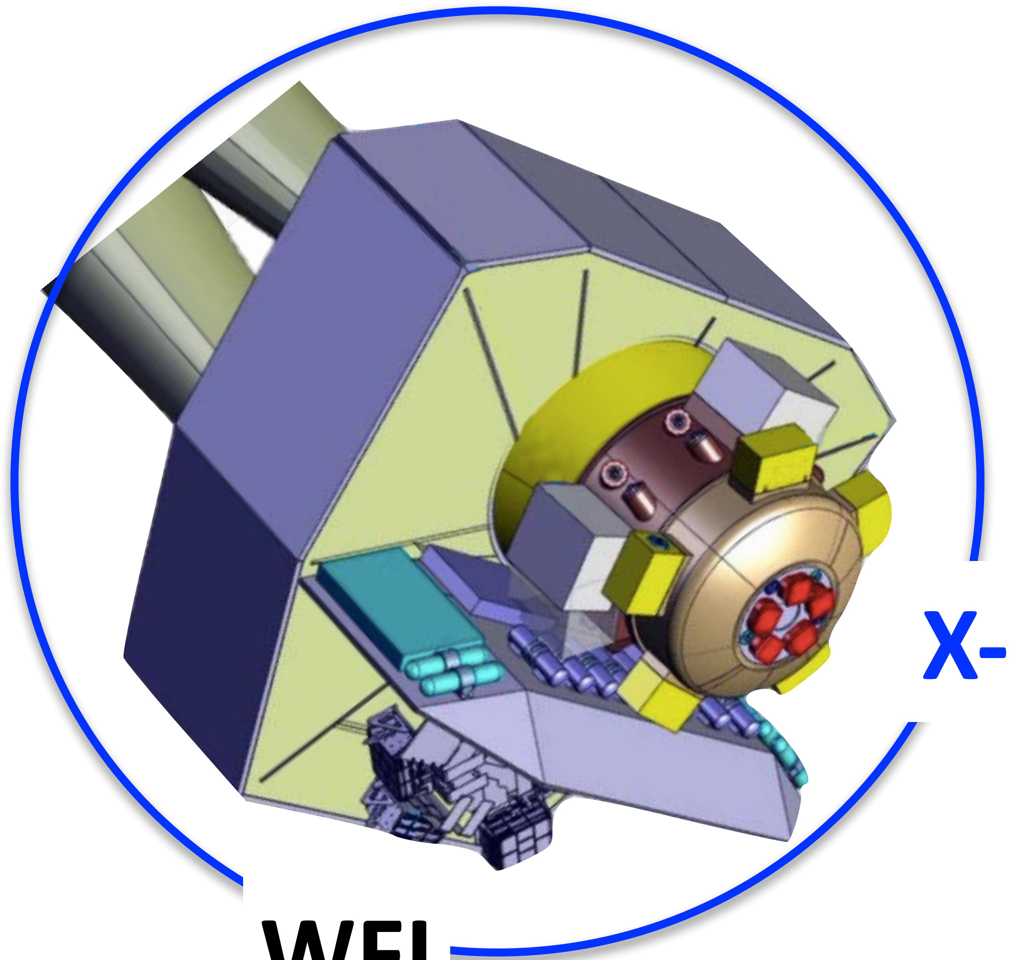
14th Workshop of International Astronomical Consortium for High Energy Calibration
Shonan Village Center - May 20th, 2019

Athena in a nutshell

- Early 2030's launch
  - with the newly developed Ariane 6 (64)
- A 7 ton spacecraft to be placed in a L2 (L1) orbit
- Unprecedented collecting area in X-rays
  - 1.4 m^2 at 1 keV and 0.17 m^2 at 7 keV
  - 5'' angular resolution
- Two focal plane instruments with a movable mirror assembly
  - The Wide Field Imager (WFI) optimized for surveys
  - The X-ray Integral Field Unit (X-IFU) optimized for spatially resolved high resolution spectroscopy

