Chasing high-energy counterparts of Gravitational Wave events with *Athena*

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on behalf of the *Athena* Science Study Team

Outline

- *Athena* scientific goals and mission profile
- High-energy counterparts of (Neutron Star)^2 merger events with *Athena*
- High-energy counterparts of (Super-Massive Black Holes)^2 mergers with *Athena*
    - Synergies with LISA

Scientific goals of *Athena*

Science theme: **The Hot and Energetic Universe**

- The Hot Universe: How does baryonic matter assemble in the large-scale structures? How do they evolve from the formation epoch to the present day?

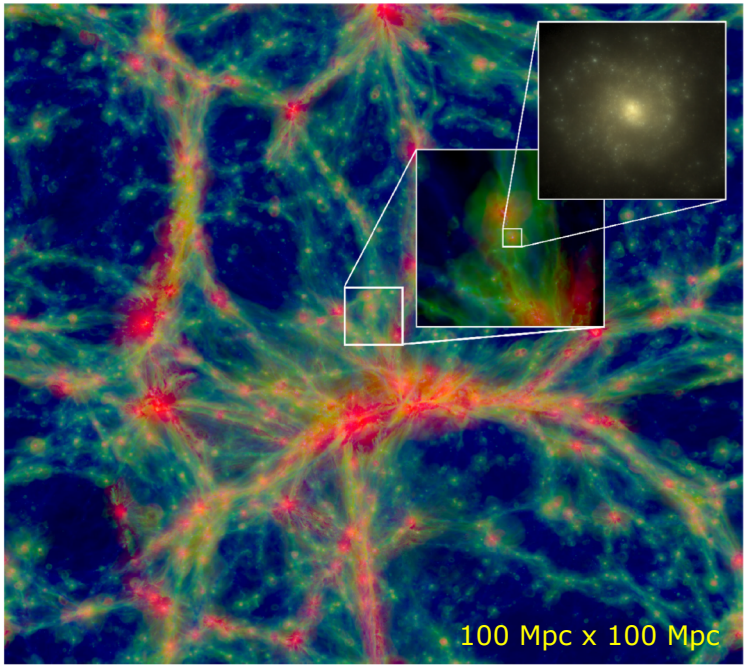
- The Energetic Universe: How do black holes grow and shape galaxies?

- The Observatory and Discovery science:
  - Observatory science across *all corners of astrophysics*
  - Fast response (≤4 hours) capability to study transient sources
  - ~2/3rd of the time during nominal operations open to the community

The "Hot Universe" with *Athena*

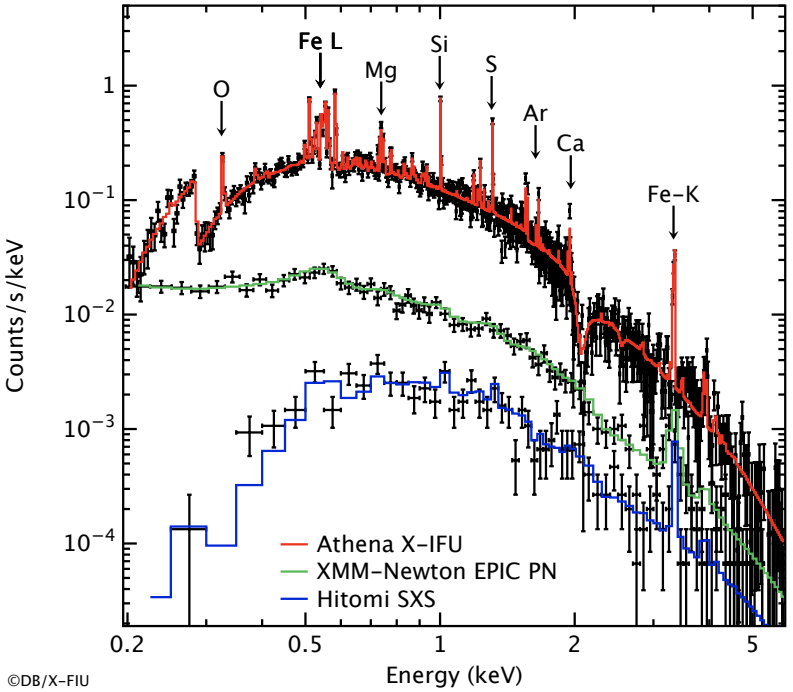
EAGLE cosmological simulation

$T<10^{4.5}$ K $10^{4.5}\leq T\leq 10^{5.5}$ K $T>10^{5.5}$ K



Schaye et al. 2015, MNRAS, 446, 521

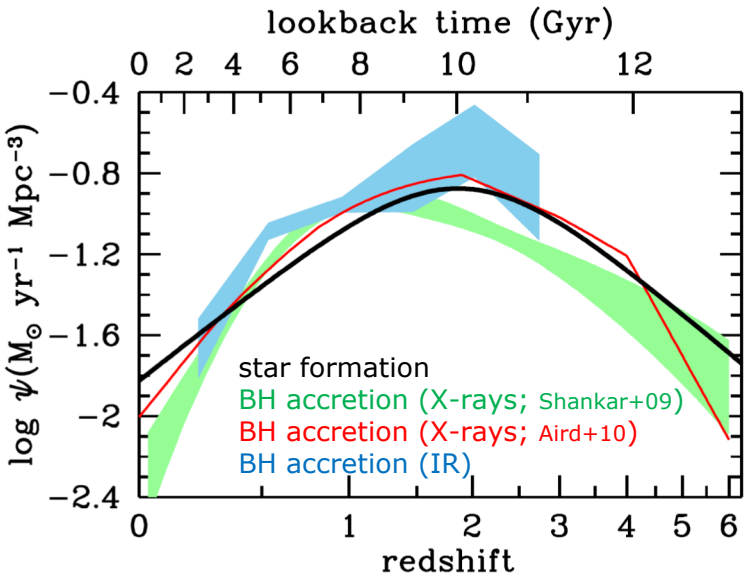
z=1 galaxy cluster (*Athena* vs. XMM/*Hitomi*)



