# The prospects of observing stellar mass black holes with the Athena X-ray Integral Field Unit (X-IFU)

Didier Barret (IRAP, Toulouse, FR)
*X-IFU Principal Investigator*
@DidierBarret

with inputs from Elias Kammoun (IRAP) and Philippe Peille (CNES)

On behalf of the X-IFU Consortium

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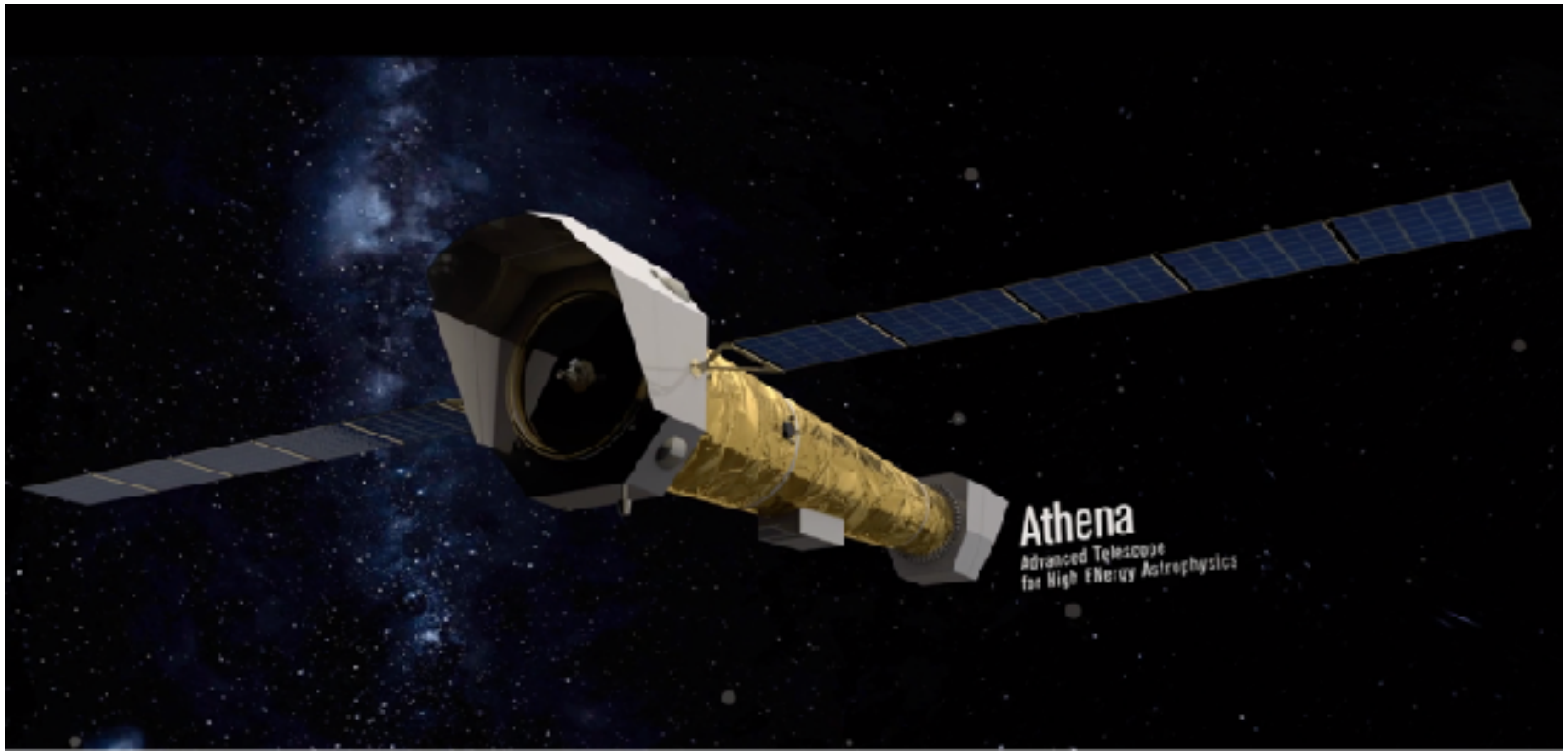
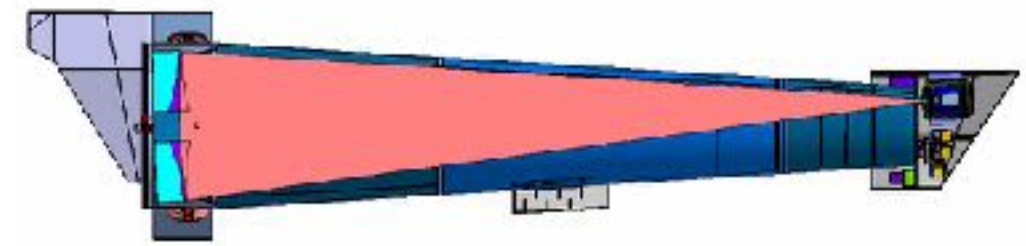
# Athena in a nutshell

- Athena: Advanced Telescope for High ENergy Astrophysics
  - To succeed to XMM-Newton and Chandra, and to follow XRISM, as a pathfinder to Athena
- Second Large mission of the European Space Agency Cosmic Vision Science program (possibly operating simultaneously with the third large mission : LISA)
  - With NASA and JAXA contributions to the mission and the payload
- Dedicated to The Hot and Energetic Universe
  - With broad impacts in many corners of astrophysics: stars, galaxies, planets… which define the Observatory science of Athena

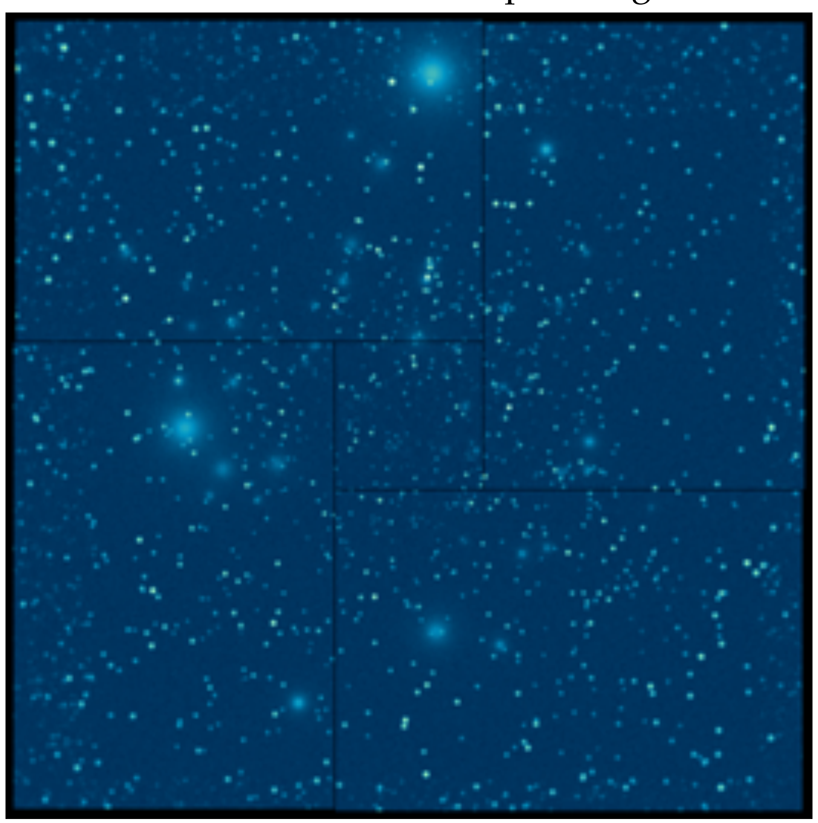


# Athena in a nutshell

- A large aperture **movable** X-ray telescope (ESA)
- Two focal plane instruments
  - A **Wide Field Imager** (WFI, PI: K. Nandra, MPE, DE)
  - An **X-ray Integral Field Unit** (X-IFU)
- Making up a very powerful observatory available to the world wide community through a Guest Observer program