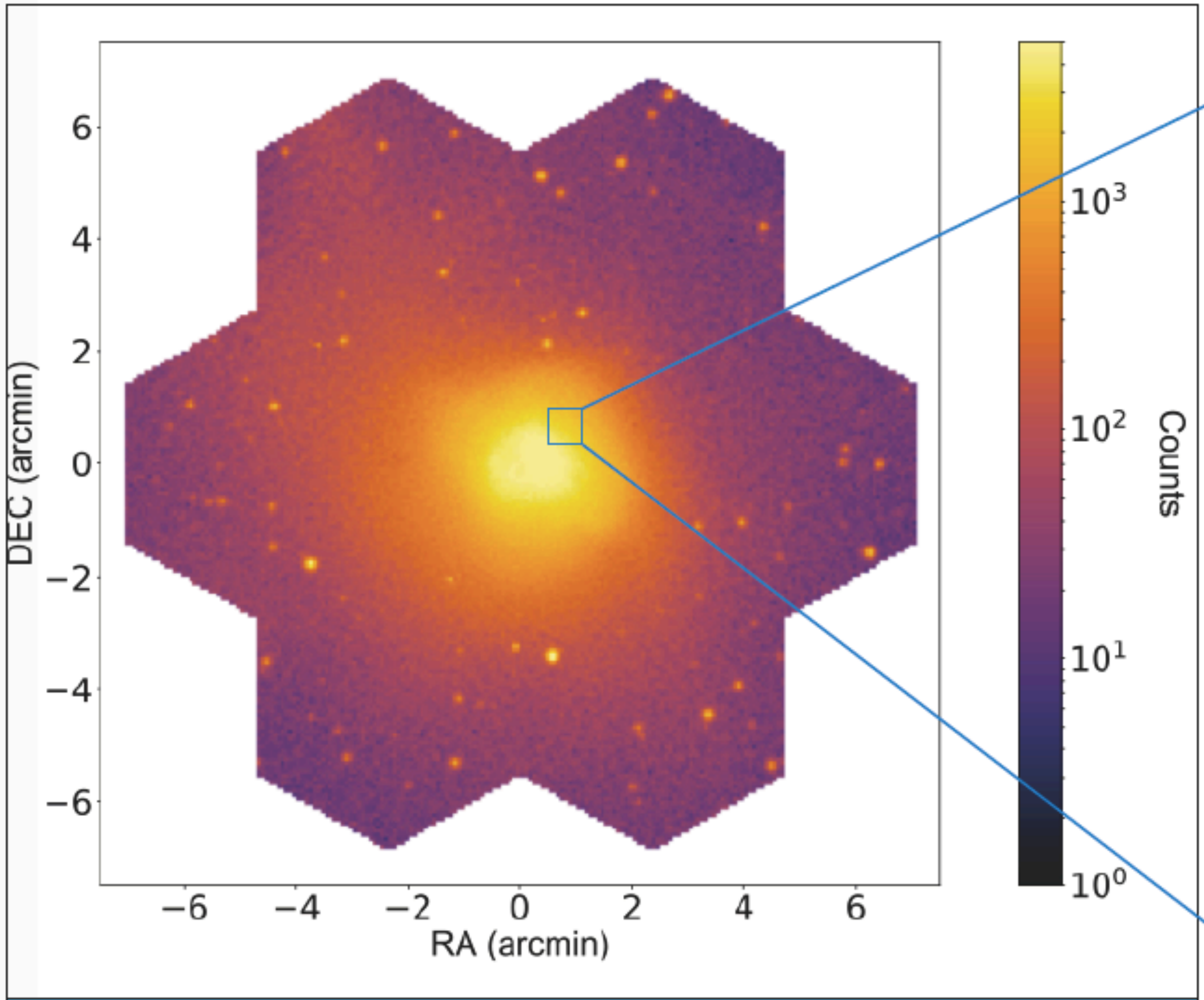
Ayre+ SPIE 2018



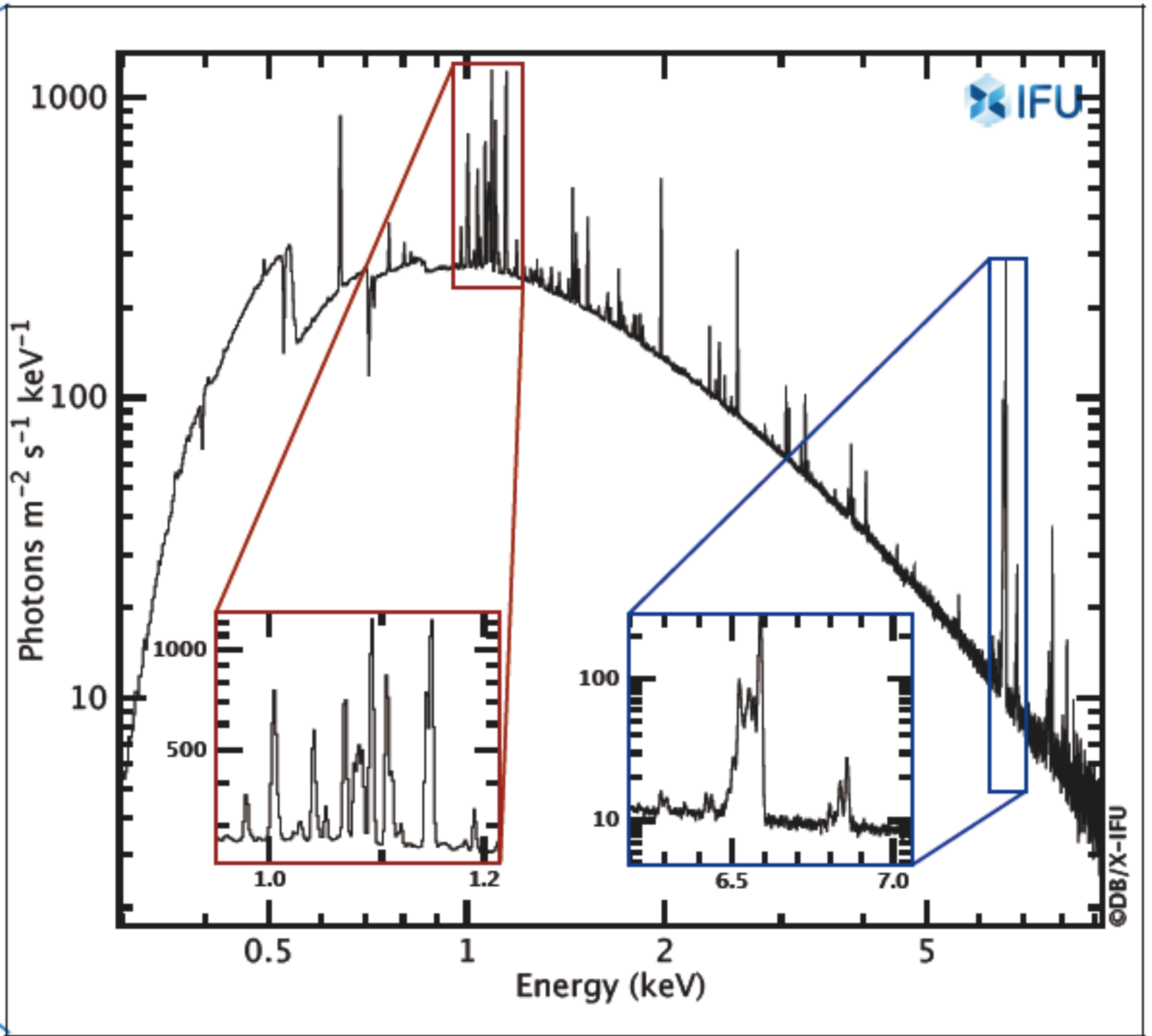


Ayre+ ESA study team

A new era in high spectral resolution fine imaging



2D X-ray image: surface brightness of a galaxy cluster (Cucchetti et al. 2018)

