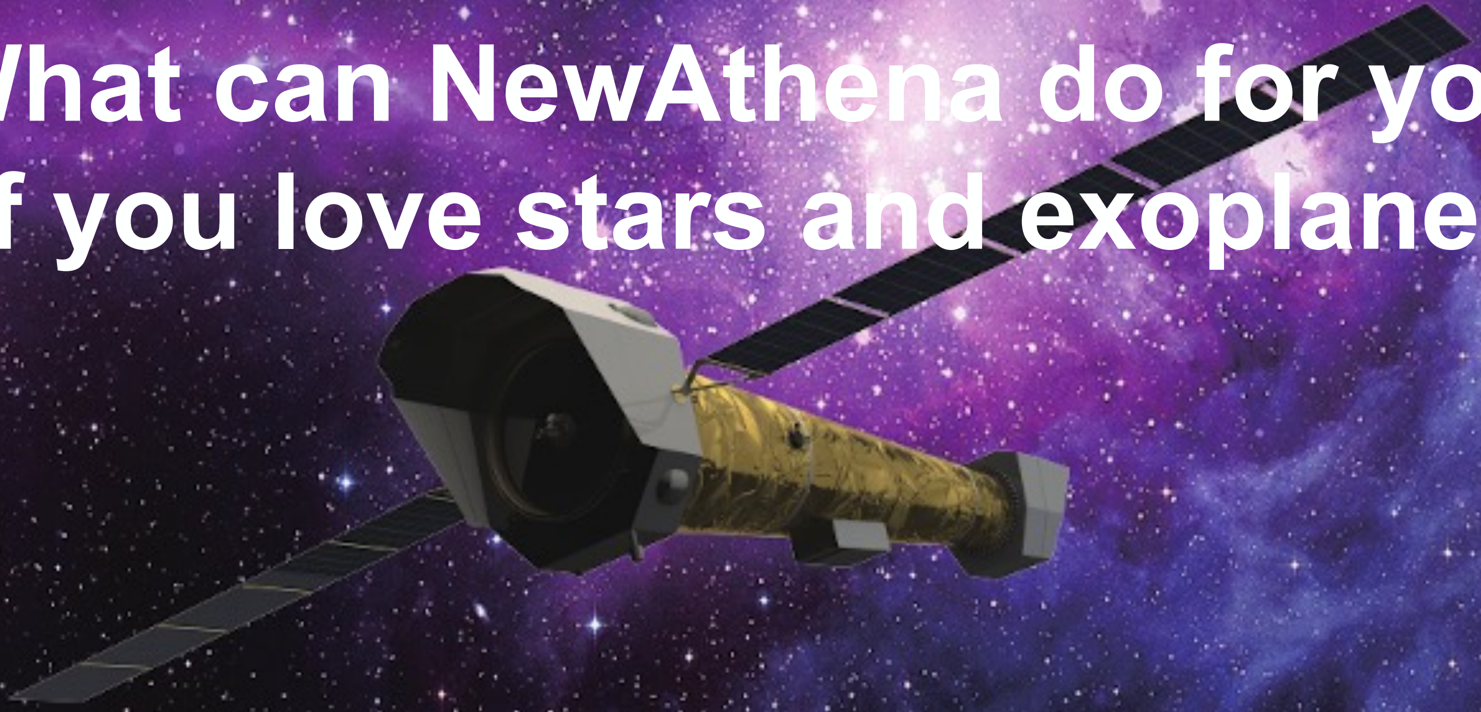
What can NewAthena do for you (if you love stars and exoplanets)



Matteo Guainazzi

NewAthena Project Scientist, ESA/ESTEC

Credit: IRAP, CNES, ESA & ACO

Outline

1. *Athena*: science case and performance
    - "The Hot and Energetic Universe" science theme
    - *Athena* prospective contributions to stellar and exoplanet astrophysics
        - **Thanks to: Marc Audard (University of Geneva), Fabio Favata (ESA/ESTEC), Rachel Osten (STScI & JHU), Jorge Sanz-Forcada (CAB)**

2. The transition from *Athena* to NewAthena

What is *Athena*?

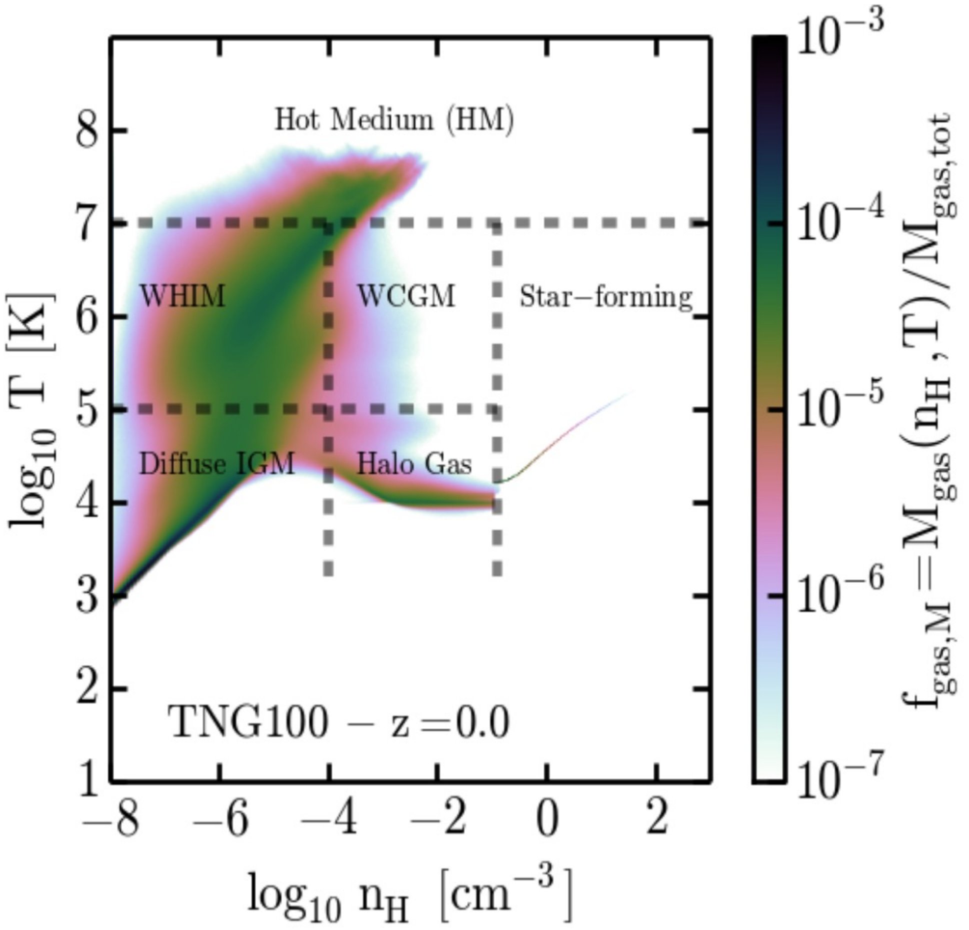
Martizzi et al., 2019,MNRAS, 486, 3766

Athena is a large-class X-ray *observatory* of ESA

Designed to address:

- 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."*
- The 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."*

IllustrisTNG simulation



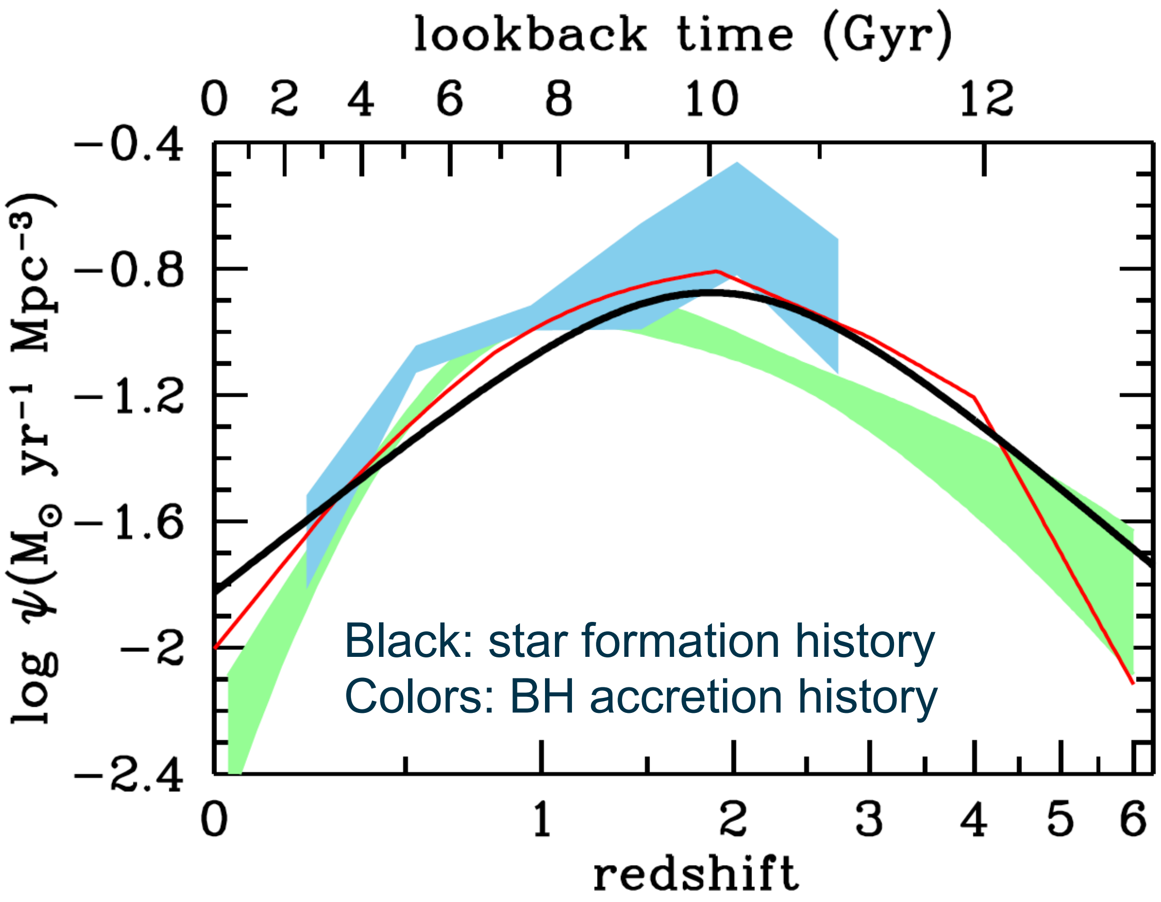
Most baryons in the Universe have $T>10^5$ K

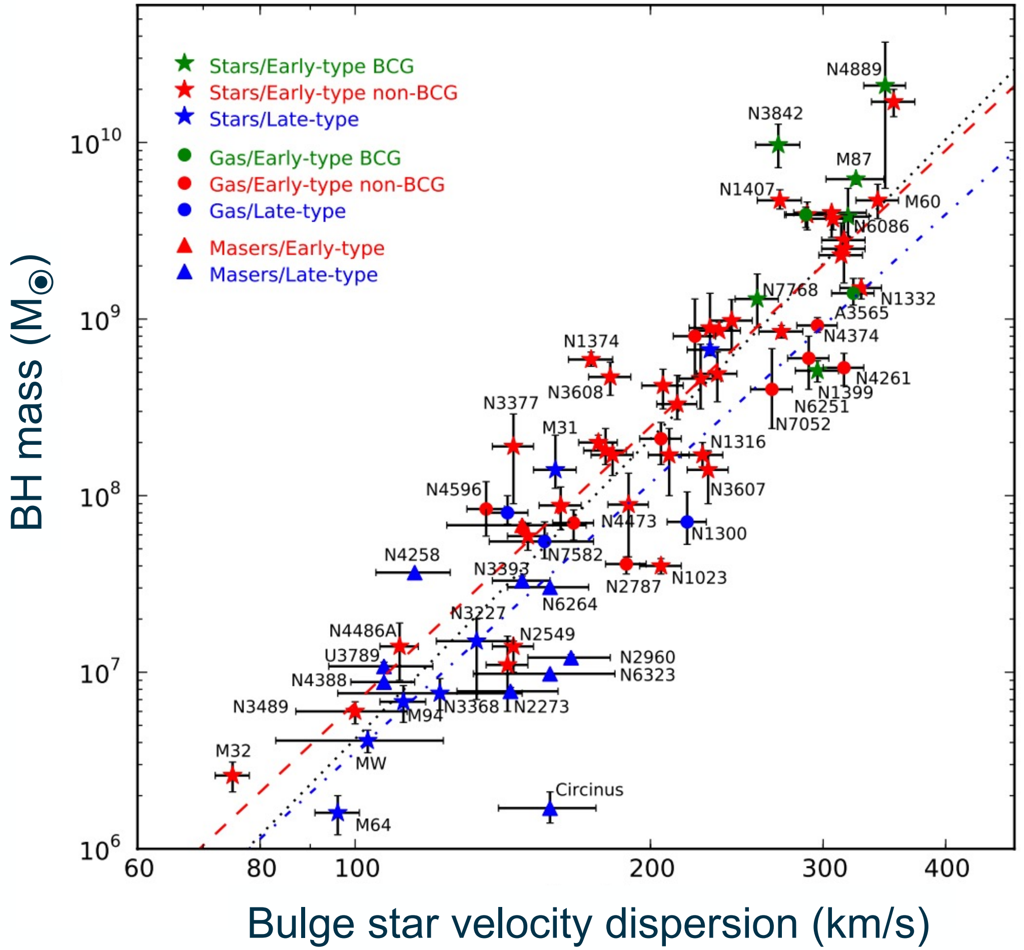
Science context I. – Galaxy clusters as probe of large-scale structure evolution