Athena will trace the evolution of heavy elements from z~2 to the local Universe

Pointecoteau et al., 2013, arXiv:1306.2319

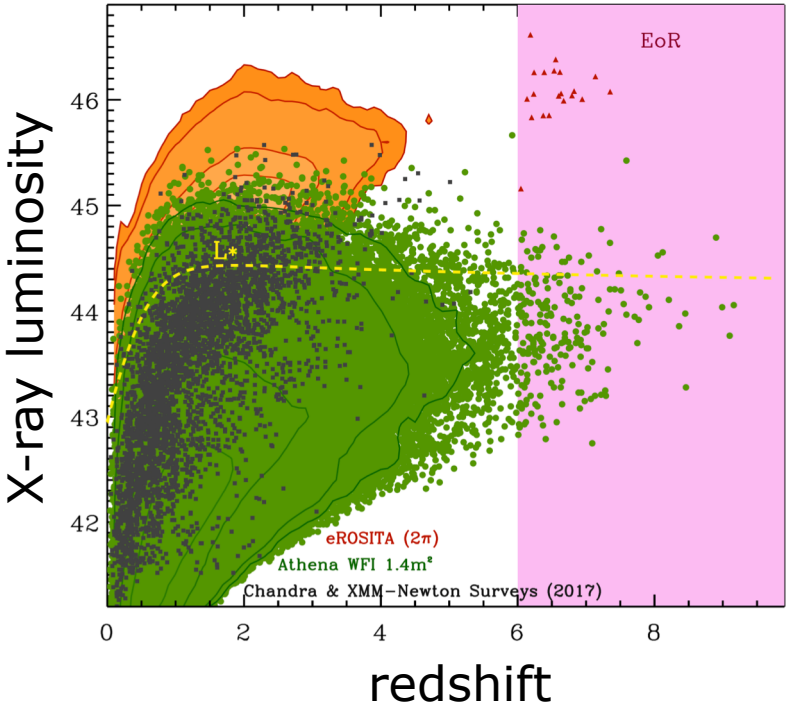
The "Energetic Universe" with *Athena*



The cosmological history of black hole accretion is **uncertain** at z>3, **unknown** at z>6

Madau & Dickinson, ARA&A, 52, 415

AGN L_X versus z plane



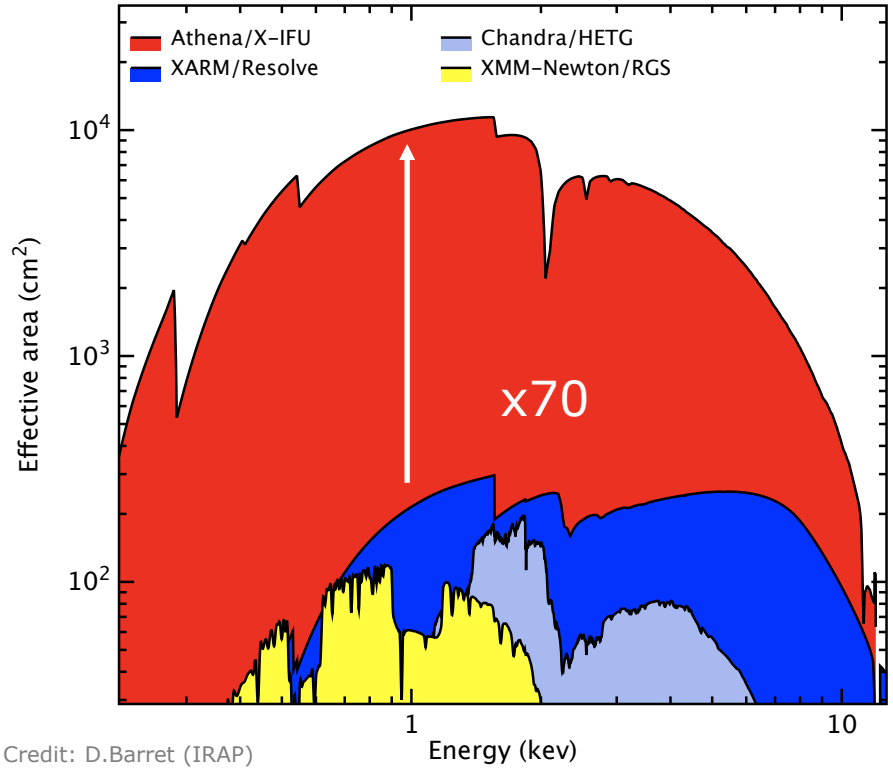
Aird et al., 2013, arXiv:1306.2325. Courtesy A.Rau (MPE)

Mission profile

- **Single telescope**, Silicon Pore Optics (SPO) technology, 12 m focal length (f.l.), ≥1.4 m^2 area @1 keV, 0.25 m^2 @6 keV
- **WFI** (Active Pixel Sensor Si detector): wide-field (40'x40') spectral-imaging, CCD-like energy resolution (120-150 eV @6 keV)
- **X-IFU** (cryogenic imaging spectrometer): 2.5 eV energy resolution (R>2000 @5 keV), 5' diameter effective field-of-view, ≤5" pixel size
- Count rates capabilities: >1 Crab (WFI)/~1 Crab (X-IFU; 50% throughput)
- **≤4 hours response with a ~50% efficiency** to observe a Target of Opportunity (ToO) in a random position in the sky (FoR: 50%, 60% goal)
    - Under study an Autonomous ToO capability
- Launch early 2030s, Ariane 6.4, L2 halo orbit (TBC)