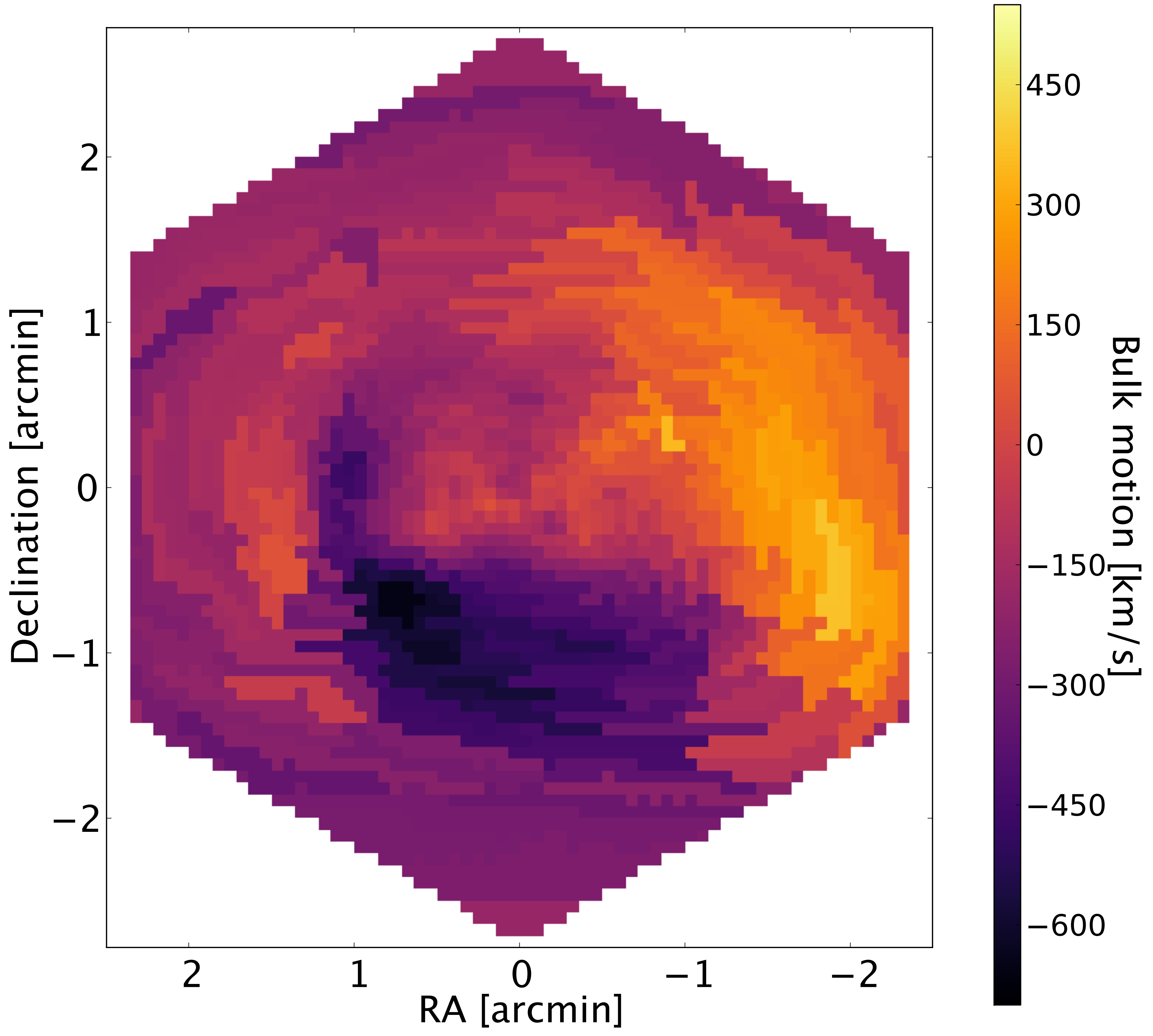


X-ray spectrum of a small region of the image

X-IFU key requirements: High spectral resolution imaging

- Spectral resolution: 2.5 eV up to 7 keV
  - Cluster physics (broadening down to 20 km/s) and missing baryons
- Energy band pass: 0.2 to 12 keV
  - Missing baryons
  - Black hole spins, winds and ultra-fast outflows
- Background requirement: $<5\ 10^{-3}$ cps $s^{-1}cm^{2}keV^{-1}$ (2-10 keV)
  - Cluster physics and cluster chemical evolution
- Field of view: 5 arcmin (equivalent diameter)
  - Cluster physics out to their outskirts
  - Defocus capability for bright point sources
- Pixel size: <5 arcsec
  - Cluster feedback on structure size and to minimize confusion