Science context II. – Black Hole (BH)/galaxy evolution

Madau & Dickinson, 2014, ARA&A, 52, 415

McConnell & Ma, 2013, 764, 184

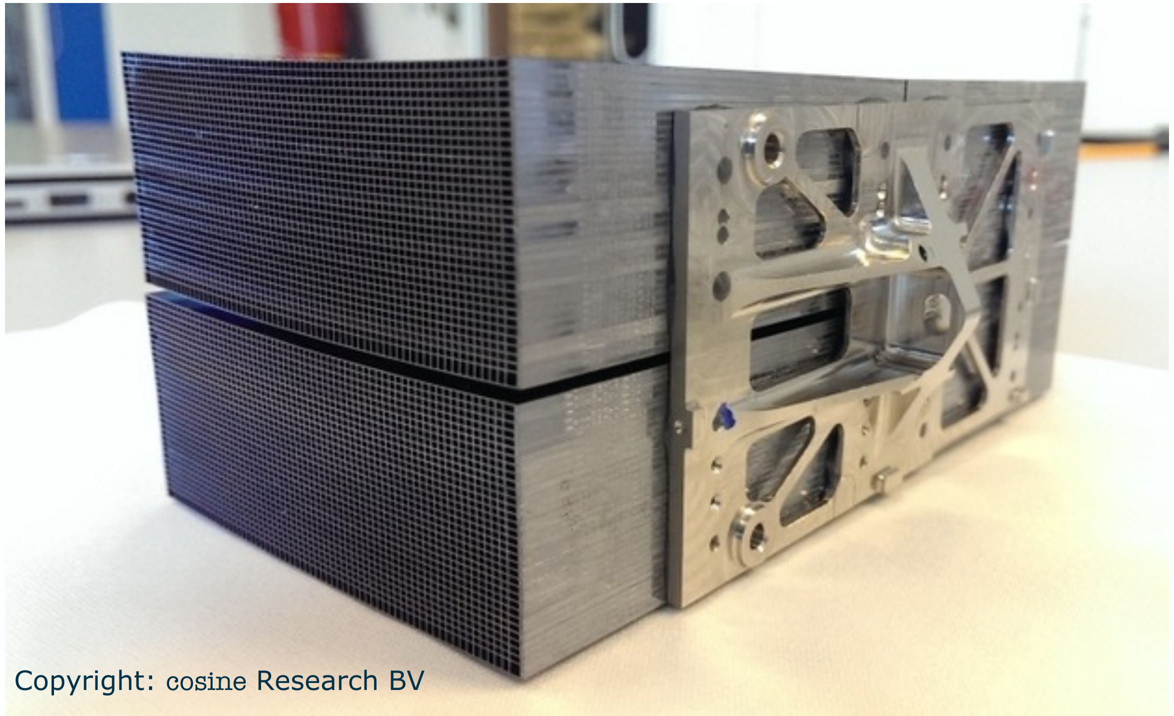


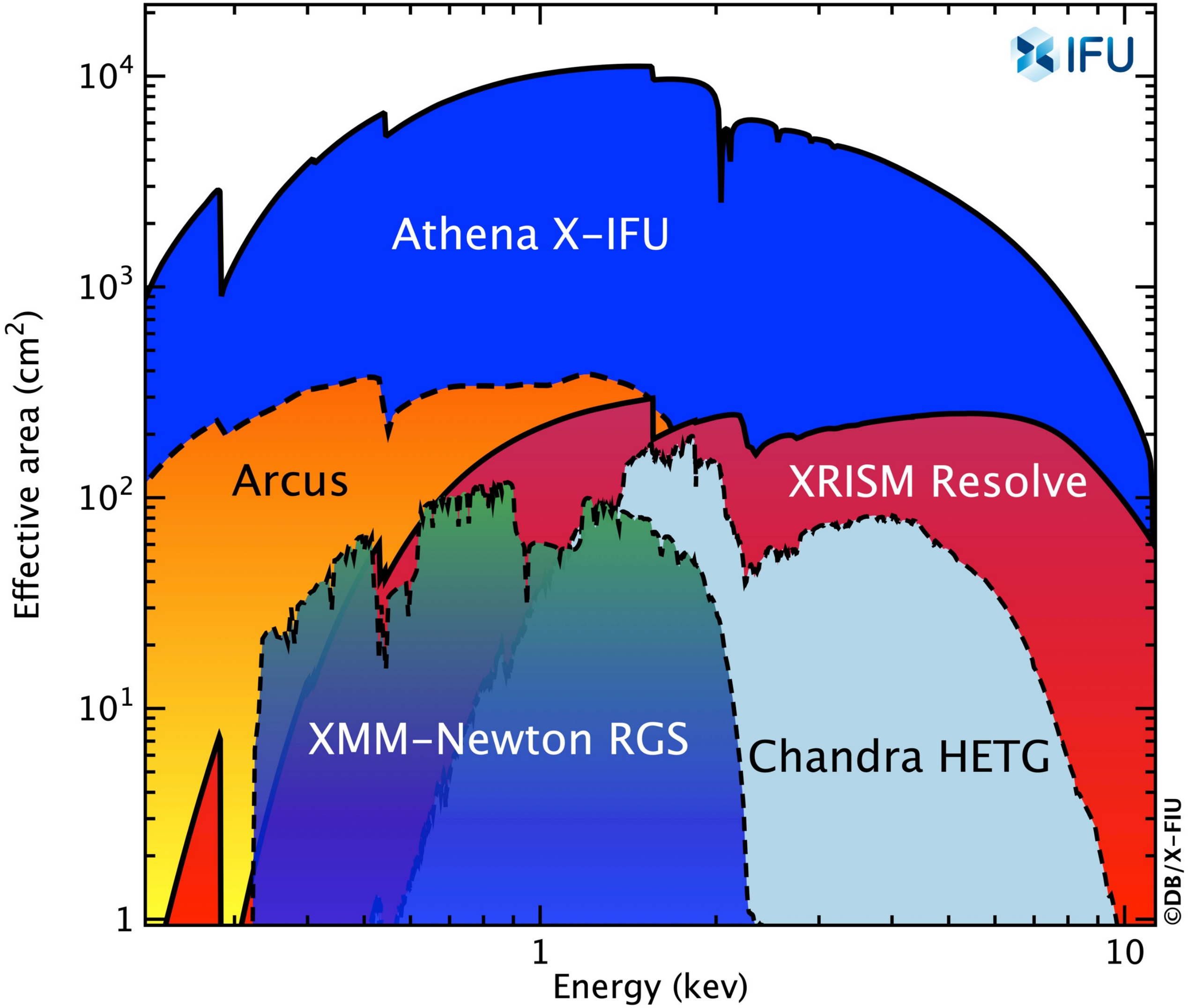


Understanding **BH/galaxy co-evolution** is one of the big quests of modern astrophysics

Athena performance I. – effective area

Credit: X-IFU Consortium



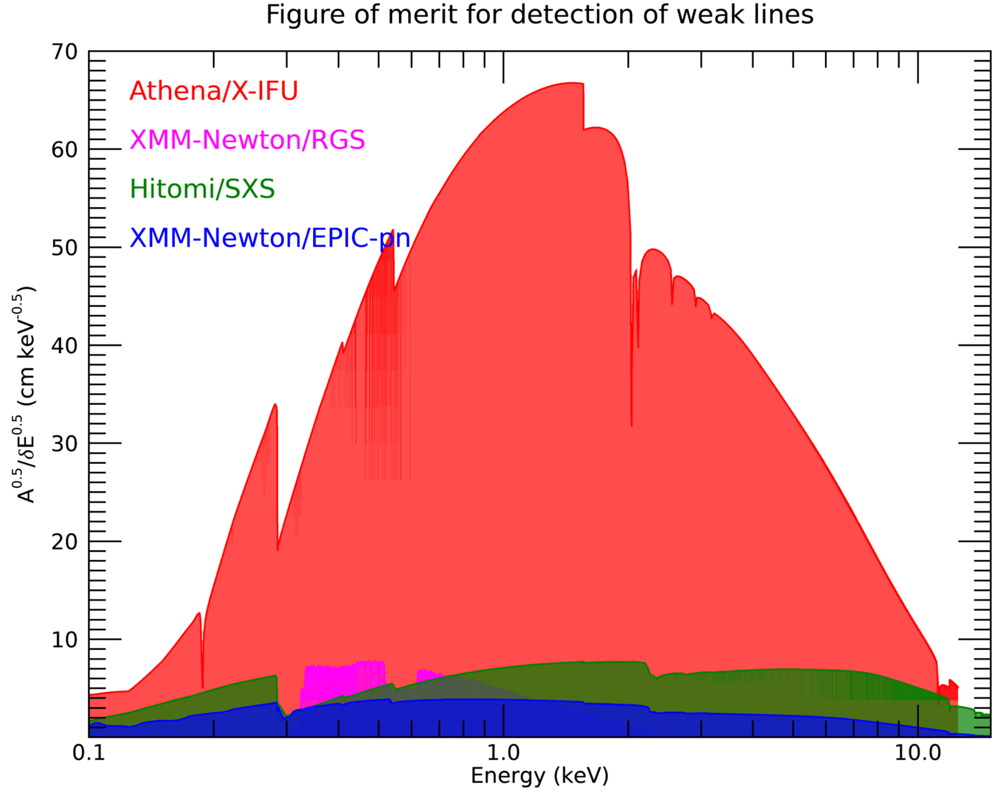


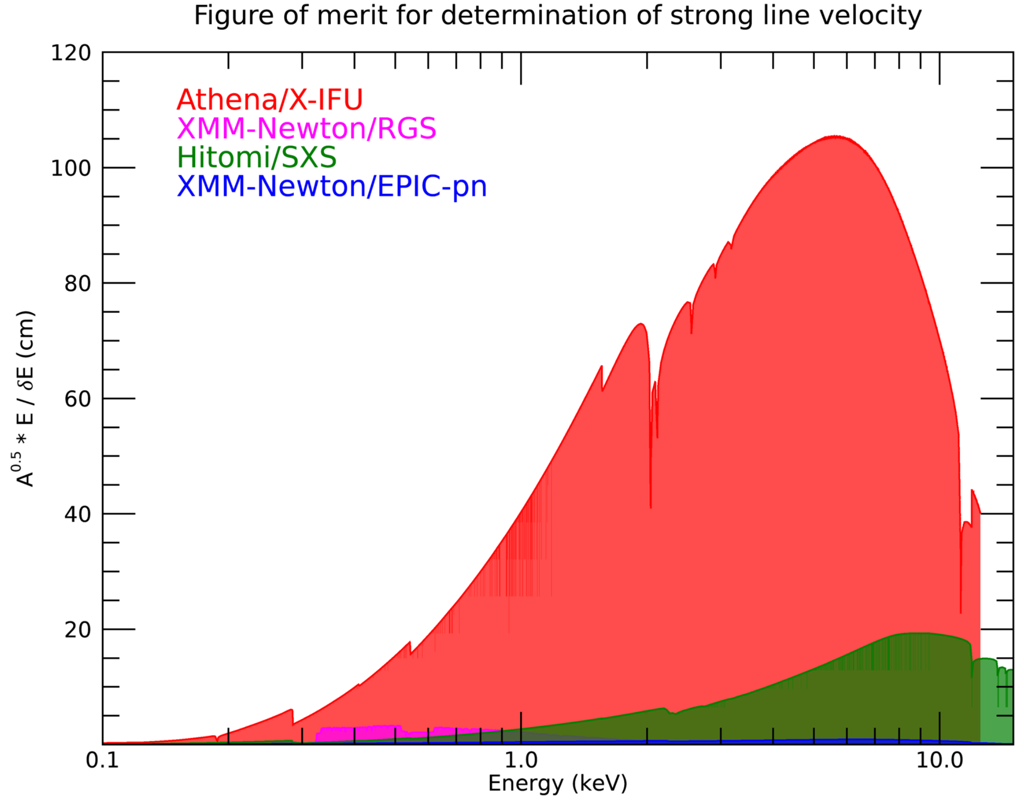
The *Athena* telescope is based on the Silicon Pore Optics technology

