The Athena X-ray observatory Integral Field Unit

New perspectives in the study of the Universe using high resolution X-ray spectroscopy

François Pajot
IRAP, for the X-IFU consortium

The ATHENA science theme

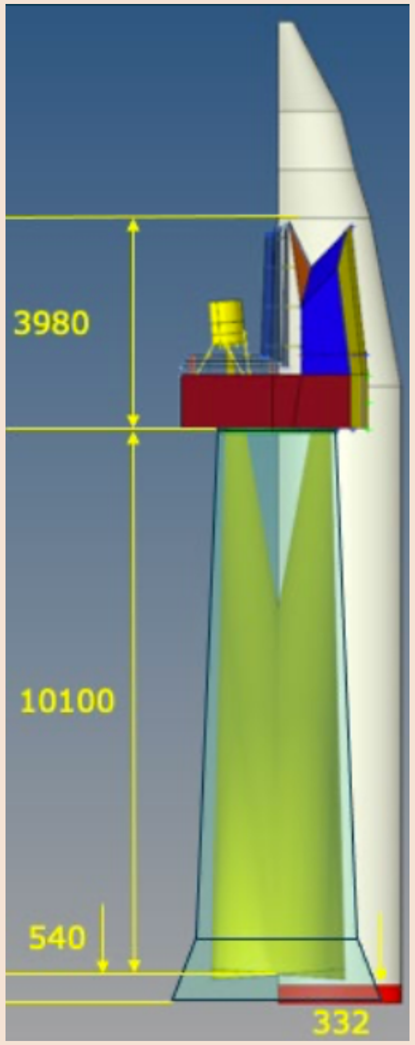
- ESA selected the Hot and Energetic Universe theme in 2013
  - second Large mission of the ESA Cosmic Vision science program (L2)
  - based on the Advanced Telescope for High ENergy Astrophysics (Athena), an X-ray observatory
- Core scientific objectives of Athena
  - The Hot Universe
    - Determine how and when large-scale hot gas structures formed in the Universe and track their evolution from the formation epoch to the present day
  - The Energetic Universe
    - Perform a complete census of black hole growth in the Universe, determine the physical processes responsible for that growth and its influence on larger scales, and trace these and other energetic and transient phenomena to the earliest cosmic epochs
  - *Observatory and Discovery Science*
    - *Provide a unique contribution to astrophysics in the 2030s by exploring high-energy phenomena in all astrophysical contexts, including those yet to be discovered*

The ATHENA mission

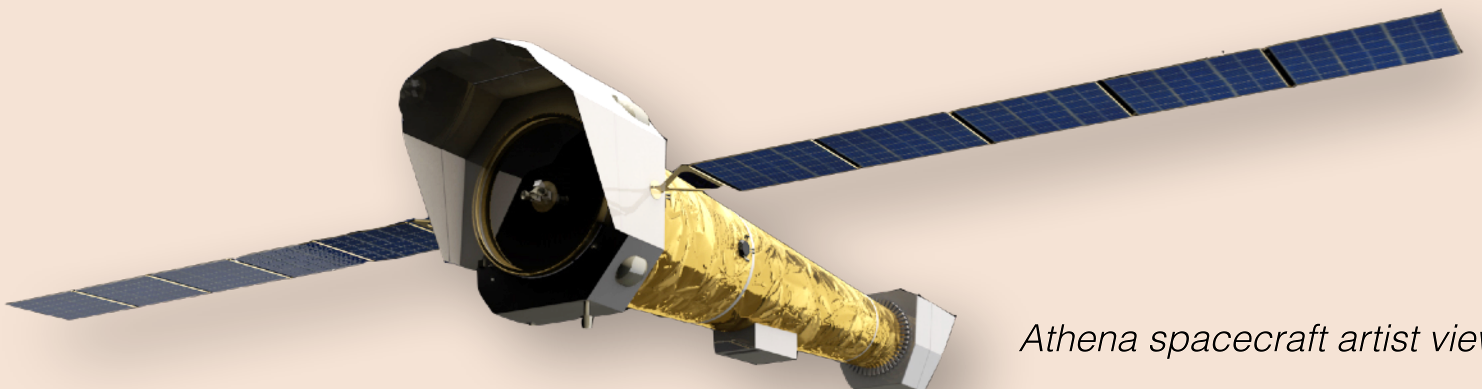
- Main requirements on instruments derive from science objectives
  - high resolution X-ray spectroscopy
  - large field X-ray imaging
  - large collecting area
- Development follows phases as all space programs
  - [A] Assessment of feasibility
    - concluded successfully in Jan 2020
  - [B] Preliminary definition
    - phase [B1] concluded in 2022: *Athena budget over the cost cap led to restart the phase B with a simplified concept (instrument, spacecraft)*
    - end of 2023 ESA will confirm the new Athena mission as a L-class mission. The new instrument baseline has already received very positive feedback.
    - end of new phase [B1] expected in 2026: **Mission Adoption**
  - [C] Detailed definition starts after phase [B2] in 2029
  - [D] Qualification and production in 2032
  - [E] Exploitation: following launch in ~2036

The [new]ATHENA mission

- Mid 2030's launch
  - with the newly developed Ariane 6
- A 7 ton spacecraft to be placed in a L2 orbit
- Unprecedented collecting area in X-rays
  - ~1.0 m2 at 1 keV and ~0.13 m2 at 7 keV
  - 8" (5" goal) mirror angular resolution
- Two focal plane instruments switchable with a movable mirror
  - the Wide Field Imager (WFI) optimized for surveys
  - the X-ray Integral Field Unit (X-IFU), a micro-calorimeter spectrometer optimized for spatially resolved high resolution spectroscopy
    - X-IFU developed under IRAP scientific responsibility (D. Barret, PI) and CNES technical responsibility (V. Albouys, project manager)
    - A consortium of ~300 people from 12 European countries plus US and Japan

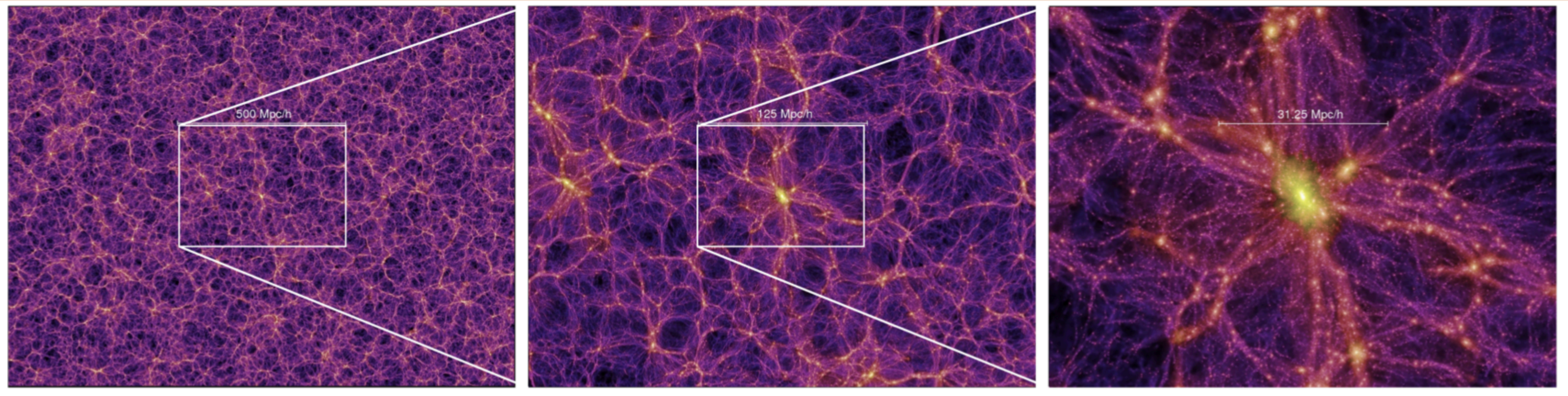


ESA study


Athena spacecraft artist view (ESA-IRAP)

The Hot Universe

- Galaxy clusters are the largest structures, which formed last, accreting matter via the cosmic web's filaments



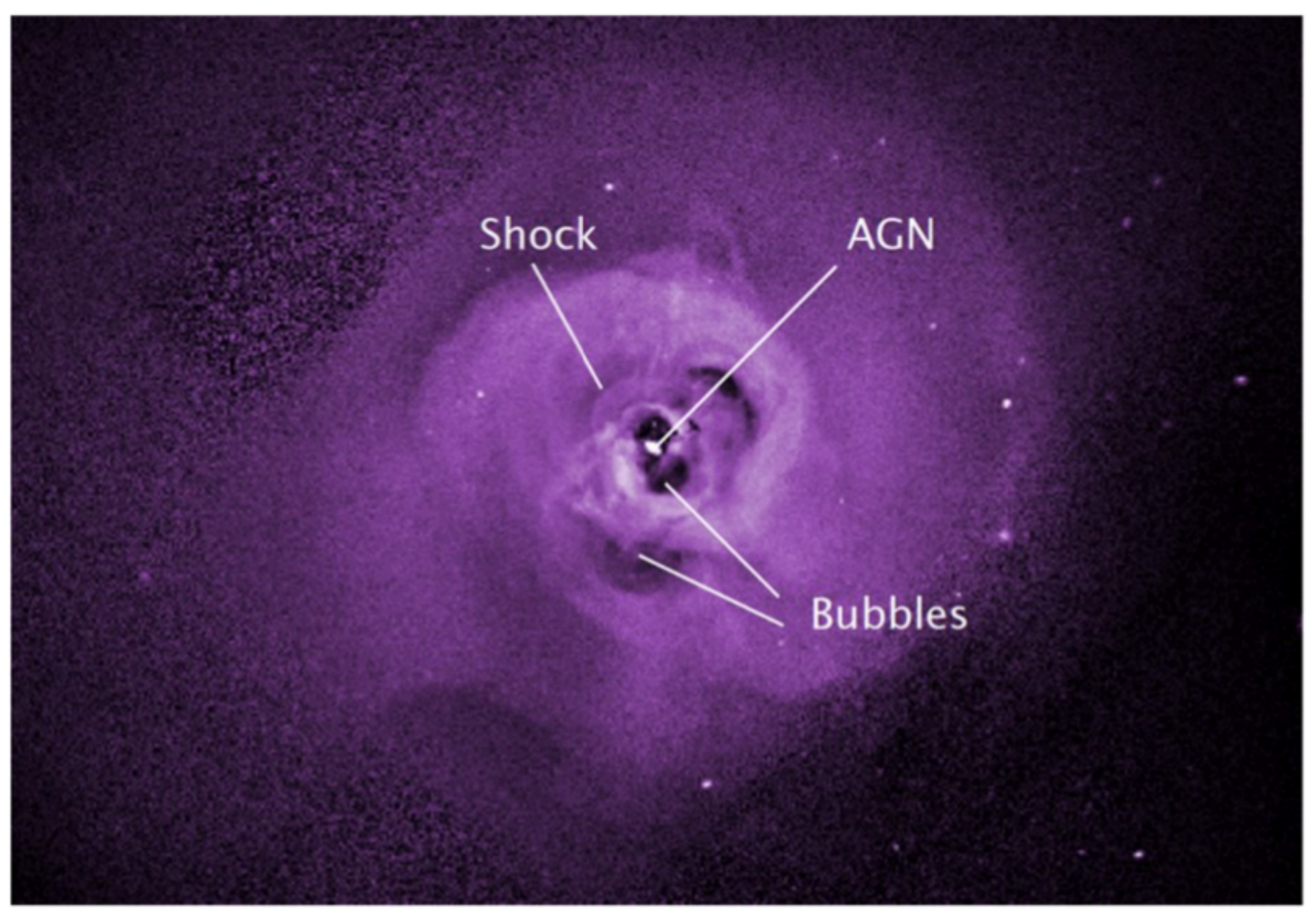
Millenium simulation - Springel 2005

  - few tens to thousands of galaxies bound together by gravity. They are the largest known gravitationally bound structures in the Universe, with typical masses ranging from 10^{14} – 10^{15} solar masses

- Composed of 3 components
  - the galaxies [stars, interstellar medium], which contributes only to a low percentage of the cluster mass
  - the intra-cluster medium (ICM), where most of the baryons in the cluster reside (85%), contributing to close to ~10% of the cluster mass
  - the dark matter, which hasn't been directly detected yet but was inferred from the discrepancy between the total estimated mass and the luminous mass, contributing to ~90% of the cluster mass