Peille+ SPIE 2016 — Cucchetti+ SPIE 2018 - A&A 2018

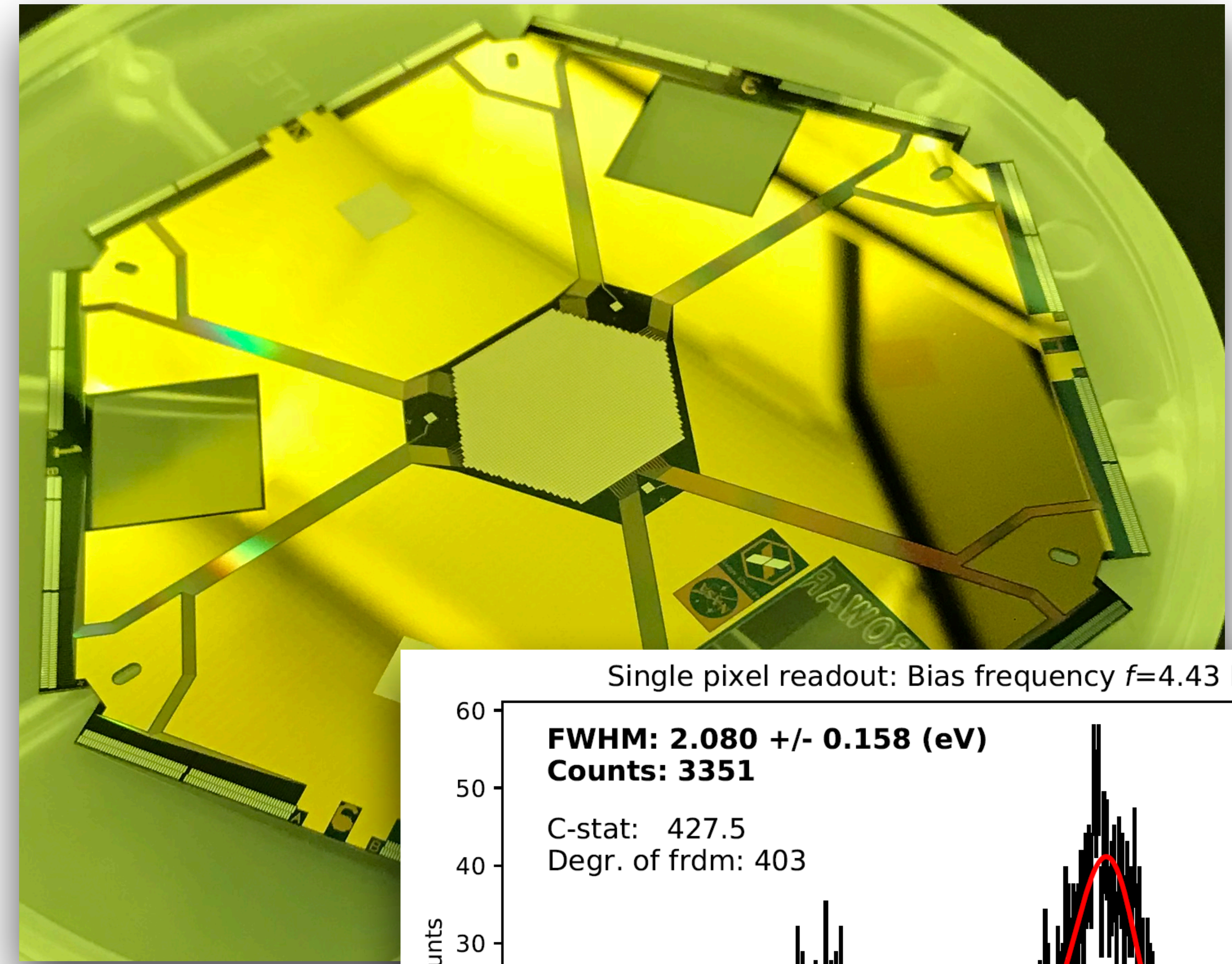


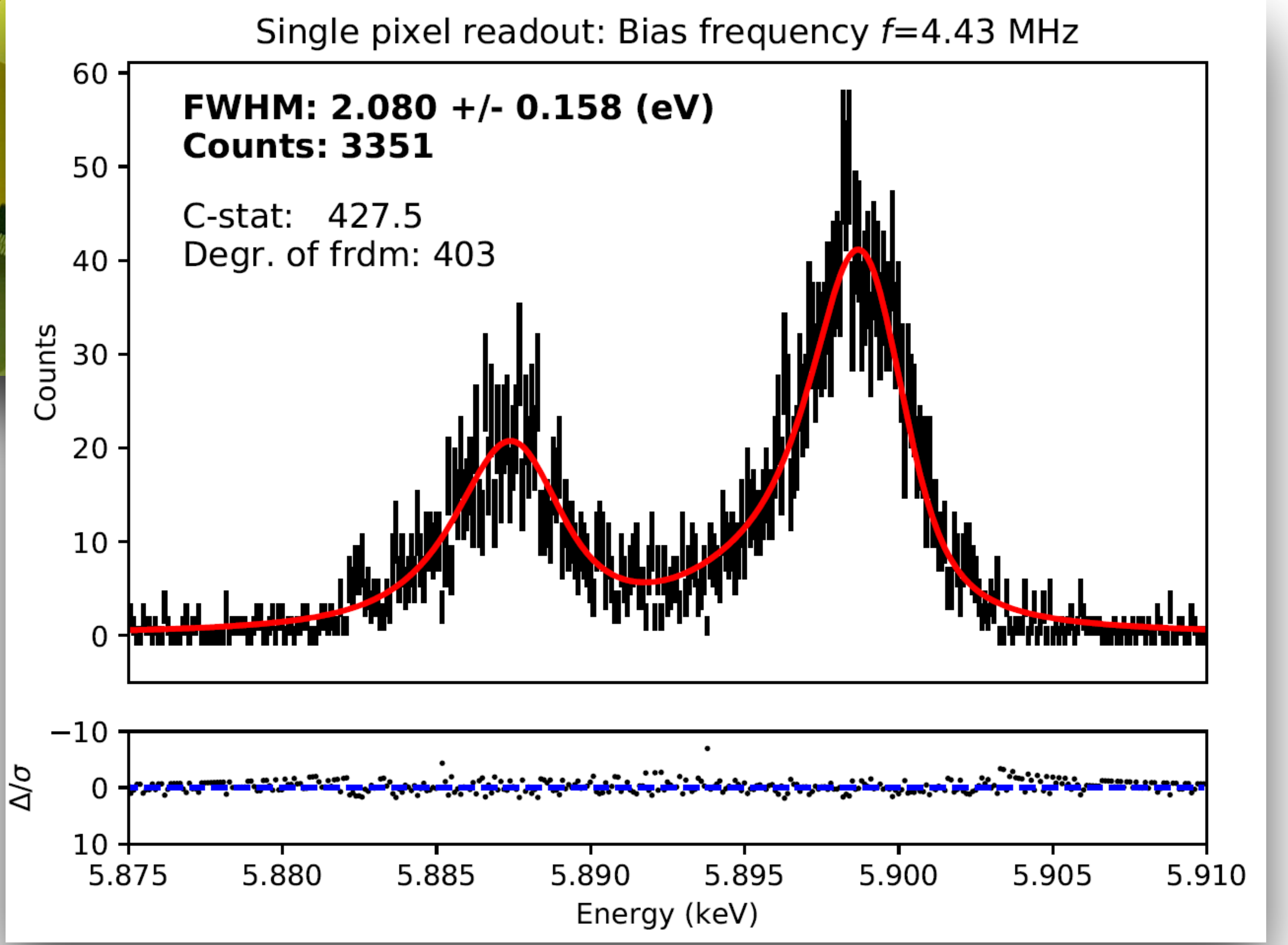
- Reconstructed bulk motion velocity field of the hot intra-cluster gas for a 50 ks X-IFU observation of the central parts of a Perseus like cluster considered at a redshift of 0.1