Modular, high throughput, low mass, large area

Athena performance II. – spectroscopic performance

The spectroscopic instrument on **Athena** is an *X-ray microcalorimeter* (X-IFU)



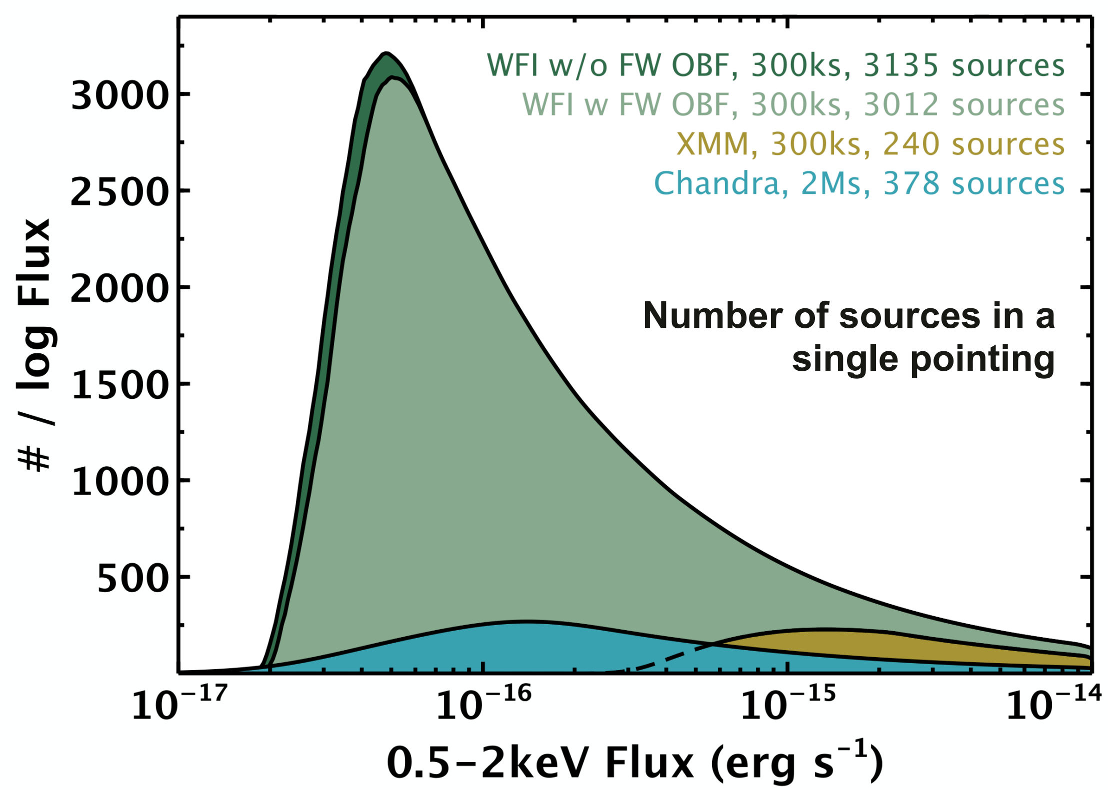


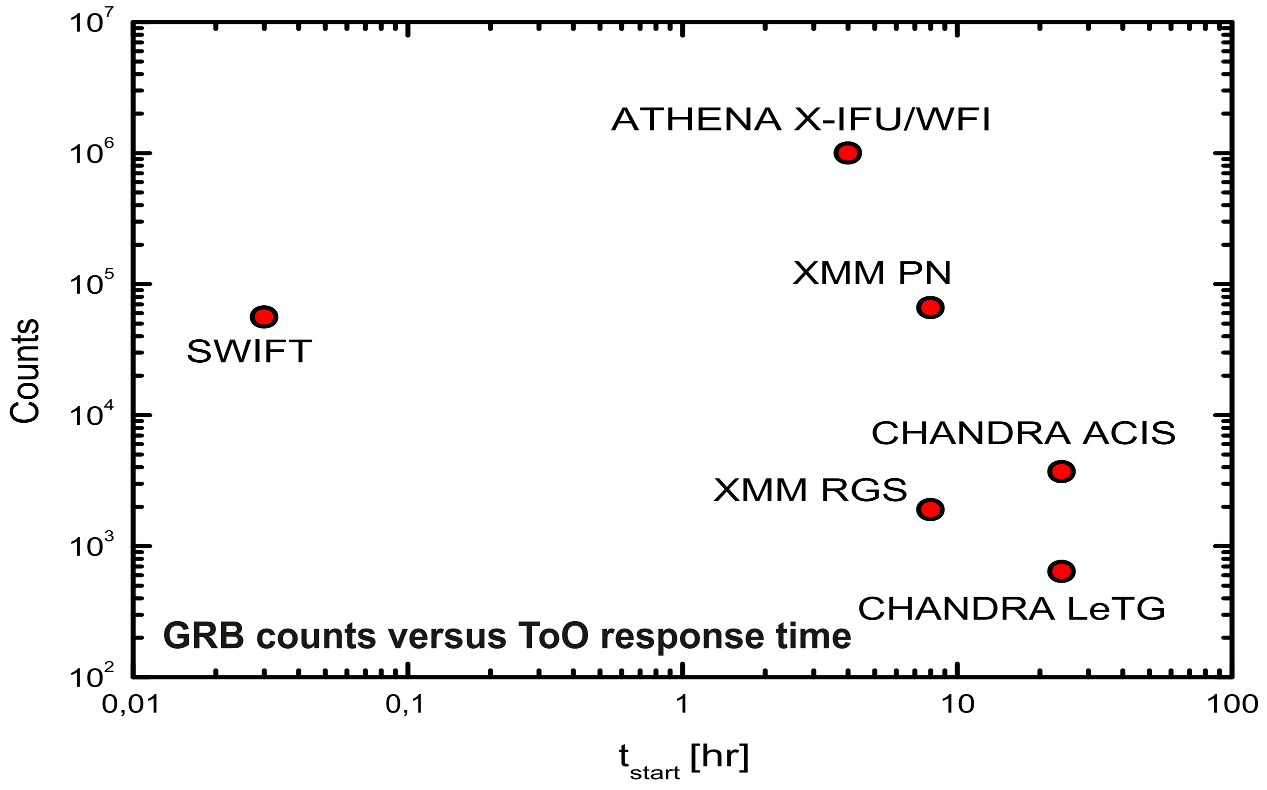
Enables non-dispersive (i.e., spatially-resolved) X-ray spectroscopy over 5” side pixels

Athena performance III. – survey performance

Credit: WFI Consortium

The survey instrument on *Athena* is an active sensor DEPFET (WFI) - 40′x40′ field-of-view

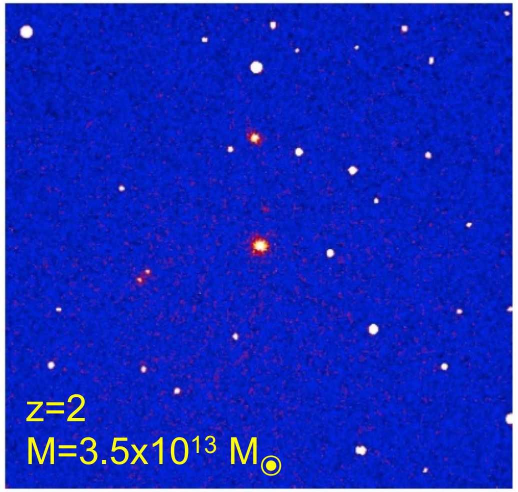


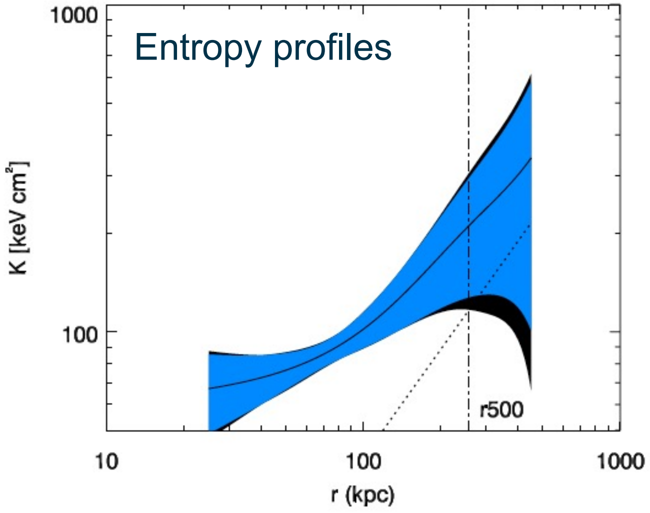


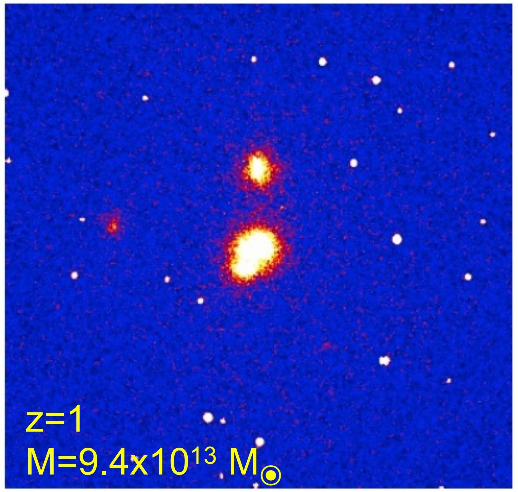
Enables a flexible survey → ≥10^5 X-ray sources down to a confusion limit of $2x10^{-17}$ cgs

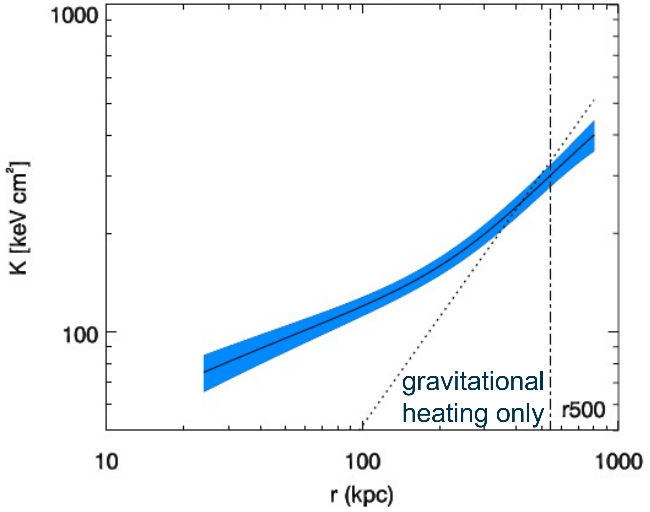
Question I: how do galaxy clusters form and evolve?