The Hot Universe

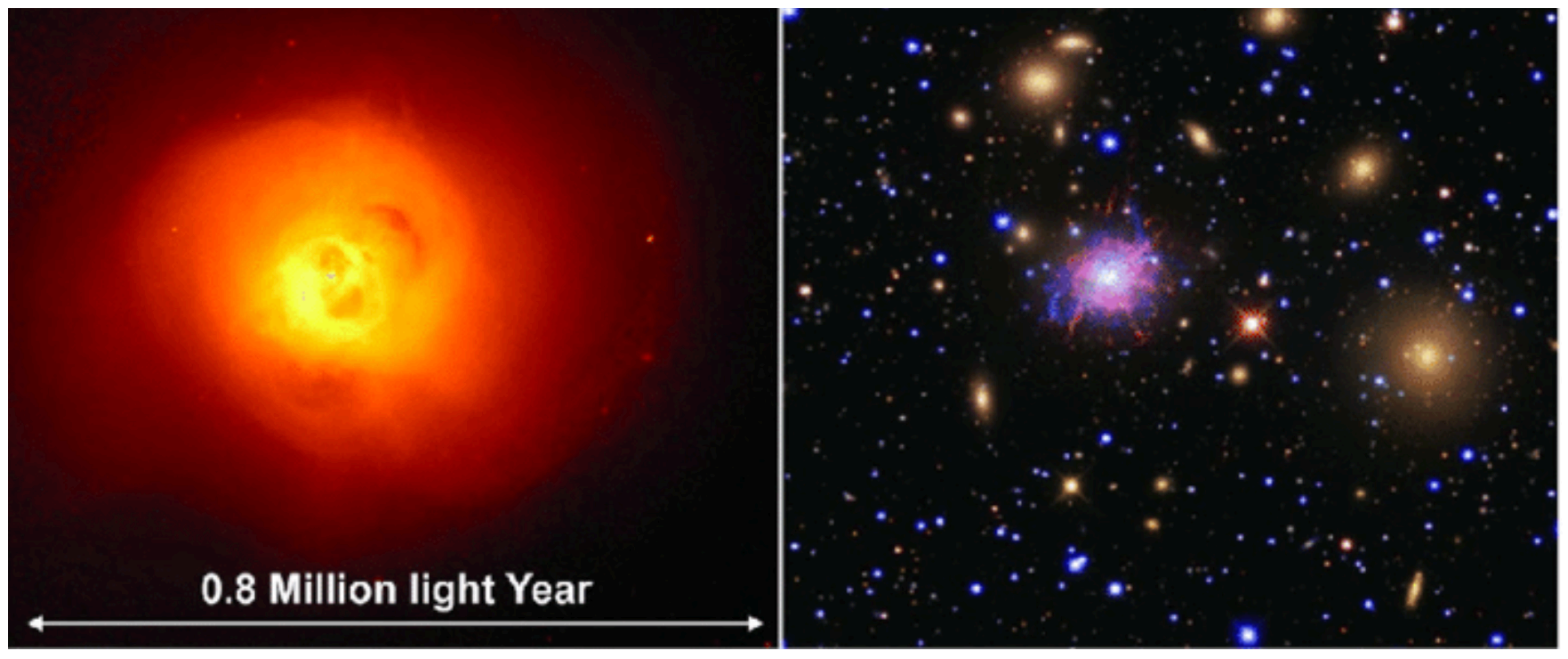
- The Intra-Cluster Medium (ICM)
  - a key component to study as it hosts the majority of observable matter in clusters
  - a very low density (10^{-3} – 10^{-2} cm^{-3}) and optically thin medium
    - weakly collisional gas
    - very high temperature of 10^6 – 10^8 K due to shock heating (from accretion and merger shocks)
    - mostly composed of hydrogen
    - enriched in heavy elements via AGN feedback



Simionescu et al., 2019

The Hot Universe

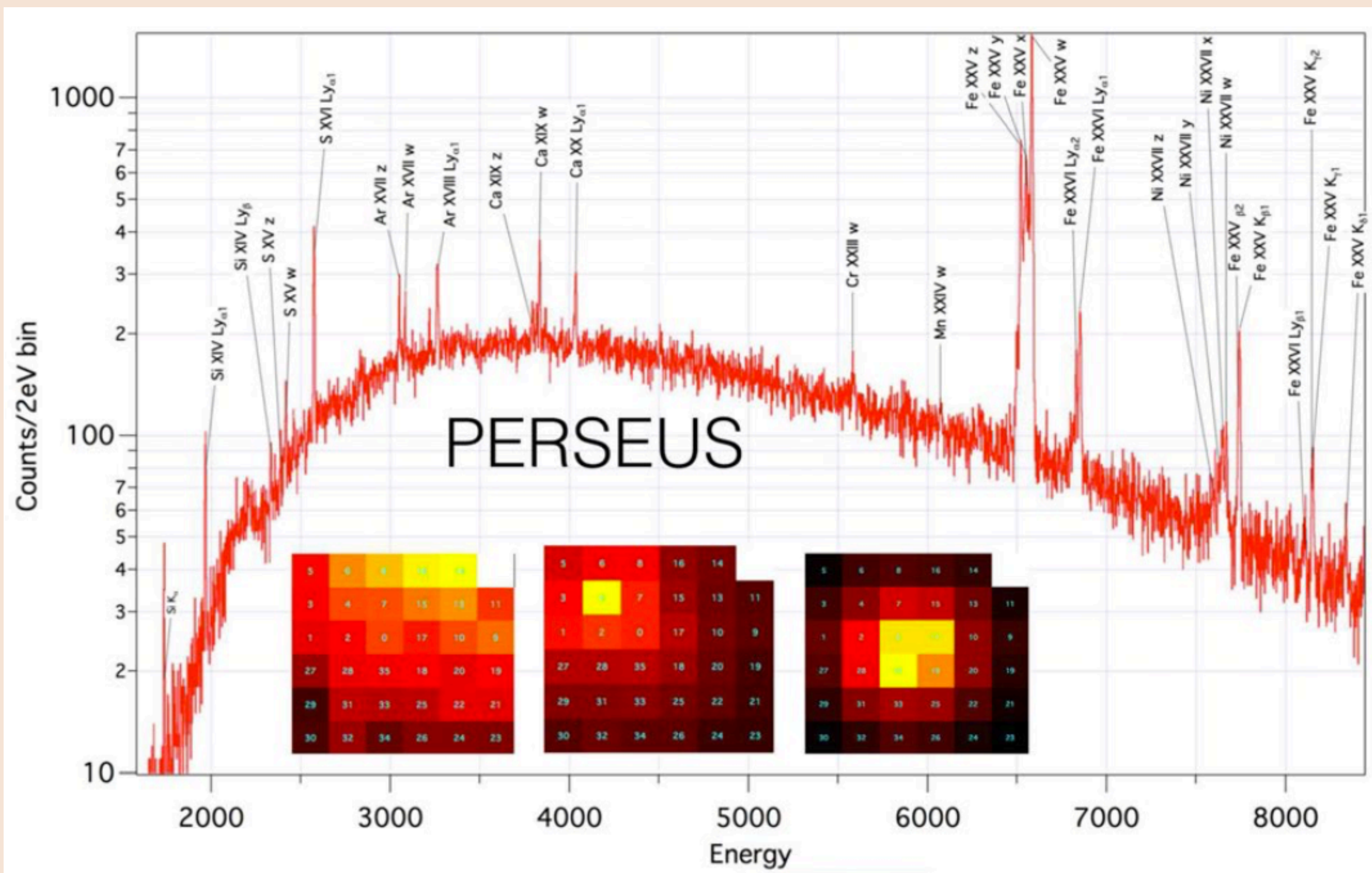
- The Intra-Cluster Medium (ICM)
  - mainly emits X-rays via the Bremsstrahlung process
  - recombination continuum and lines due to atomic transitions in highly ionized atoms of heavy elements



Perseus cluster in X-rays (left) and optical (right), from Fabian (2011) and Gabany (2009)

The Hot Universe

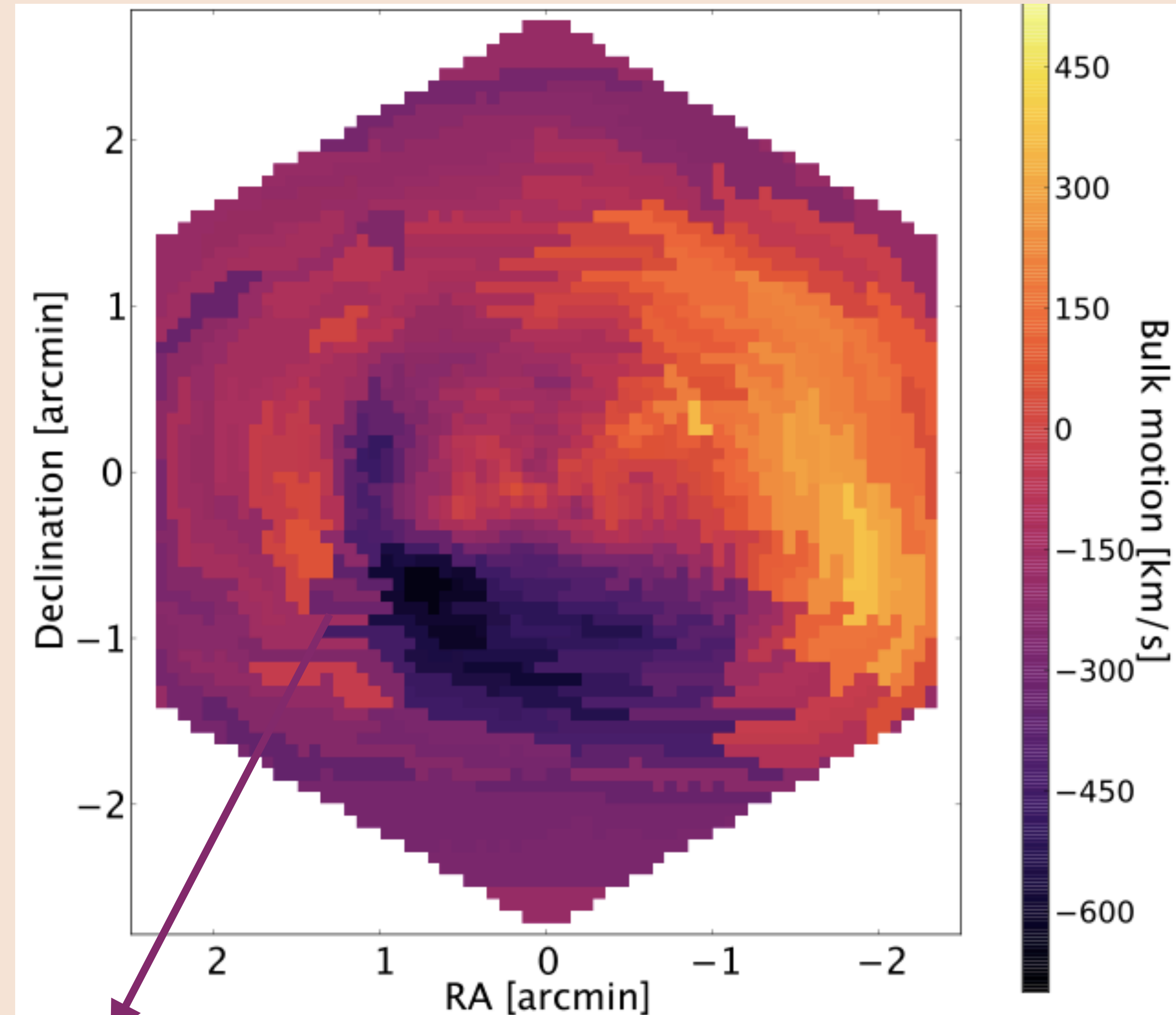
- The Intra-Cluster Medium (ICM)
  - absolute need for high resolution X-ray spectroscopy
  - intrinsic line width plus broadening by turbulence, bulk motion, gravitational redshift,…
  - need of better than a few [3-5] eV energy resolution in the 6-7 keV range (Fe lines)