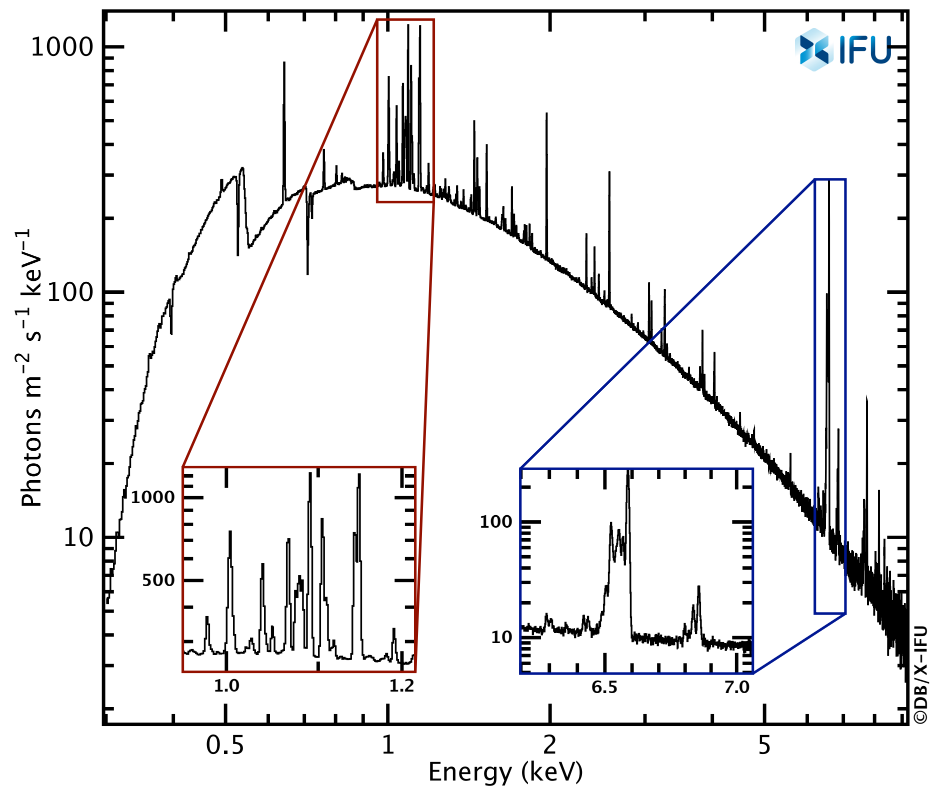


WFI simulated image
**Hundreds** of sources per image



Credits: WFI team

X-IFU simulated spectrum of a Perseus like galaxy cluster.
**Hundreds** of lines per spectrum

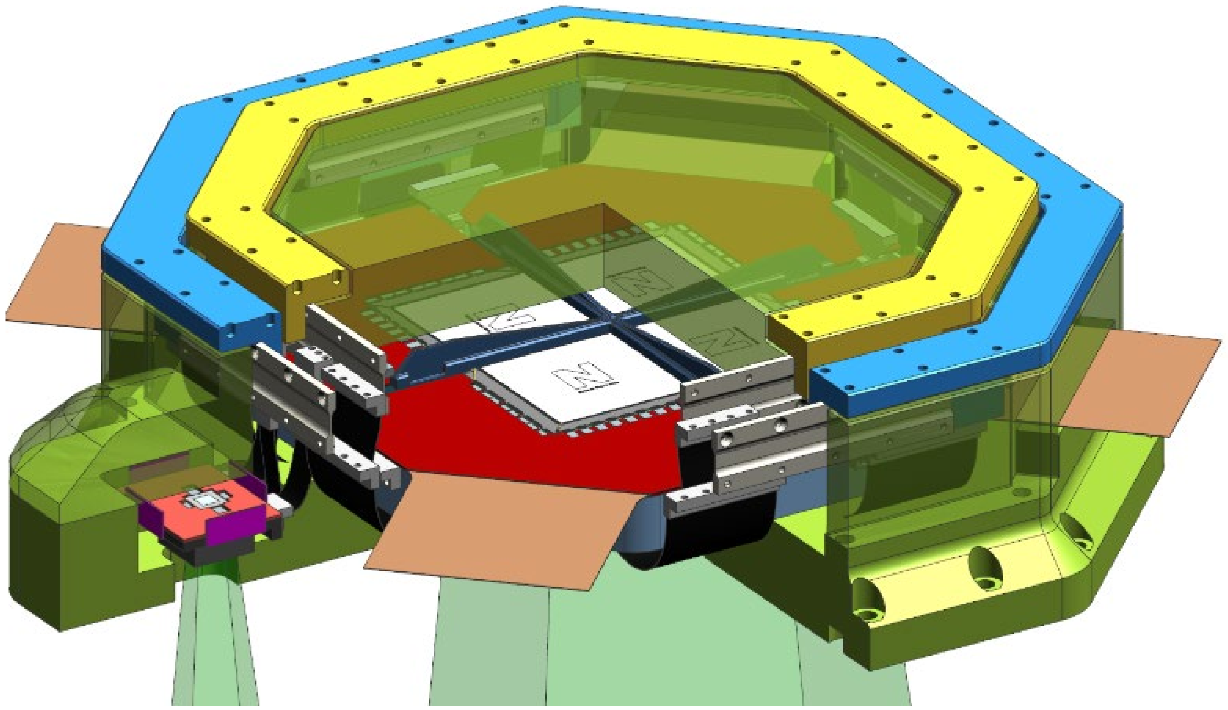



Credits: X-IFU team (data courtesy of C. Pinto and A.C. Fabian)

# Science payload

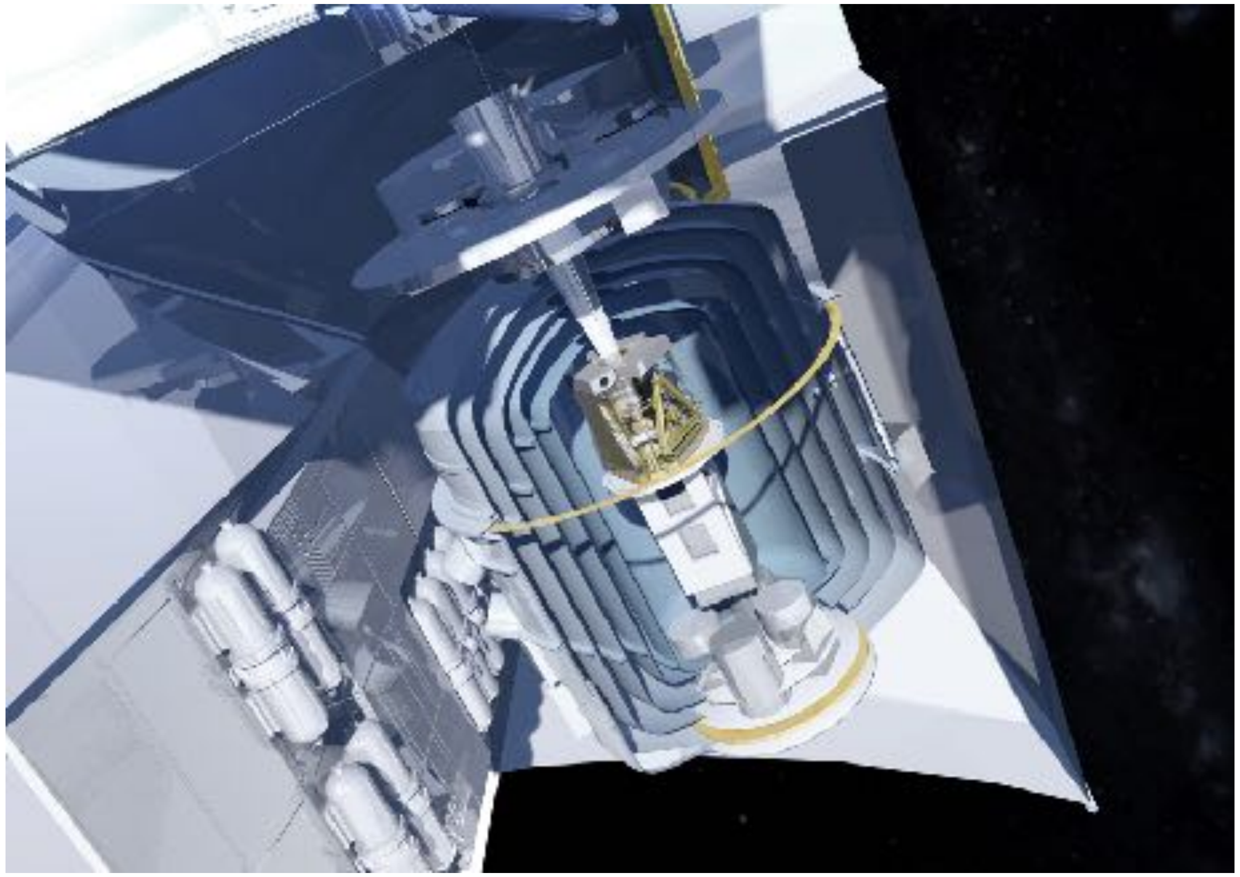
| Wide Field Imager (WFI) | X-ray Integral Field Unit (X-IFU) |
|---|---|
| Silicon Active Pixel Detector based on DEPFET technology | Large format micro-calorimeter array (Transition Edge Sensors) |
| Field of view: 40´×40´ square | 5′ hexagonal field of view (equivalent diameter) |
| Spectral resolution < 80 (<170) eV @ 1 (7) keV | 2.5 eV spectral resolution up to 7 keV |
| Separate chip for fast readout of very bright sources (10 Crab,170 eV ) | Out of focus observations of bright sources (1 Crab, 10 eV) |