Pointcouteau et al., 2013, arXiv1306.2319





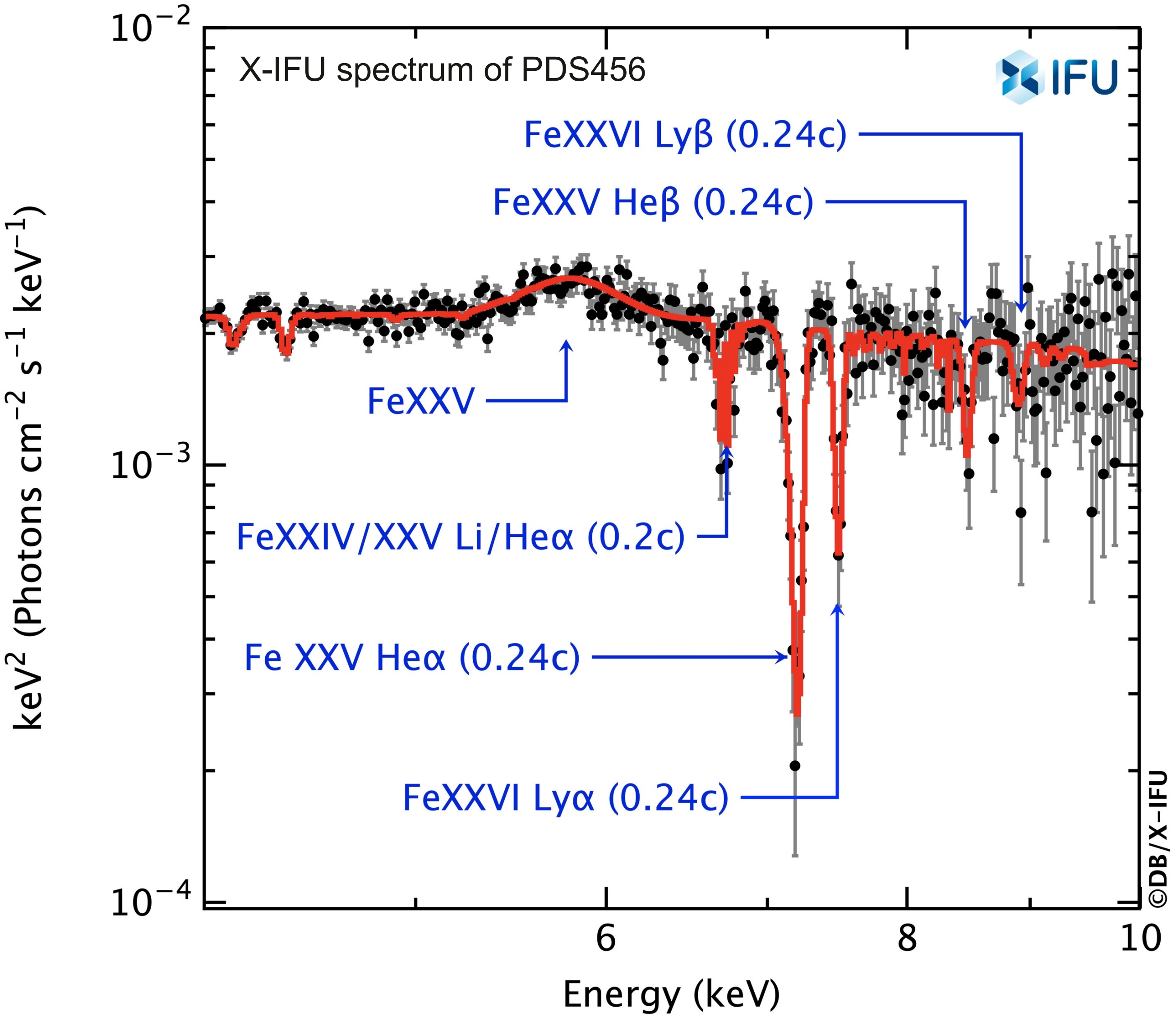




- *Athena*/WFI characterizes the thermodinamics of the Intra-Cluster Medium (ICM) in galaxy groups (M>10^{13} M$_\odot$) and clusters to z~1.5-2
- Enables to study the evolution of physical scaling relations (*e.g.*, L_X vs kT)
- Entropy profiles allow to compare gravitational heating versus BH/SNe feedback

Question II: what is the driver of BH/galaxy evolution?

Credit: X-IFU Consortium



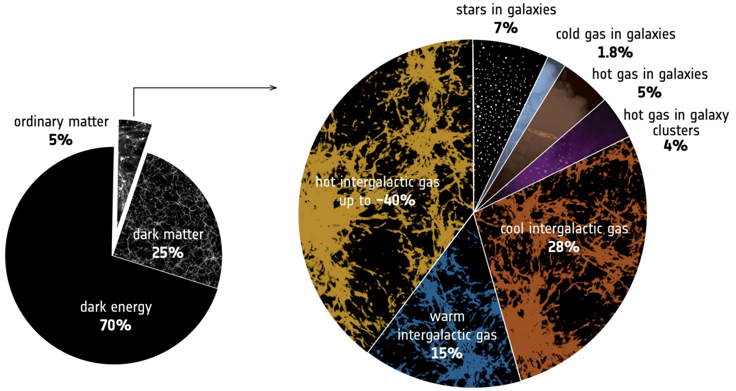
- Sub-relativistic (v≤0.3 c) accretion disk outflows suspected to carry "AGN feedback" [AGN=Active Galactic Nuclei]
- Best probed via spectroscopy of heavy metal ionised transitions (X-rays)
- Physical characterization impossible at CCD-resolution
- X-IFU enables robust measurements of outflow momentum and kinetic energy
- Bonus: micro-physics of feedback by relativistic jets on ICM via spatially-resolved spectroscopy of galaxy clusters in the local Universe

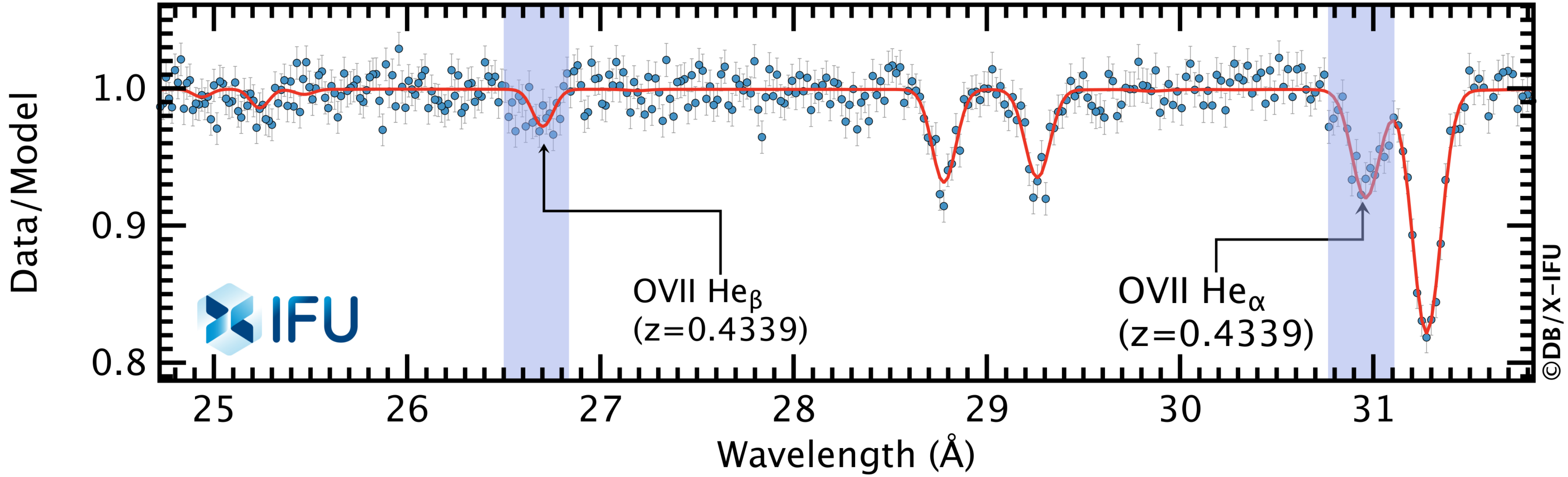
Question III: where are the mission baryons?

Credit: X-IFU Consortium

Nicastro et al., 2017, AN, 338, 281

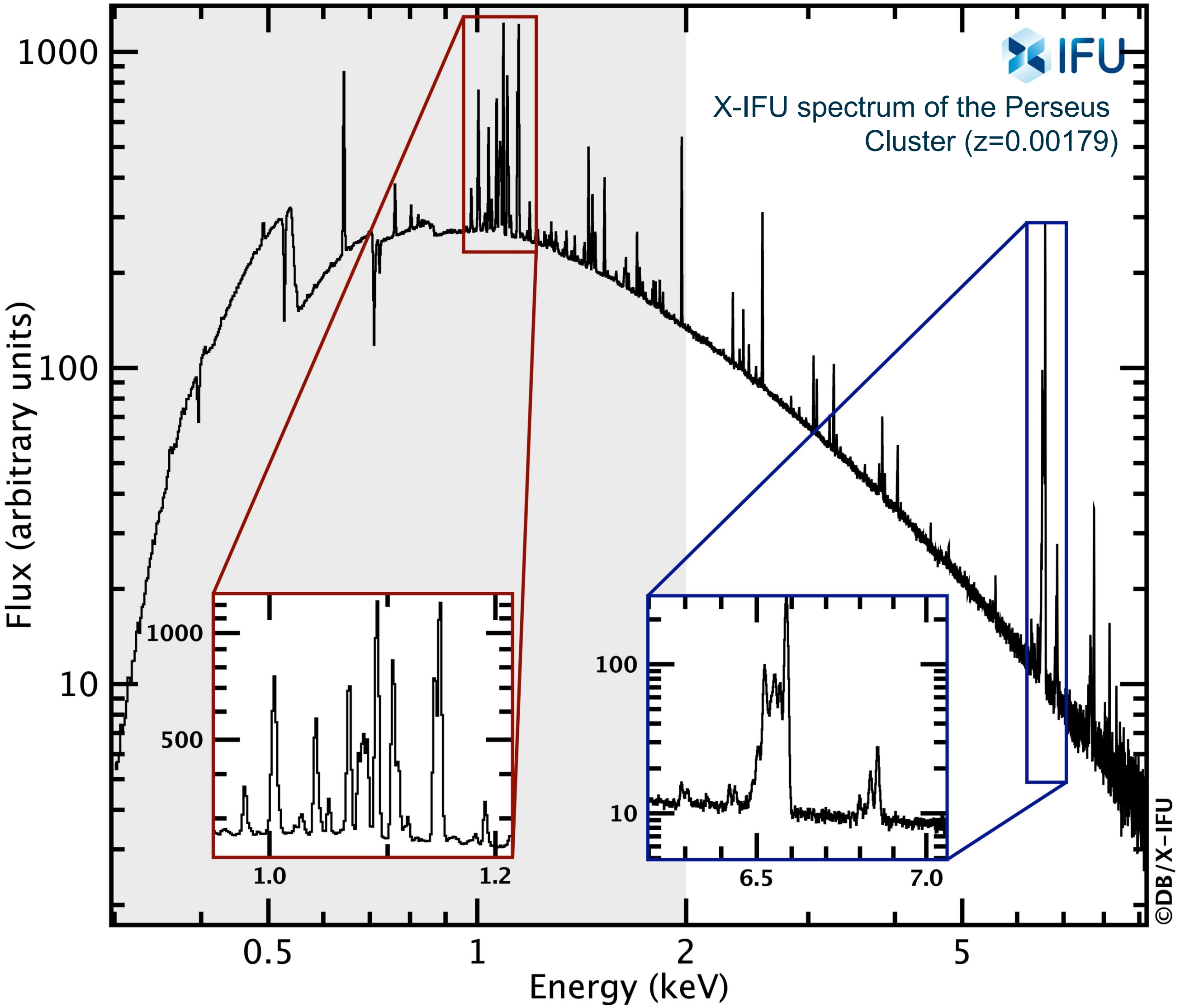
- ~40% of the baryonic matter in the local Universe remains elusive to detection
- Postulated to be in the form of a hot plasma (kT>$10^{5.5}$K) permeating the cosmic web
- ***Athena*** detects 100s of sight lines





Question IV: how are elements spread around?

