The Athena X-ray Integral Field Unit

Didier Barret
X-IFU Principal Investigator (IRAP, FR)

Thien Lam-Trong
X-IFU Project Manager (CNES, FR)

Jan-Willem den Herder (SRON, NL) & Luigi Piro (IAPS, IT)
X-IFU Co-Principal Investigators

On behalf of the X-IFU Consortium with strong support from the X-IFU Science Advisory Team (Massimo Cappi, IASF-BO, IT & Etienne Pointecouteau, IRAP, F)

AthenaXIFU

@AthenaXIFU

http://x-ifu.irap.omp.eu

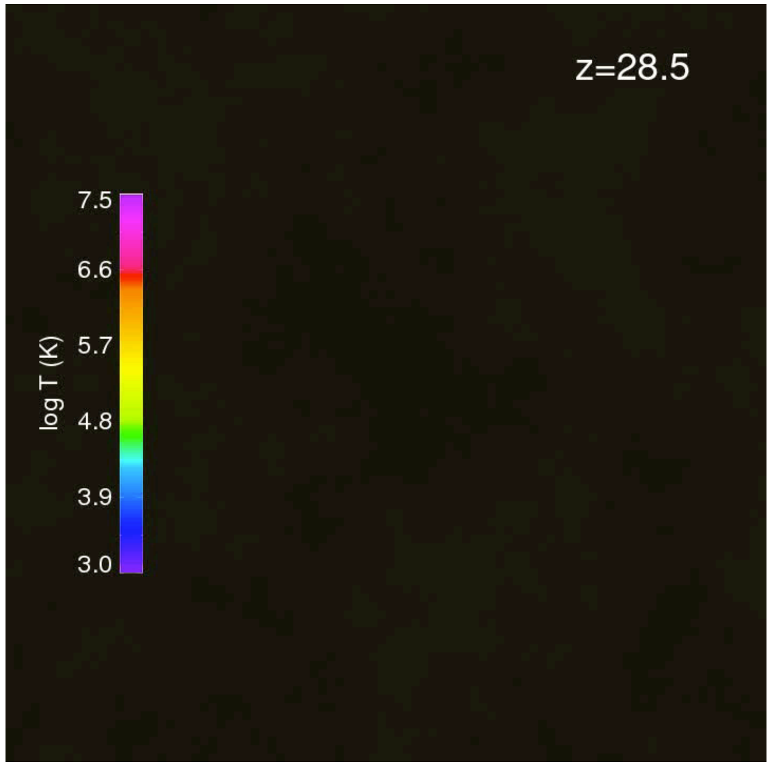
The Athena X-ray Integral Field Unit

- X-IFU will be the Athena cryogenic high-resolution X-ray spectrometer
- It is developed under the leadership of IRAP and CNES (France) by a worldwide consortium (more than 45 institutes involved today)
  - ✓ with major contributions from Netherlands and Italy (CoPIs)
  - ✓ and additional important contributions from **six** other ESA member states (Belgium, Finland, Germany, Poland, Spain ☛ J. Gomez Elvira talks, Switzerland)
  - ✓ and from two international partners (Japan and the United States)

Outline

- Athena science: **The Hot and Energetic Universe** (☛ F. Carrera & G. Miniutti talks)
- How does ordinary matter assemble in the large-scale structures?
  - ✓ Tool: X-ray emitting hot gas in clusters
- How do black holes grow and shape the Universe?
  - ✓ Tool: Accretion powered X-rays onto compact objects
- Observatory and discovery science enabled by the mission capabilities

1. X-IFU: The first X-ray Integral Field Unit
2. Six key scientific drivers for X-IFU
3. Performance requirements
4. Current baseline configuration
5. Performance assessment
6. Conclusions



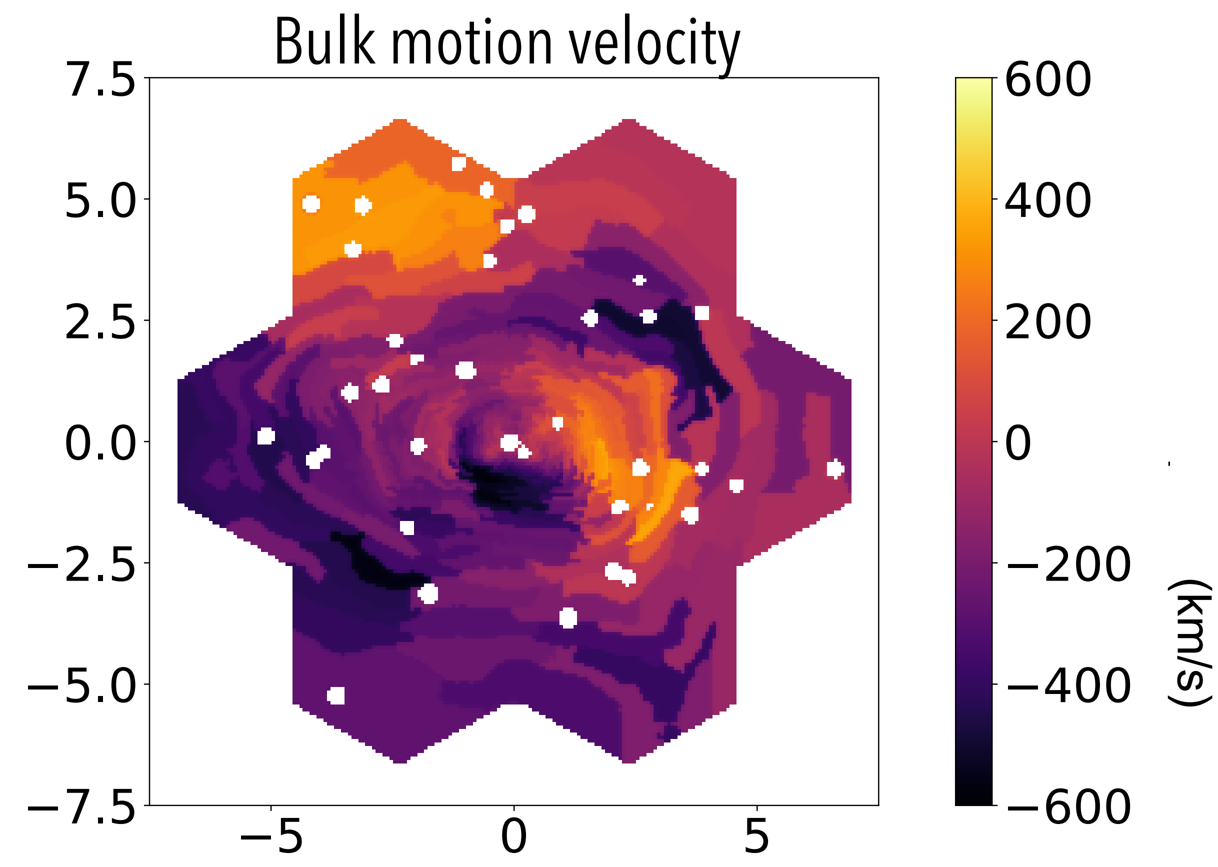
What the X-IFU will do for you ?

- The X-IFU will measure the physical properties of hot plasmas: velocity, turbulence, metal abundances, ionization, density, temperature, variability, energy dependent time lags…
  - ✓ 3D mapping over a **5’ field of view**,
  - ✓ imaging with **5 arcsecond** pixels,
  - ✓ absorption/emission line spectroscopy with **2.5 eV** resolution up to **7 keV**,
  - ✓ continuum measurement from ~**0.2 keV** up to **12 keV**,
  - ✓ spectral-timing analysis with time resolution down to **10µs**.
- From the faintest extended diffuse sources (e.g. filaments, distant clusters) to the brightest nearby X-ray point sources (e.g. galactic black hole binaries)
  - ✓ To be used also predominantly for observatory and discovery science

Large scale structure formation

- How matter assembles in dark matter potential?
  - ✓ Mapping bulk motion and turbulence of hot cluster gas through multiple line shifts and broadenings
    - ➡ To constrain models of cluster formation
- Drivers: Field of view, background, spectral resolution, quantum efficiency at 6-7 keV, pixel size

Simulated bulk motion velocity maps predicted from cosmological simulations. Point sources blanked.

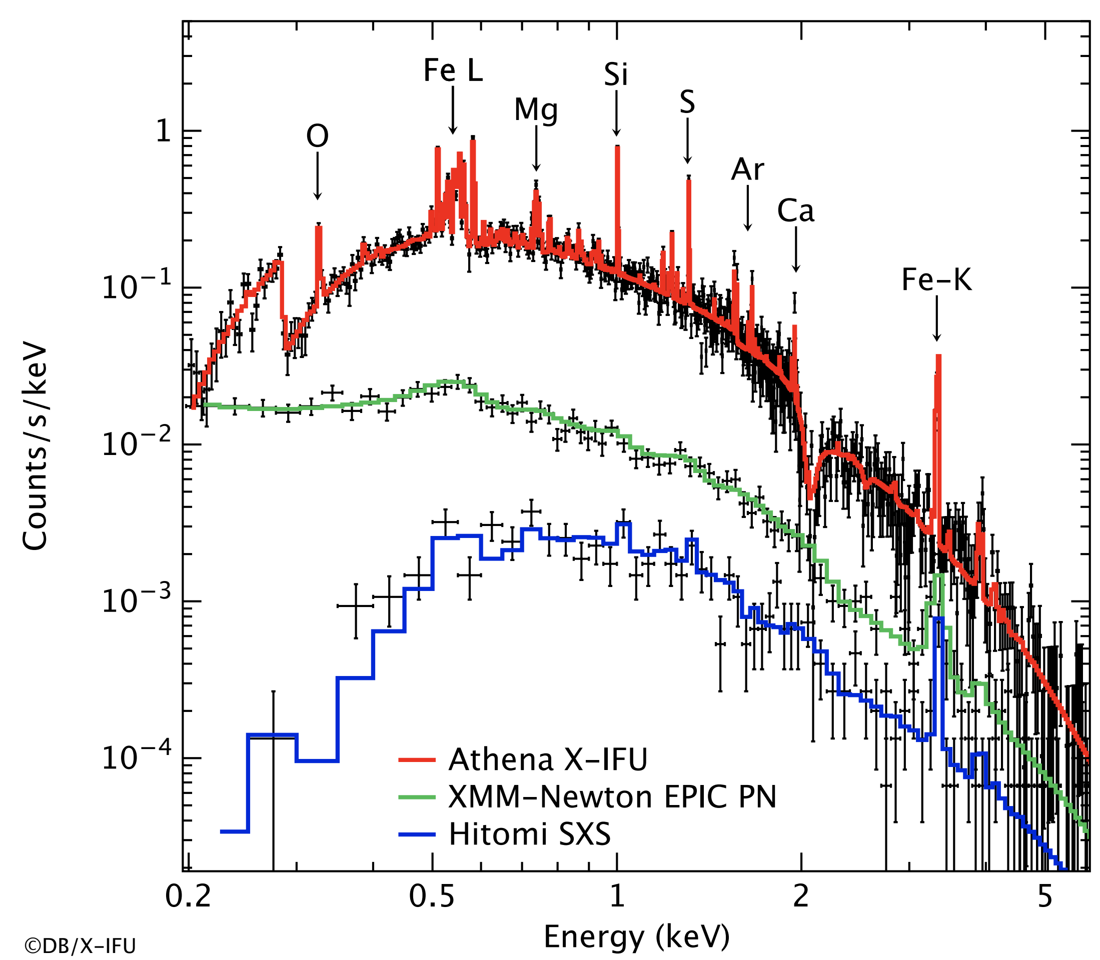


Courtesy E. Cucchetti, E. Pointecouteau, P. Peille, et al.