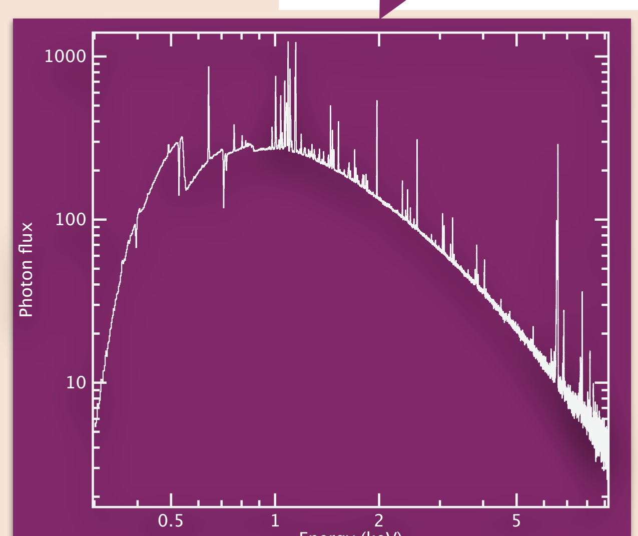
Perseus cluster observed by Hitomi/SXS (Tsujimoto,et al. 2009)

The X-IFU core science

- Probing the dynamical and chemical state of baryonic matter across cosmic time
  - by mapping hot gas trapped in dark matter potential wells to measure bulk velocities, turbulence, abundances, temperatures, densities…
  - from the first galaxy groups to the local massive clusters
- Hitomi has unveiled in one single cluster observation the true power of high-resolution spectroscopy, leading to unexpected discoveries



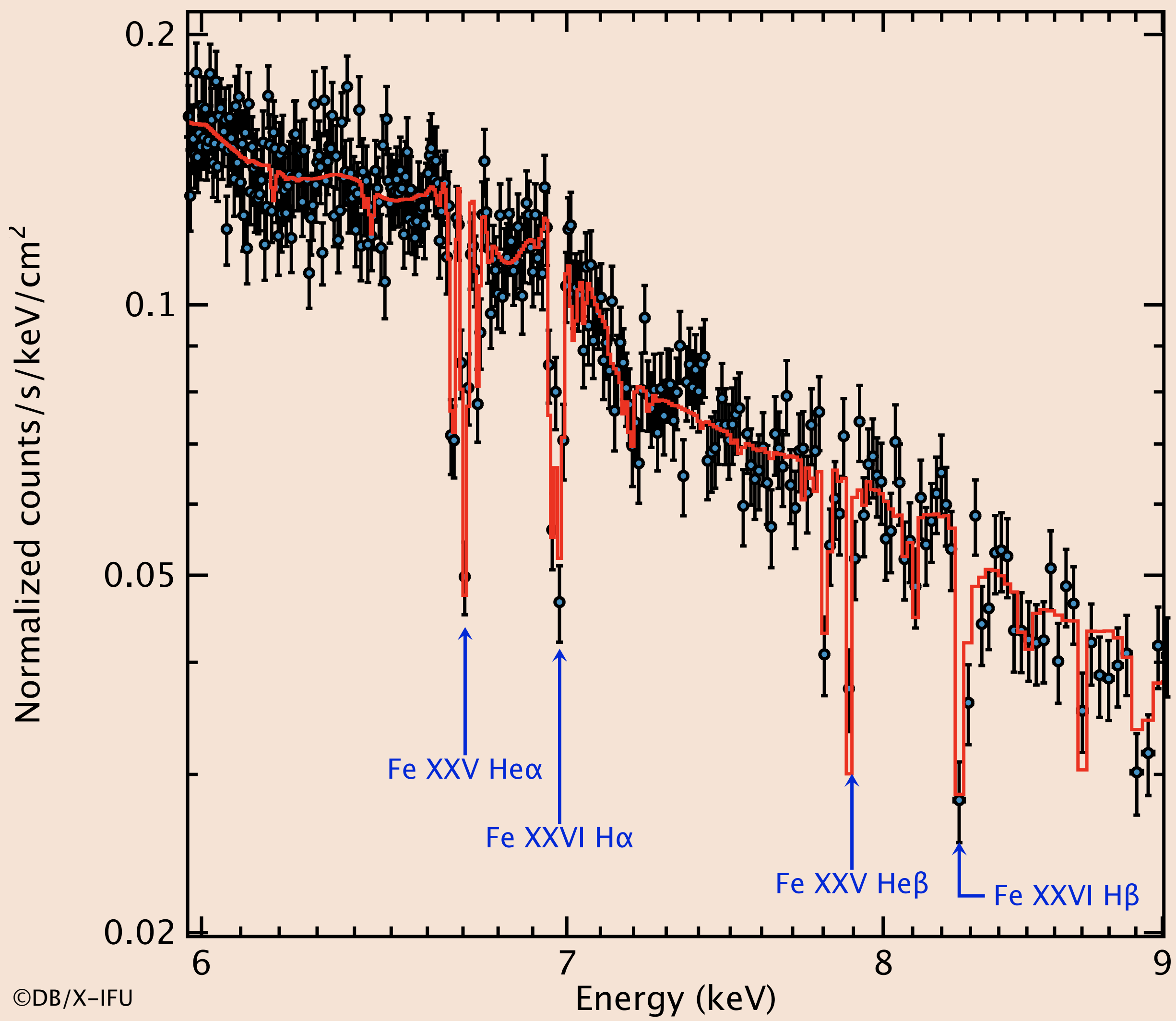
Simulated velocity map of bulk motions of hot plasma in cluster
Peille et al. — Cucchetti et al. 2016



Each pixel in the map is associated to a high resolution X-ray spectrum

The X-IFU core science

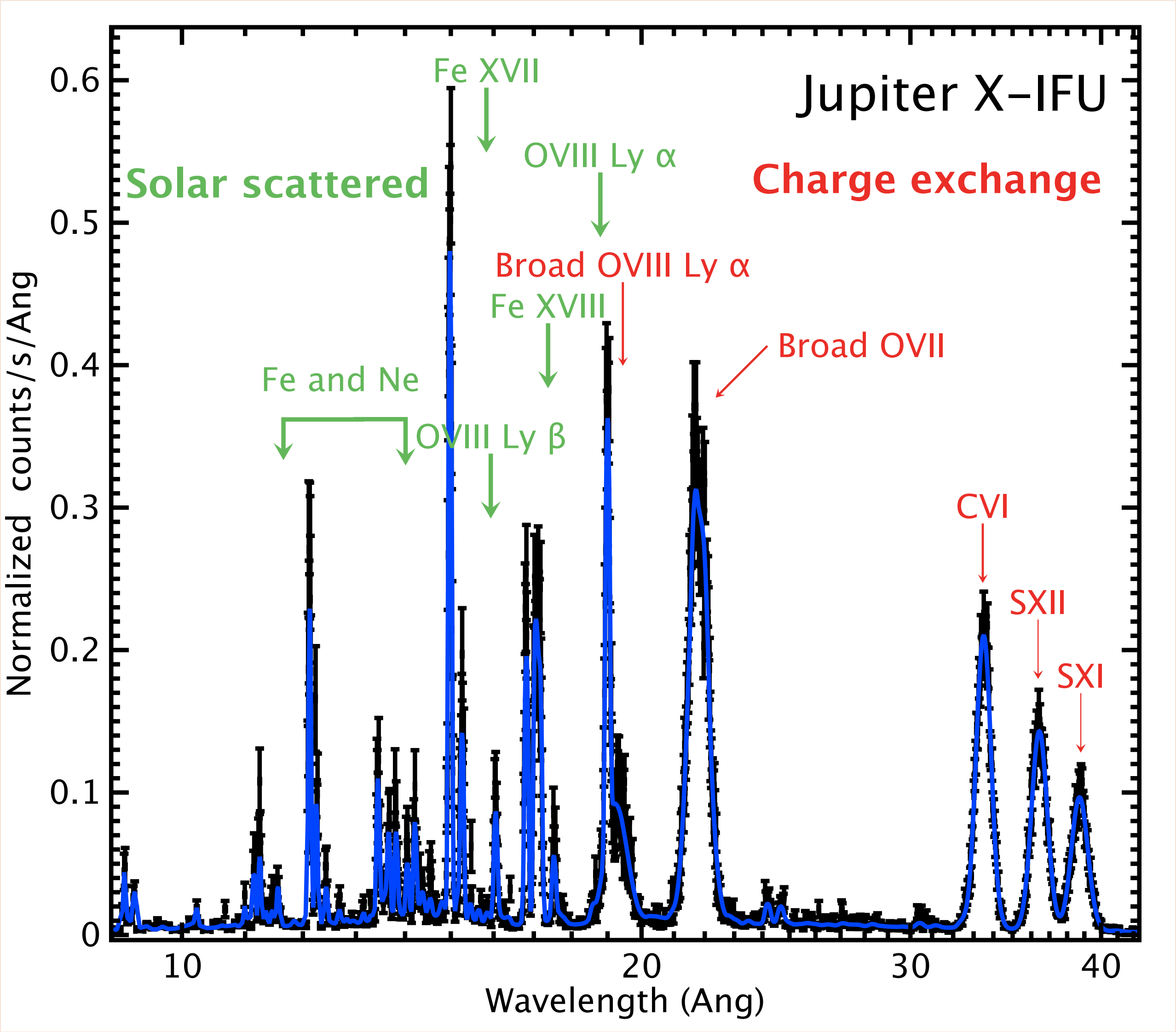
- Probing black holes at work in shaping the Universe and their surroundings
  - by performing time resolved spectroscopy of accretion disks, winds, outflows and jets
  - from the faintest AGN to the brightest X-ray binaries



X-ray binary spectrum with high velocity wind absorption features
J. Miller et al.

The X-IFU core science

- By providing hot plasma diagnostics in a wide range of astrophysical settings
  - planets: interaction of solar wind with planet environment
  - exoplanets and their host stars
  - stellar physics across the mass/age range
  - supernovae: explosion mechanism, heavy element production
  - stellar endpoints: dense matter
  - interstellar dust and medium: composition
- Huge discovery space with ToO follow-up in the era of time domain astrophysics
  - detection of filaments of hot baryon against bright sources
  - follow up of new transient objects



Jupiter X-IFU spectrum showing different line emission mechanisms G. Branduardi-Raymont et al.