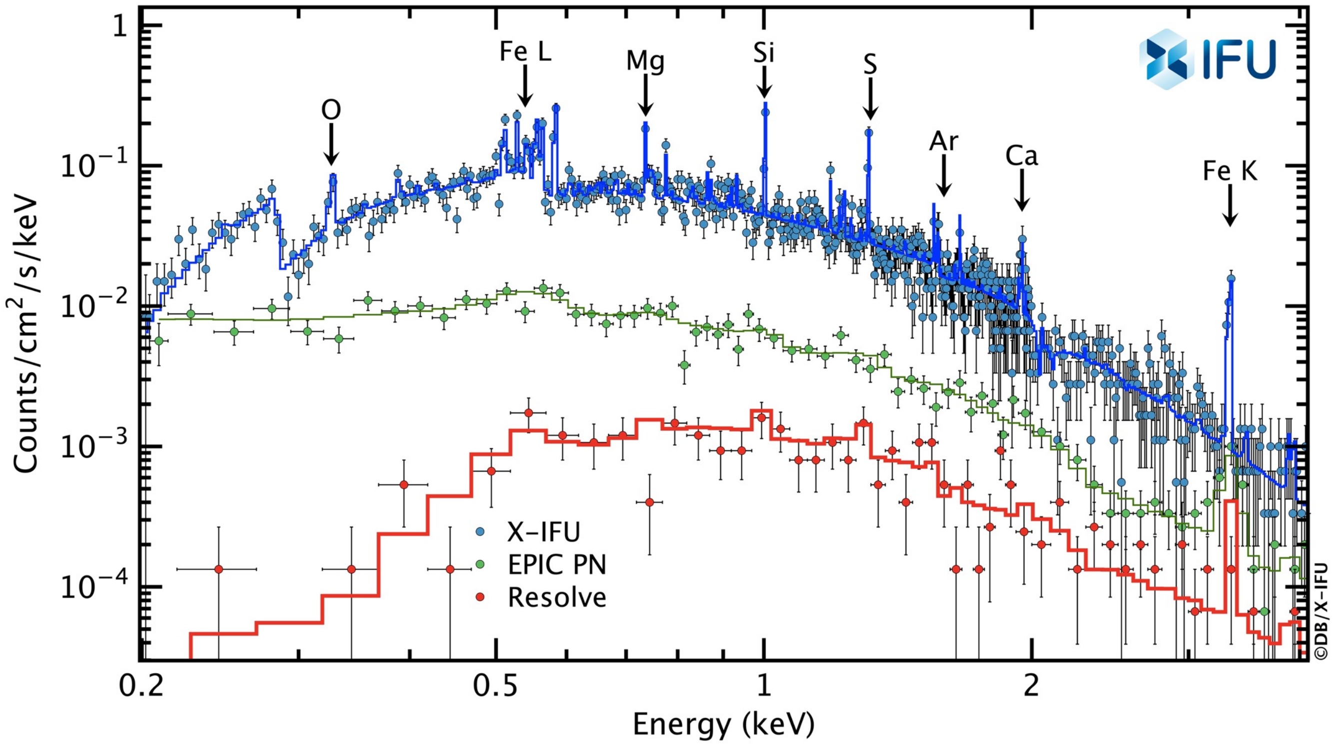
Credit: X-IFU Consortium



- ICM metallicity is the fossil remnant of the cosmological history of metal formation and circulation
- Different metals trace the contribution of AGB stars, CC and Type Ia supernovae (SN)
- X-IFU enables metallicity evolution studies up to z~2
- Bonus: direct study of thermal vs. non-thermal energy channeles in local Universe massive clusters
  - "Hydrostatic bias" needed to employ cluster mass distribution function for cosmology

Question IV: how are elements spread around?

Credit: X-IFU Consortium

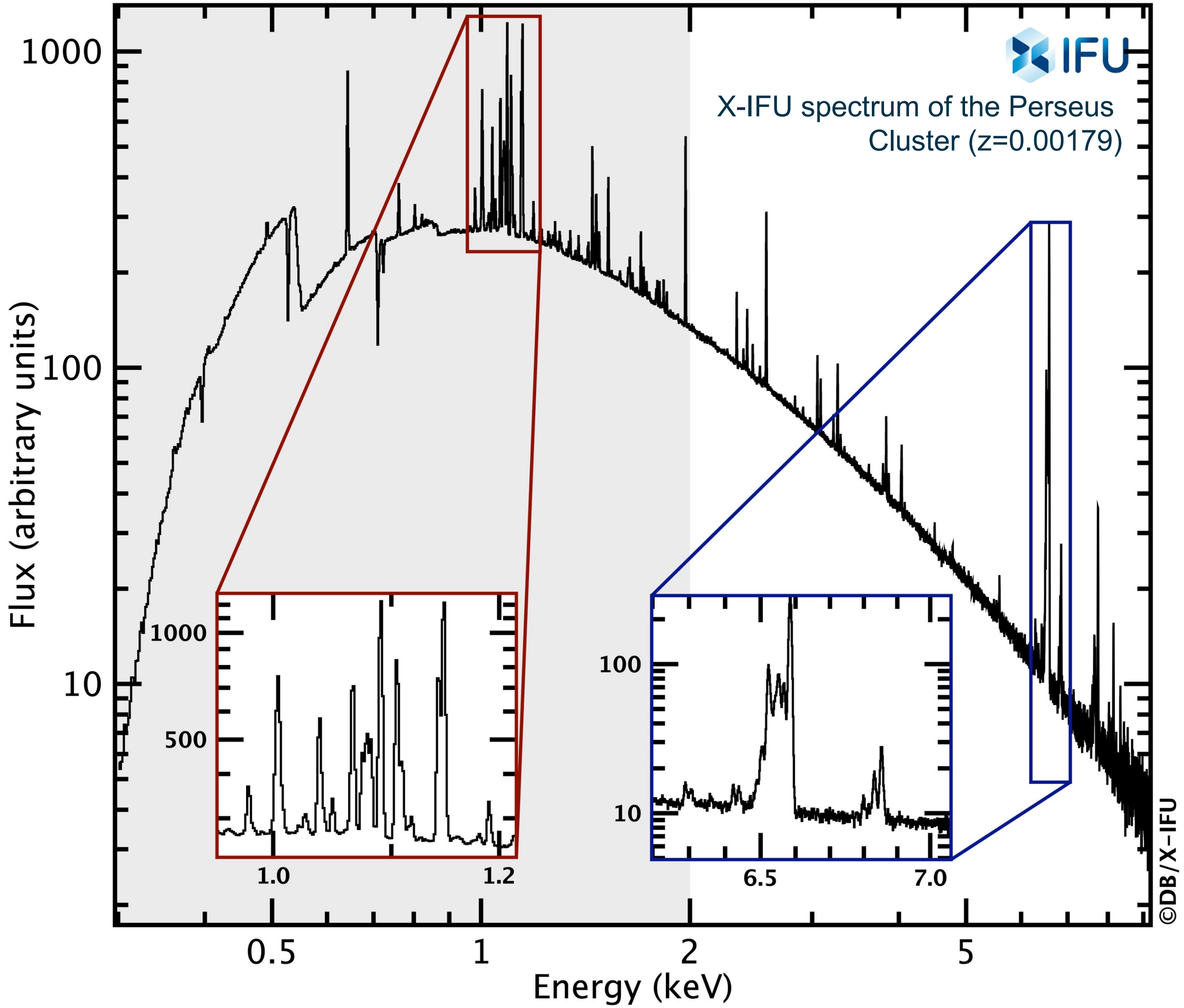


The same cluster at z=1

- ICM metallicity is fossil remnant of the cosmological history of metal formation and circulation
- Different metals trace the contribution of AGB stars, CC and Type Ia supernovae (SN)
- X-IFU enables metallicity evolution studies up to z~2
- Bonus: direct study of thermal vs. non-thermal energy channeles in local Universe massive clusters
    - "Hydrostatic bias" needed to employ cluster mass distribution function for cosmology

Question IV: how are elements spread around?

Credit: X-IFU Consortium



- ICM metallicity is fossil remnant of the cosmological history of metal formation and circulation
- Different metals trace the contribution of AGB stars, CC and Type Ia supernovae (SN)
- X-IFU enables metallicity evolution studies up to z~2
- Bonus: direct study of thermal vs. non-thermal energy channels in local Universe massive clusters
  - ”Hydrostatic bias” needed to employ cluster mass distribution function for cosmology

The full *Athena* science case

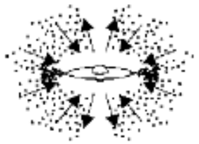
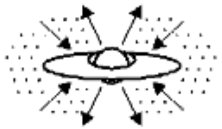
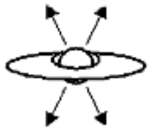
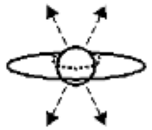
cf. the *Athena* Science Requirement Document. Small characters purposedly employed

- **"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."*
  - First galaxy groups, cluster bulk motions and turbulence, cluster entropy profile evolution, cluster chemical evolution, physics of cluster feedback, missing baryons
- **"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."*
  - High-redshift SMBH, Complete AGN census, AGN outflows, Feedback in local AGN and star-forming galaxies, AGN spin census, GBH and NS spins and winds, black hole accretion, high-redshift GRBs, TDEs
- **"The 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."*
  - Planetary X-ray spectroscopy, Stellar activity in exoplanets systems, Colliding winds in binaries, Magnetopheric accretion in low-mass stars, magnetic activities in ultra-cool dwarfs, mass loss in massive stars, EoS of ultradense matter, masses of accreting white dwarfs, magnetars, pulsar-wind nebulae, novae and PNe, double-degenarate binaries, SN, chemistry of the cold ISM, dust scattering halos, physics of the warm and hot ISM, Mapping of SNR

The observational program of ESA observatories is driven by the worlwide community

X-ray emission in stars

Feigelson & Montmerle, 1999, ARA&A, 37, 363

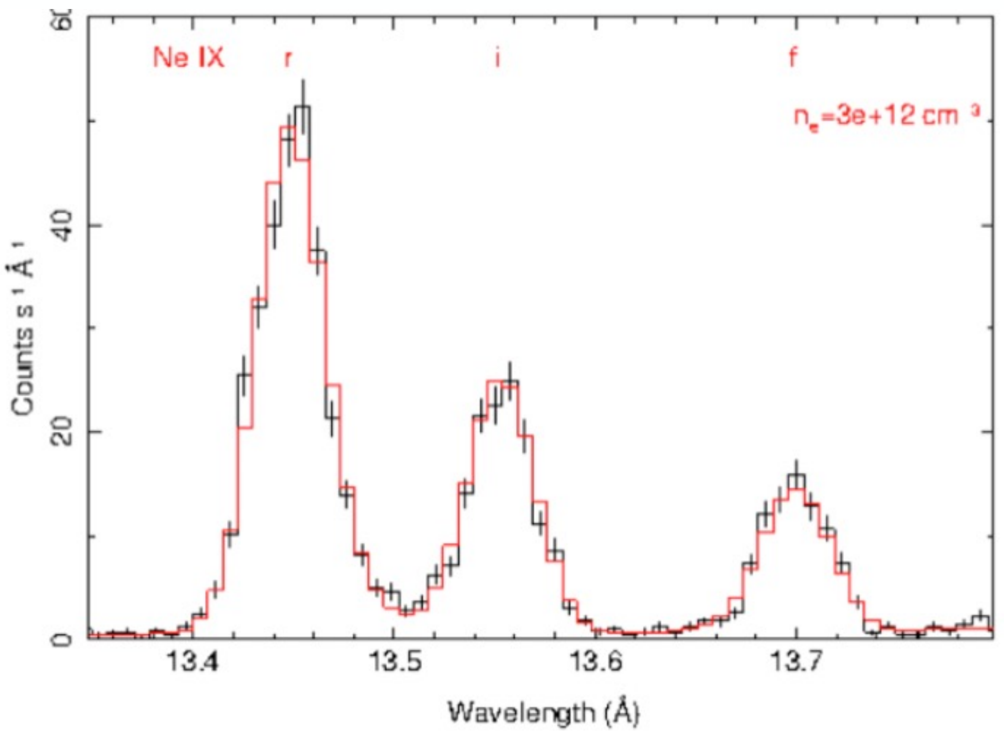
Properties	*Infalling Protostar*	*Evolved Protostar*	*Classical T Tauri Star*	*Weak-lined T Tauri Star*	*Main Sequence Star*
Sketch					
Age (years)	10^4	10^5	$10^6 - 10^7$	$10^6 - 10^7$	$> 10^7$
mm/Infrared Class	Class 0	Class I	Class II	Class III	(Class III)
Disk	Yes	Thick	Thick	Thin or Non-existent	Possible Planetary System
X-ray	?	Yes	Strong	Strong	Weak
Thermal Radio	Yes	Yes	Yes	No	No
Non-Thermal Radio	No	Yes	No ?	Yes	Yes