Chemical enrichment

- How was the Universe chemically enriched?
  - ✓ Mapping metals and measuring abundances from proto-clusters to local massive clusters
    - ➡ Synthesize the abundances using yields of various SN types and AGB stars
    - ➡ To determine when the largest baryon reservoirs in galaxy clusters were chemically enriched and by which processes
- Drivers: Field of view, background, broad band quantum efficiency

Metal rich X-IFU spectrum of a z=1 cluster compared with XMM-Newton and Hitomi/SXS

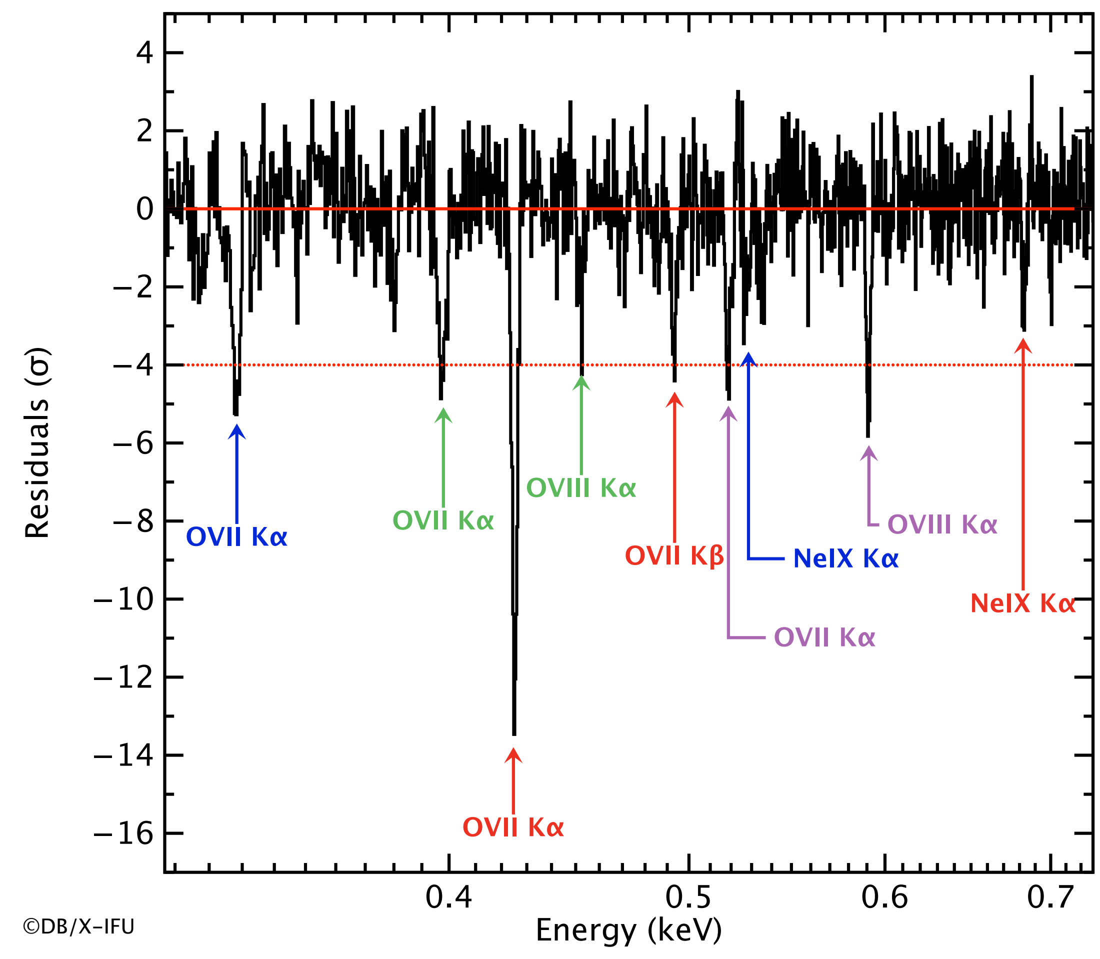


Courtesy E. Pointecouteau. From Barret et al. (2016)

Missing baryons

- Where are the missing baryons and what is their physical state?
  - ✓ Observing the Warm Hot Intergalactic Medium in absorption using background light sources (AGN and GRB afterglows) and in emission to:
    - ➡ Measure the chemical composition, density, temperature, ionization and turbulence of the missing baryons at z<2
    - ➡ Reveal the underlying mechanisms driving their distribution on various scales, from galaxies to galaxy clusters
- Main drivers: Spectral resolution, quantum efficiency at 1 keV, low energy threshold, duty cycle of the cooling chain

Multi-filament WHIM absorption X-ray spectrum using a bright GRB afterglow.

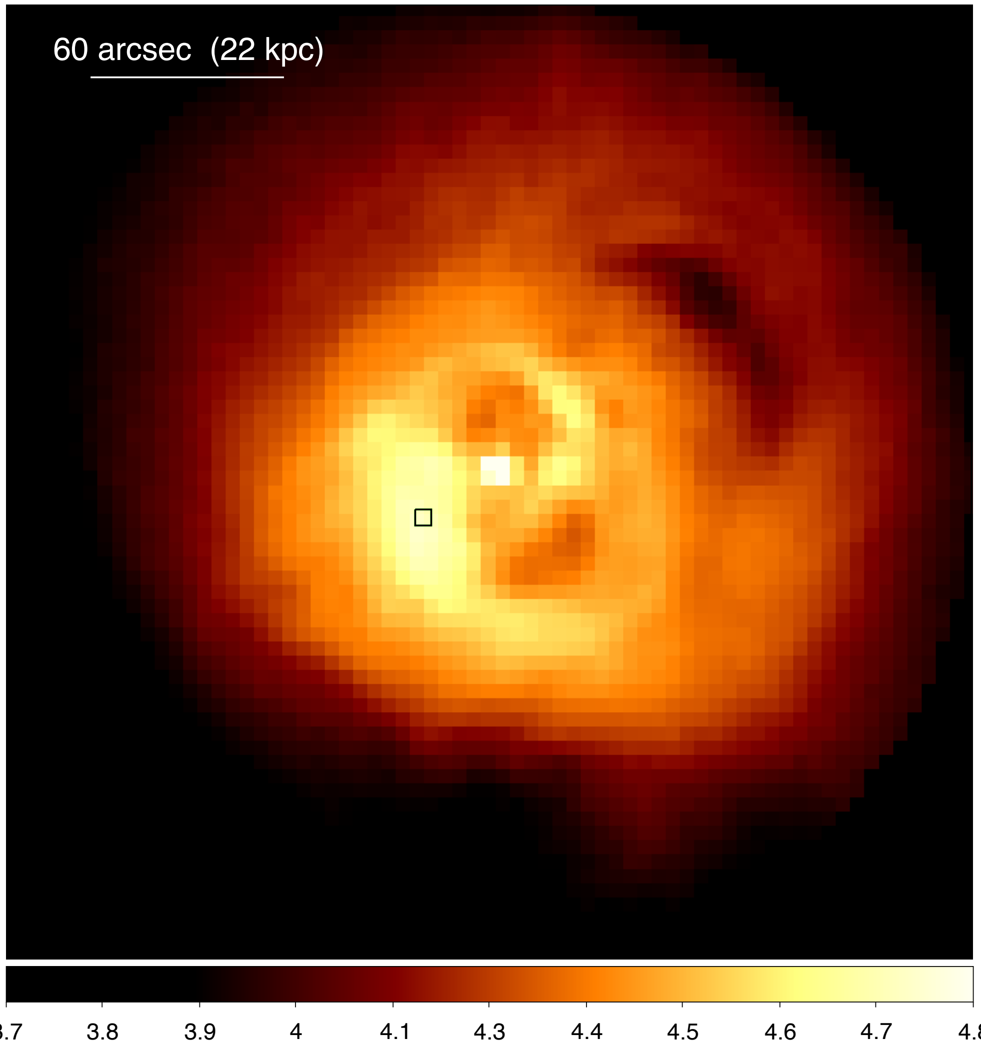


Courtesy F. Nicastro (from Barret et al. 2016)

Cluster feedback

- How do black holes work and interact with their surroundings?
  - ✓ Observing feedback in galaxy clusters
    - ➡ Measure hot gas bulk motions and energy stored in turbulence directly associated with the expanding radio lobes to understand how AGN jets dissipate their mechanical energy in the ICM, and how this affects the hot gas distribution.
- Drivers: Field of view, background, pixel size