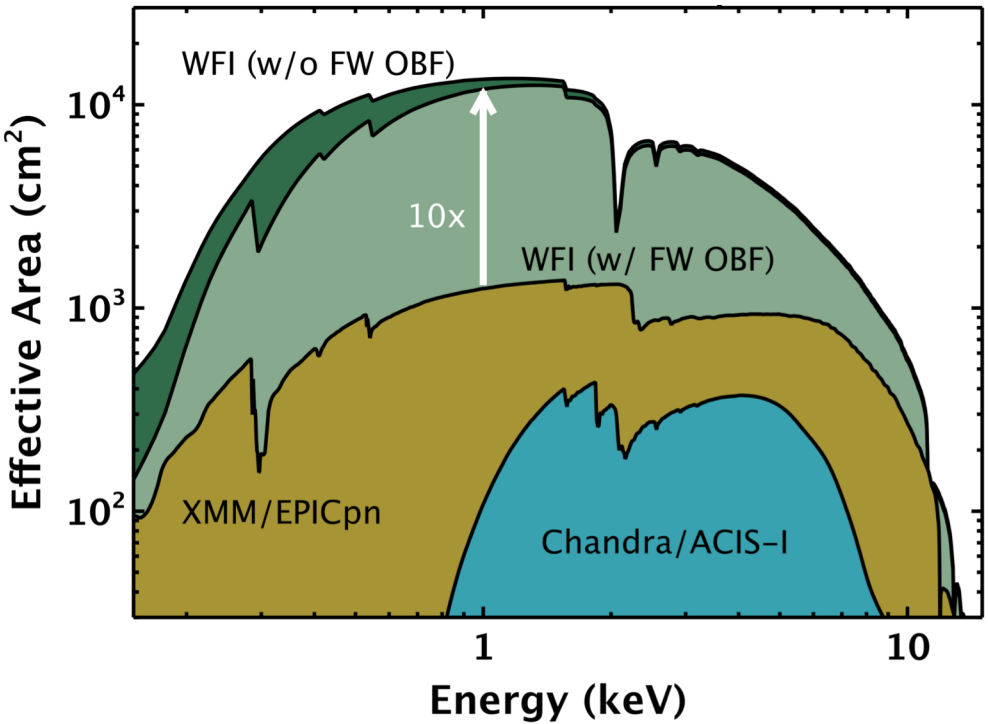
Athena: a large effective area mission

X-IFU+mirror collecting area



Credit: D.Barret (IRAP)

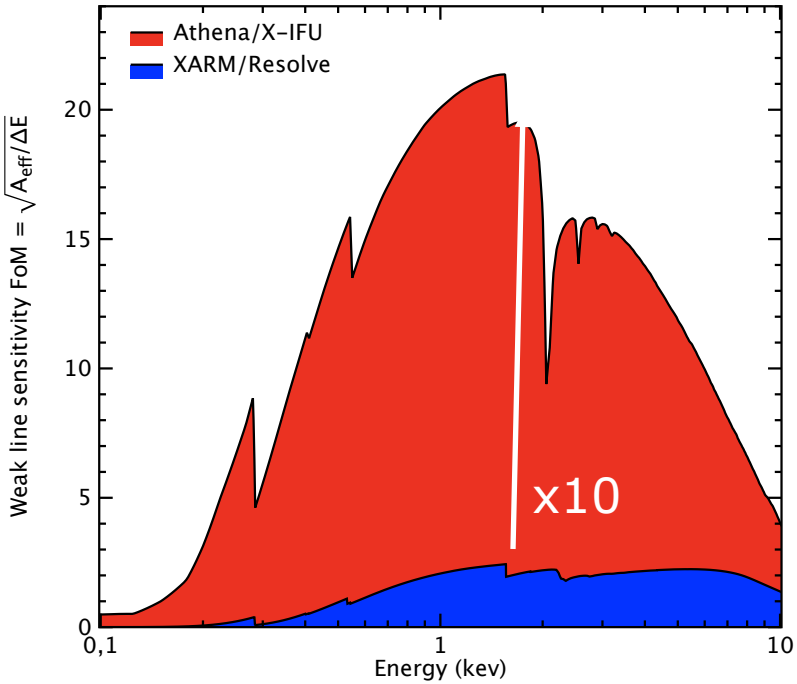
WFI+mirror collecting area



Credit: A.Rau (MPE)

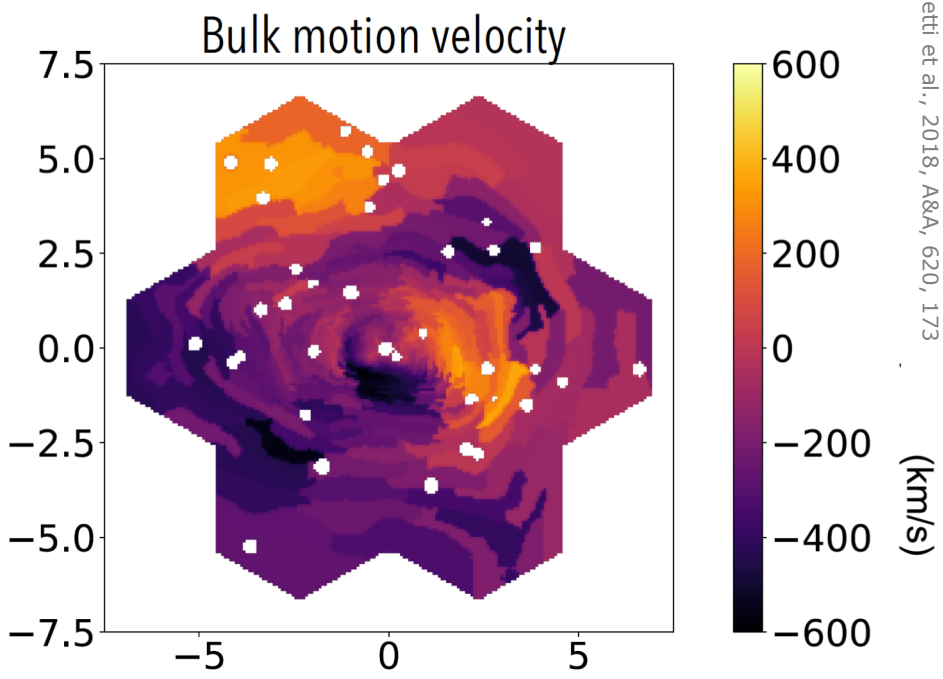
A giant leap in high-resolution spectroscopy

X-IFU weak line sensitivity



Credit: D.Barret (IRAP)