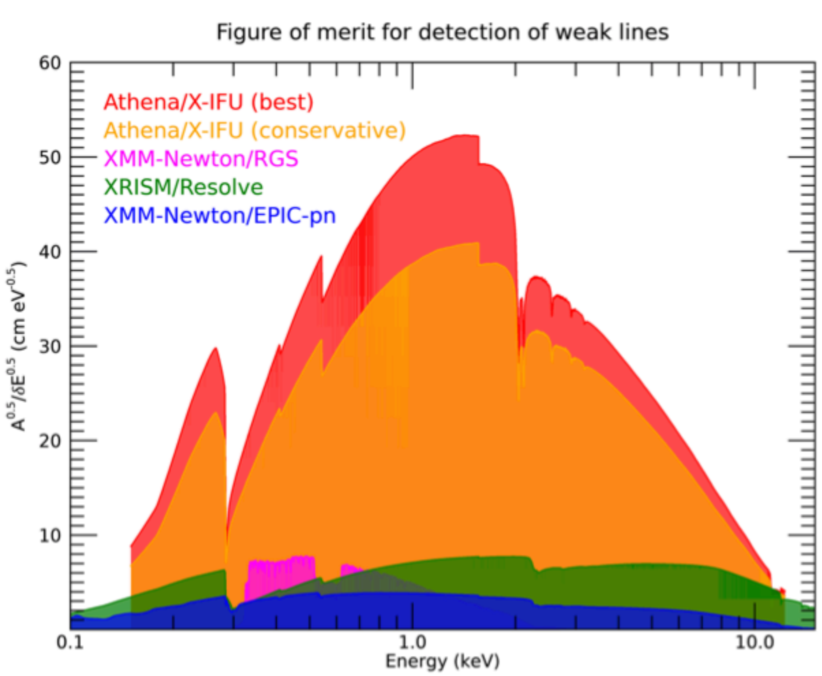
The [new]X-IFU key requirements

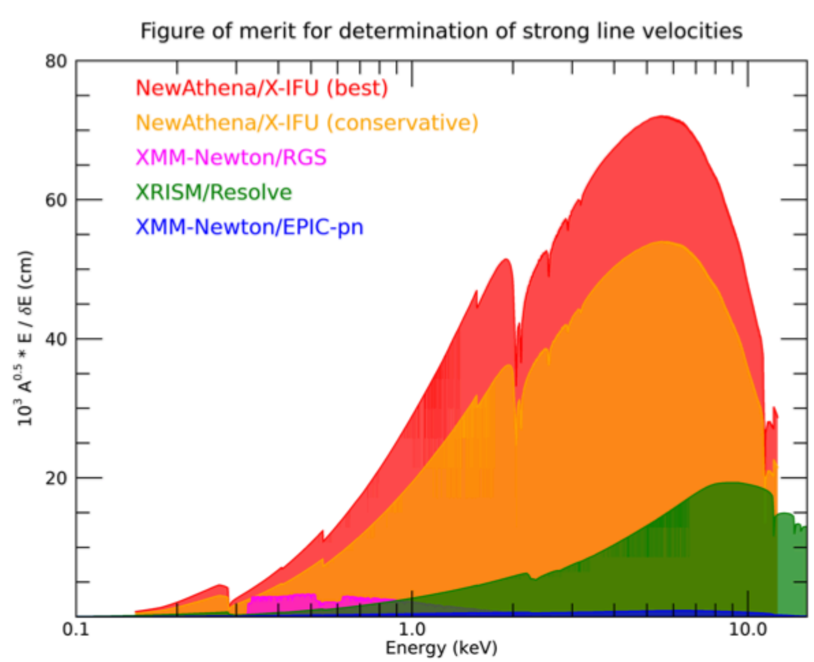
- Spectral resolution: ~3 eV up to 7 keV
  - cluster physics (broadening down to 20 km/s)
  - missing baryons
- Energy band pass: 0.2 to 12 keV
  - missing baryons
  - black hole spins, winds and ultra-fast outflows
- Background requirement:
  <5 10^{-3} cps $s^{-1}cm^{-2}keV^{-1}$ (2-10 keV)
  - cluster physics and cluster chemical evolution
- Field of view: 4 arcmin (equiv. diameter)
  - cluster physics out to their outskirts
- Pixel size: <~6 arcsec (mirror limiting)
  - cluster feedback (AGNs) on relevant spatial scales
  - minimize confusion

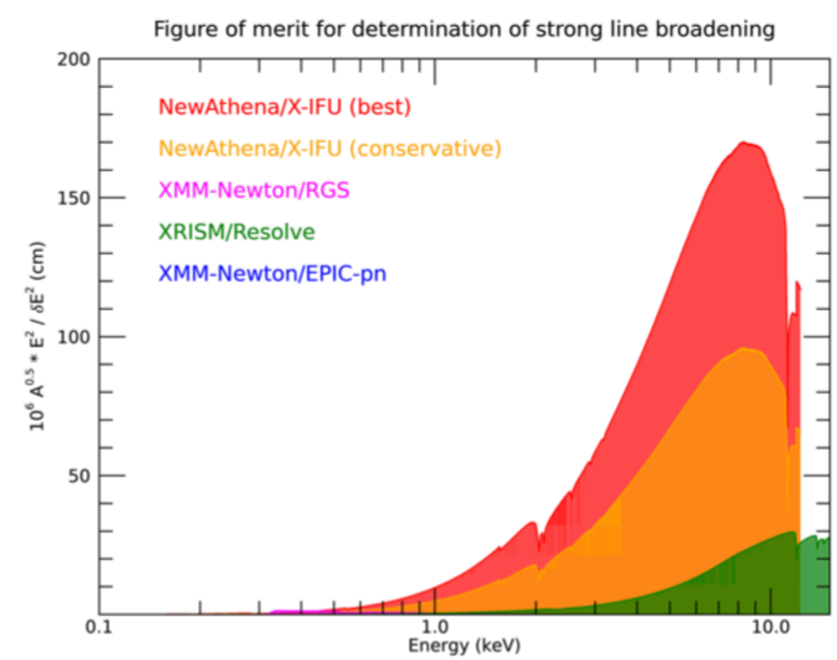
The [new]X-IFU key requirements

- A new era in high sensitivity high resolution spectroscopy

Weak line detection	Strong line velocity	Strong line broadening







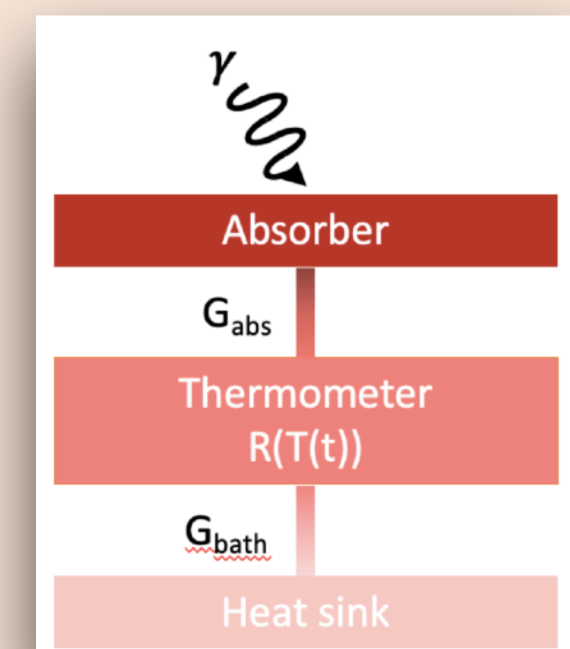
<u>NewAthena/XRISM:</u>

1 keV: 6-7	1 keV: 7-11	1 keV: 17-39
6 keV: 3-5	6 keV: 4-5	6 keV: 8-16

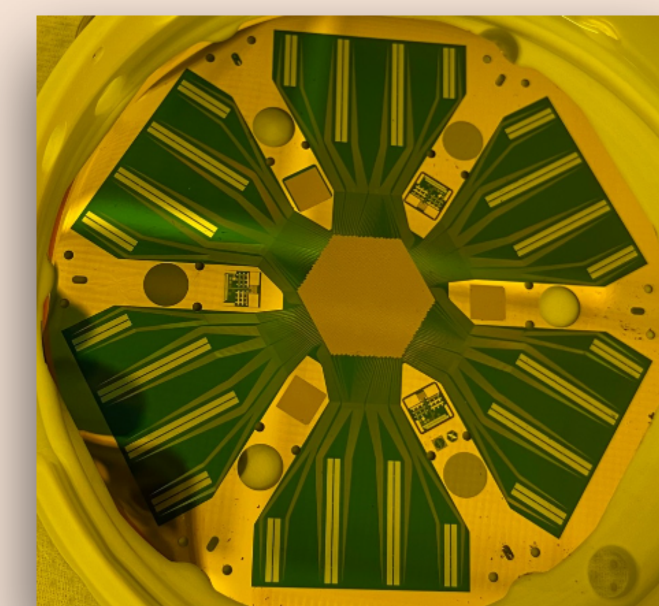
ESA SRDT status
M. Guainazzi

X-IFU design - Detectors

- The Transition Edge Sensor (TES)
  - a micro-calorimeter connected to a cold source at 55 mK
  - measures the energy of each individual photon
    - photon energy converted to heat then evacuated (in a few ms)
  - increase of temperature measured by a superconducting thermometer operated at its transition
  - gives access to high resolution X-ray spectroscopy
- X-IFU detection array
  - composed of 1536 Mo/Au Transition Edge Sensors (NASA-Goddard)



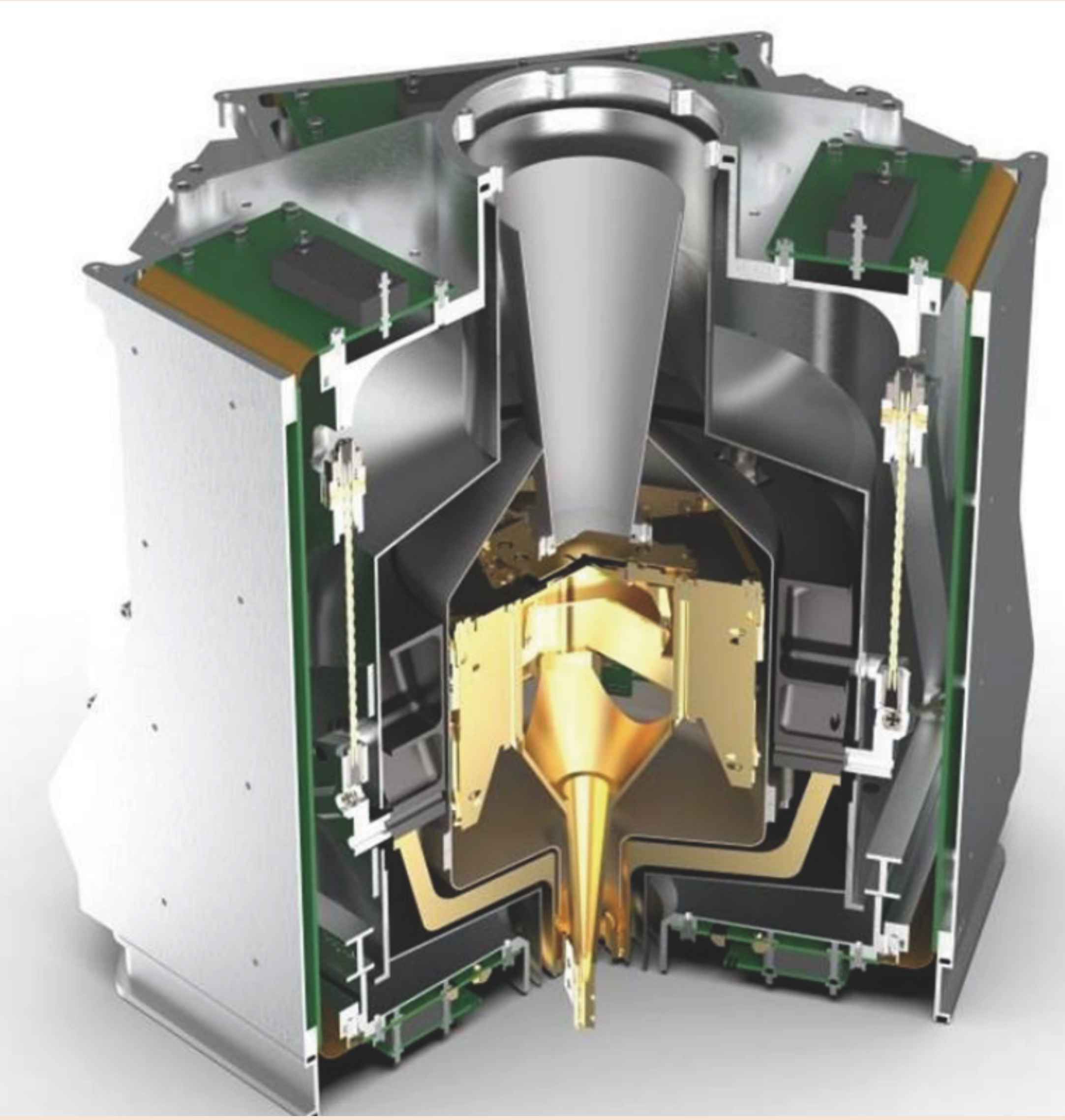
S. Beaumont thesis



NASA/Goddard

X-IFU design - Detection chain

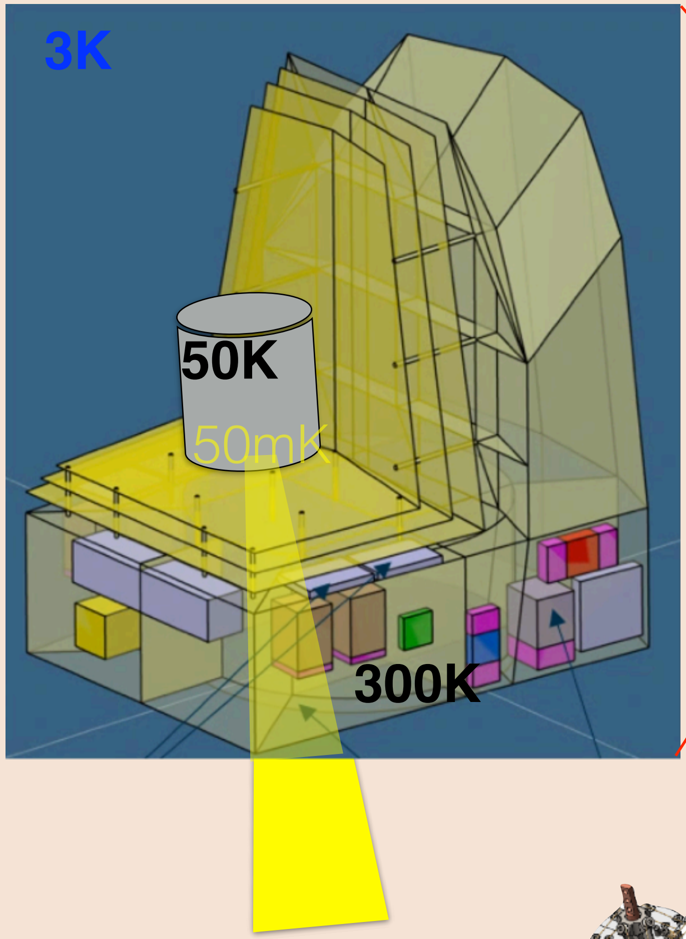
- Focal Plane Assembly
  - TES array integrated in a Focal Plane Assembly (SRON) including the proximity cold readout electronics and an active anti-coincidence TES detector (INAF)
- Time Domain Multiplexing readout (NIST, VTT, APC, IRAP)
- Pulse processor (INTA, CEA)
- Optimized high transmission thermal and optical blocking filters (U Palermo)
- Modulated X-ray source for gain monitoring (SRON)
- Filter wheel (Be filters, optical filters, …) (U Geneva)