Simulated image of the Perseus cluster

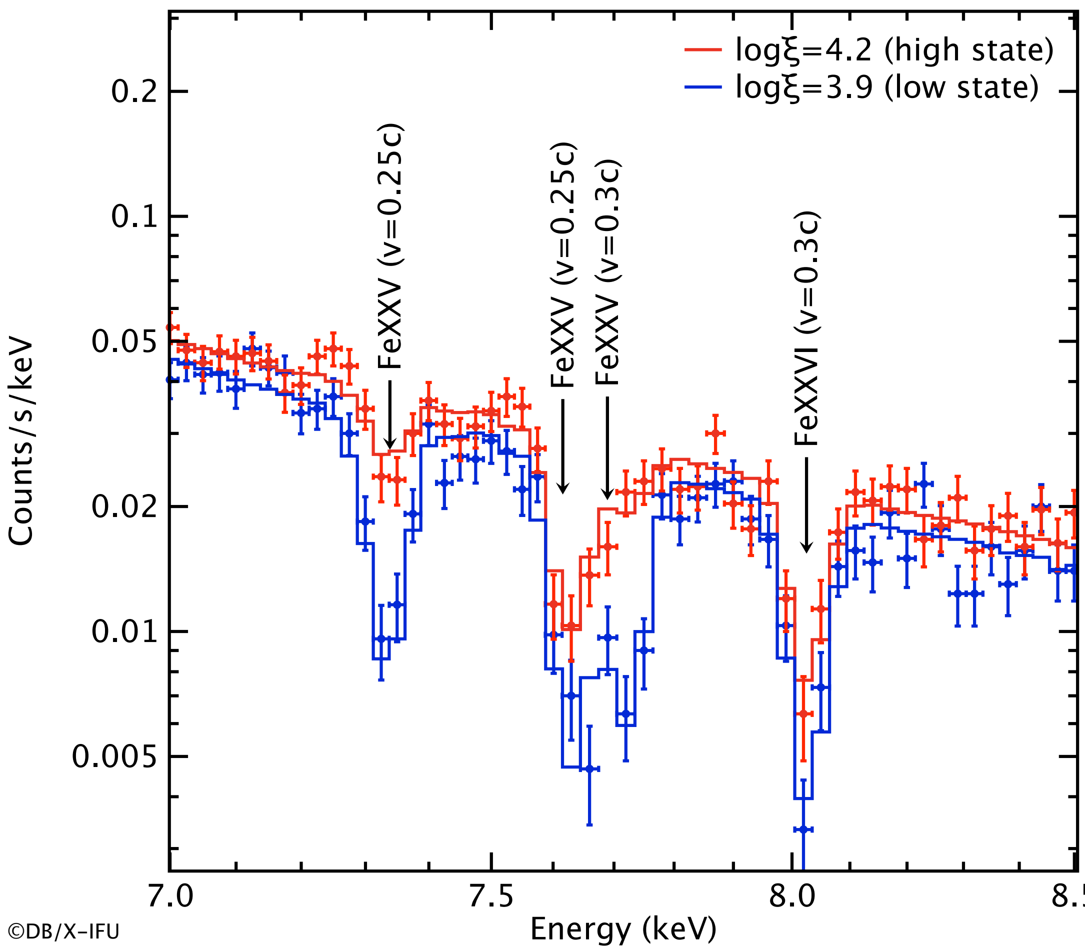


Courtesy J. Sanders. From Barret et al. (2016)

AGN outflows

- How do black holes work and interact with their surroundings?
  - ✓ X-ray absorption spectroscopy of bright AGN enabling to:
    - ➡ Characterize ejecta, by measuring ionization state, density, temperature, abundances, velocities and geometry of absorption and emission features of the winds and outflows
    - ➡ Determine how much energy these winds and outflows carry
  - ✓ Similar winds to be observed in black hole/ neutron star binaries (see next)
- Drivers: Quantum efficiency above 6-7 keV

Simulated ultra-fast outflow spectrum for two different luminosity states and two outflow speeds

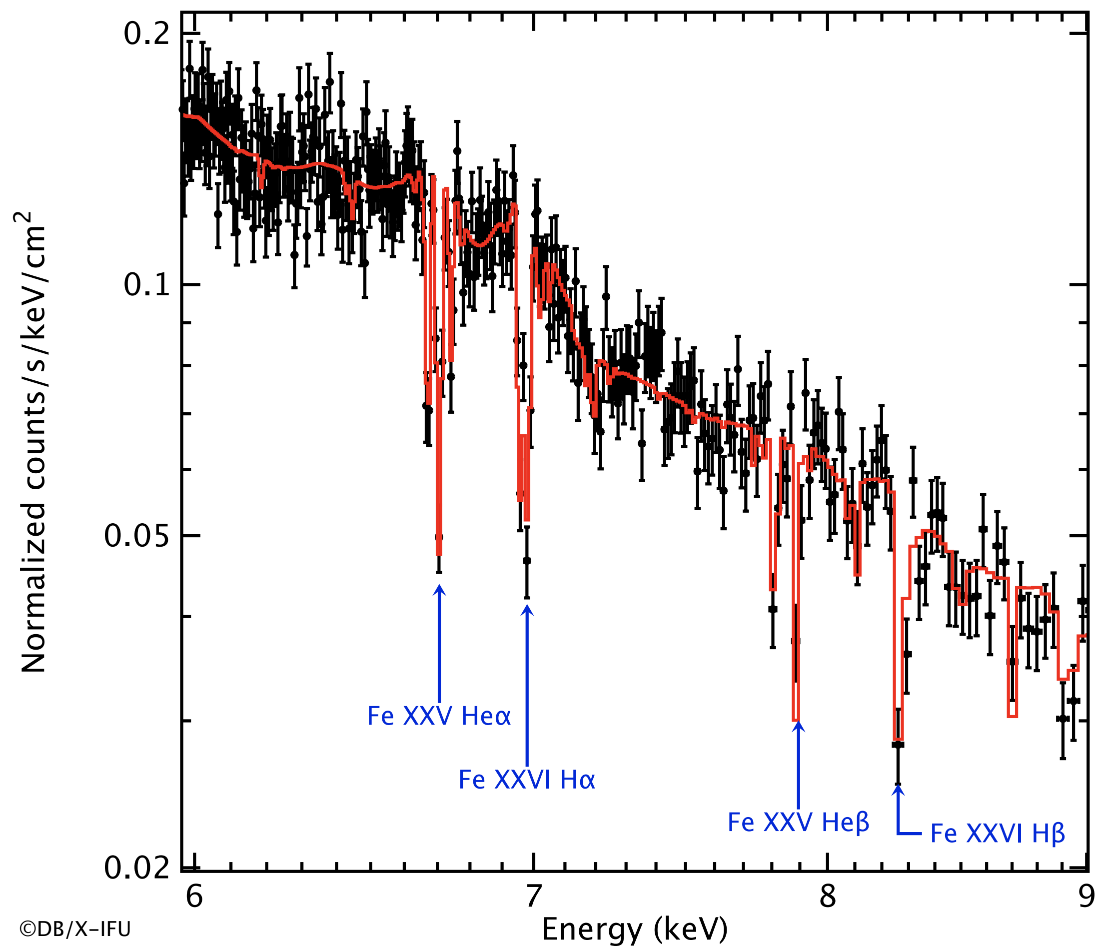


Courtesy M. Cappi et al.

Accretion physics

- What power disk winds?
  - ✓ Broad band spectroscopy of X-ray binaries:
    - ➡ Probe outflow properties and disk magnetic fields in galactic binaries
    - ➡ Determine the relationship between the accretion disk and its hot electron plasma
    - ➡ Understand the interplay of the disk/corona system with matter ejected in the form of winds and outflows.
  - ✓ Reverberation mapping done with the same data set for all sources below 1 Crab
- Drivers: Count rate capability and quantum efficiency above 7 keV

Disk wind spectrum of the stellar mass black hole GRS1915+105

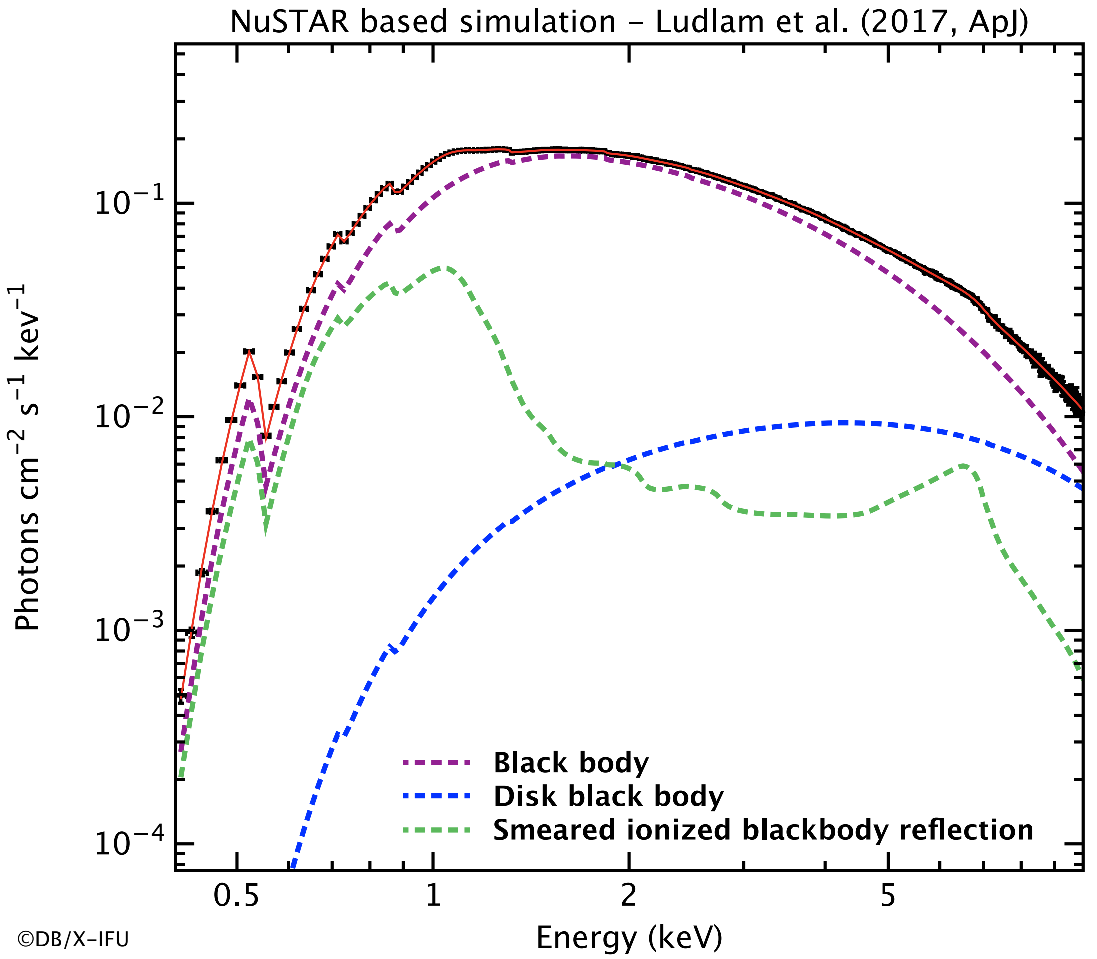


Courtesy J. Miller (from Barret et al. 2016)