The mechanical layout of the WFI instrument



Credits: MPE and WFI team

The X-IFU cryostat and focal Plane Assembly



Credits: X-IFU team

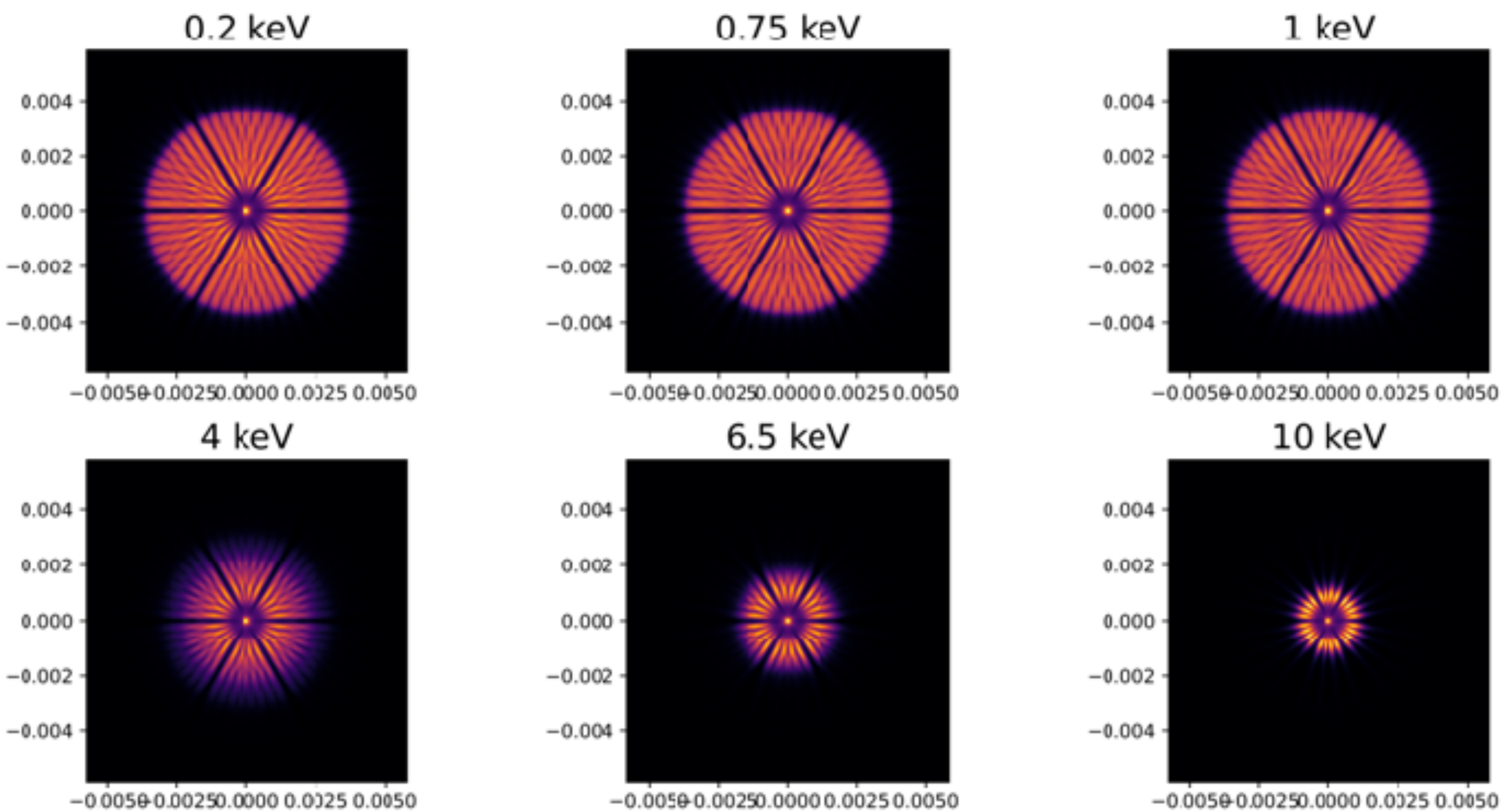
# Things that you may not know

- X-IFU has a time resolution of 10 $\mu$s
- X-IFU will observe bright X-ray binaries out of focus to spread the PSF of the mirror on hundreds of pixels (so that each pixel receives a small fraction of the counts, hence with negligible pile-up, Peille+2018)
- X-IFU has two soft X-ray blocking filters (on the filter wheel) to reduce the source count rate
- X-IFU has the capability to observe sources up to the intensity of ~1 Crab, yet providing better than 10 eV spectral resolution (10 times better than any CCD)
  - Extending the capability of XRISM which may be limited to a few 100 mCrab
  - To be extended by the separate WFI Fast Detector (to reach 10 Crab with CCD resolution)
- X-IFU will have cold time to observe ToOs within a few hours
- X-IFU band pass extends from 0.2 to 12 keV

# X-IFU bright source observations

- Enabled by the mirror capability to change its focal length (35 mm out of 12 m)
  - distributing the point spread function over several hundreds of pixels so that each pixel receives a small fraction of the source flux
    - ➡ which is further reduced by the addition of filters to suppress the numerous low energy photons

Energy dependent out-of-focus point spread function of the Athena optics



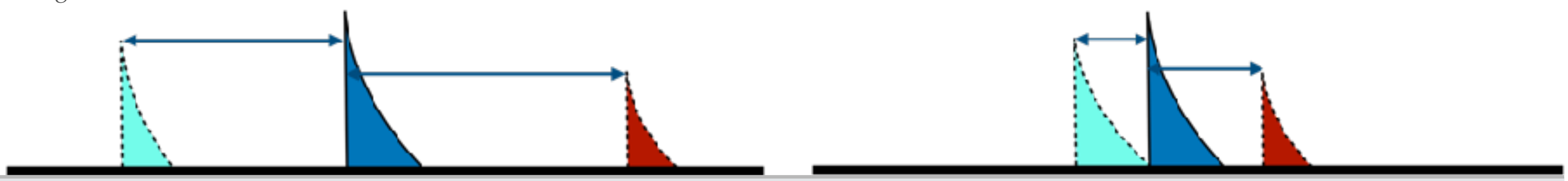

Credits: Dick Willingale/Elias Kammoun

# Count rate dependent energy resolution

- X-IFU will time tag each photon with a relative time resolution of 10 $\mu$s
- The accuracy with which the energy of the photon is reconstructed depends on its energy, as well as on the time separation with the preceding and succeeding photons
  - Several grades will be defined : high (2.5 eV), medium (3 eV), limited (<7 eV)
  - We define the throughput as the fraction of events reconstructed at a given grade as a function of the source intensity over an energy band pass
  - To limit the source flux on the detector and to preserve high energy photons (above 2-3 keV), bright sources will always be observed with one of the two Beryllium filter (20 $\mu$m or 100 $\mu$m)