Accretion in Young Stellar Objects (YSOs)

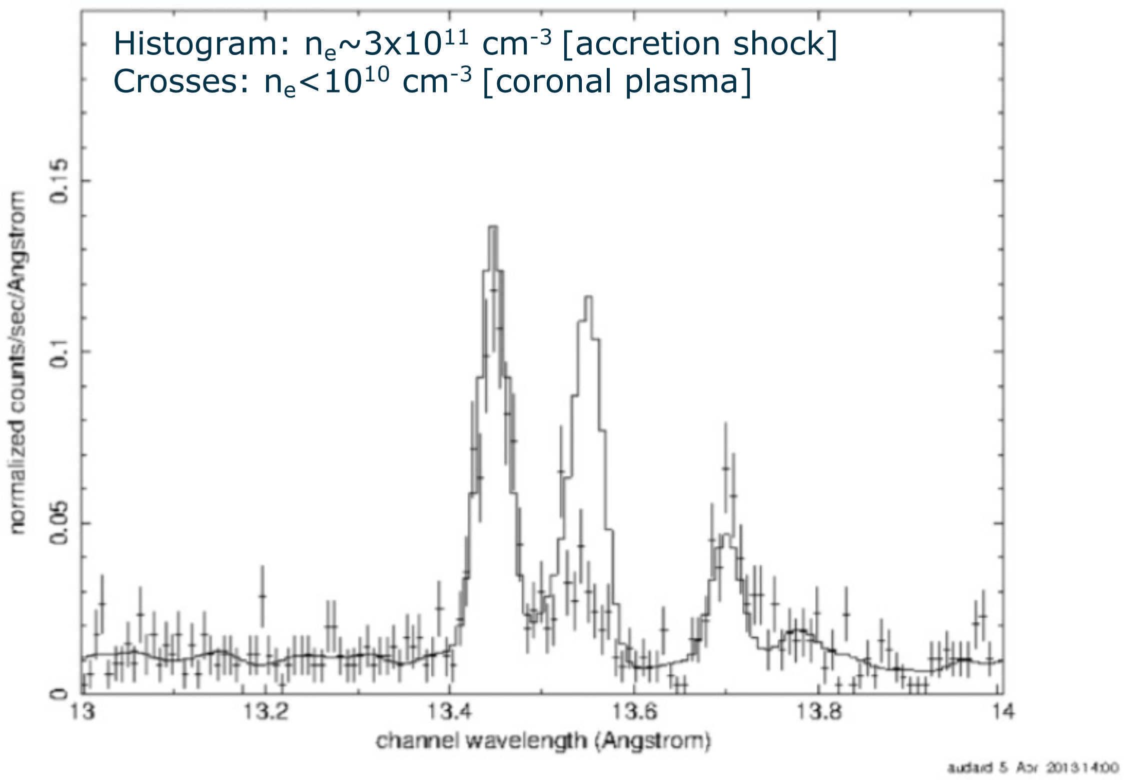
Sciortino et al., 2013, arXiv:1306.2333

Discriminating between coronal and accretion shock X-rays through:

TW Hya (~50 pc) – 1ks X-IFU



BPTau@Orion (~500 pc) – 50ks X-IFU



Time-resolved density evolution of bright/nearby objects

Average density determination for farther/weaker objects

Stellar winds in massive stars

Sciortino et al., 2013, arXiv:1306.2333

- Massive stars exhibit winds - $v>10^3$ km s^{-1}

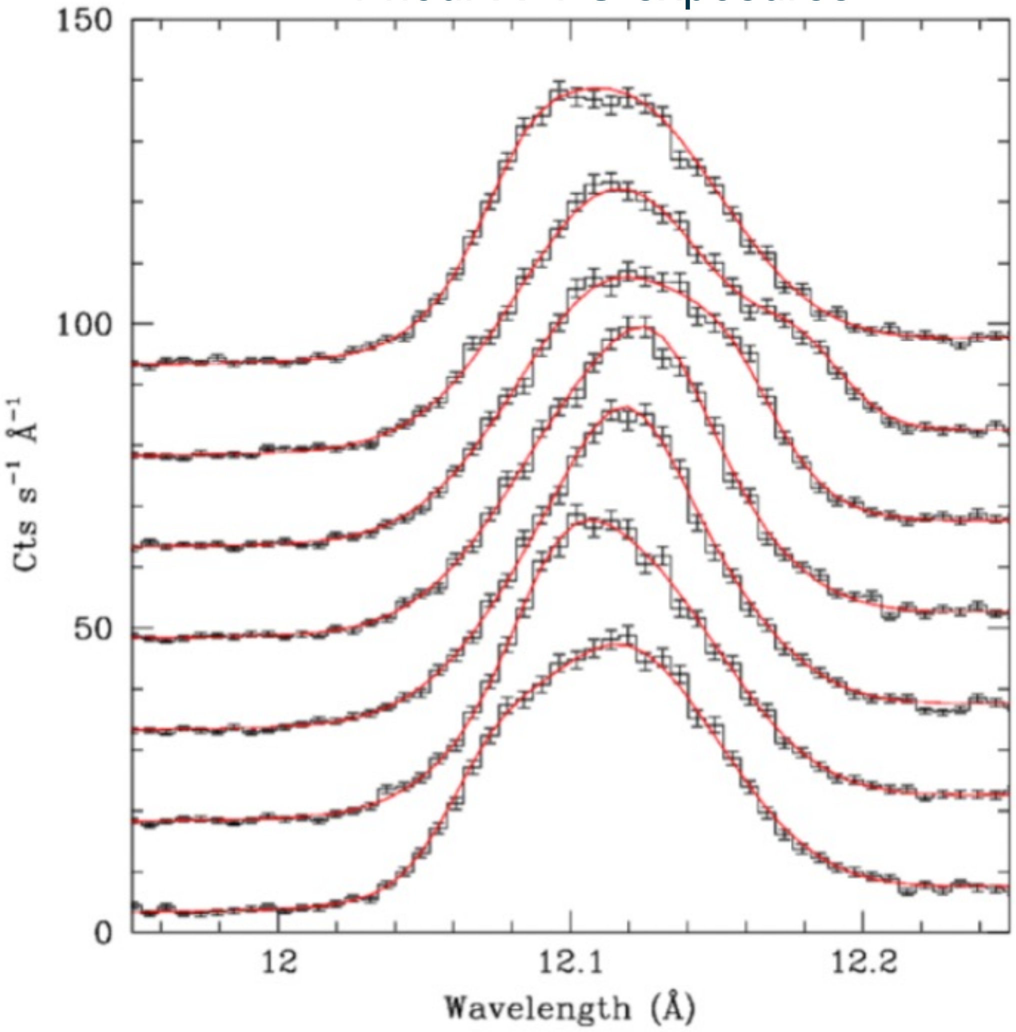
- Small- and large-scale wind structure
  - Hampers accurate determination of mass loss rates

- Current X-ray spectrometers provide constraints on the wind structure only on a few bright sources
[*e.g.*, ζ Puppis, 700 ks RGS, Hervé et al., 2013, A&A, 551, 83]

- Line modulation by co-rotating wind (expected) only hinted in current data

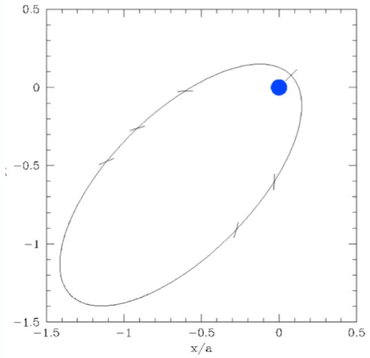
- **X-IFU opens the way** to:
  - Enlarging the star sample
    - For compact object binaries: Lomaeva et al. 2020, A&A, 614, 144
  - Time-resolved spectroscopy

ζ Puppis – NeX Lα line
1 hour X-IFU exposures



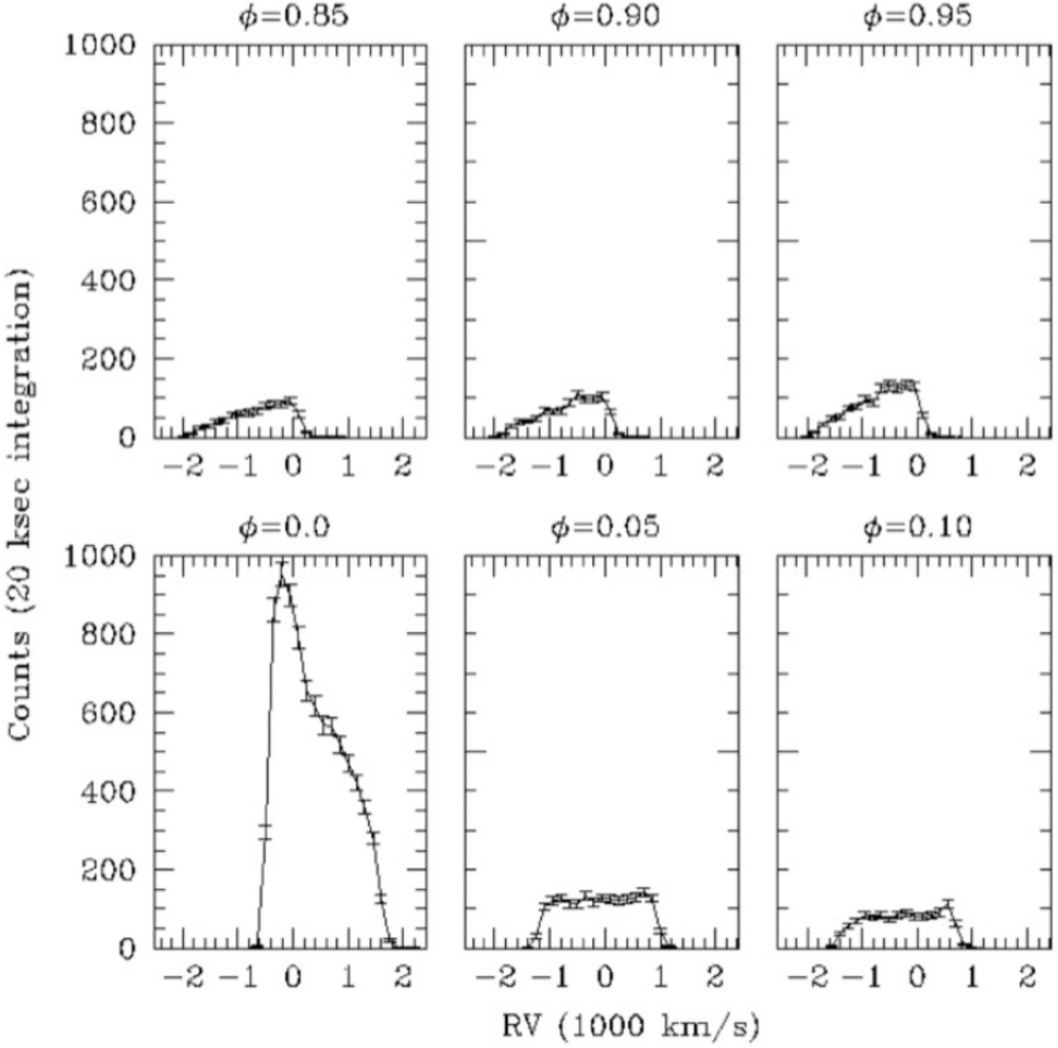
Colliding winds in binary systems

Sciortino et al., 2013, arXiv:1306.2333



- ≥50% of O-type stars are in binaries
- Laboratory of shock physics in region of wind-wind interaction
- Emission line orbital changes probe geometry and physics of the shock and post-shock regions