Observatory science with X-IFU

- Solar system bodies: Sun-planet interaction
- Exoplanets: magnetic interplay
- Star formation: brown dwarfs
- Massive stars: stellar winds
- Supernovae: explosion mechanisms
- Supernovae remnants: shock physics
- Interstellar medium: composition
- Stellar endpoints: dense matter at supra nuclear densities
  - ✓ To constrain neutron star radii from continuum spectroscopy
- Discovery science: unknowns

X-IFU spectrum of smeared reflection from 4U1705-44 based on NuSTAR modeling



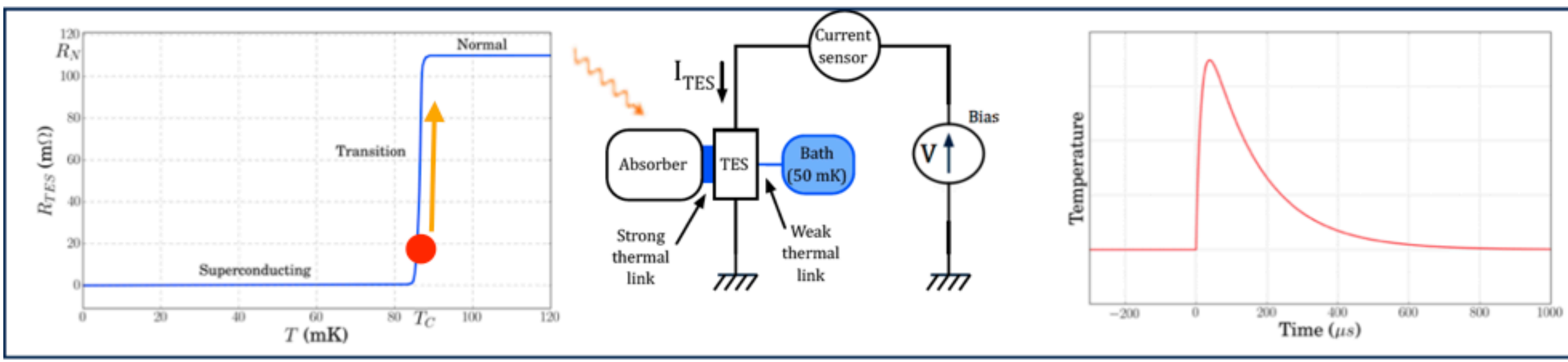
Courtesy R. Ludlam

Main X-IFU performance requirements

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 down to 20 km/s - Weak line sensitivity - Resolving OVII like triplet***
Field of view	5' (equivalent diameter)	Matter assembly in clusters - X-ray cooling cores - Metal production and dispersal - Jet energy dissipation in clusters - ***To map 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 - ***Matches structure size and minimizes confusion***
Background level	<5 10^{-3} count/s/cm^2/keV	Matter assembly in clusters - Metal production and dispersal - ***For low surface brightness sources***
Low-energy threshold	0.2 keV	Census of warm-hot baryons - Physical properties of the WHIM - ***OVII and C V lines at 0.31 keV***
High-energy threshold	12 keV	Probing black hole spins and winds, ultra-fast outflows. ***Fe XXVI absorption line (0.3 c) at 8 keV***
Count rate capability	1 mCrab (2.5 eV, 80% eff.) 10 mCrab (2.5 eV, 80% eff.,goal) 1 Crab (<30 eV, 30% eff.)	Probing the WHIM with GRB afterglows, Probing black hole and neutron star accretion & winds - ***Observation of sources up to 1 Crab intensity levels***

Transition Edge Sensors (TES)

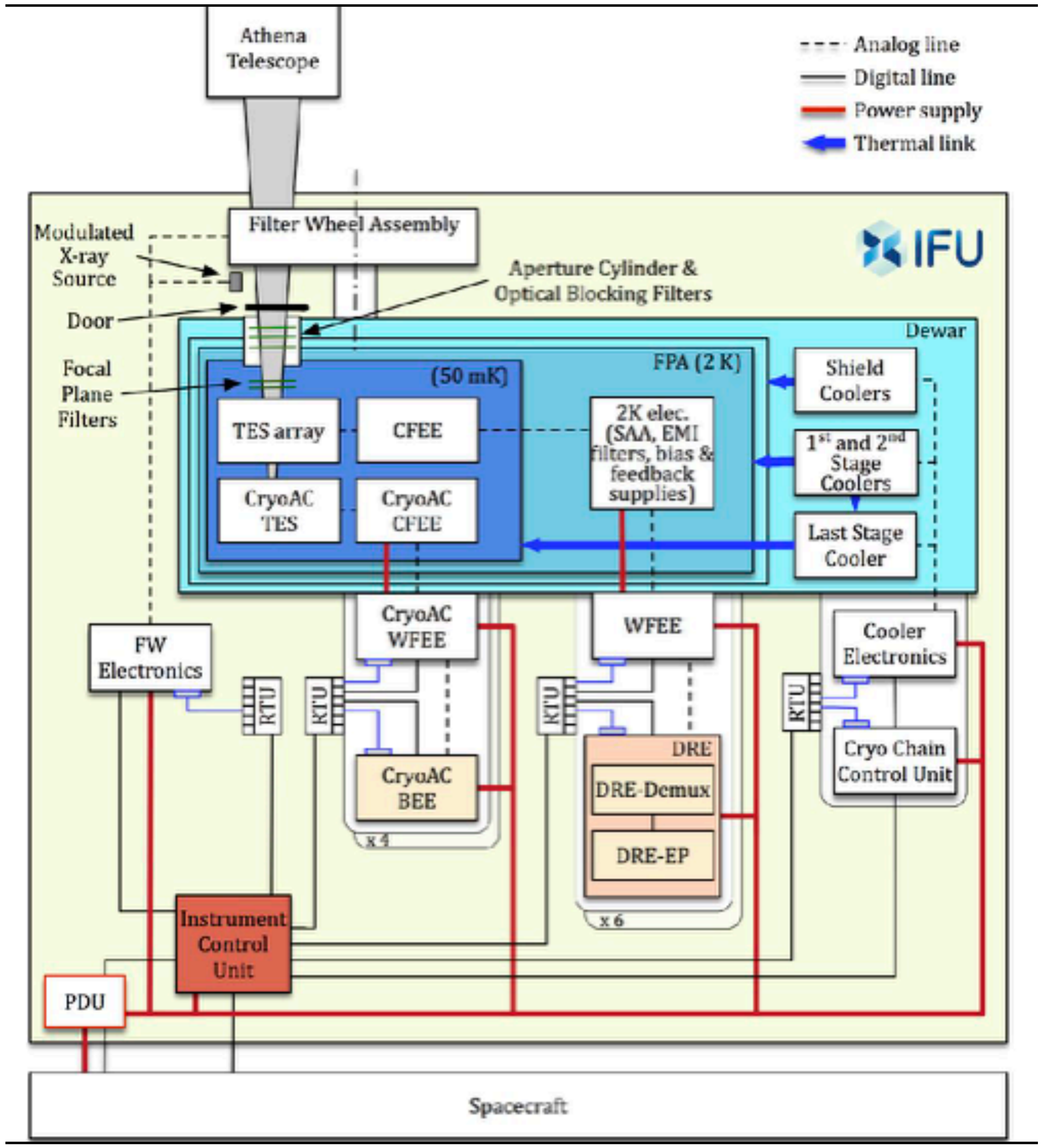
- The X-IFU will be based on a large format Transition Edge Sensor (TES) hexagonal array (~3800 pixels with a ~250 μm pitch)
- A TES is a μcalorimeter (superconducting resistive material) biased in its transition region to sense the heat deposited by an X-ray photon on its absorber



X-IFU block diagram

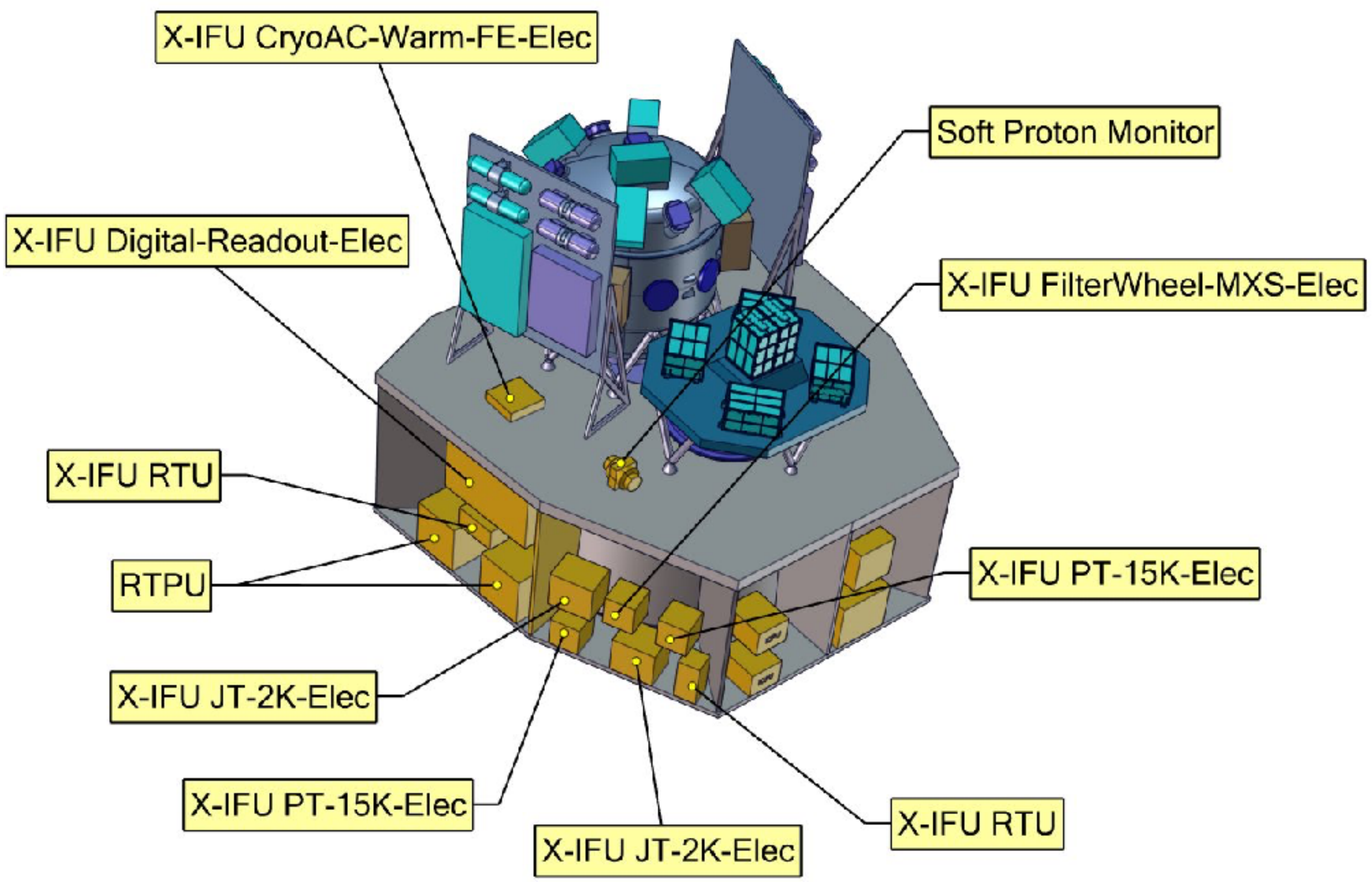
- The prime TES array (hexagonal) is actively shielded by a second TES array to meet the low background requirement
- Cryogenic chain down to 50 mK as an assembly of mechanical coolers to guarantee mission lifetime and high observing efficiency
- Frequency domain multiplexing readout (40 pixels readout) to keep heat load at 50 mK as low as possible
- Event processing returning arrival time, energy, grade of each photon
- On-board calibration sources for accurate energy calibration
- A set of user selectable filters on a filter wheel (optical, Be, grey ,….)