Higher resolution events will have no close events before and after

Lower resolution events will have close events before and after



Timeline for a high resolution event

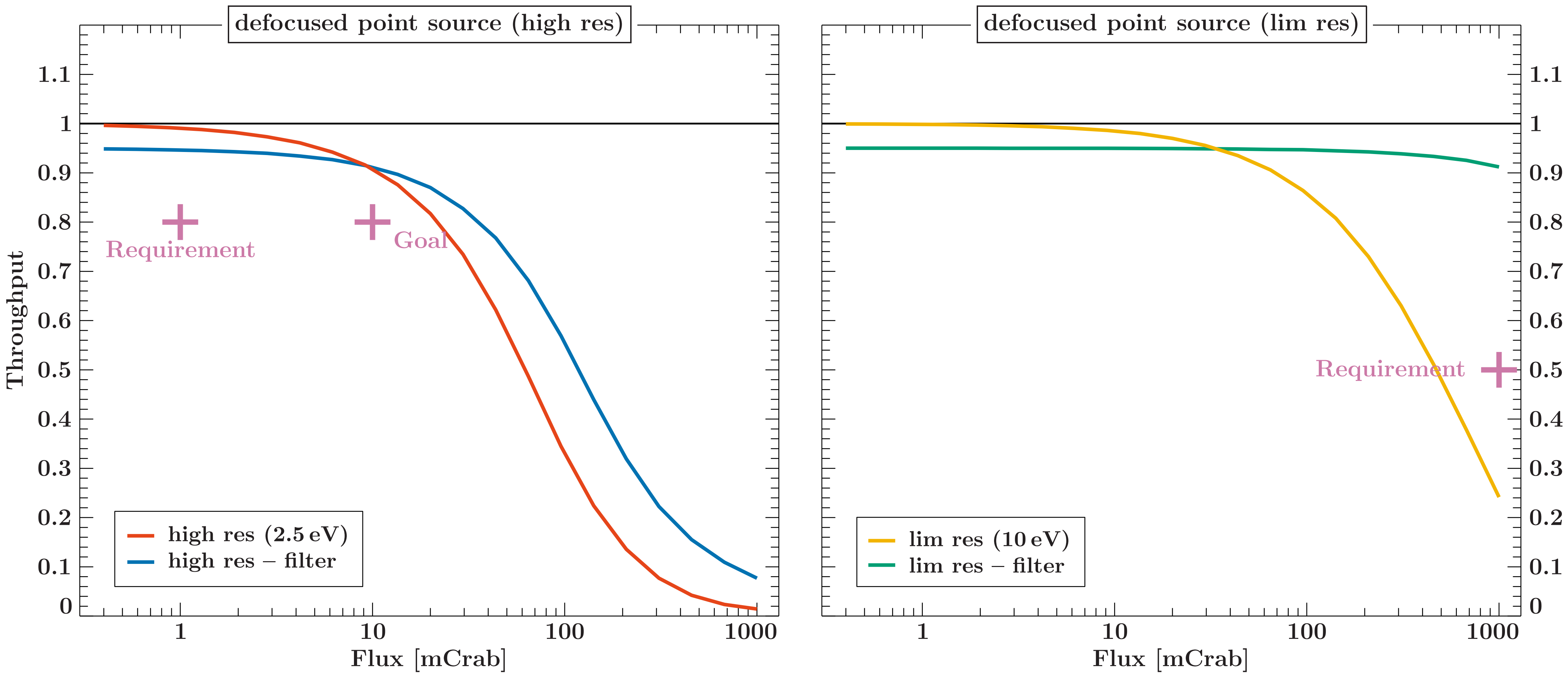
Timeline for a medium resolution event

| Grade | Time since previous pulse | Record length (time between the start of the record and the next | Resolution for primary events |
|---|---|---|---|
| Very high resolution | > 3676 samples (20 ms) | > 8192 samples (44.6 ms) | **2.5 eV** |
| High resolution | > 3676 samples (20 ms) | > 4096 samples (22.3 ms) | **>~ 2.5 eV** |
| Intermediate resolution | > 1838 samples (10 ms) | > 2048 samples (11.1 ms) | **2.6 eV** |
| Medium resolution | > 1838 samples (10 ms) | > 512 samples (2.8 ms) | **3 eV** |
| Limited resolution | > 1838 samples (10 ms) | > 256 samples (1.4 ms) | **7 eV** |

# X-IFU requirements & performance

| Key requirement | Science drivers |
|---|---|
| 2.5 eV throughput for point sources : 80% at 1 mCrab (Requirement)<br>2.5 eV throughput for point sources : 80% at 10 mCrab (Goal) | X-raying missing baryons with bright line of sights GRB afterglows and bright quasars |
| **10 eV throughput for bright point sources : 50% at 1 Crab (5-8 keV)** | Probing stellar mass black hole and neutron star accretion disks & winds/outflows |

X-IFU performance assessment with the current baseline — X-IFU exceeds with margins its key requirements

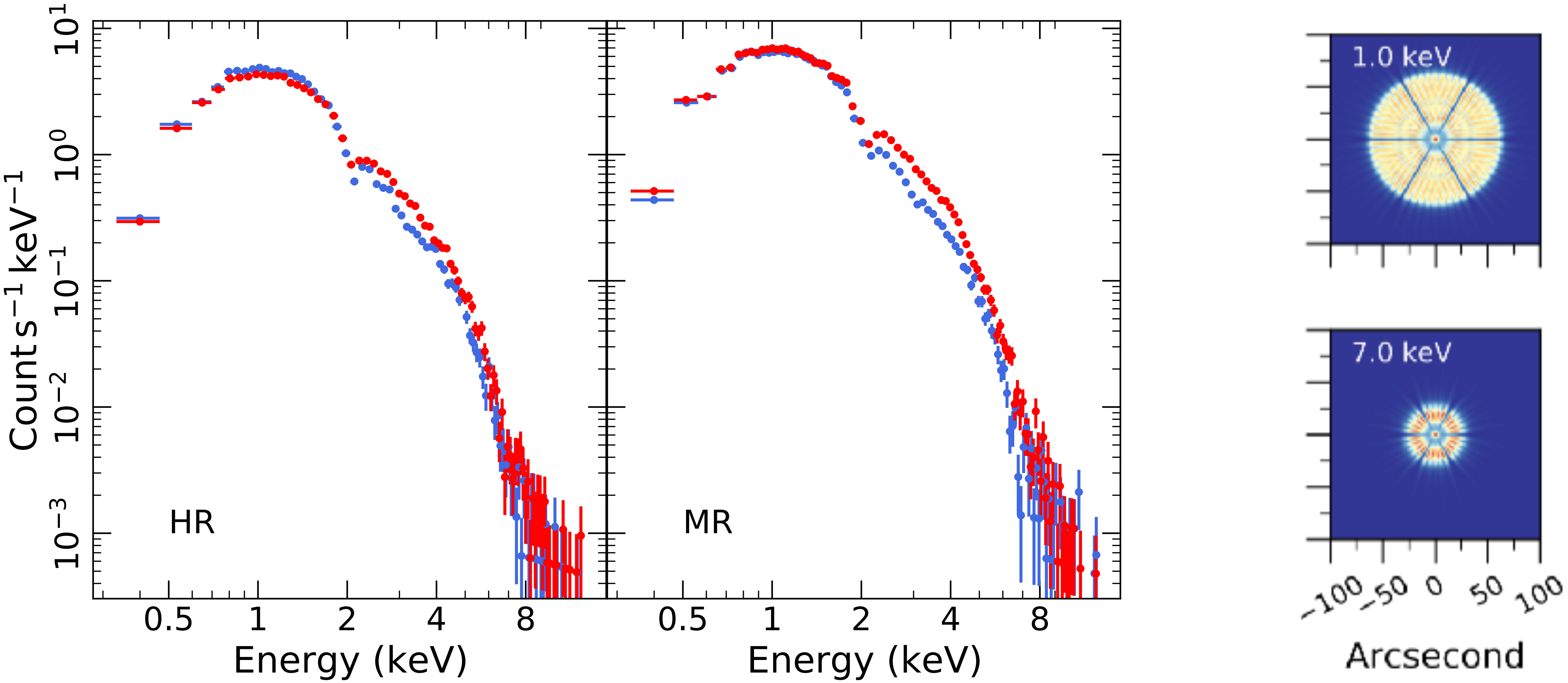



Credits : Philippe Peille and the X-IFU performance team

# A proper deconvolution method

- The grading scheme at each pixel depends on the count rate the pixel is exposed to
- It depends on the actual shape of the PSF and on the spectrum of the source
  - Per grade, each pixel has its own arf (auxiliary response file) response

The spectra extracted (in units of count/s) from two adjacent pixels (shown in red and blue) for the High Resolution (HR) and Medium Resolution(MR) event grades (left and right, respectively). The spectra are rebinned for clarity

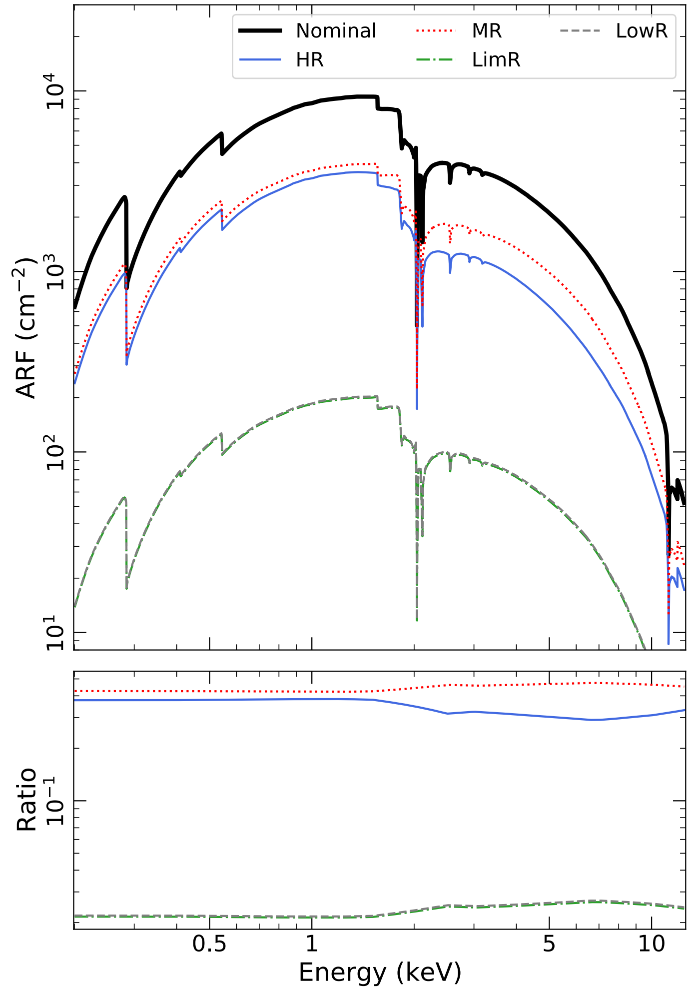



Elias Kammoun+ (in preparation)

# PSF-grade weighted arf

- Integrate the energy dependent PSF in the pixel to compute a arf at pixel level
- Compute the different grade fraction given the total count rate received by the pixel
- Sum up the PSF-grade weighted arf over all the pixel to obtain one global arf per grade

Upper panel: The reconstructed ARFs for the various event grades. The thick solid line shows the nominal ARF for comparison. Lower panel: The ratio of the ARF at each grade divided by the nominal ARF.