Introduction to the X-IFU calibration

- The only space instrument using microcalorimeters calibrated and operated so far is Hitomi/SXS
- X-IFU has 2 orders of magnitude more pixels (3168 Mo/Au Transition Edge Sensors) and is a factor ~2 better in energy resolution than Hitomi/SXS [XRISM/Resolve]
- X-IFU is a complex system and calibration data depend on a large multi-parameter space (detectors operating temperature and electrical biasing parameters, magnetic field, thermal background on detectors, readout electronics gain,…)
- Lab data and modelling of atomic X-ray emission processes of the innermost electron shells (K, L,…) of many elements of astrophysical interest are not yet known to the required accuracy to derive the full physical conditions of the astrophysical sources (metallicity, velocity, turbulence,..) that X-IFU data will allow

NASA/GSFC prototype arrary





Single-pixel demo
δE = 2.08 eV@ 4.4 MHz
NASA/GSFC

X-IFU calibration requirements

Parameter	Value	Context	Comment
Energy scale			
High grade events	0.4 eV	0.2 - 7 keV	At pixel level
Low grade events	TBD% nominal FWHM resolution at 7 keV	0.2 - 7 keV	At pixel level
Energy resolution			
High grade events	6% of high grade FWHM resolution	0.2 - 12 keV	At pixel level
Non-gaussian componant	TBD%		refer to [AD3]
Low grade events	6% of low grade FWHM resolution		
Quantum efficiency			
Absolute calibration	4%		Same QE for each pixel of the array
Relative calibration	3% of QE or 0.01 when QE < 0.33	0.2 - 12 keV excluding edges	At pixel level
Calibration in edges	3% (on ground) and 2% (in-flight)	0.2 eV resolution and energie scale knowledge <0.4 eV	At least C, O, N, Al K-edges, Au and Bi L-edges, and Au and Bi M-edges
Background knowledge			
Non focused charged particles	2%	100 ks, 9 arcmin^2, >1 keV	
Timing			
Absolute	5 µs	3 σ, 50 ks	
Relative	10 µs	1 σ, 50 ks	
Dead time knowledge	1%		

0.15 eV

- The X-IFU calibration requirements derive from the Athena calibration requirements