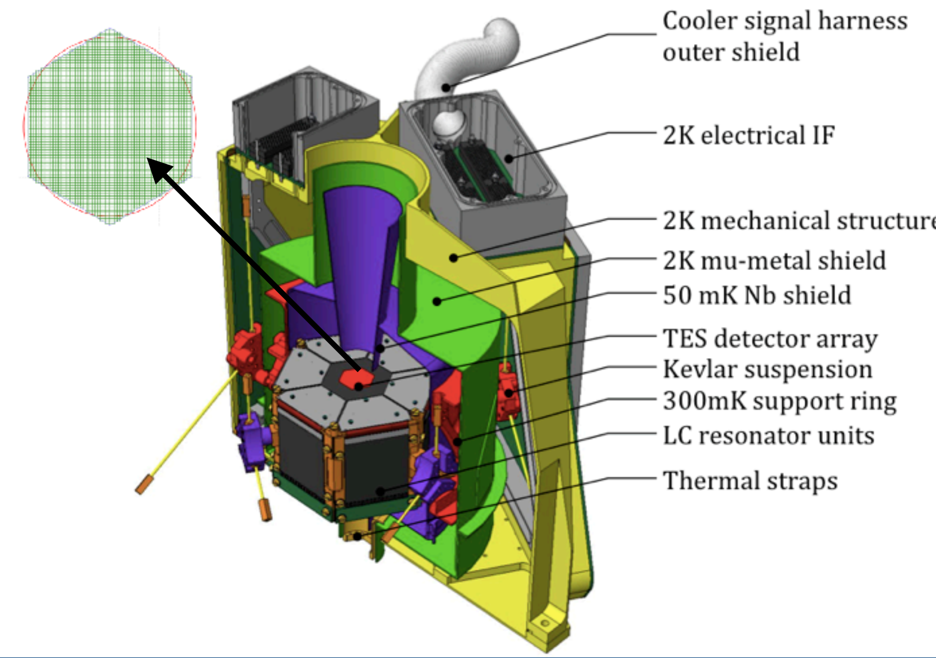
X-IFU functional block diagram

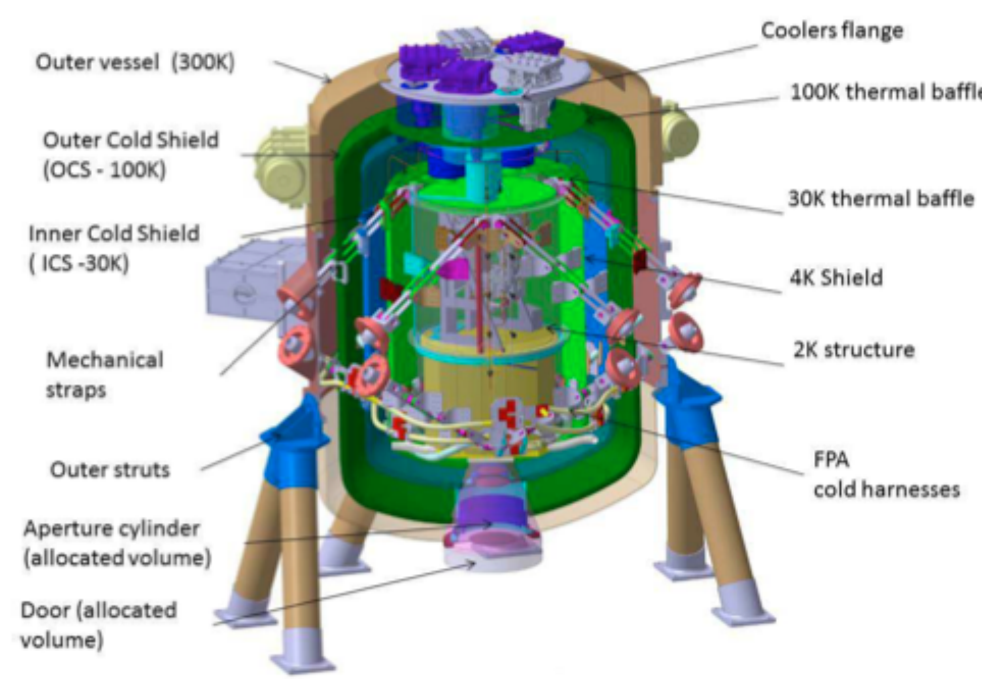


Courtesy L. Ravera. From Barret et al. (2016)