Spatially-resolved spectroscopy on ~5" scale

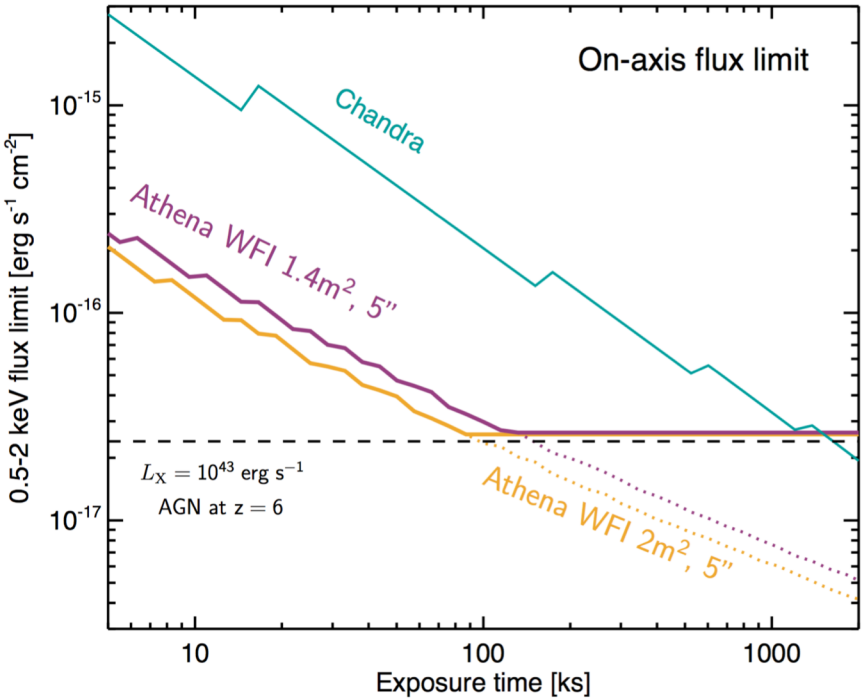


Cucchetti et al., 2018, A&A, 620, 173

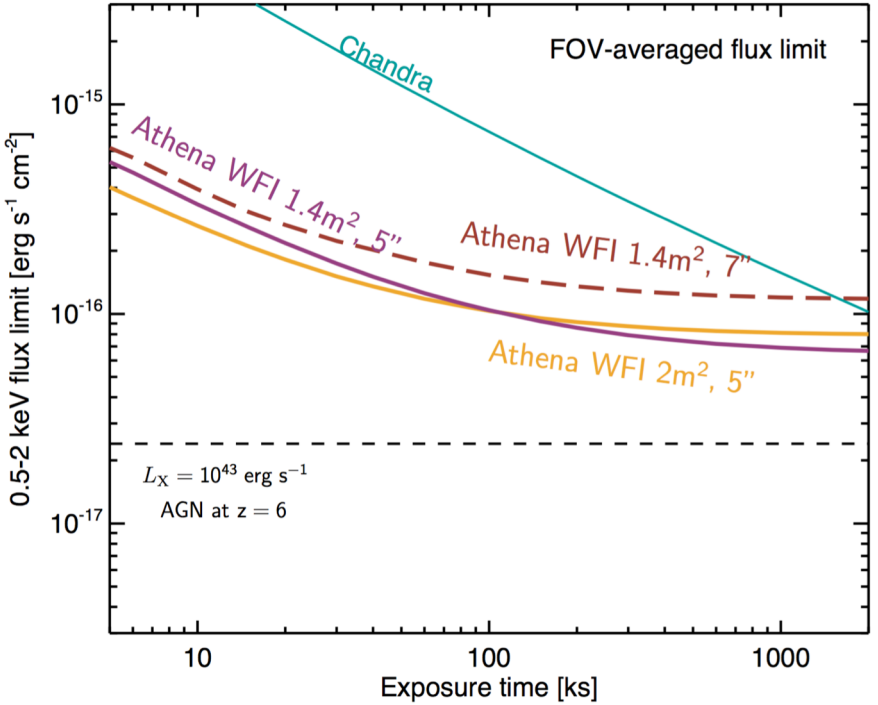
X-IFU velocity field of the ICM in a z=0.1 galaxy cluster

Athena WFI sensitivity

Source at the boresight



Random position in the FoV

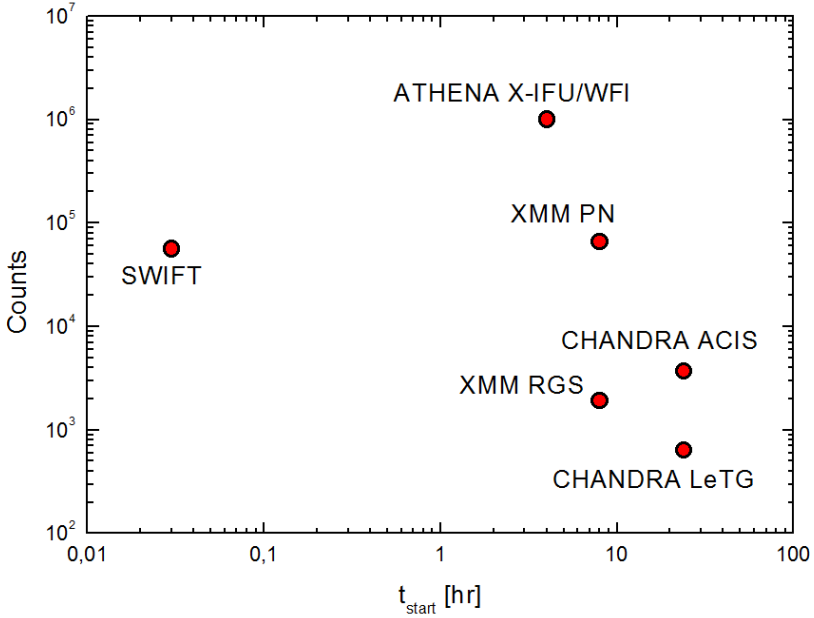


Credit: J.Aird (IoA)