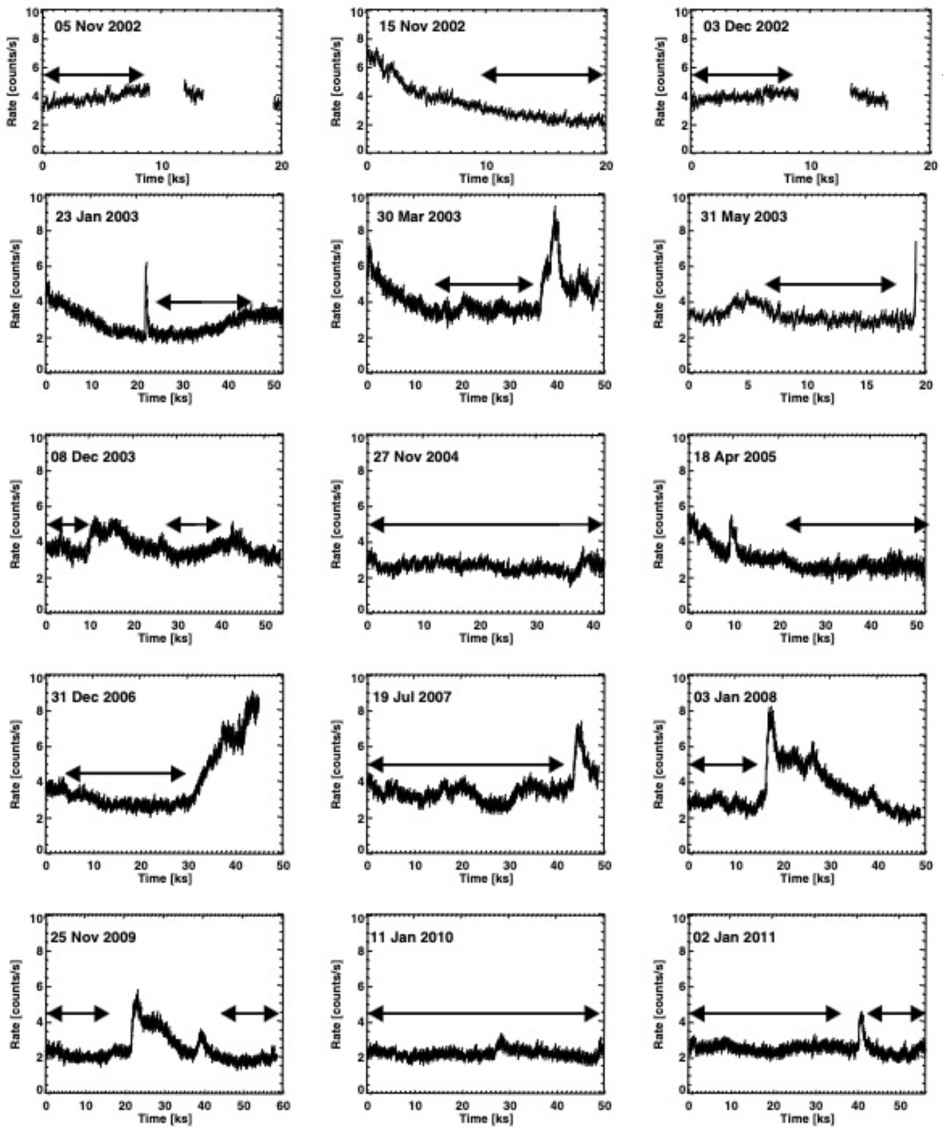
WR40 – X-IFU 20 ks



Plasma dynamics in stellar flares

Lalitha & Schmitt, 2013, A/A, 559, 119

Sciortino et al., 2013, arXiv:1306.2333

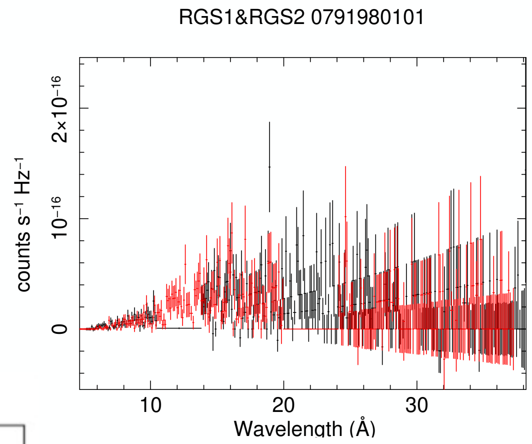


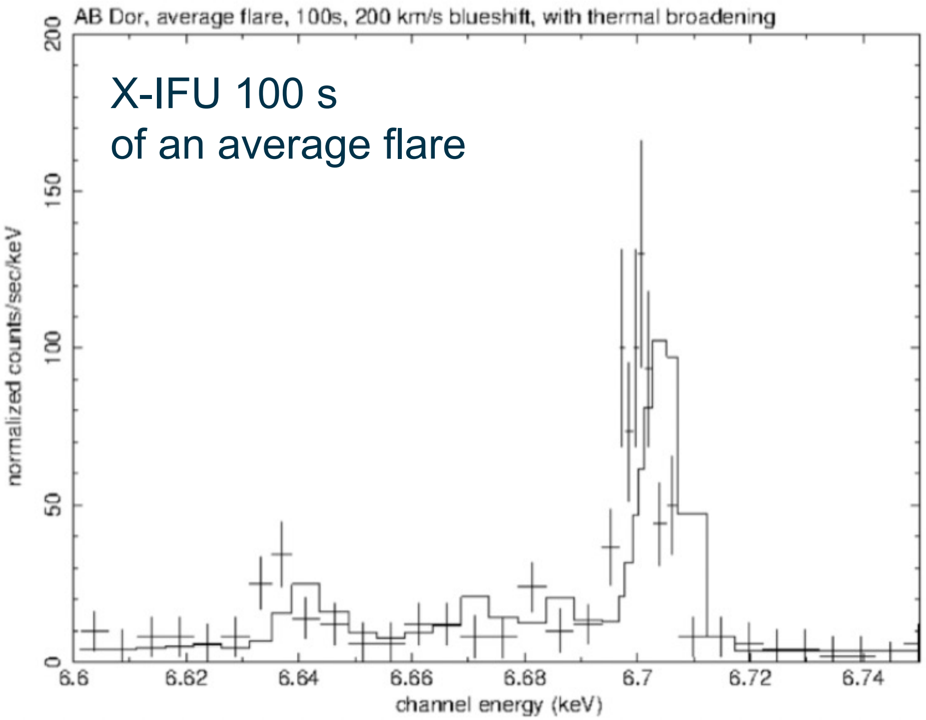
ABDor RGS

Light curves

100 s spectrum: pure noise!

[credit: A. Ibarra (ESAC)]

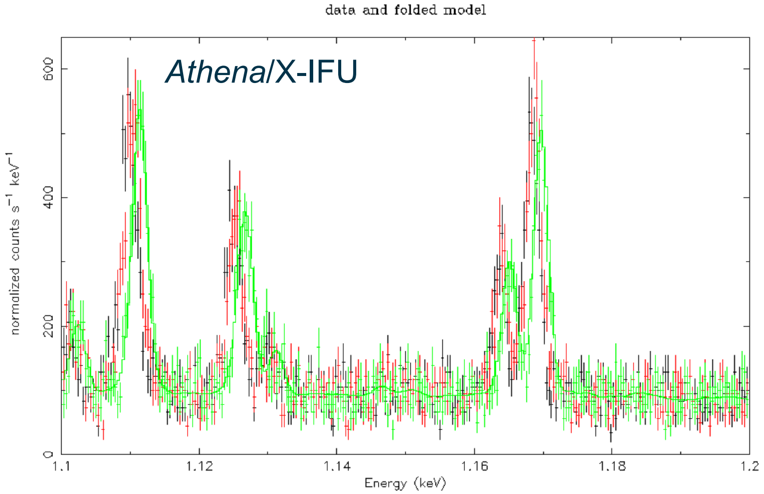


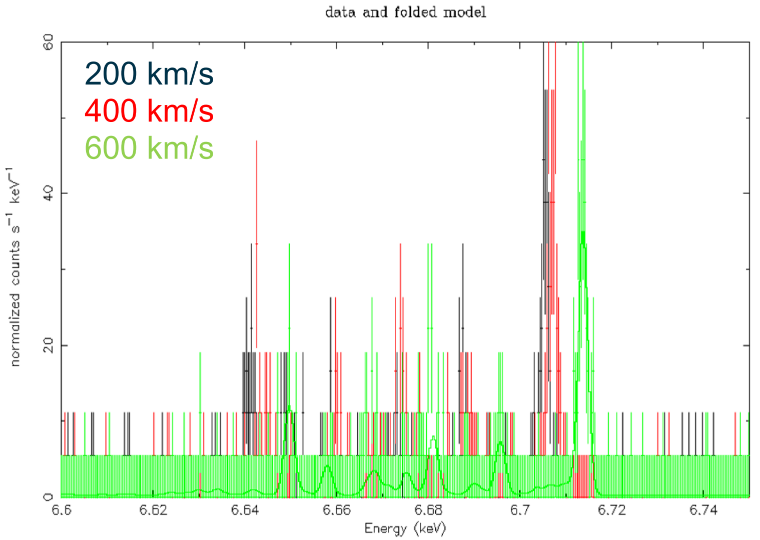


X-IFU enables measurements of density, abundance, velocities

Planet-induced stellar activity interactions

Credit: R. Osten (STScI) based on Pillitteri et al. (2022)

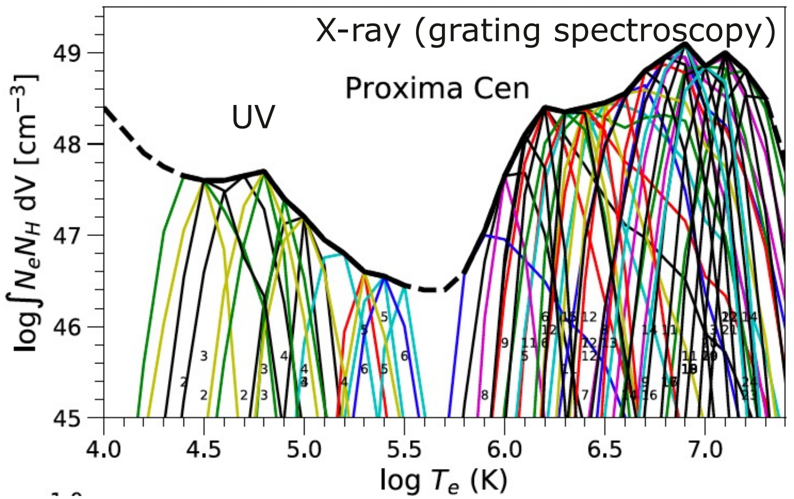


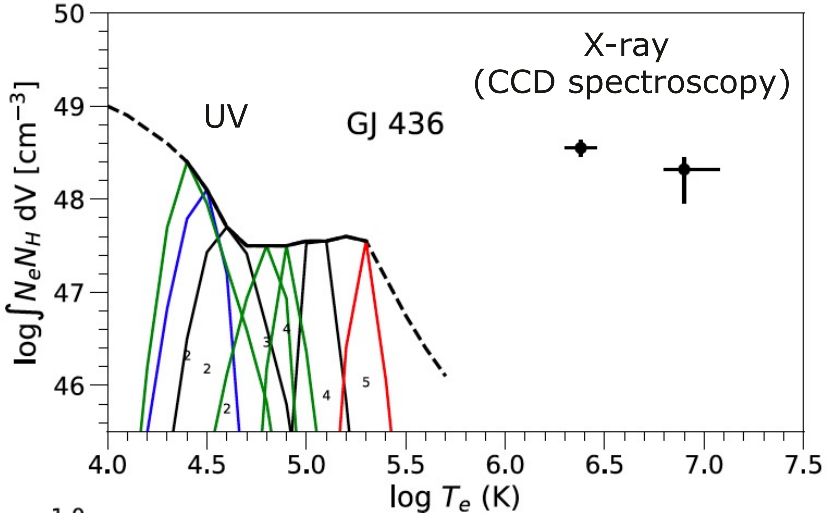


- Exploration of stellar flares (potentially) triggered by planet interactions
- Requires time-resolved spectroscopy over the dynamical flare time-scales (typically beyond current capabilities)
- Magnetic reconnection events? "Triggered flares"?
  1. Comparison against flares in non-planet hosting system and;
  2. Magnetohydrodynamic simulations
- HD189733 (8 years of XMM-Newton monitoring): flares around planetary eclipses more energetic than around primary transit [Pillitteri et al., 2022, A&A, 660, 75]
- **Low-hanging fruit** for X-IFU (cf. T_{exp}=500 s simulations)