X-IFU design views

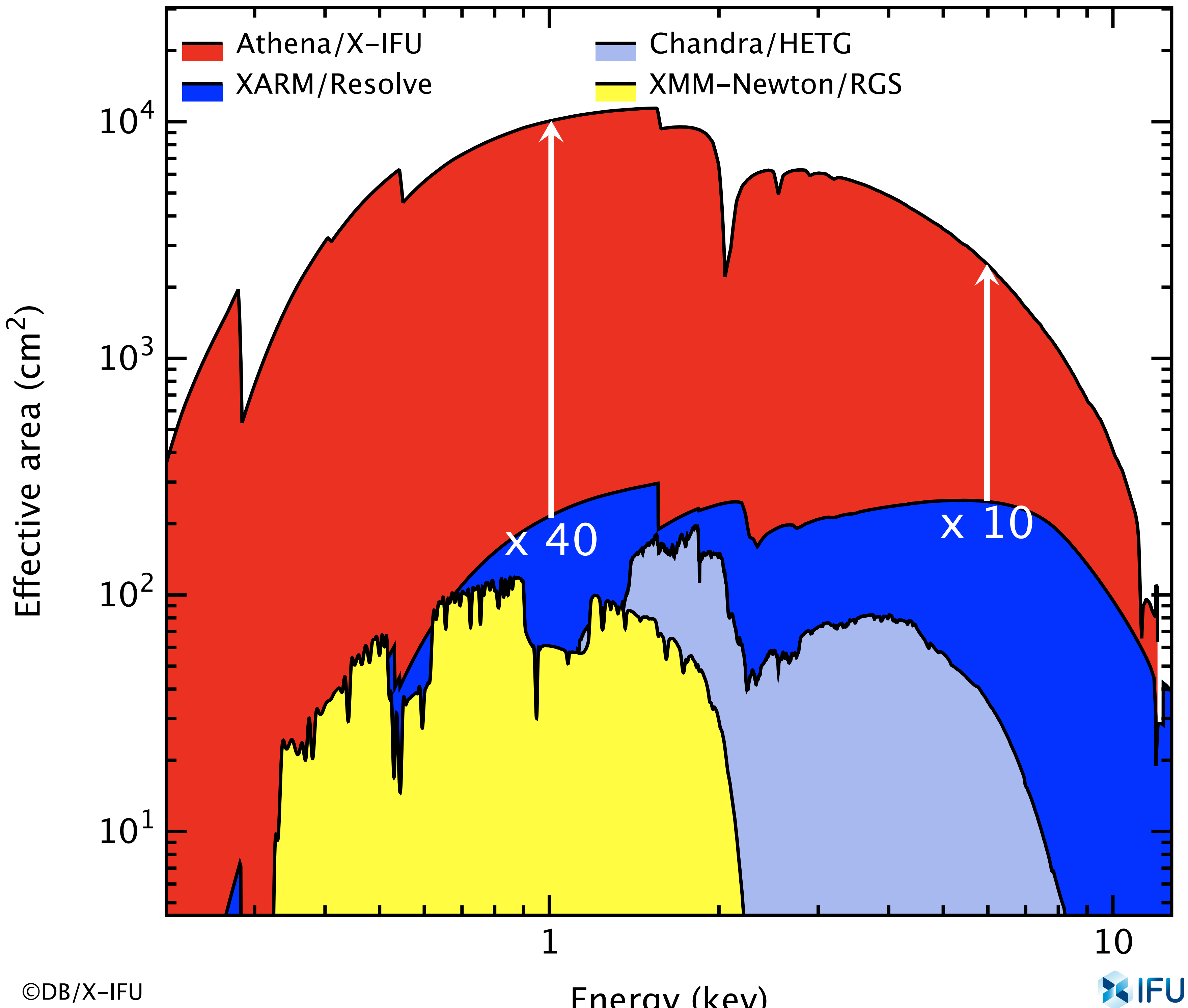




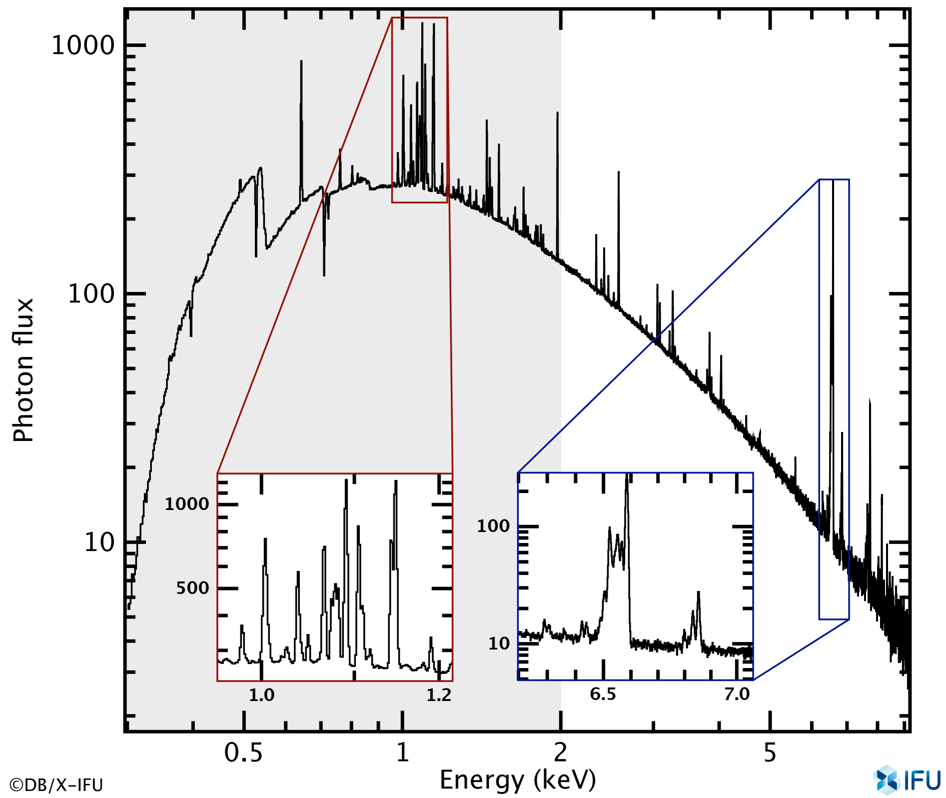


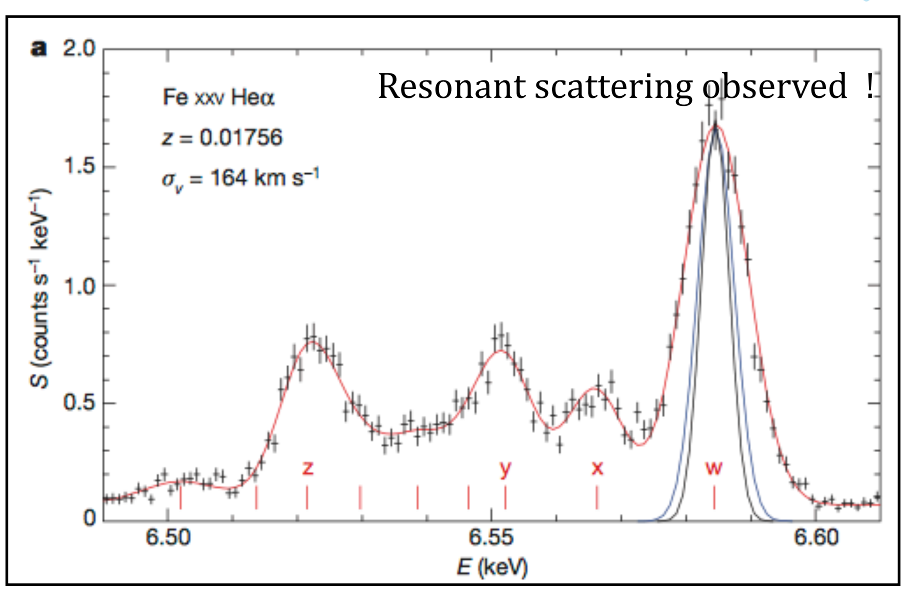
800 kg — 2900 Watts — Courtesy of ESA, SRON, CNES

Effective area

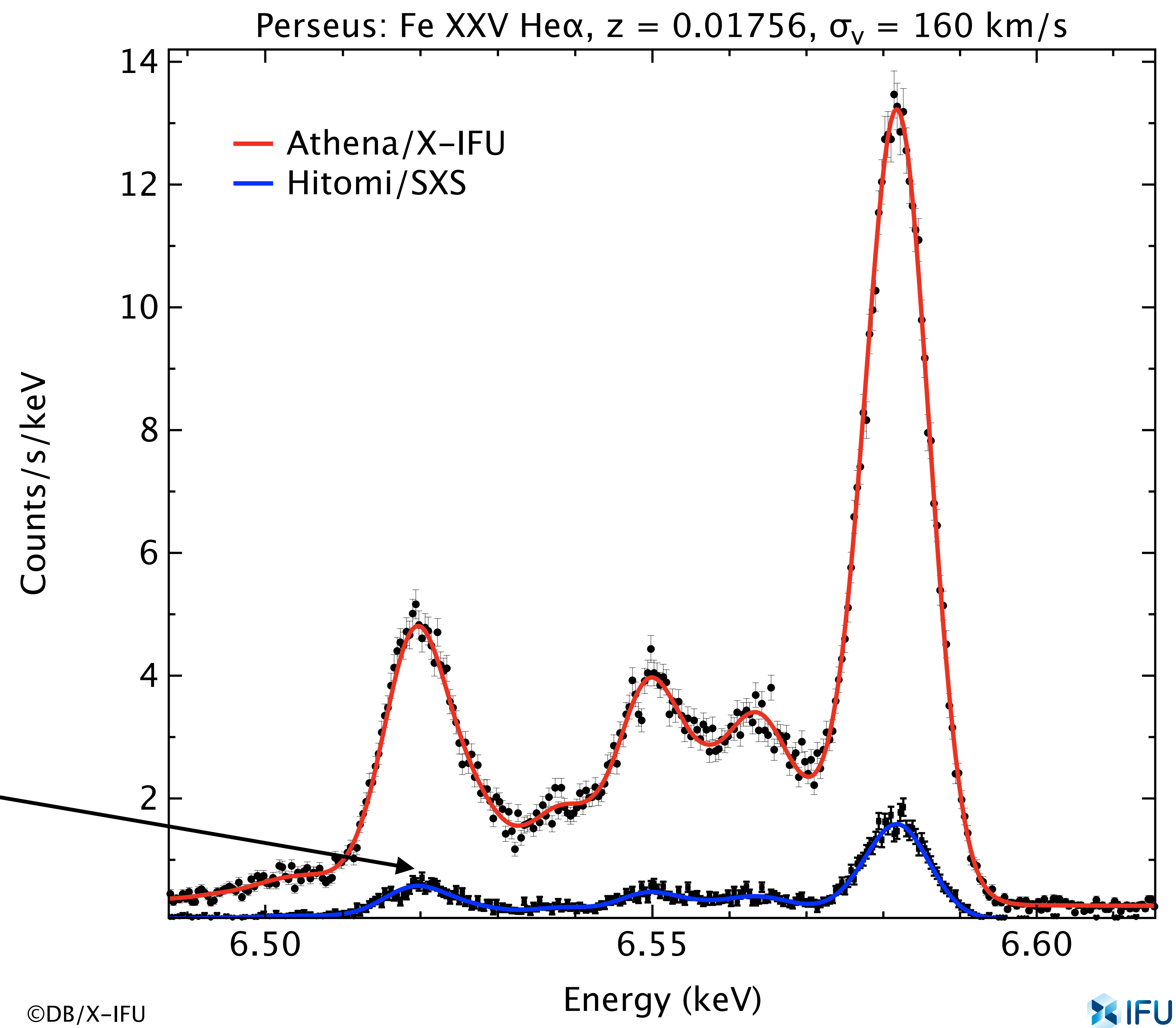


Giant leap in sensitivity

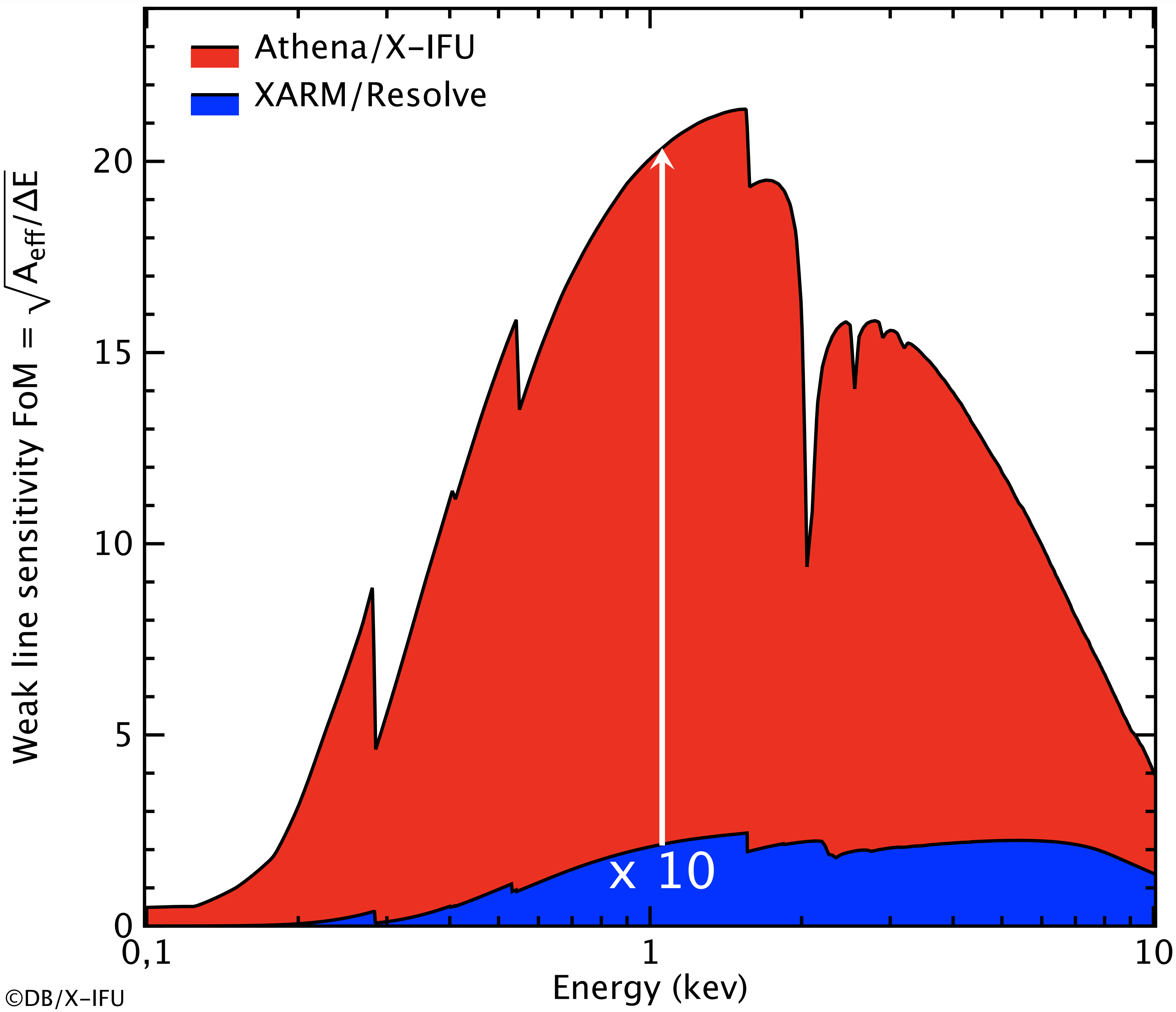




Hitomi collaboration Nature (2016, 2017)