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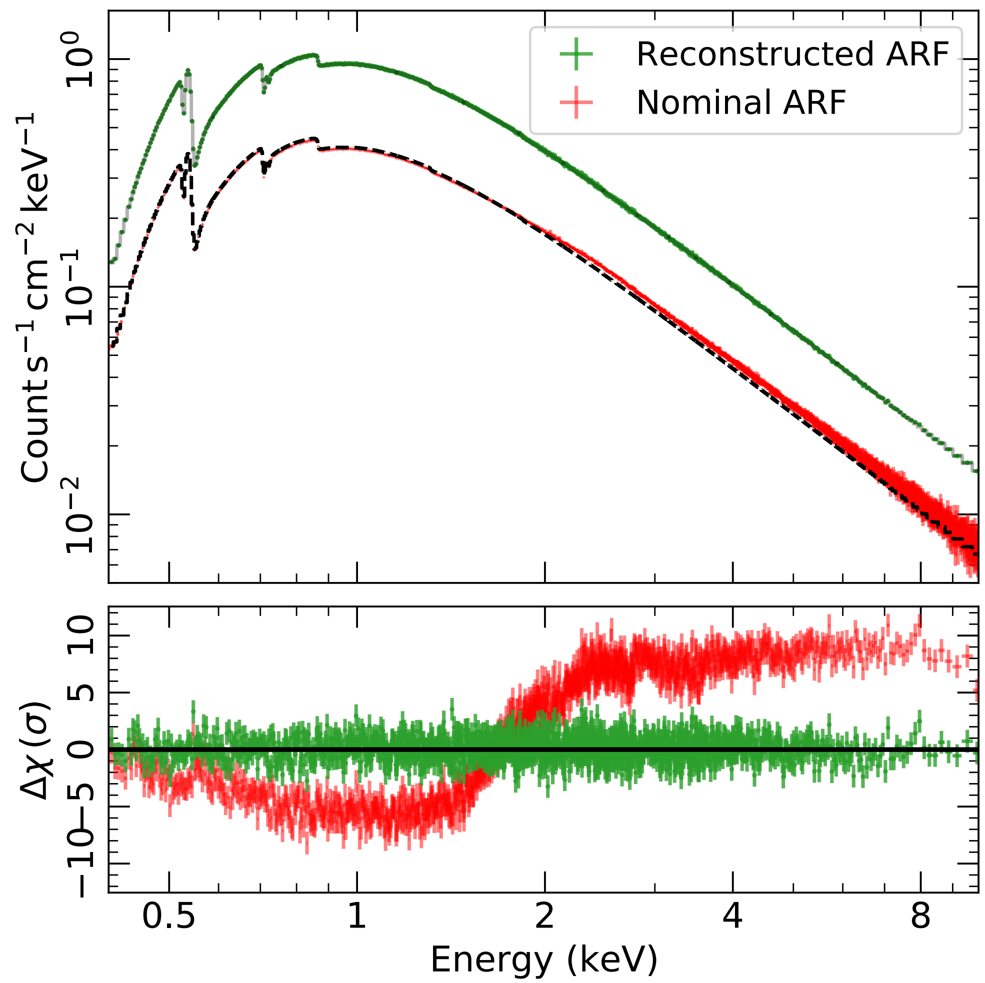
Simulated MR spectrum assuming a flux level of 200 mCrab, using the nominal ARF (i.e., without applying any reconstruction) in red red and the reconstructed ARF in green.

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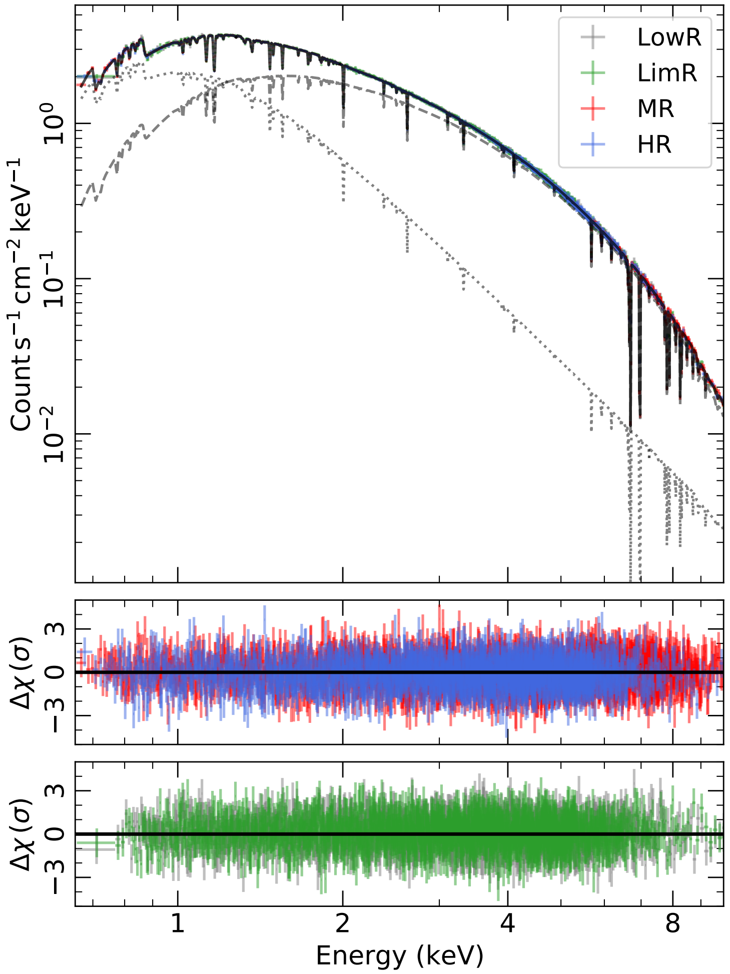
# A more complex spectrum

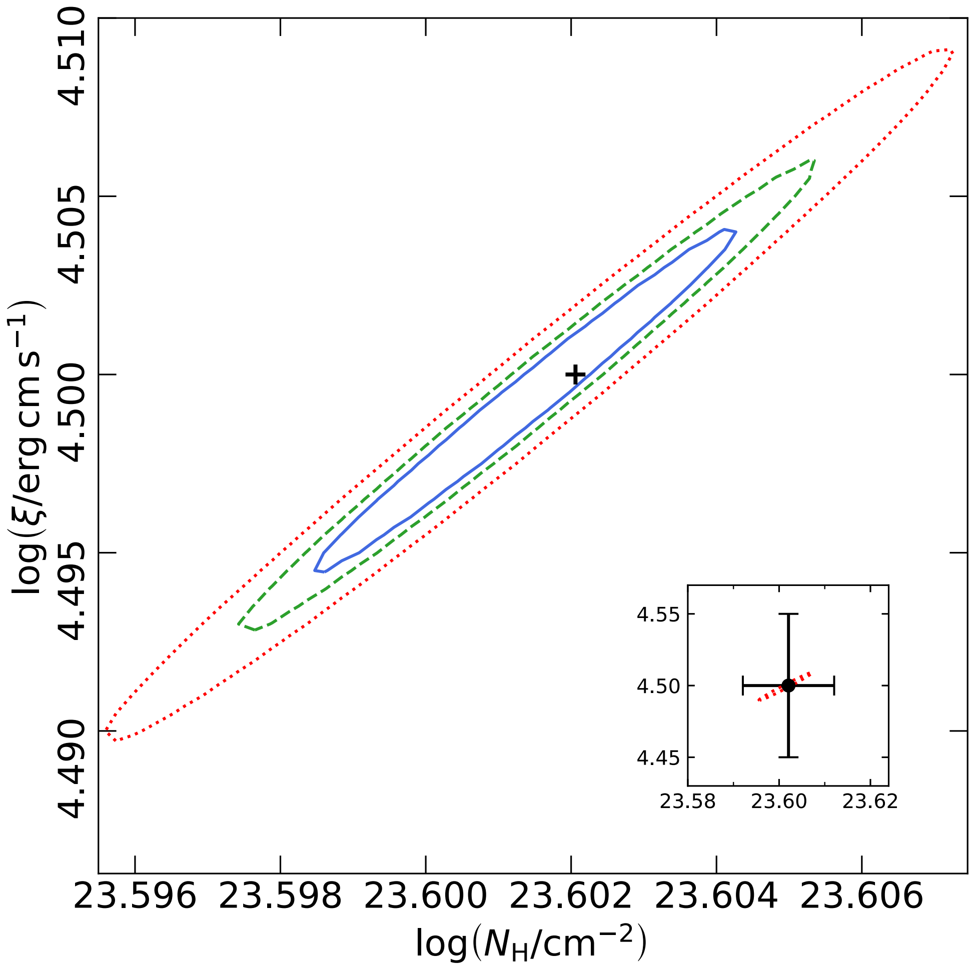
- GROJ1655-40: A stellar mass black hole showing strong absorption in a highly ionised dense wind (Miller+ 2008)

The reconstructed simulated spectra of GRO J1655-40 for t exp = 10 ks at a flux level of 1 Crab. The dotted and dashed lines represent the blackbody and the power-law components, respectively. The spectra are rebinned for clarity reasons.