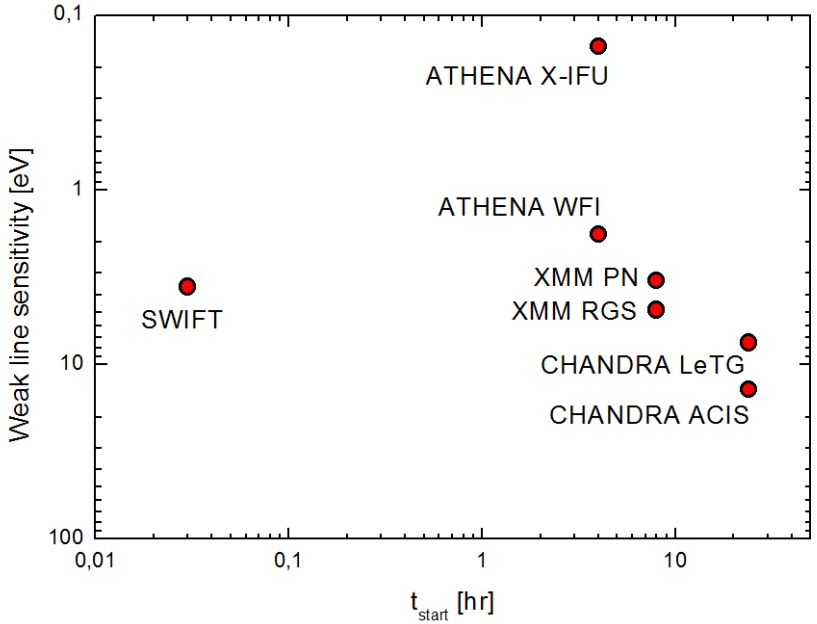
For comparison: eROSITA: ~10^{-14} cgs

Athena ToO performance

Counts vs. time (50 ks obs.^{n})



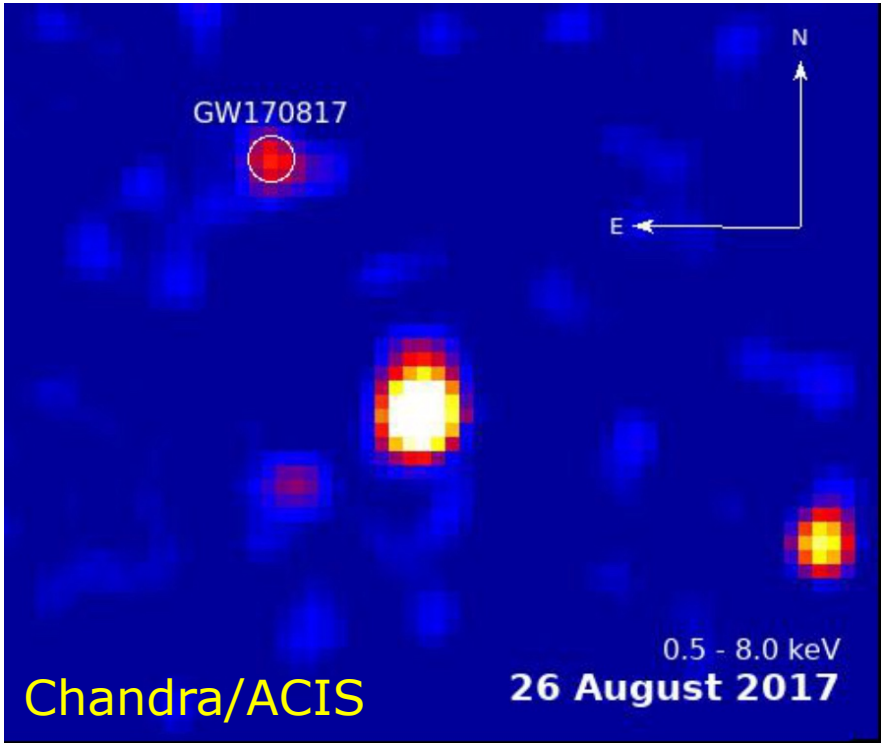
Weak line sensitivity



Credit: L.Piro, M.d'Andea, S.Lotti (IASP/INAF)