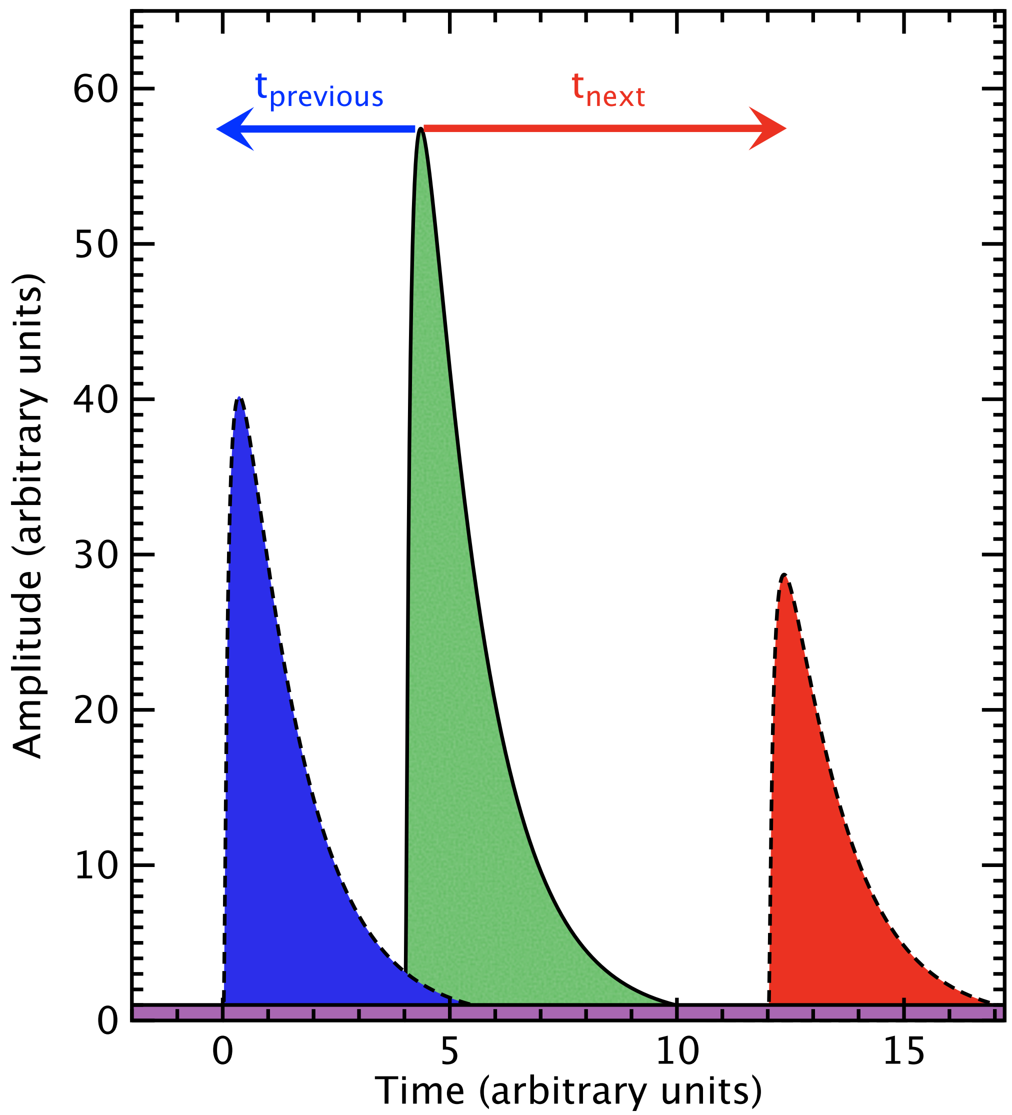


Weak line sensitivity

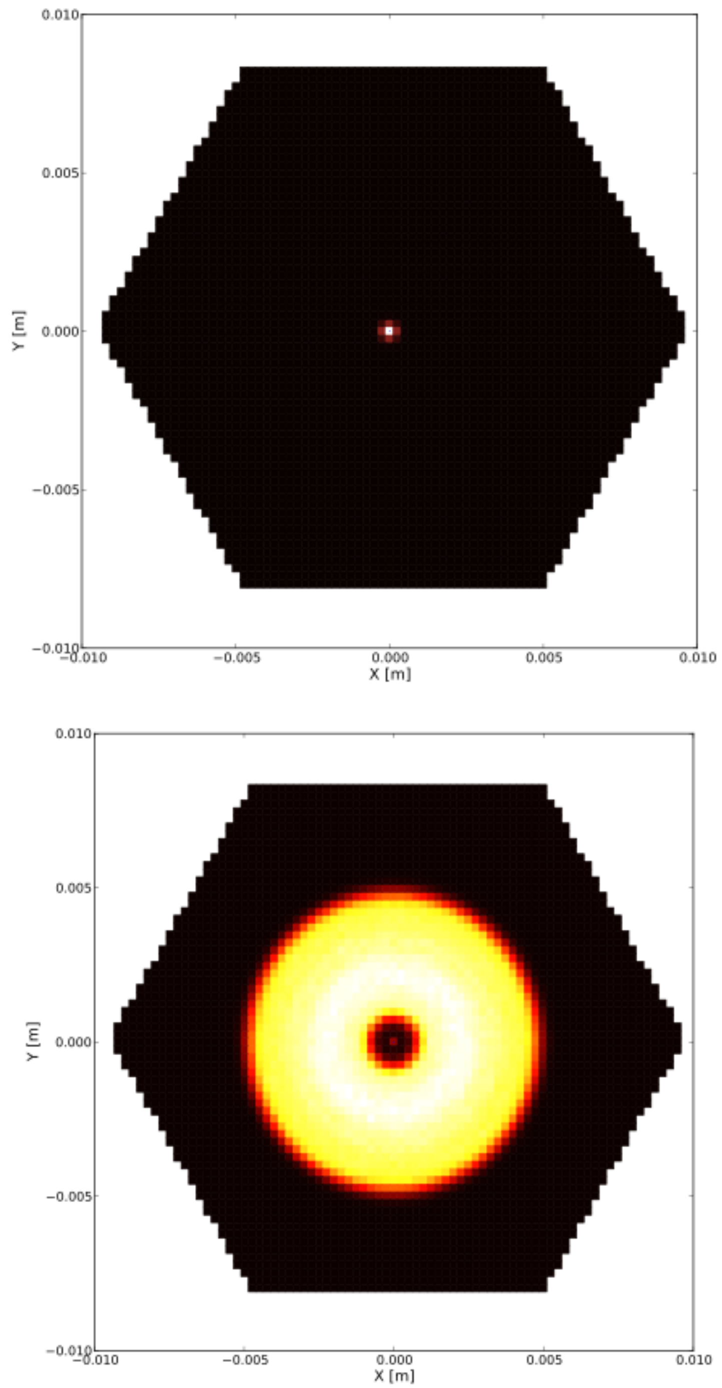


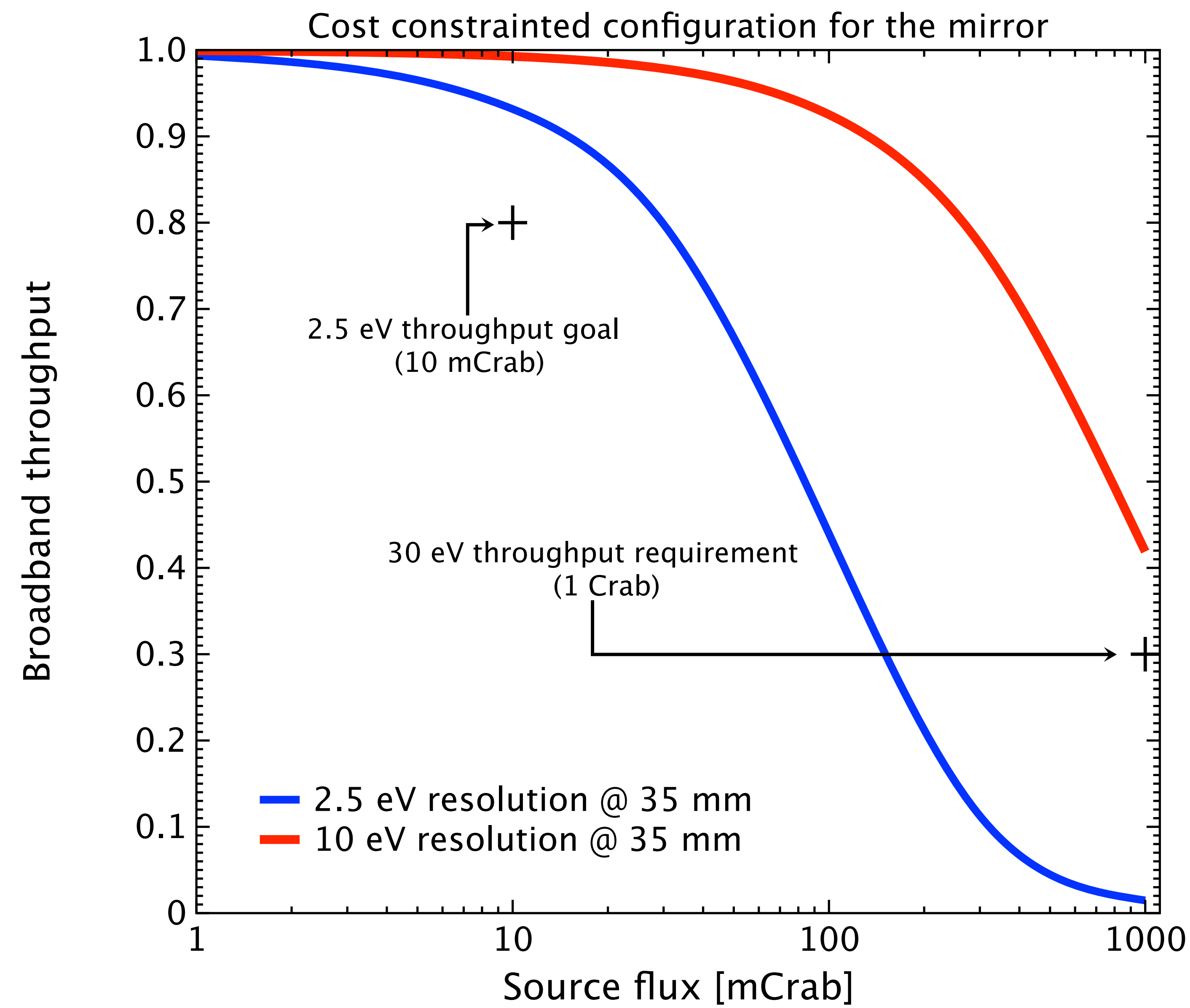
X-IFU count rate performance

- Time resolution is ~10 µs (pile-up free)
- The grade of an event depends on the separation between the preceding and subsequent pulses
  - ✓ Highest grade (the largest time separations) corresponds to a 2.5 eV resolution
  - ✓ Lowest grade would correspond to ~10 eV resolution
    - ➡ Throughput at a given spectral resolution depends on source count rate (more precisely the distribution of counts over the pixels)
- Defocussing of the optics spreads the mirror PSF over a larger number of pixels, hence enable the X-IFU to cope with brighter sources and still deliver high resolution events