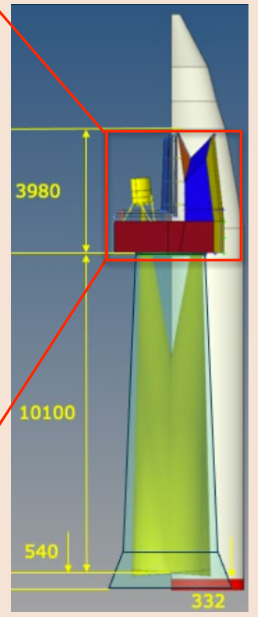


SRON

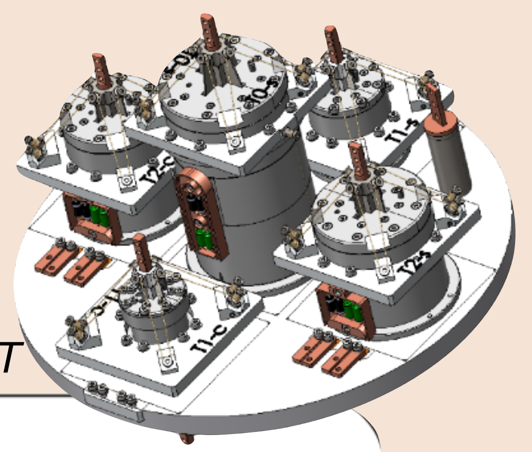
X-IFU design - Cooling chain

- Passive cooling down to 50 K
  - Planck mission heritage
  - avoid any cryocooler down to this temperature
  - provided by spacecraft
- 50 K to 4 K active cryocooler
  - similar to the JWST cryocooler
  - industrial procurement through NASA
- 4 K to 55 mK Adiabatic Demagnetisation Refrigerator
  - 4 stages ADR developed by CEA/SBT

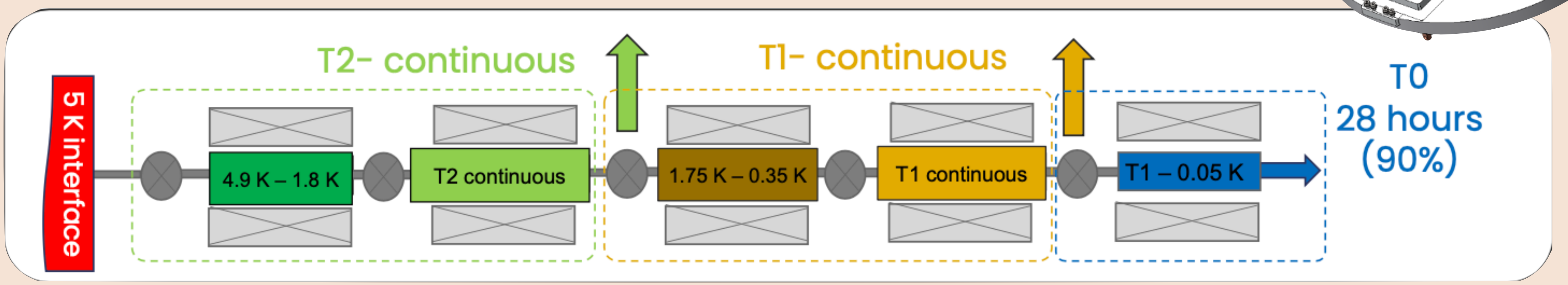




ESA

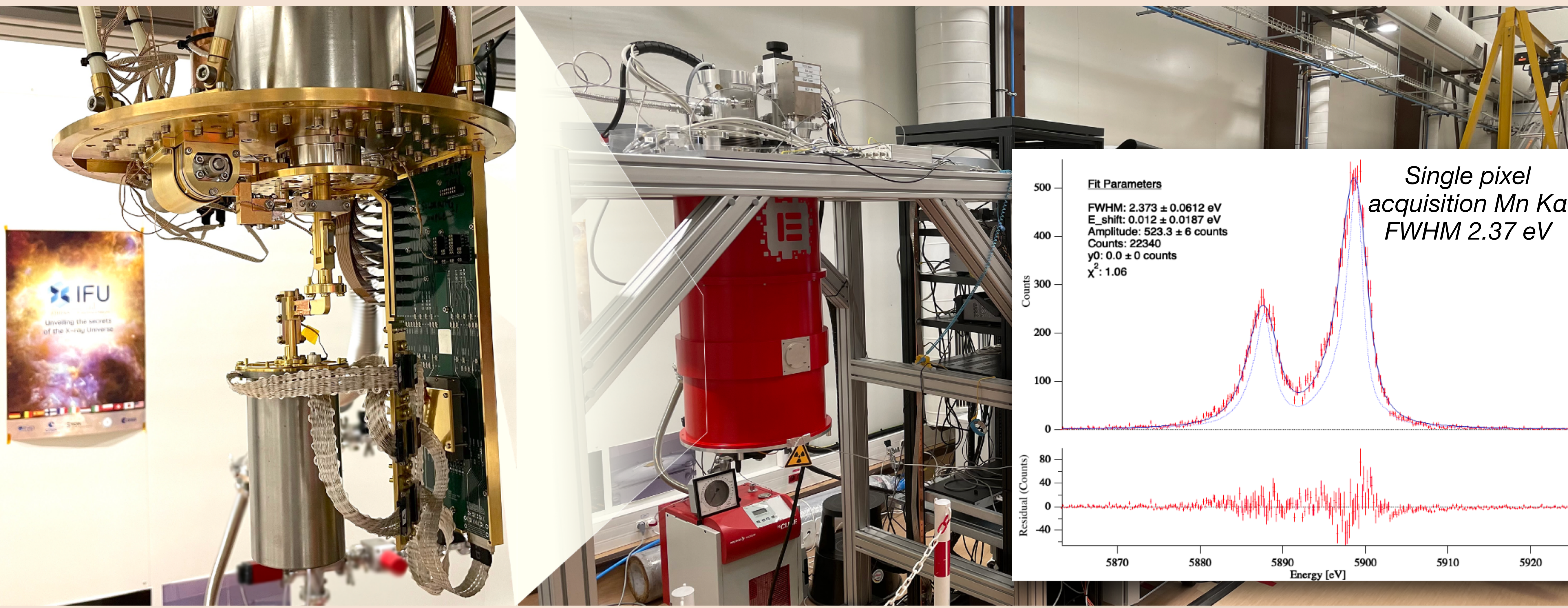


CEA/SBT



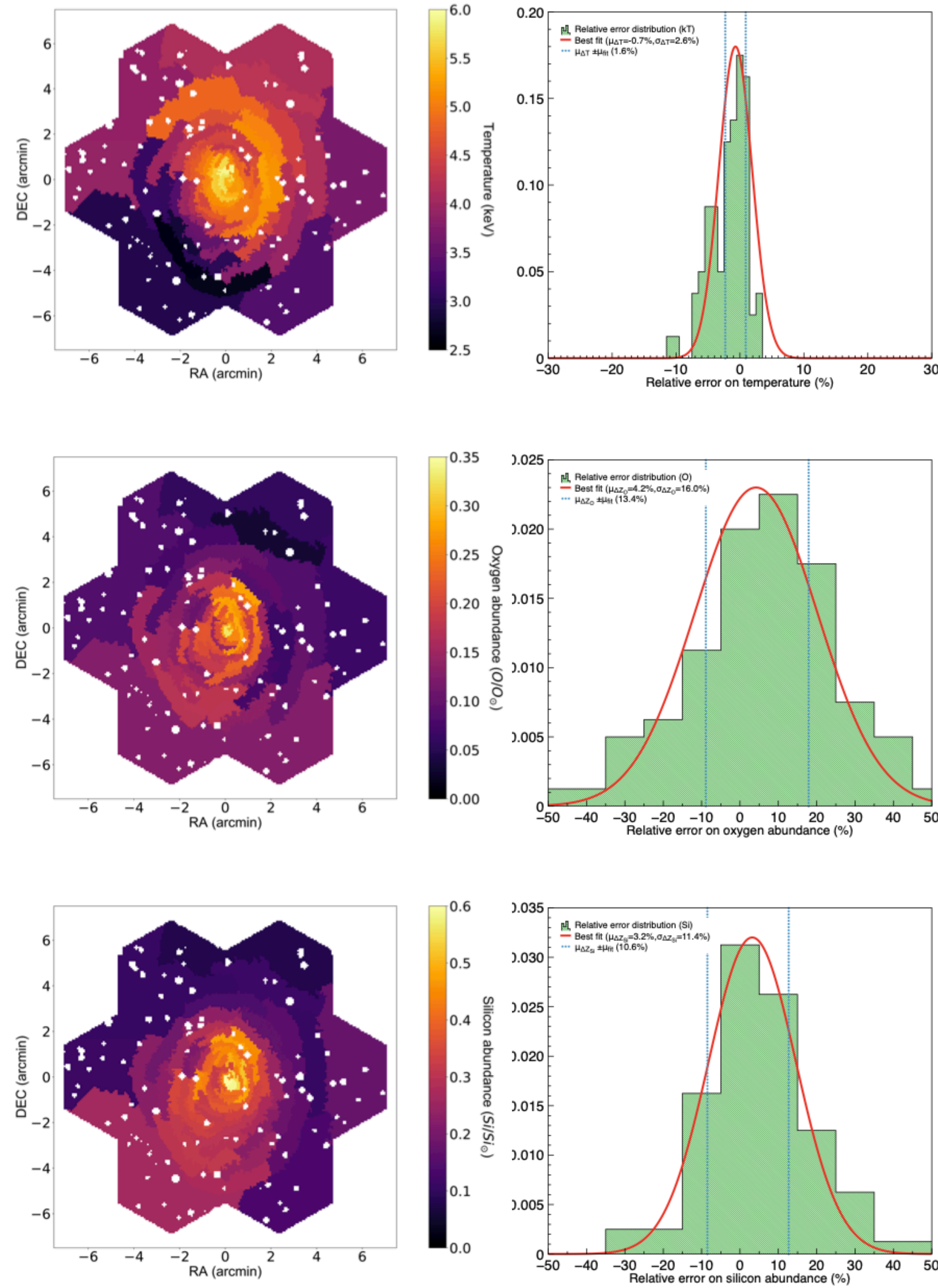
X-IFU Readout chain demonstration

- 50 mK IRAP-CNES test bench in IRAP clean room (Toulouse)
  - 50 mK with commercial ADR cryostat (Entropy GmbH), T_{min} 30 mK, stability 1.5 µK rms
  - 1 kpixel TES array, 2 x 32 pixels TDM readout (NASA/Goddard, NIST), 2.5-3eV energy res.
  - substituting warm electronics by X-IFU flight prototypes developed at IRAP and APC
  - test bench will be used to characterise the calibration sources (RTS with EBIT)