Adapted from Miller+2008 by Elias Kammoun+ (in preparation)

Confidence contours of Nh vers the ionisation parameters

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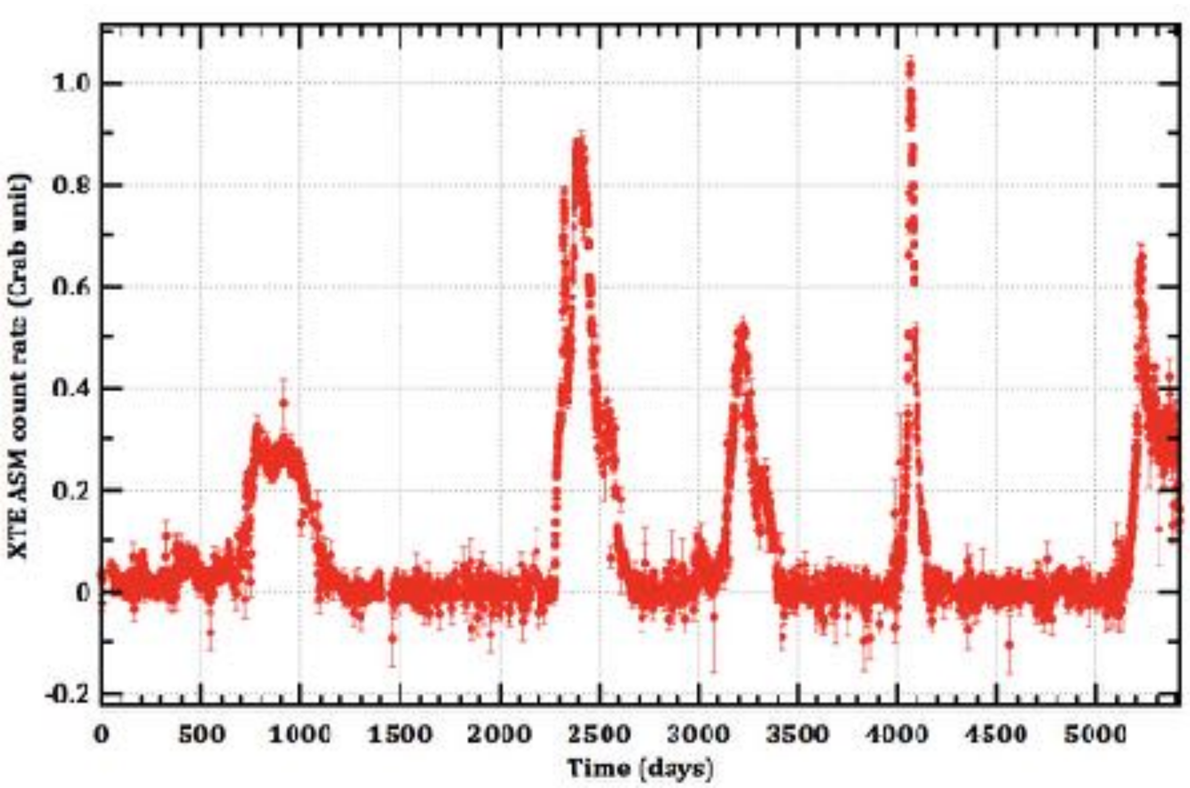
# Probing black hole spins and winds

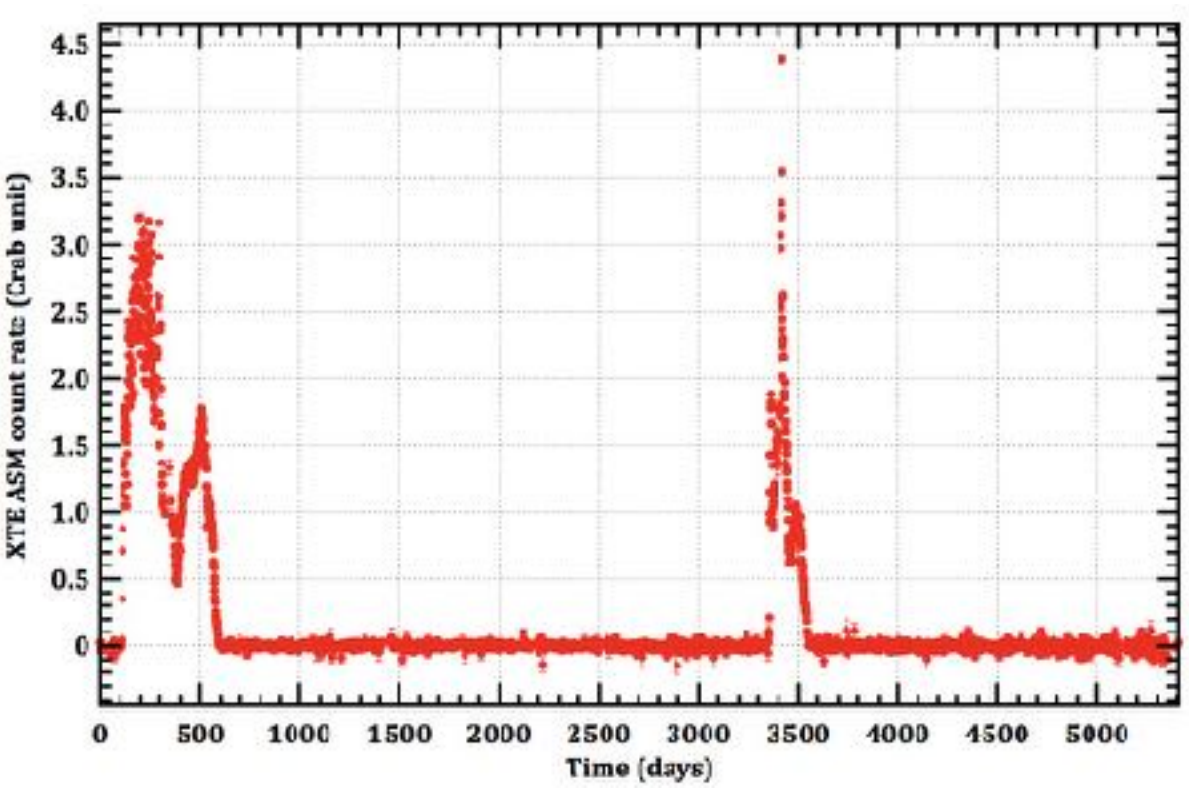
- Key Athena requirement: **SCIOBJ-251 GBH and NS spins and winds:** Athena shall observe 10 stellar-mass black holes and 10 neutron star X-ray binaries in order to measure black hole spins, constrain neutron star radii, detect winds and outflows, and study the accretion disk and coronal physics
  - Would benefit from an all sky monitor to pick up the source at the right luminosity/spectral state