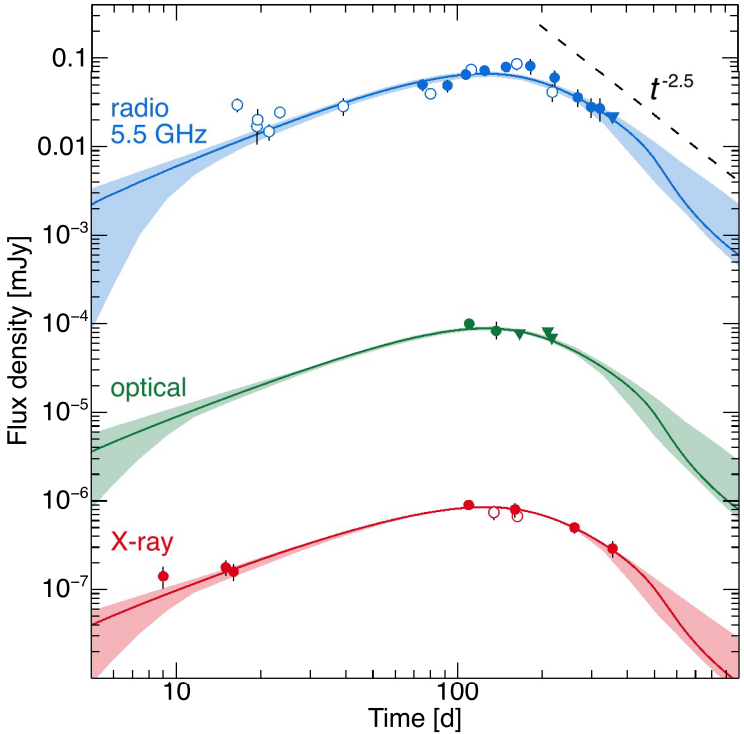
X-ray counterpart of the NS-NS merger

GW170817 EM counterpart



Troja, et al., Nature, 2017, 551, 71

Radio and X-ray light curves



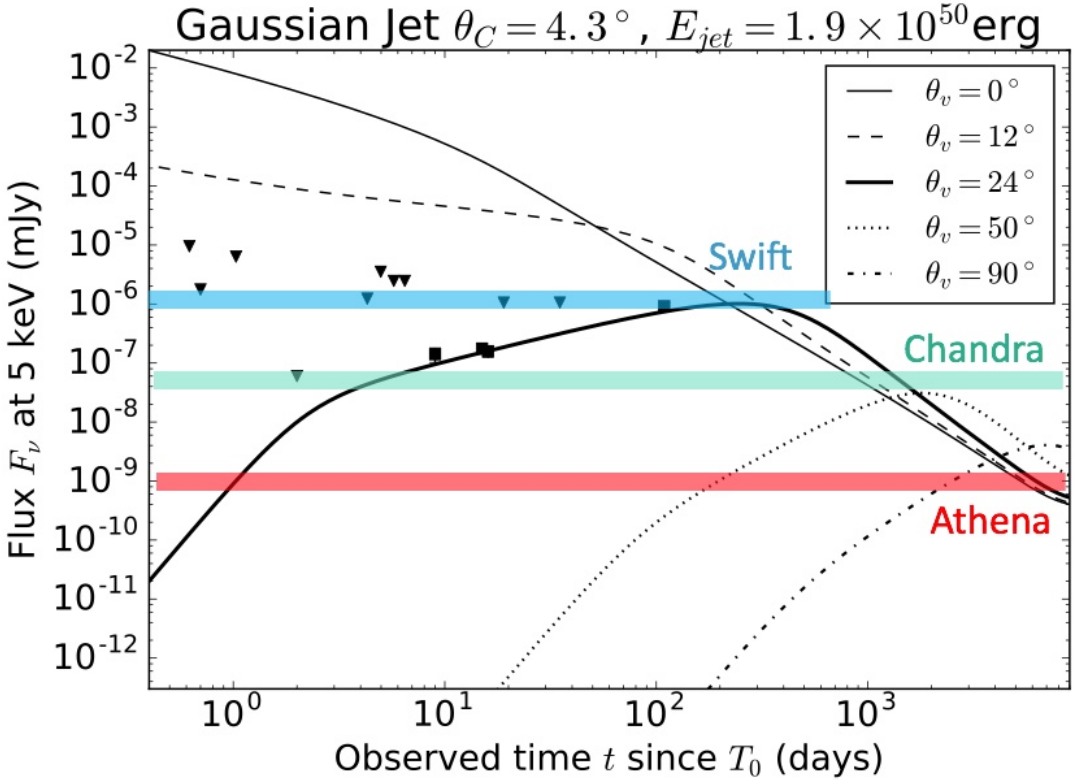
Troja et al., 2018, MNRAS, 478, 18

Athena will see them all …

X-rays probe:
- Jet: GRB afterglow (from radio to X-rays)
- Isotropic features:
  - Off-axis (orphan) afterglows
  - Cocoon

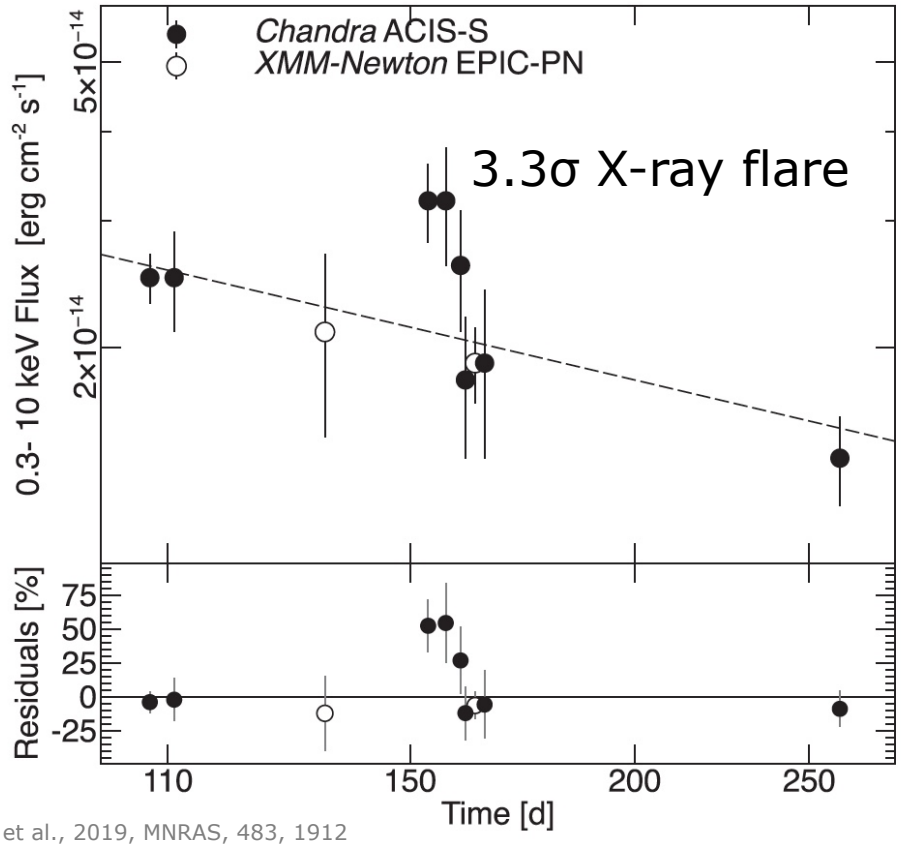
- Beaming angle ~1/Γ

Athena needed:
- for any line-of-sight ≥50^0
- to sample the most distant counterparts sampled by GW facilities