Performance validation

- Method
  - cluster model using input parameters
  - photon list using collisional diffuse thermal plasma using the APEC code
  - simulation of observations with X-IFU
  - data analysis and recovery of input parameters



Recovered ICM parameters maps for a galaxy cluster at z ~ 0.1

(left) Temperature, Oxygen abondance, Silicon abondance maps

(right) Histograms of corresponding deviations with input maps

Also available for Fe, Mg, S, Ca, Ni

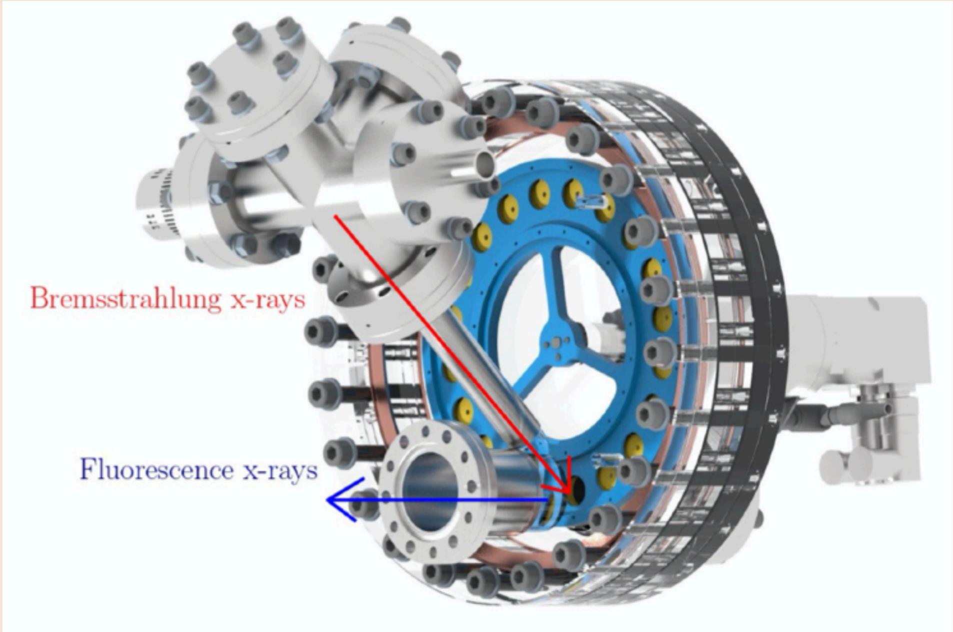
Cucchetti et al. 2018

Calibration plan of X-IFU

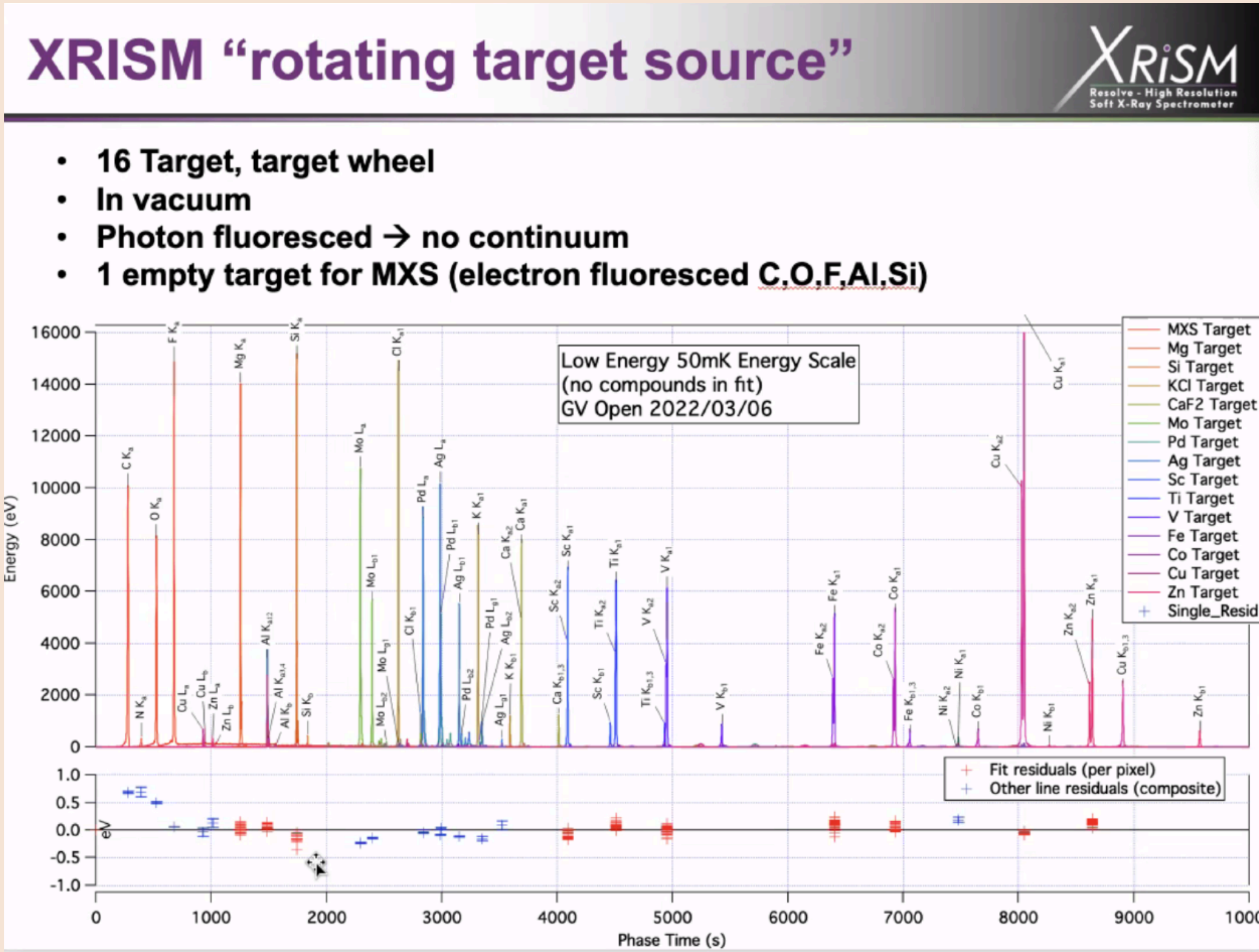
- Calibration strategy
  - on ground from sub-systems to complete instrument in a specific Thermal Ground Support Equipment
  - a check that the performance is not degraded when the instrument is integrated on the spacecraft
  - in-flight re-calibration or calibration using internal sources or astrophysical sources
- Main parameters, requirements and strategy
  - Energy Scale knowledge: ~0.45 eV [0.2-7keV]
    - set of reference curves on-ground, in-flight monitoring using internal modulated electron fluoresced source (MXS)
  - Energy resolution or LSF (Line Spread Function) knowledge: ~0.2 eV [0.2-7keV]
    - extended LSF on-ground, in-flight for core LSF (derives from readout noise)
  - Instrument Efficiency knowledge: 4% [0.2-12 keV] (specific requirement on edges)
    - measured on-ground, monitored in-flight on MXS and stable astrophysical sources (optics contamination monitoring)
  - Non X-ray Background: 2%
    - simulations on-ground and measured in-flight when filter wheel on closed position

Calibration plan of X-IFU

- Ground calibration sources
  - Channel Cut Cristal Monochromators for Energy Resolution (LSF) calibration
  - use of a Rotating Target Source (X-ray fluorescence) for Energy Scale calibration
    - this RTS will be calibrated using an EBIT (Electron Beam Ion Trap) as primary calibrator



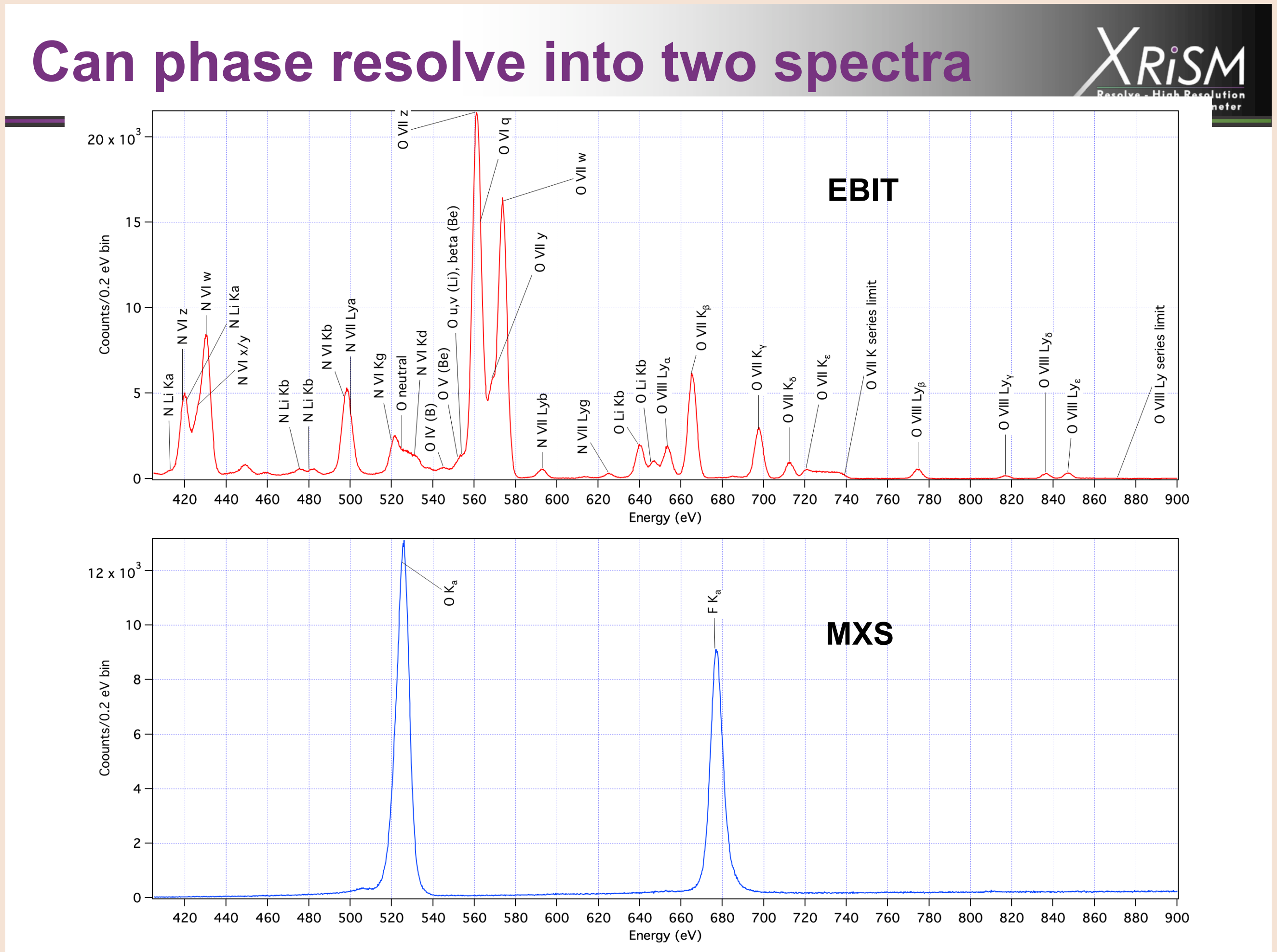
Athena/X-IFU calibration RTS
F. Richters / SRON