15 years of RXTE ASM light curve of GX339-4




ASM light curve data downloaded from HEASARC

15 years of RXTE ASM light curve of GROJ1655-40

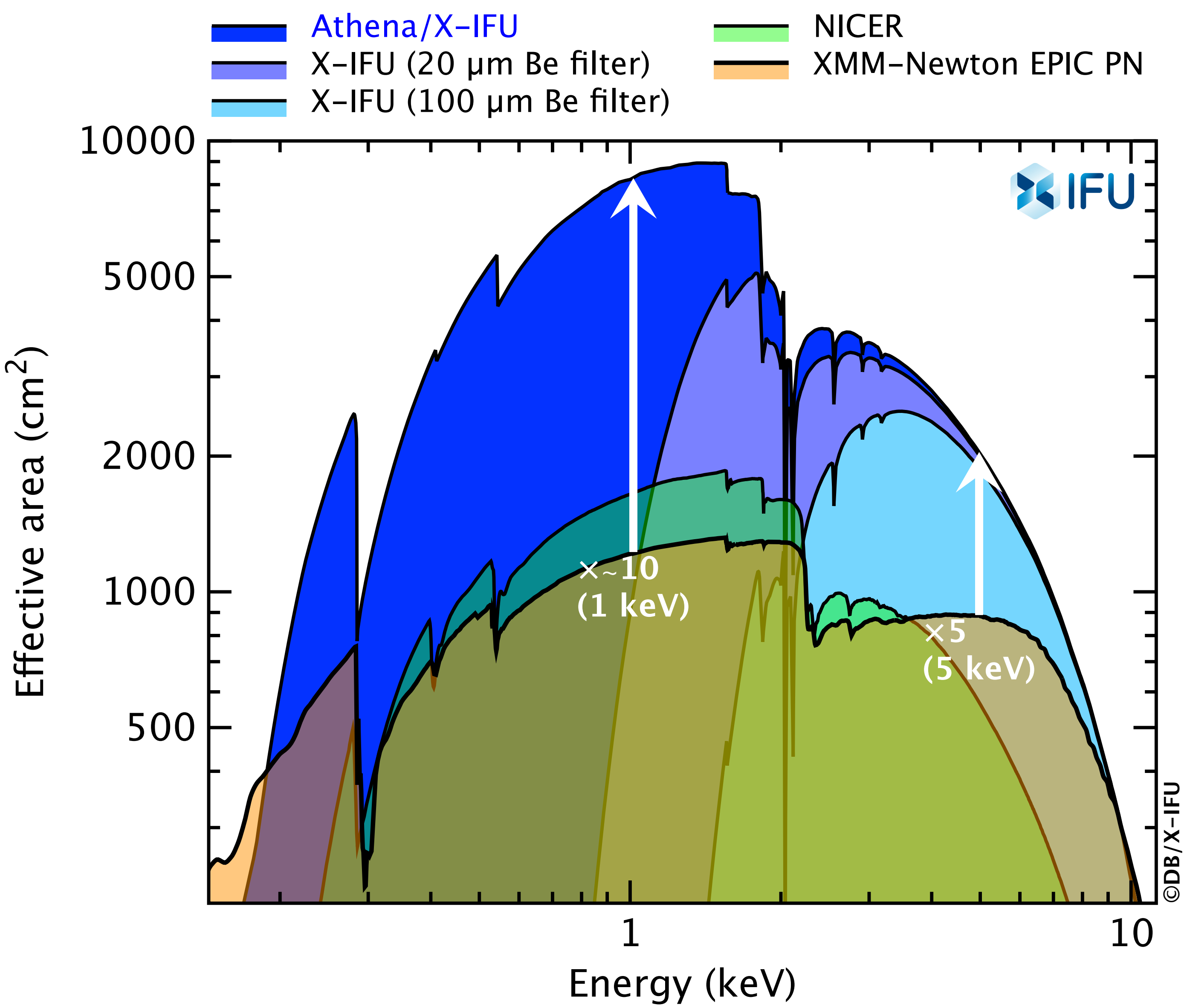



ASM light curve data downloaded from HEASARC

# Effective area comparison

- For black hole spins (smooth relativistically smeared features), broad band effective area is what matters !
  - X-IFU will have > 5 times higher effective area than XMM-Newton (PN) at 5 keV

Effective area of X-IFU versus non high-res spectrometers. Two Be filter thicknesses are shown for X-IFU

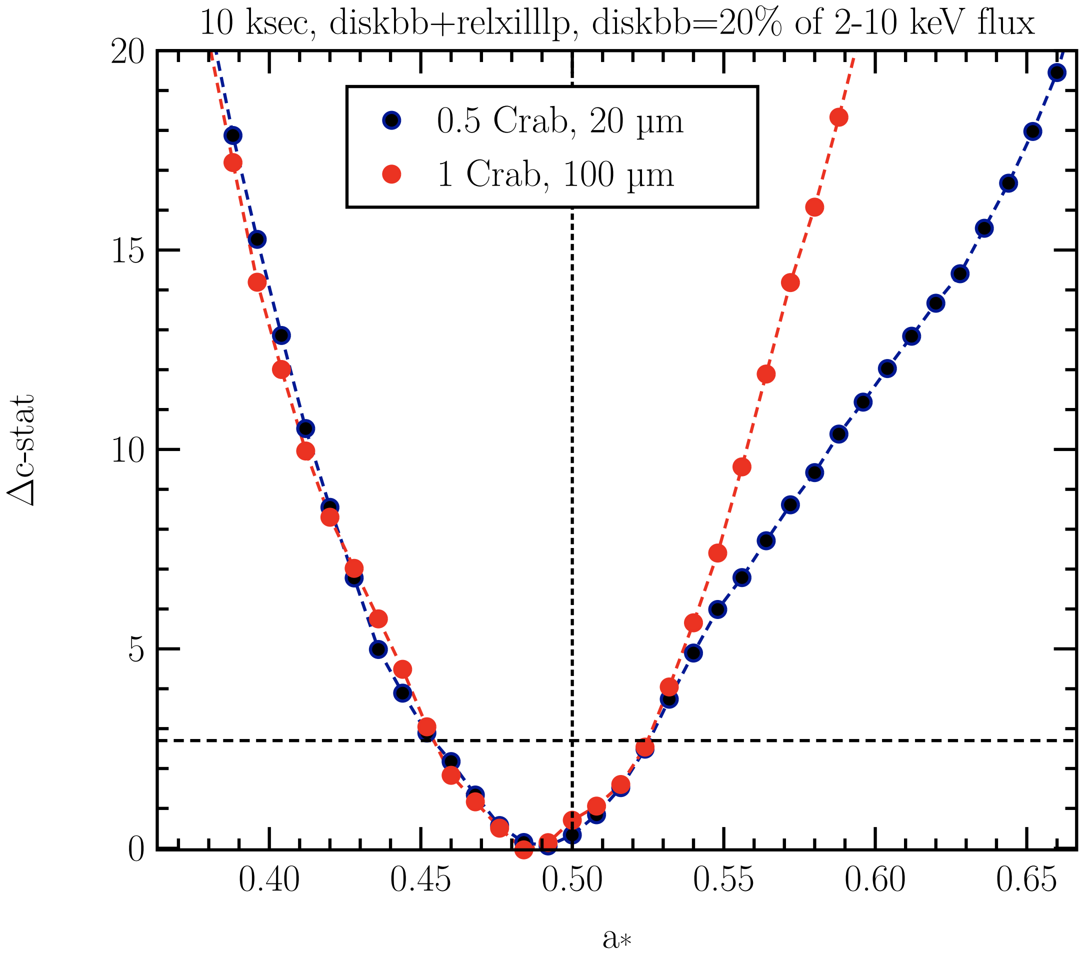



Credits : X-IFU team

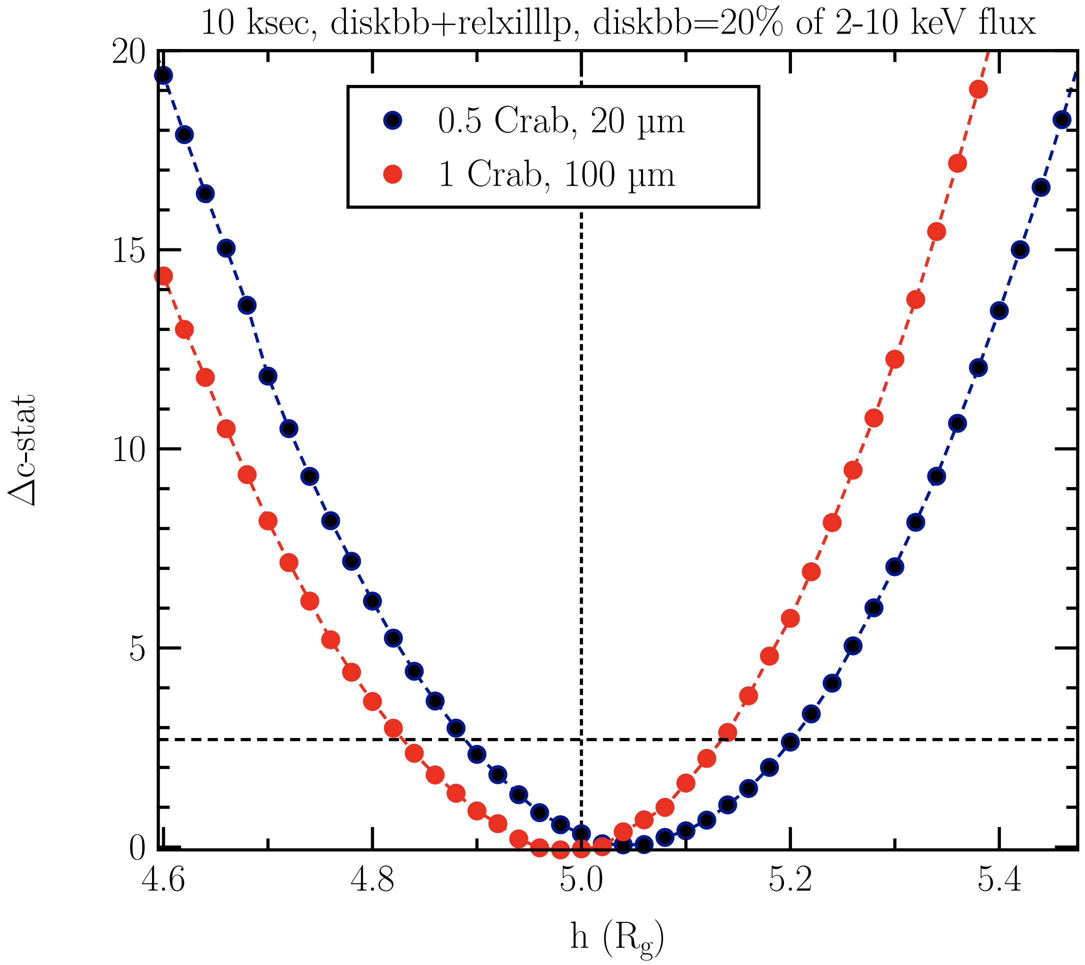
# Probing black hole spins

- Ideal test case with a simple two component model : disk + relxilllp (lamppost geometry, Garcia+)
  - diskbb contributes to ~20% of the 2-10 keV flux — dilutes the reflected spectrum
  - Iron abundance fixed to 1, logxi=1.5, gamma=2.0
  - a = 0.5, h=5 Rg with reflection computed from the geometry by the model
- Comparison between 2 source fluxes with two filters (1 Crab, 100 $\mu$m versus 500 mCrab, 20 $\mu$m)
  - Comparable errors on spins and source heights — to be confirmed with more realistic simulations