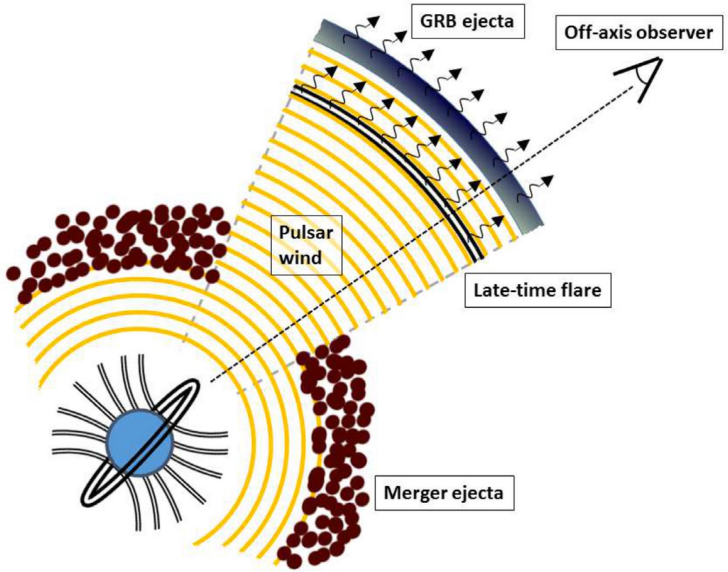


Credit: L.Piro (IAPS/INAF)

Breaking the NS-BH degeneracy



Piro et al., 2019, MNRAS, 483, 1912

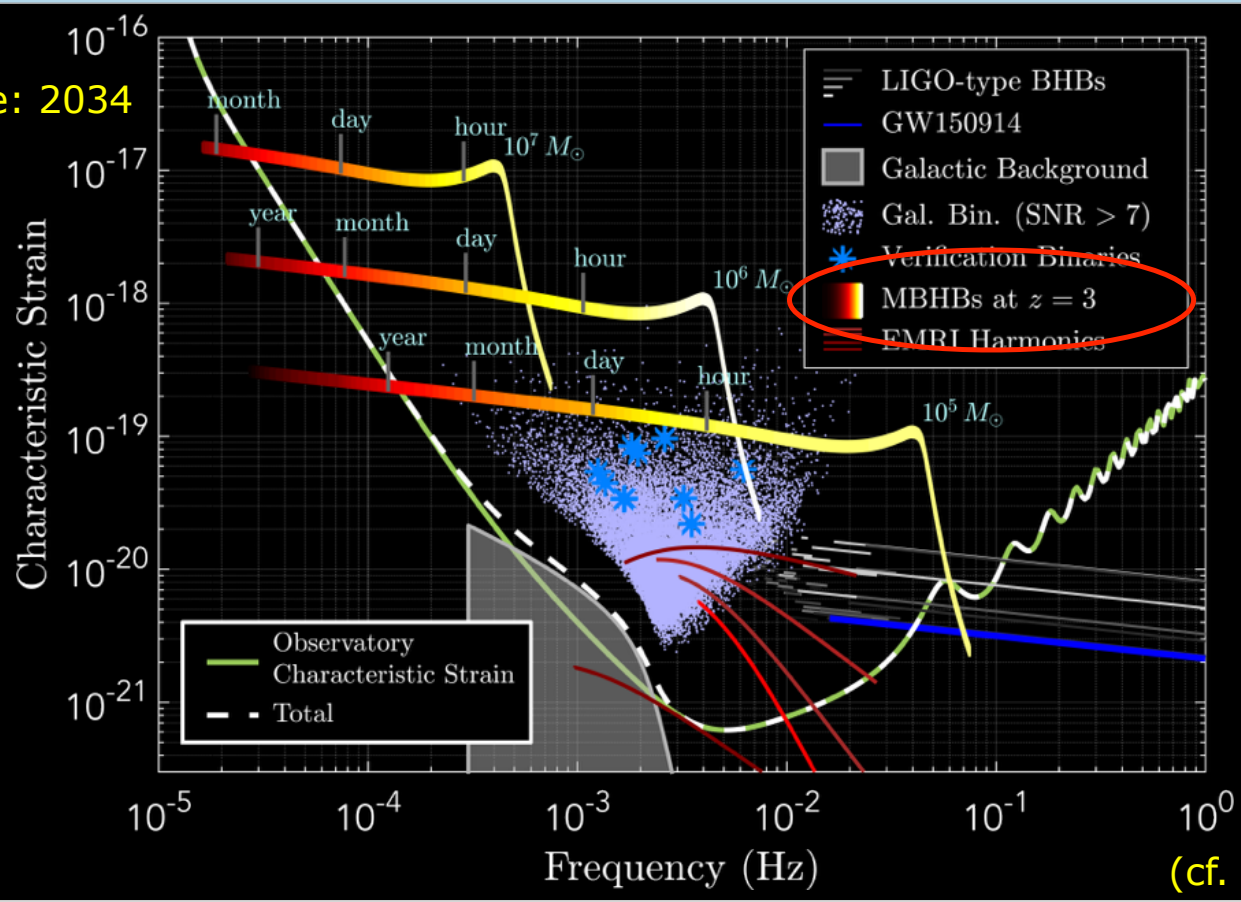


Moreover (on year time-scales):

- Long-lasting X-ray plateau
- X-ray kilonova remnants

LISA Sensitivity Curve

LISA launch date: 2034



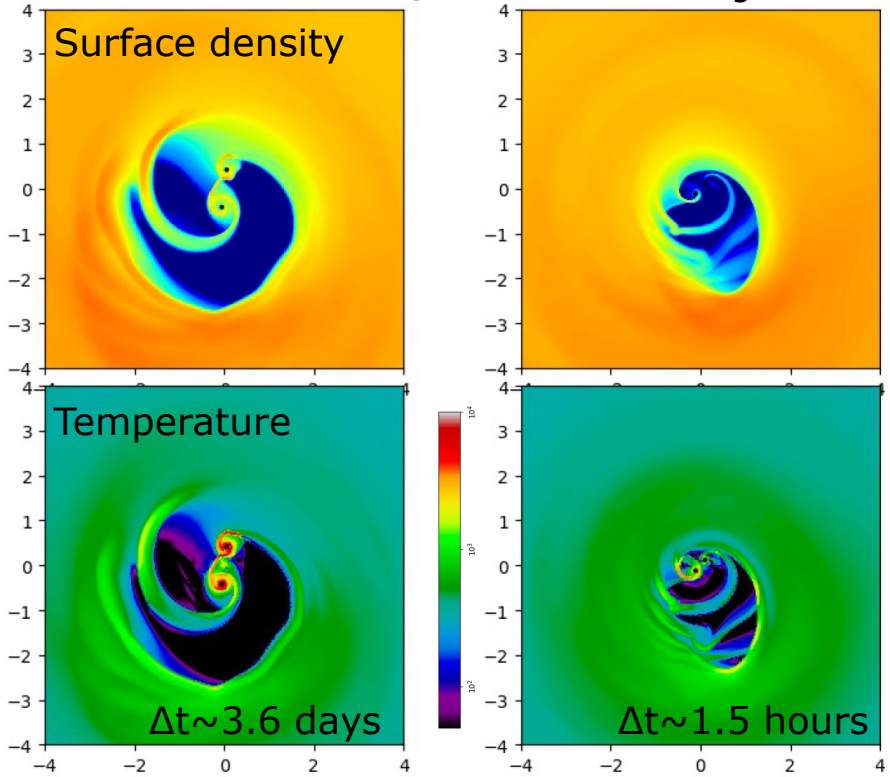
(cf. talk by P. Jetzer)