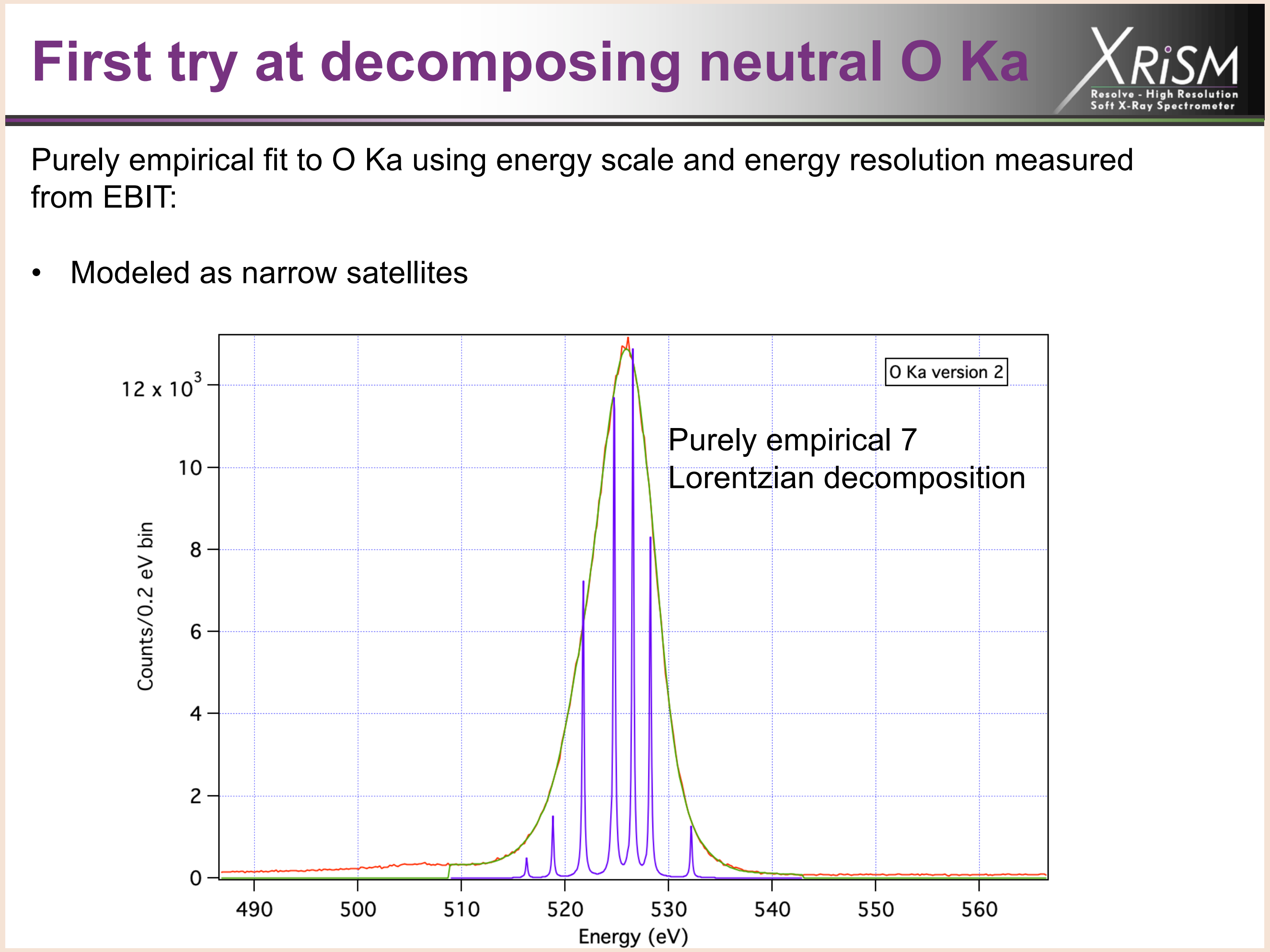


XRISM calibration RTS
Scott Porter/ NASA/Goddard

Calibration plan of X-IFU

- Ground calibration sources
  - Channel Cut Cristal Monochromators for Energy Resolution (LSF) calibration
  - use of a Rotating Target Source (X-ray fluorescence) for Energy Scale calibration
    - this RTS will be calibrated using an EBIT (Electron Beam Ion Trap) as primary calibrator



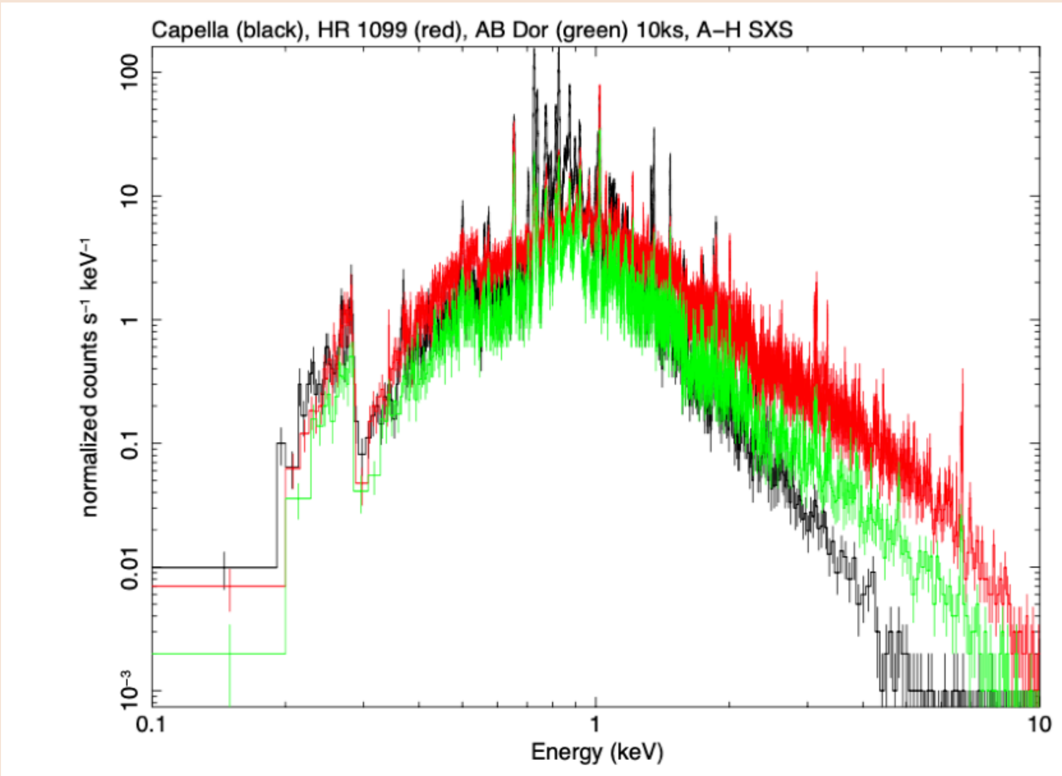


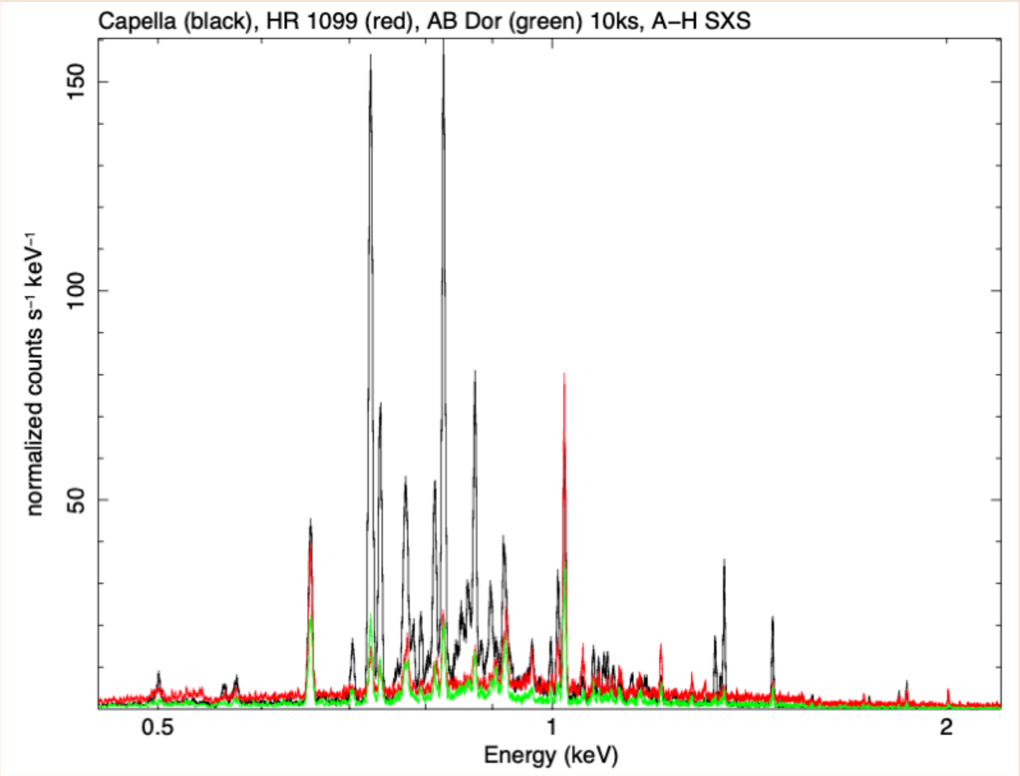
XRISM calibration MXS
Scott Porter/ NASA/Goddard

Stars as energy and line calibrators

- Use magnetically active cool stars, not massive stars with strong winds (thus broad lines)
- Cool stars display a line-rich emission spectrum due to their hot coronae (1-100 MK)
- The emission spectrum is largely consistent with an optically thin collisional ionization equilibrium plasma (minor departures: optical depth of OVIII Lyα lines, Fe XVII lines)
- Non-equilibrium effects expected in very initial phases of flares but for very short timescales (< 10 s, negligible)
- With the improvement in energy calibration and energy resolution, physical effects begin to appear
  - bright magnetically active stars are very often binaries (movement of lines)
  - X-ray activity is enhanced with vsini (broadening of lines)

Simulations for XRISM/Resolve (Marc Audard, Université de Genève)



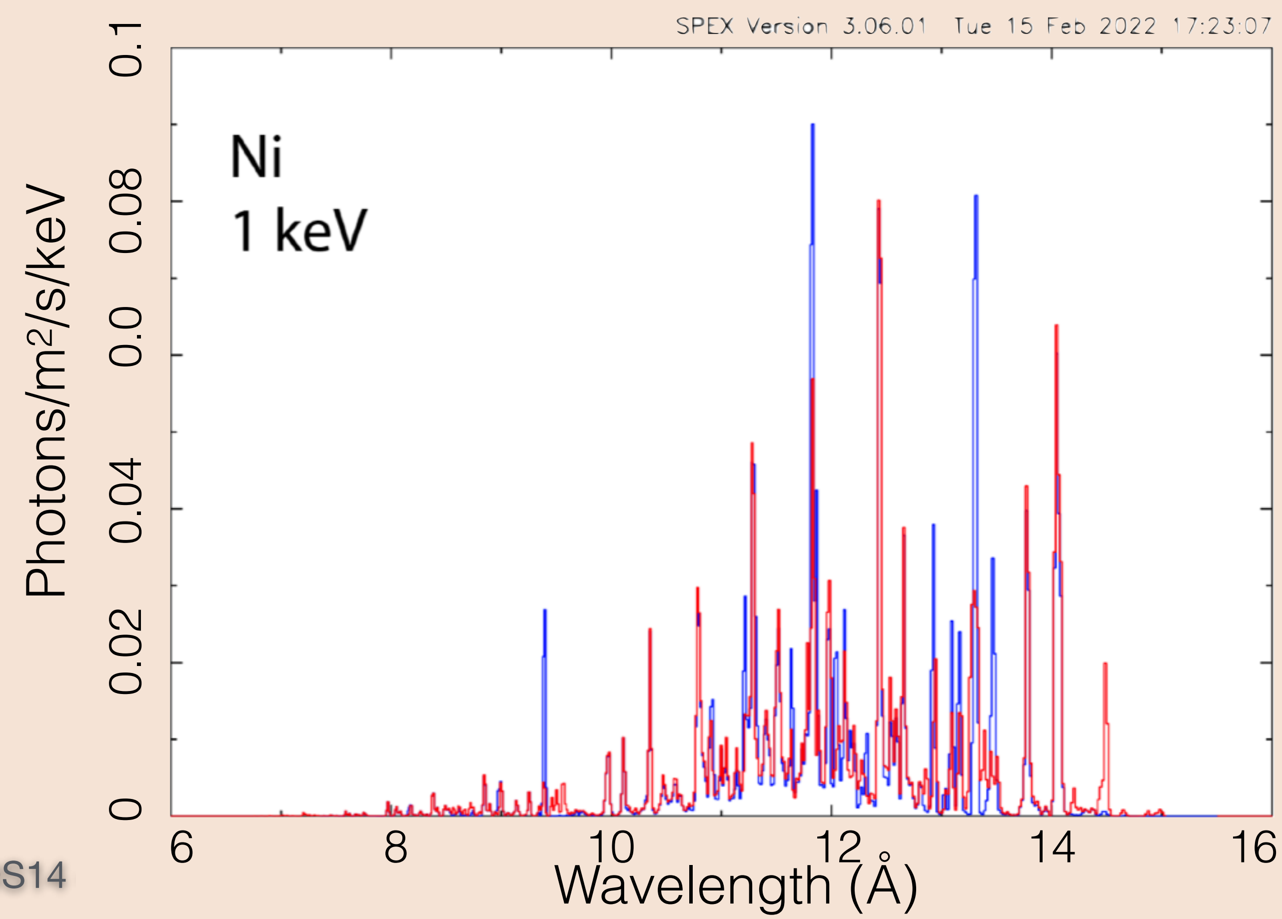


Spectroscopic needs for Athena/X-IFU

- Needs for improved X-ray databases
  - high resolution X-ray spectroscopy will reveal a huge variety of sources and physical conditions
  - accuracy of existing databases is challenged
- AHEAD (Activities for the High Energy Astrophysics Domain) EU program
  - specific work package on « Laboratory Astrophysics » (WP13): improving the knowledge of the atomic physics relevant for the next generation high resolution X-ray telescopes
  - three topics under this WP will address challenges in laboratory astrophysics related to Athena/X-IFU spectroscopy