Count rate capability



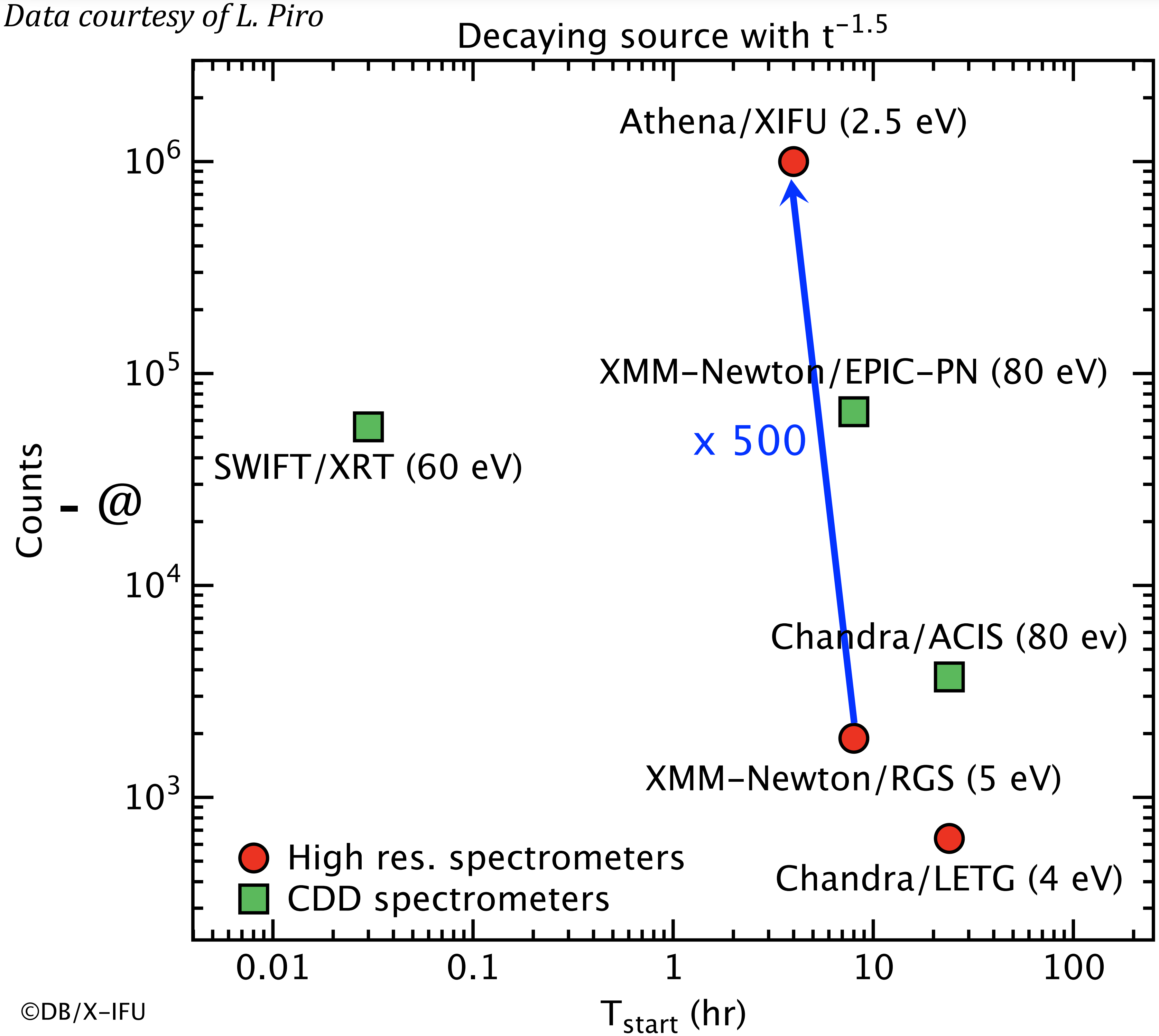


Courtesy of the e2e simulator team led by J. Wilms (Ph. Peille & T. Dauser)

1 Crab~65000 cps

Response to transients

Data courtesy of L. Piro



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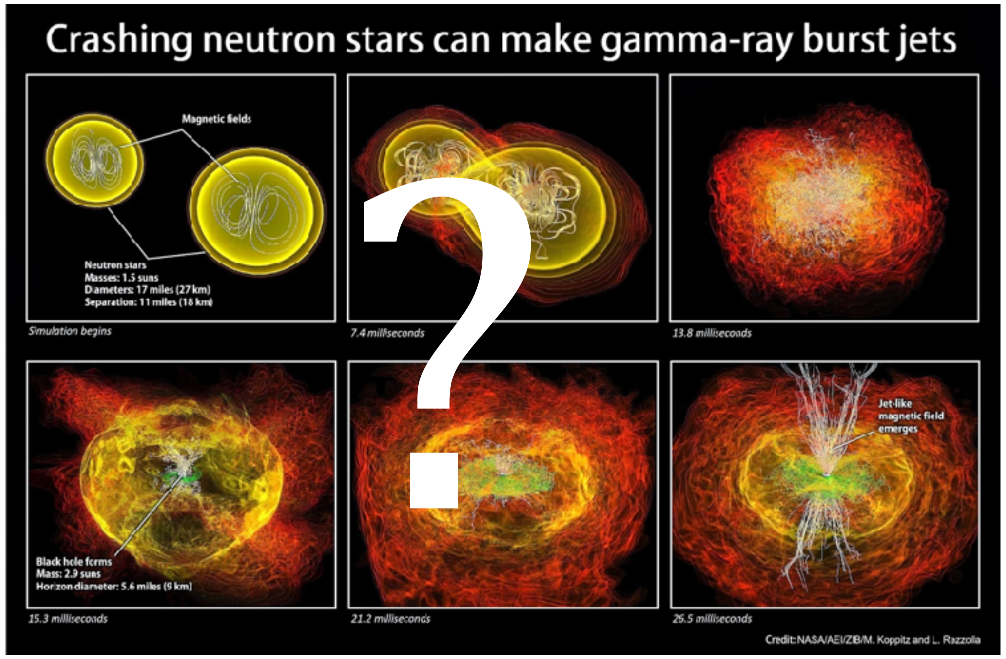

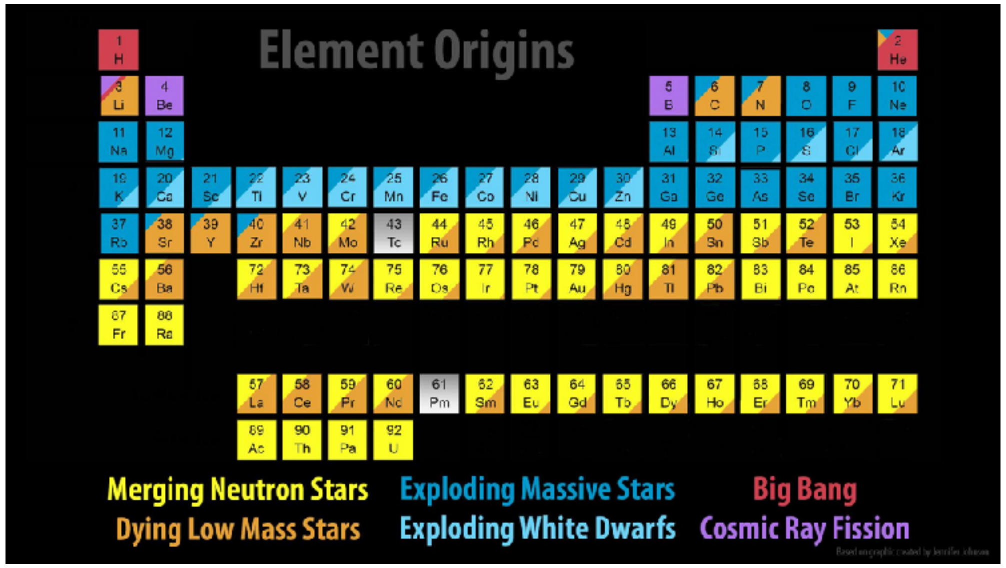

On-going activities

- Consolidate the baseline design of the instrument (thermal budgets, mass and power budgets…)
- Consolidate the performance requirements flowing down from the new science requirements
- Work on reducing the costs to ESA of the Athena mission (coolers, ground segment, science instrument module)
- CNES programmatic review very successful
- Vigorous technology developments in all corners of the instrument: TES array, readout electronics, cooling chain components, filters… to meet the required technology readiness levels of all critical components
- Instrument Preliminary Requirement Review towards the end of 2018 with the PDR (Q4/21), CDR (Q4/24), FM delivery (Q3/28)

Conclusions

- The X-IFU as a true X-ray Integral Field Unit will revolutionize astrophysics well beyond the sole X-ray window
  - ✓ XARM/Resolve following upon Hitomi/SXS will pave the way and may define completely new science objectives for X-IFU
- The X-IFU performance requirements are very ambitious, at the very edge of what can be achieved with state of the art technology
  - ✓ This should not be otherwise for a flagship mission such as Athena
- The X-IFU as a space experiment represents clearly a major challenge, but the X-IFU consortium carries all the expertise to face it, bringing together all major institutions involved in large previous space missions
  - ✓ Spain is a major contributor to the X-IFU and your support and contribution are as critically needed as appreciated

Thanks to you and to them !