Error on spin



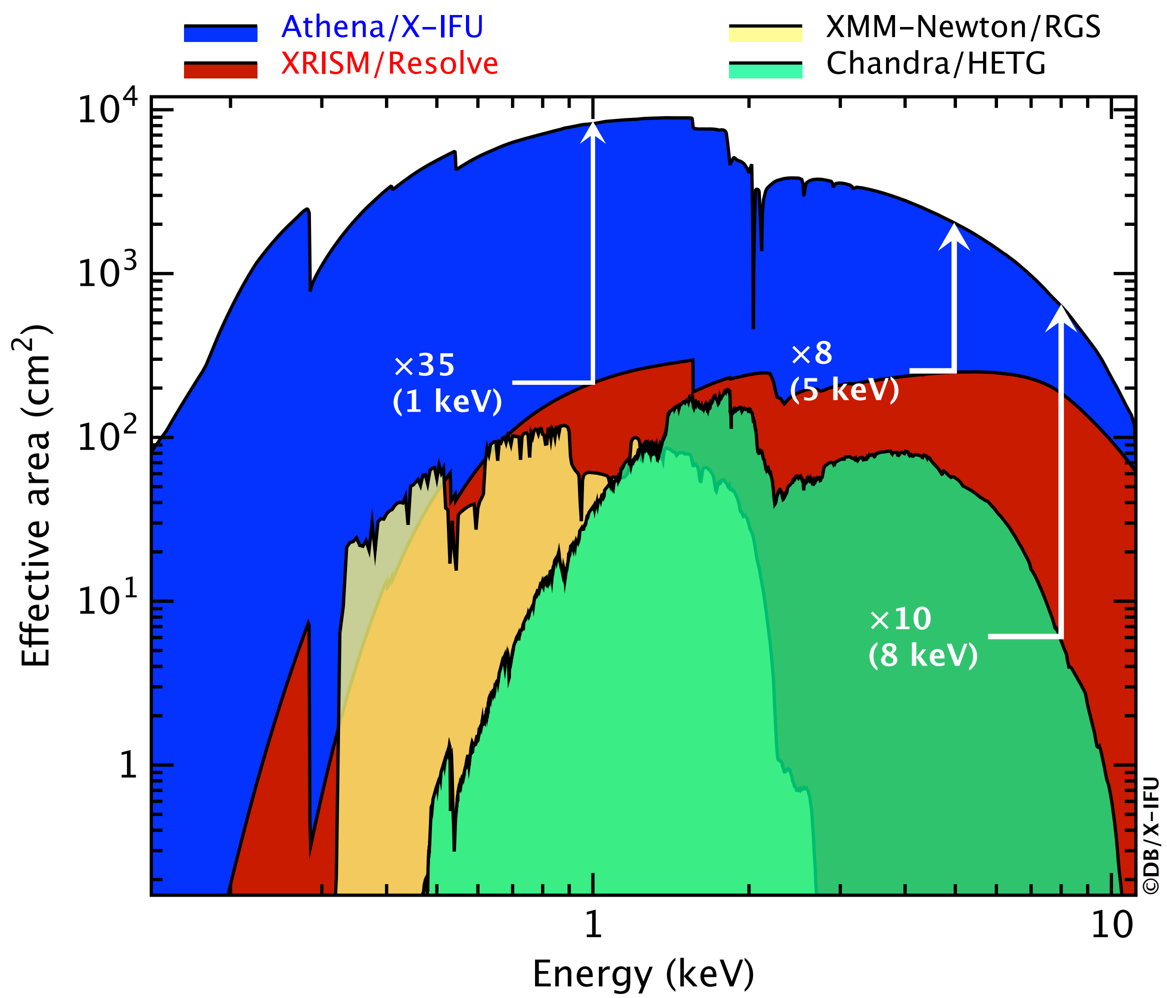

Error on source height (h)



# Probing black hole winds

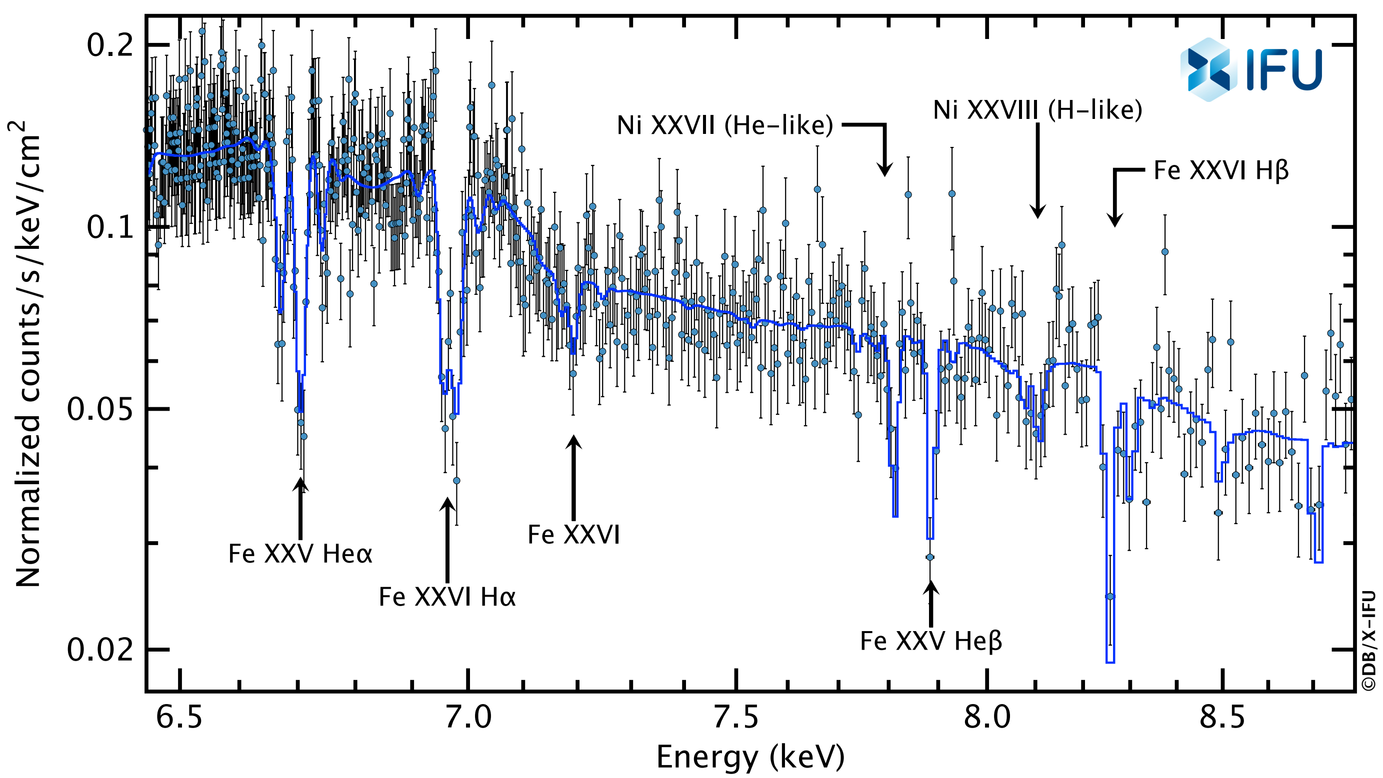
- For probing winds/outflows, what really matters is effective area and spectral resolution
  - X-IFU will have 8 times the effective area of XRISM at 5 keV and about 10 times more effective area than the Chandra HETG

Effective area comparison with high resolution spectrometers




Credits: X-IFU team

X-IFU simulated observation lasting only ~120 seconds of the Black Hole binary GRS1915+105. A disk wind, as reported in Miller et al. (2016) has been simulated. This rich set of features will enable unprecedented studies of the structure of the disk winds on dynamical timescales.




Data from J. Miller adapted from Miller et al. (2016)

# Conclusions

- X-IFU will be the first high resolution X-ray spectrometer capable of observing bright X-ray sources, up to 1 Crab intensity, with micro-second time resolution and better than 10 eV spectral resolution
  - Even brighter sources (up to 10 Crab) will be observable with the fast detector of the Wide Field Imager with better than CCD type spectral resolution (<170 eV @ 7 keV)
- This makes Athena a suitable mission for observing bright X-ray binaries, and particularly stellar mass black holes to probe their spins and outflows
  - A method has been designed to analyse bright source out-of-focus observation (Kammoun+ in prep)
- The addition of multi-layer coatings on the mirror could potentially increase the 6-7 keV effective area by up to 40%, without reducing the 1 keV area
  - This would enhance the capability of X-IFU to observe hard sources
- Athena is entering all the reviews that are necessary for its adoption in the ESA science program
  - The recently announced delay of the adoption is unrelated to the mission itself but more due to the "global" programmatic situation at ESA following the Ukraine conflict and the upcoming ministerial meeting
  - The X-IFU team is adapting the schedule of its activities (System Requirement Review and Technology Readiness Assessment) with the goal of being ready for adoption
    - ➡ So far the good news is that the X-IFU baseline presented at SRR still matches the top level performance requirements set in the original proposal, in terms of field of view, spectral resolution, count rate capability….