Spectroscopic needs for Athena/X-IFU

- (A) Goals: provide the community with precise calculations of L-shell transitions of mid-Z ions for a collisional plasma, along with an assessment of the model uncertainties
  - computation performed for Mg, Si, S, Ar, Ca, Cr, Mn, Fe, and Ni, and results implemented in SPEX.
  - all calculations are made public in SPEXv3.07, new routine implemented estimating errors stemming from atomic data
  - next: test the calculations with Chandra-LETGS Capella, and the forthcoming XRISM data

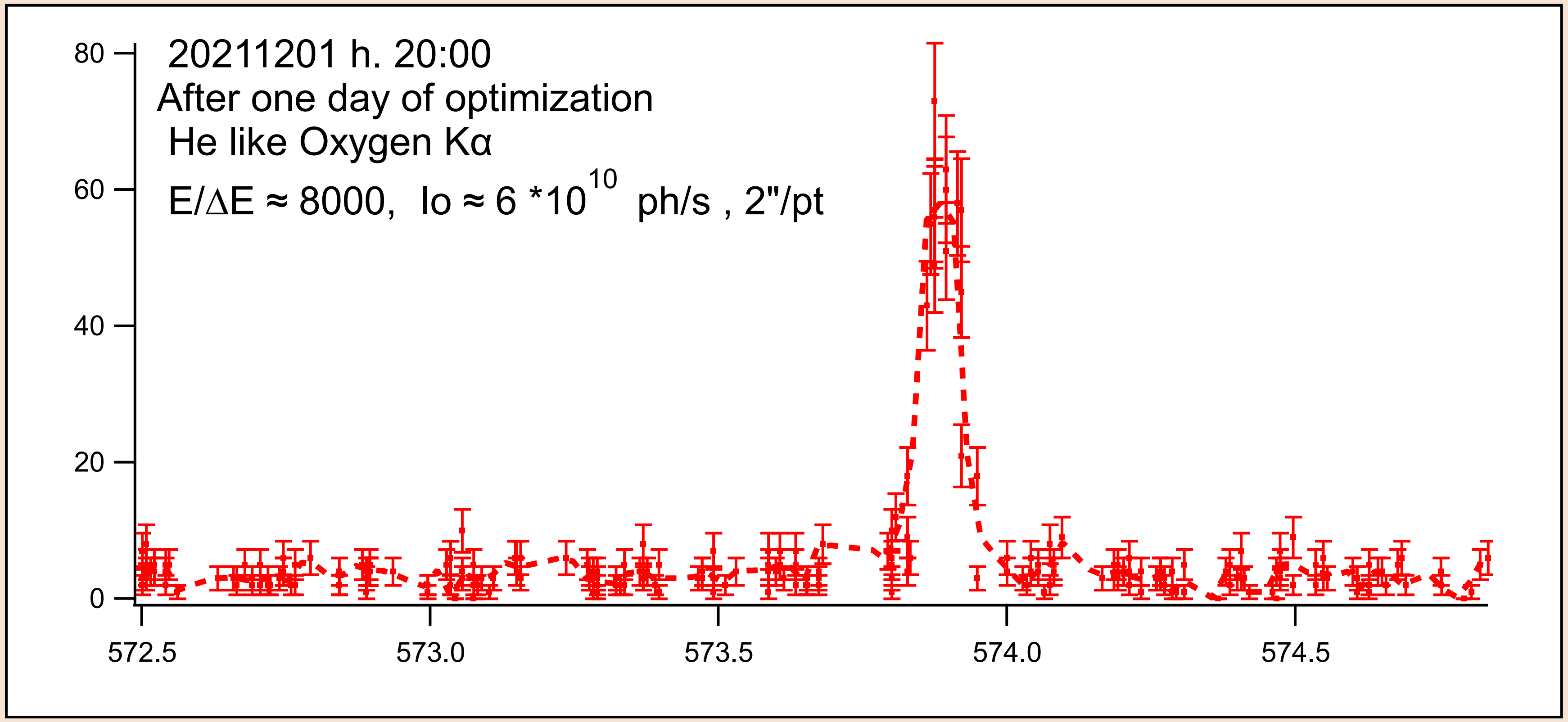


L-shell emission lines from Ni with the new/current atomic data (red) and the old/previous ones (blue)

Liyi Gu (SRON)

Spectroscopic needs for Athena/X-IFU

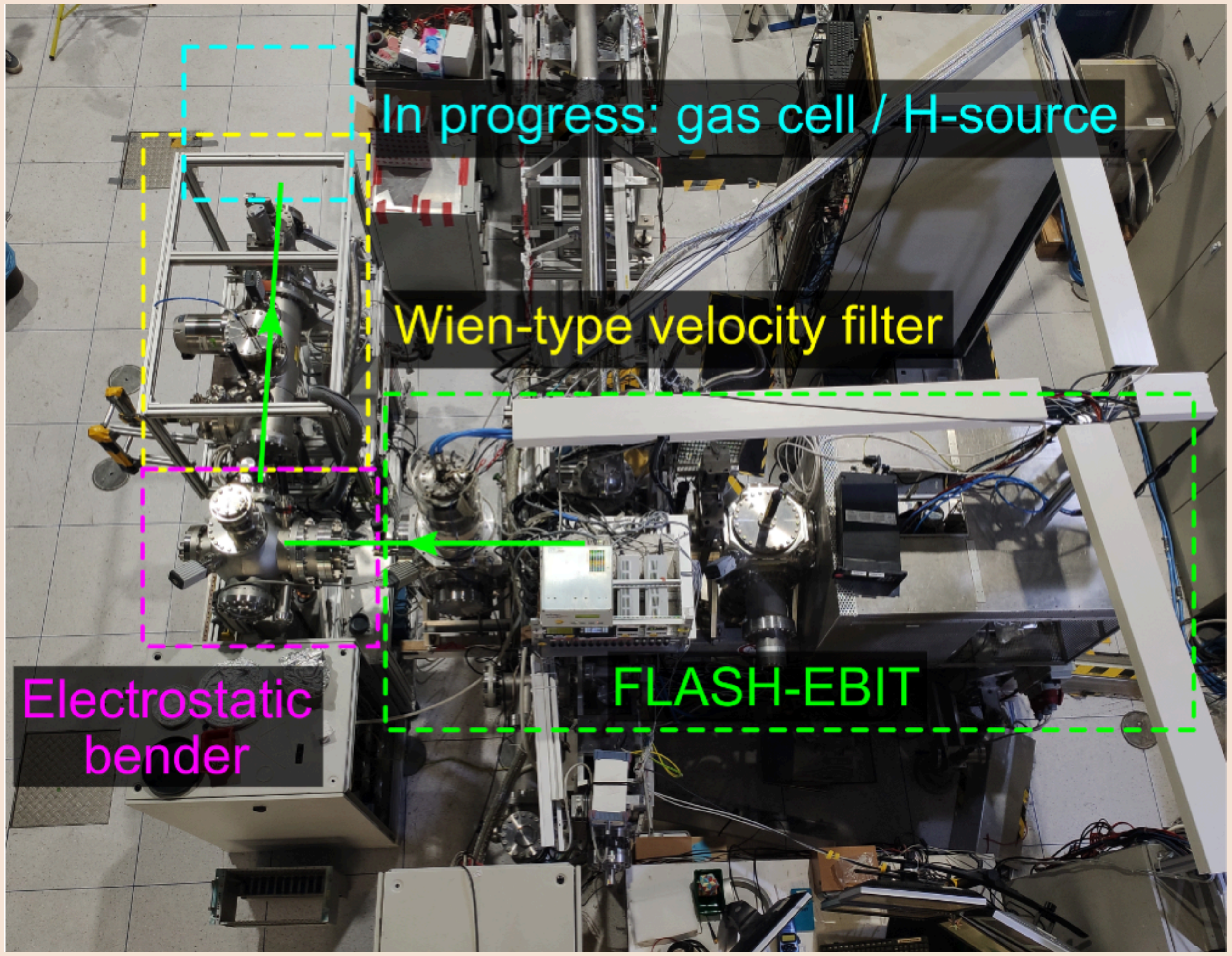
- (B) Goal: measure energies and oscillator strengths of inner shell transitions from astrophysically abundant metals
  - an Elettra-MPI collaboration
    - mini-EBIT (compact EBIT) installed at Gas-Phase at Elettra in 2021
    - measurement (setup calibration) of the OVII Kα at R=8000 resolving power
    - planned for OIV Kα,β, OVI Kα,β, NII Kα, NV Kα,β



F. Nicastro (INAF), J. Crespo (MPIK) et al.

Spectroscopic needs for Athena/X-IFU

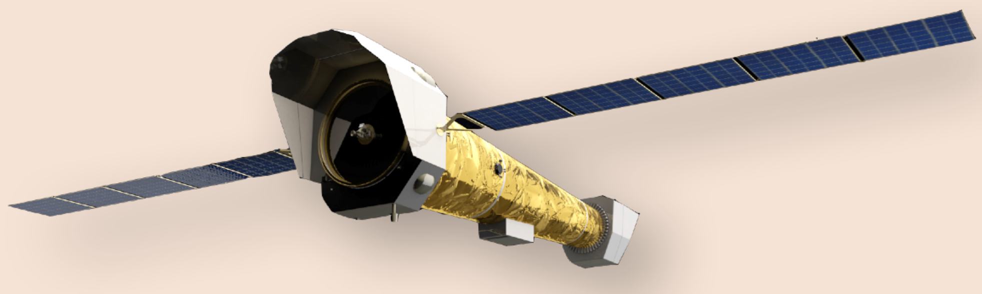
- (C) High-resolution measurements of charge exchange (CX) recombination
  - close interaction where a highly charged ion captures an electron from a neutral atom or molecule (atomic H most present in astrophysics), which subsequently radiatively de-excites, often in the X-ray energy band.
  - future high-resolution observations with the Athena X-IFU will detect CX emission.
  - benchmarking CX theory with measurement using a gas cell producing H atom and measurement campaign using highly charged ions (K-shell, L-shell Fe-group, K-shell C/N/O) from EBIT (J. Crespo and collaborators, MPIK)
    - campaign pending, student needed!



CX setup at MPIK

Conclusion

- Athena/X-IFU will open a new era in X-ray astrophysics
  - spatially resolved high resolution spectroscopy
  - XRISM/Resolve will unveil potential of this new field as soon as 2024
- Time to Athena launch (mid-2030's) allows preparation
  - X-IFU instrument and its calibration
  - on-going studies to identify the needs for astrophysical spectroscopy
- Work on laboratory astrophysics and computation has started
  - still a long way to go after AHEAD EU program (ends in 2024)
  - collaboration with atomic physicists community is needed and welcome



Thank you