see X-IFU Calibration plan

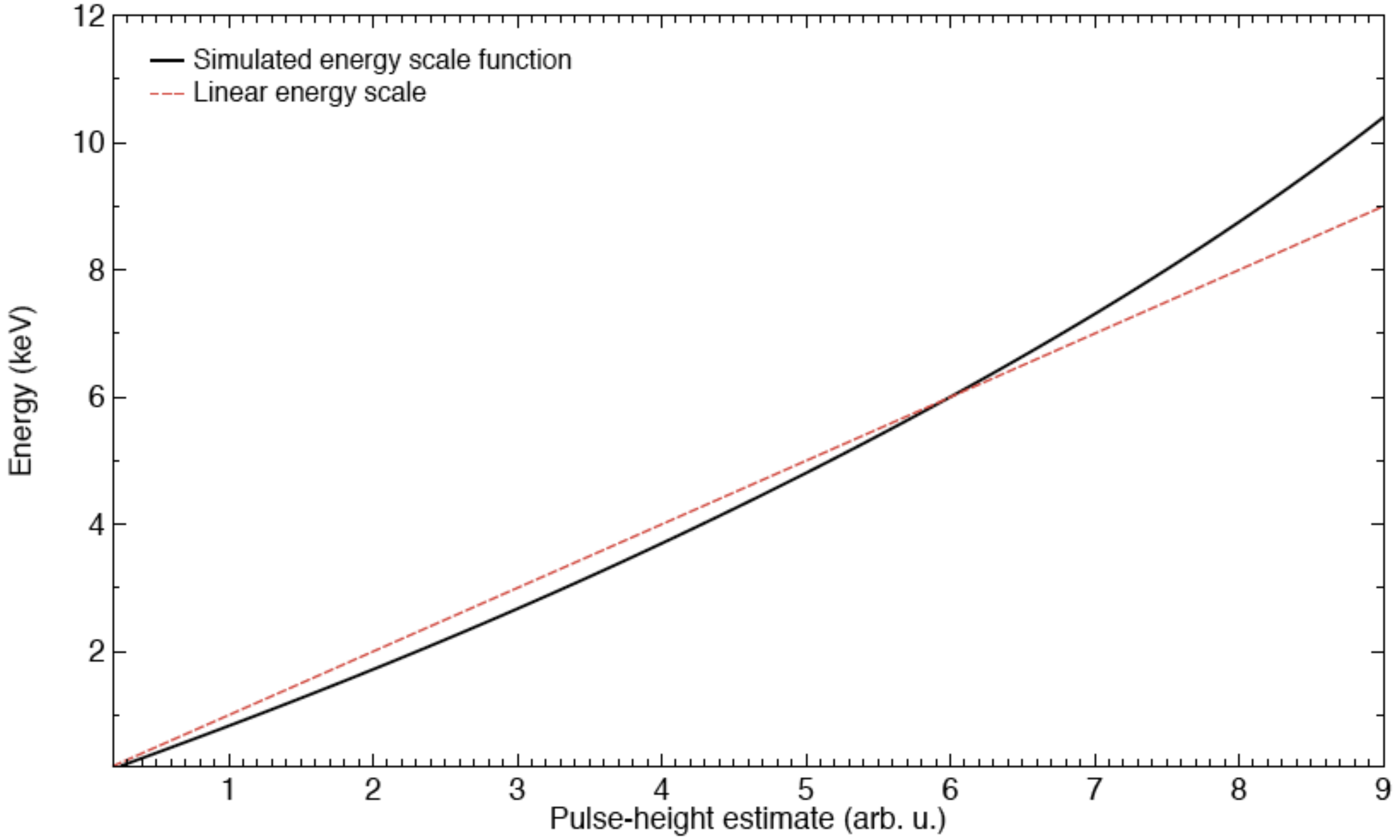
X-IFU calibration strategy outline

- The X-IFU calibration strategy combines measurements and analysis
  - at sub-system level (detector array, filters, readout electronics, Focal Plane Assembly, …)
  - at instrument level (integrated on the Science Instrument Bench)
  - in-flight on internal sources (ie on MXS) and housekeeping parameters
  - in-flight on sky sources
- It will also require additional data from
  - X-ray emission fundamental physics, from ab initio computations and ground measurements, at high energy resolution (*see talk by Gabriele Betancourt-Martinez*)
- It is not planned to bring the X-IFU in front of a synchrotron beam
  - complexity of such test (vertical optical axis, large and heavy Science Instrument Bench)
  - possibility to rely on a set of lab sources, or on measurements at sub-system level (ie the instrument quantum efficiency)
  - potential irradiation of a representative FPA in front of a *proton* beam for the validation of the simulations of the thermal impact of Cosmic Ray on the detector (*see talk by Samantha Stever*)

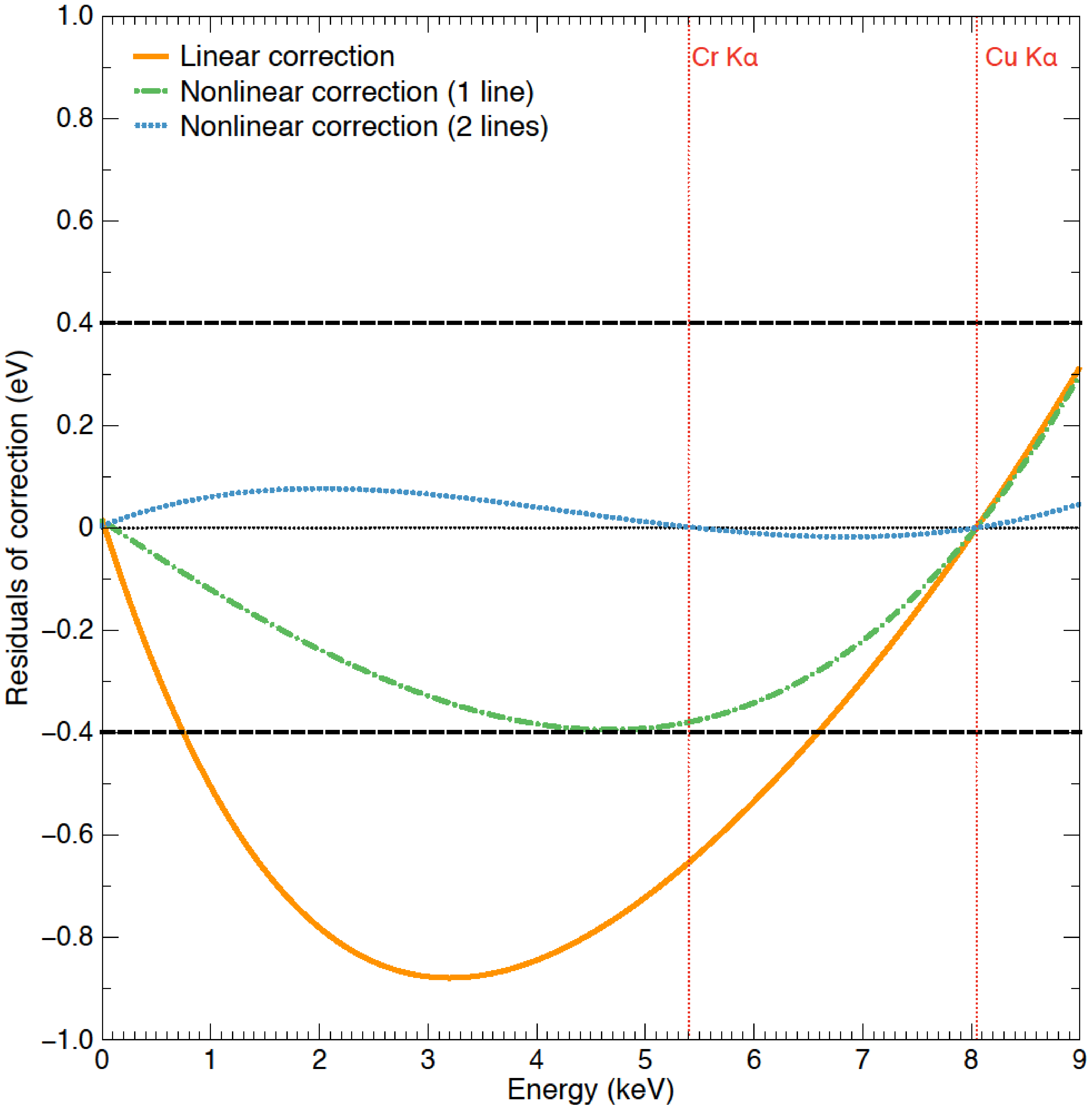
Energy scale

- Determine approximate polynomial function relating pulse ADU to photon energy
  - ~10 reference points along the energy axis
  - under a set of selected configurations covering a large space of operating conditions
  - determine event grade (HR, MR or LR) dependence
  - on-ground use of rotating target source (RTS) and Electron Ion Beam Trap (EBIT)
- In-flight gain scale monitoring
  - interpolation for actual conditions using ground calibration
  - Modulated X-ray Source (MXS) from SRON based on Hitomi-XRISM design, flashes 120 times/second for 50 µs (~1 photon/pixel/second, 2/3 Bremsstrahlung continuum, 1/6 Cr_{α} line ~5keV, 1/6 Cu_{α} line ~8keV)
  - use a multi parameters approach (MXS lines, bath temperature, bias voltage, baseline…)
- Notes
  - one calibration function per pixel: working hypothesis pixels can be grouped by 10
  - energy stability time scale is 1000s