Why a SMBH merging with Athena and LISA?

- Unique opportunity to probe the behaviour of matter in the variable space-time induced by the merging BHs
- Study the propagation velocity of the photons vs. gravitons by phase-correlating the GW with the X-ray time-modulated signal
- Extend/calibrate the cosmic distance scale to $z \leq 2$
    - GWs gave the luminosity distance, X-rays may provide the redshift
- Unique opportunity to probe AGN physics
    - Onset of relativistic jets
    - Formation of the AGN corona
    - Lack of predictive, observational-based theory hampered progress so far
- Potentially huge discovery space

X-ray emission from an inspiraling SMBH merger

$M_{BH}=10^6\ M_\odot$ - $d_{start}=60\ r_g$

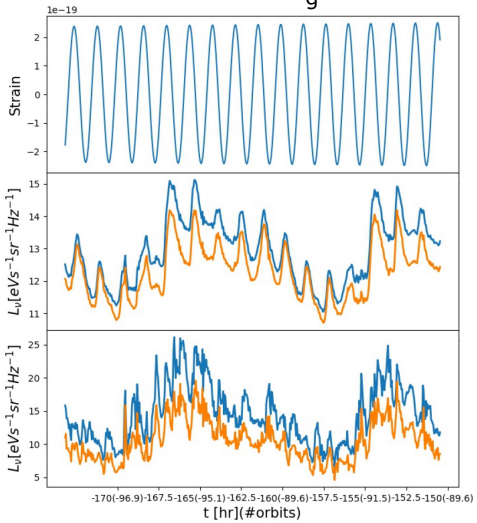


Outer disk: ≤1 keV

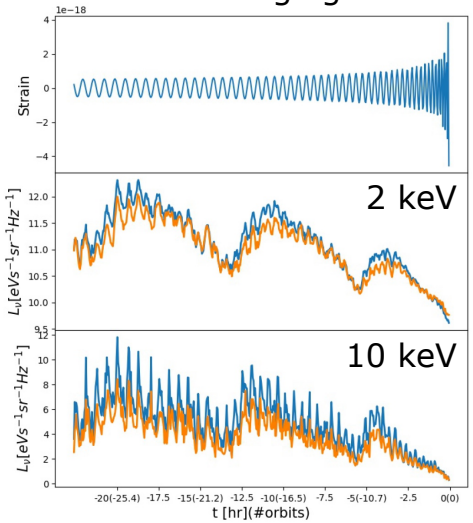
Cavity wall: ~2 keV

Mini-disks: ≥3 keV

d=60 r_g



~merging



Tang et al., 2018, MNRAS, 476, 2249

X-ray SMBH merger counterparts

- SMBH binaries may emit a time-varying X-ray signal commensurate with the GW period
- LISA will observe BH mergers throughout the Universe to z~20
- *Athena* can detect in a few ks $z \leq 1$ (10^6 $M_\odot$), or $z \leq 2$ (10^7 $M_\odot$) black holes
    - No other X-ray mission reach the required sensitivity (~a few 10^{-16} cgs)
- High-SNR binaries @$z \leq 2$ can be localised by LISA to within 10 deg^2 a few days, within 1 deg^2 a few hours before merging
- Post-merging localization can be as good as a few arcminutes
- A purely observational-based estimate of the $z \leq 2$ expected rate is ~3 yr^{-1}
    - Large unknowns on the fraction of gas-rich merging events, the expected X-ray obscuration, the dynamical range of the X-ray modulation, possible signatures in other wavelengths (LSST, …)

Possible *Athena*-LISA synergetic strategy

- Athena/WFI starts a raster scan of the error box when ≤10 deg^2
  - Can be covered with ~20 observations of ~10 ks each
- Pointing strategy shall be optimized with the improved LISA localization
- When the error box is ≤0.4 deg^2 (WFI FoV), Athena stops scanning and stares
- A % of events at z≤0.5 can be observed ≥5 times for ≥10 hours
  - The numbers are ~1 order-of-magnitude less favourable for z~1
- After merging, *Athena* can stare until confusion limit …
- … or monitor the field over different time-scales (days, months, years …)
- Crucial to select the best candidates for a pilot *Athena*-LISA program

Conclusions

- *Athena* is designed to address the topics of The Hot and Energetic Universe
- However, it is an observatory capable of impacting all fields of astronomy
- Designed to overperform any existing or planned X-ray mission by at least one order of magnitude in several parameter spaces simultaneously
- Rapid ToO response and quick agility are well tuned for future multi-messenger astronomy
- NS-NS merger events:
  - all off-axis jets with inclination $\geq 50^0$
  - the most distant counterparts of GW facilities
  - can discriminate the merger remnant nature via weak X-ray flares, or long-lasting X-ray plateaus
- SMBH merger events (synergies with LISA)
  - potentiality of studying the behaviour of matter in the variable space-time of the merging BH
  - Witness the post-merger onset of AGN activity (corona, jets)
  - **Huge discovery space** – real challenge for theorist to predict what we could see!