Energy scale

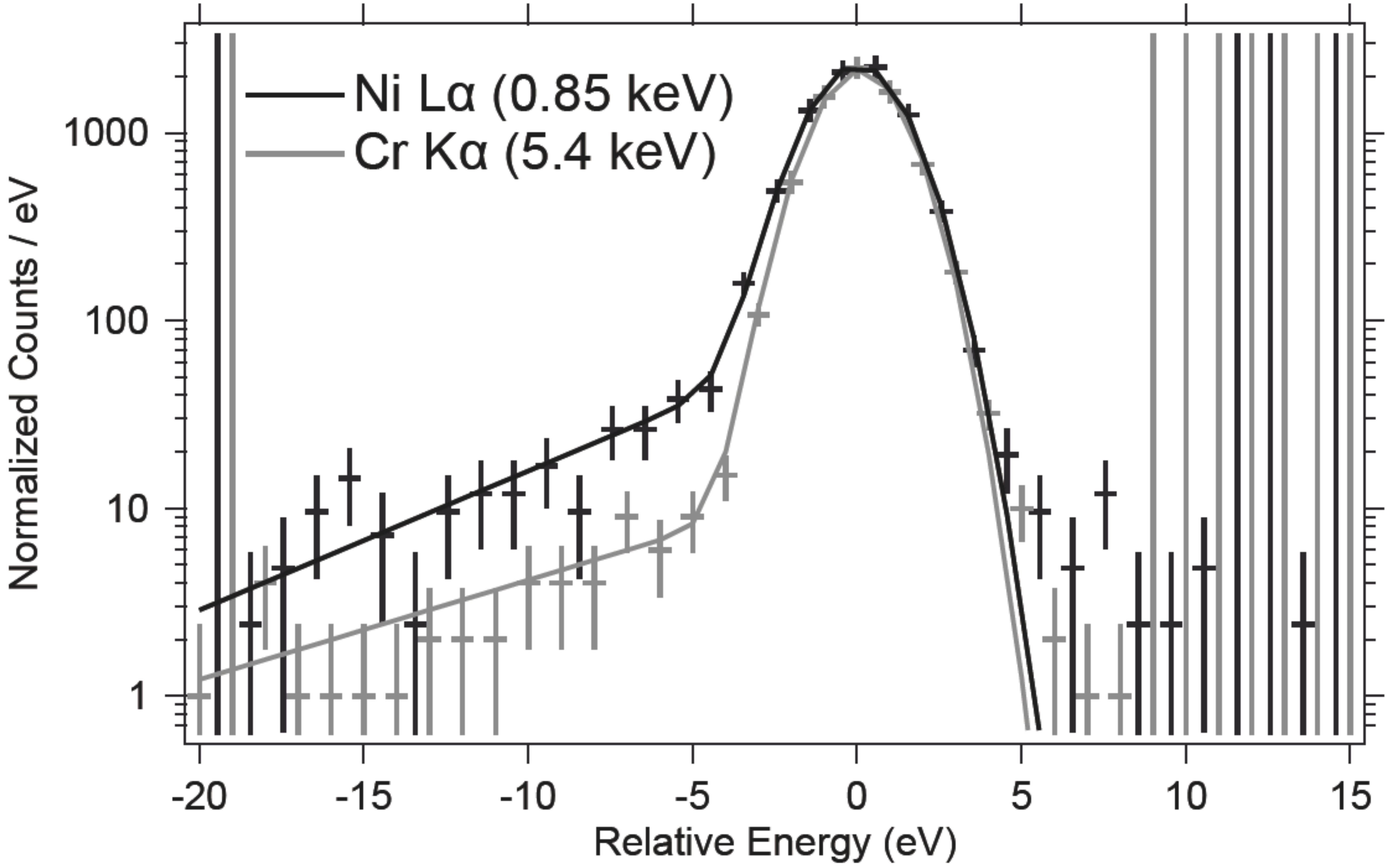


Cucchetti et al., *Energy scale calibration and drift correction of the X-IFU*
SPIE 2018



Line Spread Function

- The Line Spread Function (LSF) has two components
  - its core, gaussian to many orders of magnitude, whose FWHM defines the energy resolution
  - an extended component due to several energy loss mechanism: electron-loss continuum, escape peaks, surface effects/long lived states



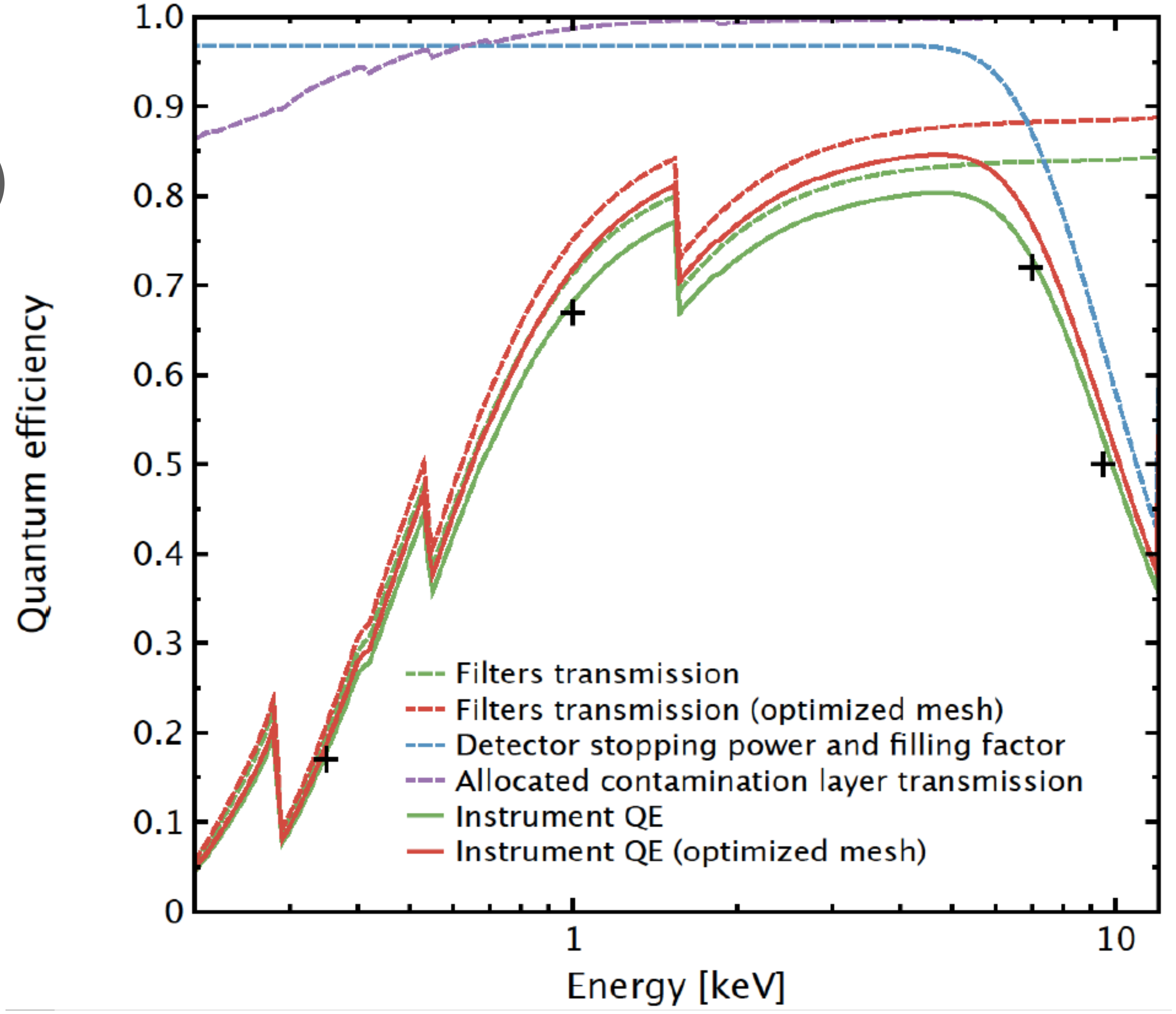
TES microcalorimeters, Eckart et al., ASC2018

Line Spread Function

- Core LSF calibration
  - core LSF depends on instrument operating conditions (noise budget)
  - needs very narrow (fluorescent) lines (0.5 eV) providing high count rate in monochromatic lines
  - use of channel-cut crystal monochromators (CCCMs) to select the Kα1 line of the anode material, in the 4.5-11.4 keV range (Goddard and LLNL development)
  - in the ~0.5-2.5 keV range, use of grating monochromators, but only with ~1-2 eV resolution
  - event grade dependence calibration
  - in-flight recalibration (MXS, astronomical sources + monitoring of parameters in the model of the noise budget)
- Extended LSF calibration
  - no changes expected on operating conditions (ground, in-flight)
  - fully calibrated of ground with deep exposures of monochromatic lines at a few energies

Instrument Quantum Efficiency

- The X-IFU QE is a multiplicative term entering the total Athena/X-IFU Effective Area
- It is divided into independent contributors
  - transmission of the thermal filters (low temperature operation and instrument background photon noise)
  - contamination of these filters
  - detector QE (absorber QE, filling fraction)
  - filter wheel (optional)



Instrument Quantum Efficiency

- Thermal filters calibration and contamination monitoring
  - synchrotron on flight filters plus witness samples
  - limit calibration sequences on flight parts
  - calibration of standards to determine fine structure of Al and polyimides components used in filters
  - calibration of witness samples to determine film component thicknesses
  - measurement of meshes
  - in-flight recurring measurements of astronomical sources (many candidates/SXS) for lines below 1 keV
- Detector QE calibration
  - use of detachable absorber samples for metrology [thickness of Au and Bi] and synchrotron measurements
  - characterization of gradients across the array from samples at various locations on the array
  - validation of method on-going at GSFC

When ?

- 2019 Ground Calibration System Requirements
- 2020 Ground Calibration Preliminary Design
- 2021 Ground Calibration Critical Design

  [11/2021 Mission Adoption Review]
- 2022 Ground calibration procurement (OTC)/manufacturing
- 2023 Ground Calibration AIT/AIV and Qualification - phase 1

  [S1 2024 EM AIT/AIV and characterisation]
- 2025-2026 Ground Calibration AIT/AIV and Qualification - phase 2

  [S2 2027 FM Calibration]

IACHEC 14

IACHEC 15

IACHEC 16

Thanks to you and to them all

ATHENA X-ray Integral Field Unit

irap astrophysique & planétologie

cnes CENTRE NATIONAL D'ÉTUDES SPATIALES

SRON Netherlands Institute for Space Research

INAF ISTITUTO NAZIONALE DI ASTROFISICA ISTITUTO DI ASTROFISICA E PLANETOLOGIA SPAZIALI DI ROMA

cnrs INSU Observer & comprendre

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Université de Liège ULg

NÉEL institut

VTT

UNIVERSITY OF HELSINKI

Università degli Studi di Palermo

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IFN Institute for Photonics and Nanotechnologies

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CBK PAN

IFCA Instituto de Física de Cantabria

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

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