Exoplanets photo-evaporation

UV/X-rays Emission Measure Distributions (EMDs)





- XUV (EUV+X) photons [5-920Å] may ionize common elements in planet atmospheres:
  - planet photoevaporation
  - inflated atmospheres (more prone to CME impact)

- However, dearth of EUV data

- Solution: extrapolate EUV from X-rays through:
  - Line-based EMDs (Proxima Cen, rare)
  - UV plus X-ray CCD (GJ436)
  - X-ray-only EMDs
  - Scaling-law between L_X and L_{EUV}
    [e.g., Johnston et al., 2021, A&A, 649, 96]

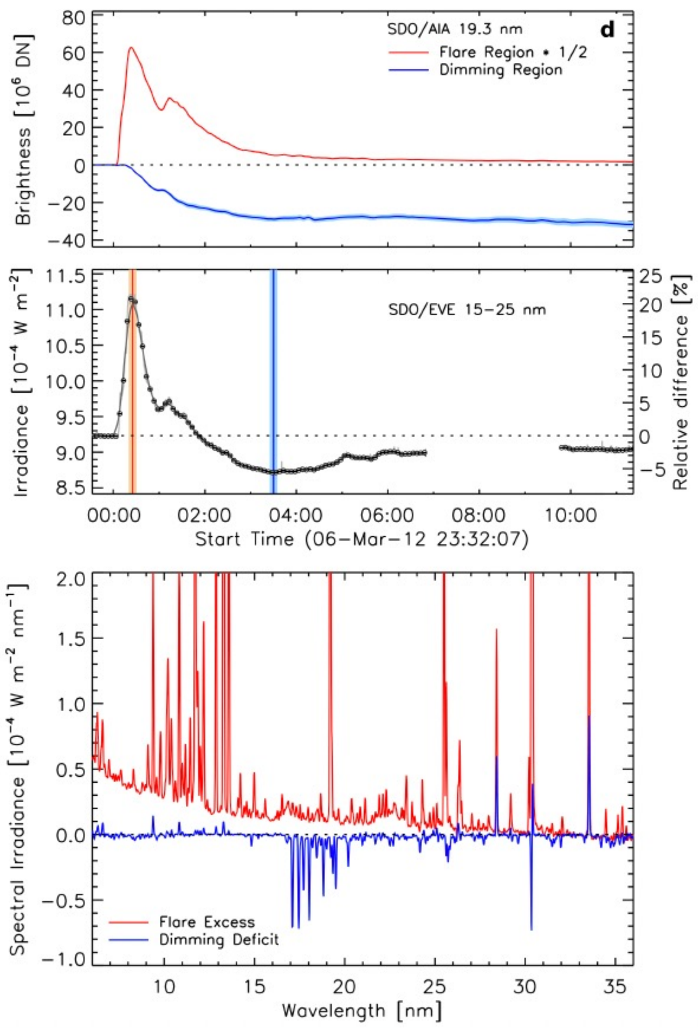
  more accurate → less accurate

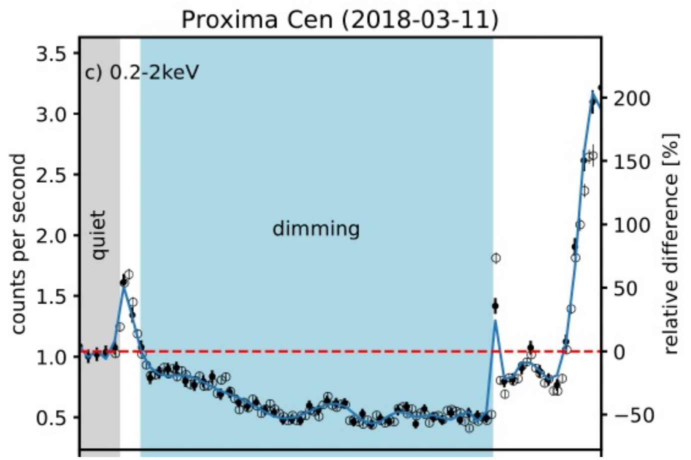
- **Key area for** a high spectral resolution, large area X-ray spectrometer such as **X-IFU**

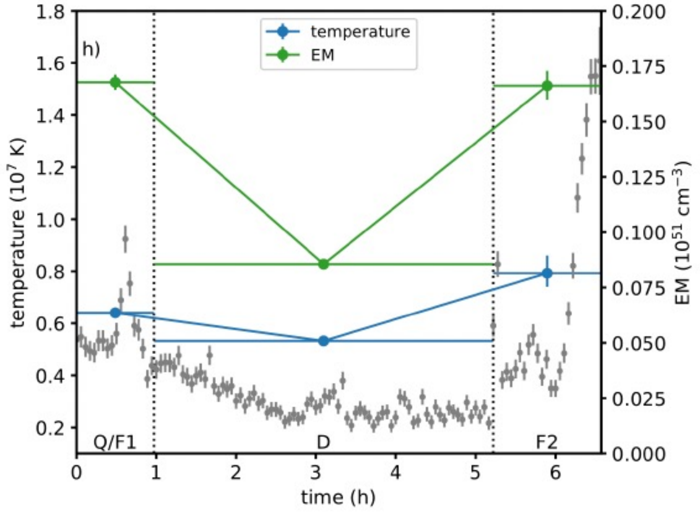
Coronal Mass Ejection-related coronal dimming

Veronig et al., 2021, NatAst, 5, 697

Sun





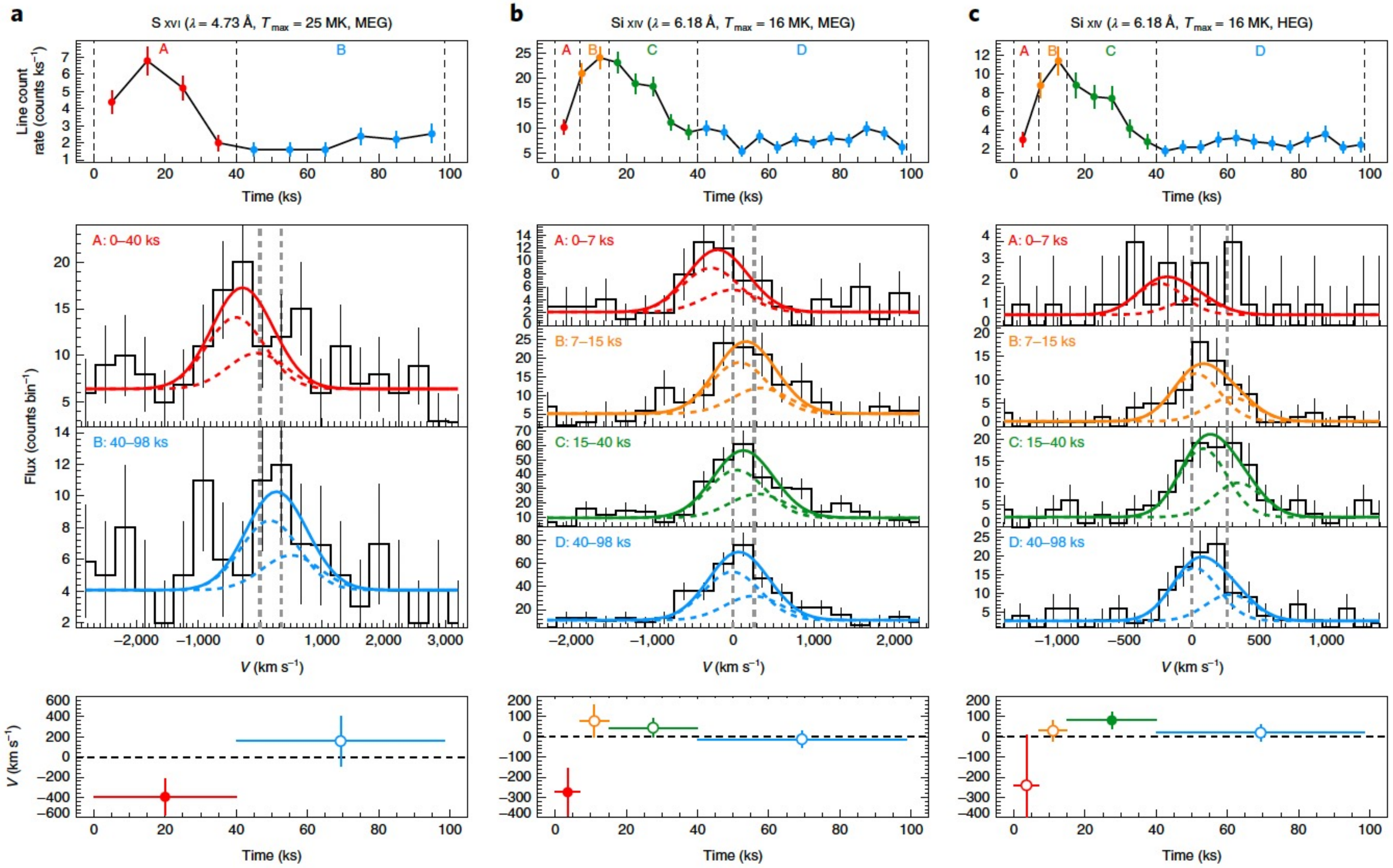


- CMEs are a potential hazard to habitabily
  - [… also important to understand star mass and momentum losses in the stars themselves]
- Only indirect evidence for CME ejection in stars so far
  - *e.g.*, increased N_H during flares
    [Schmitt & Favata, 1999, Nature, 401, 44]
- Coronal dimming following a flare signature of CME mass loss at loop footprints in the solar case
  - P(CME|dimming) ~ 97%
- Emission Measure reduction during dimming indicative of mass loss
- *Line* dimming in XUV observation of the Sun: **X-IFU territory for stars (hotter coronae)**!

Direct X-ray spectroscopic evidence for CMEs?

Argiroffi et al., 2019, NatAST, 3, 742; see also Chen et al., 2022, ApJ, 933, 92

HR9024, Chandra/HETG



- Search for outflows associated to flares with velocities larger than the escape velocity (v_{esc})
- A couple of examples with the *Chandra* gratings so far
- Velocity measurements enable determination of CME mass and kinetic energy → quantitative assessment of the hazard to exoplanet habitability
- **Low-hanging fruit for X-IFU**

[Great results, but note the huge error bars!]

Systematic studies of planet-induced stellar activity

- Stars with close-in giant planets are ~4 times more X-ray active than with more distant planets
  - *Chandra*, 46 stars, $f_X \geq 2 \times 10^{-14}$ cgs, $d \leq 2.9$ kpc [Kashyap et al., 2008, ApJ, 687, 1339]
- Positive correlation between X-ray luminosity and projected mass of the closest exo-planet
  - ROSAT, 42 stars, $f_X \geq 6.5$x10-13 cgs, $d \leq 100$ pc [Scharf, 2010, ApJ, 722, 1547]
- No significant correlation of X-ray luminosity or activity with planets parameters
  - ROSAT+XMM-Newton, 56 stars, $L_X > 10^{26}$ erg s^{-1}, $d \leq 30$ pc [Poppenhager et al., 2010, A&A, 515, 98]
- Higher-magnetic activity of the planet-hosting star in 2 out of 5 binaries
  - Chandra+XMM-Newton, $L_X > 10^{26}$ erg s^{-1}, $d \leq 270$ pc [Poppenhager et al., 2014, A&A, 565, L1]

The ROSAT All-Sky Survey contain ≥40000 F-M stars with $f_X \geq 2 \times 10^{-13}$ cgs

The stellar context of a *Chandra* COSMOS 0.9 deg^2 field is ~60 F-M stars with $f_X \geq 2.5 \times 10^{-16}$ cgs

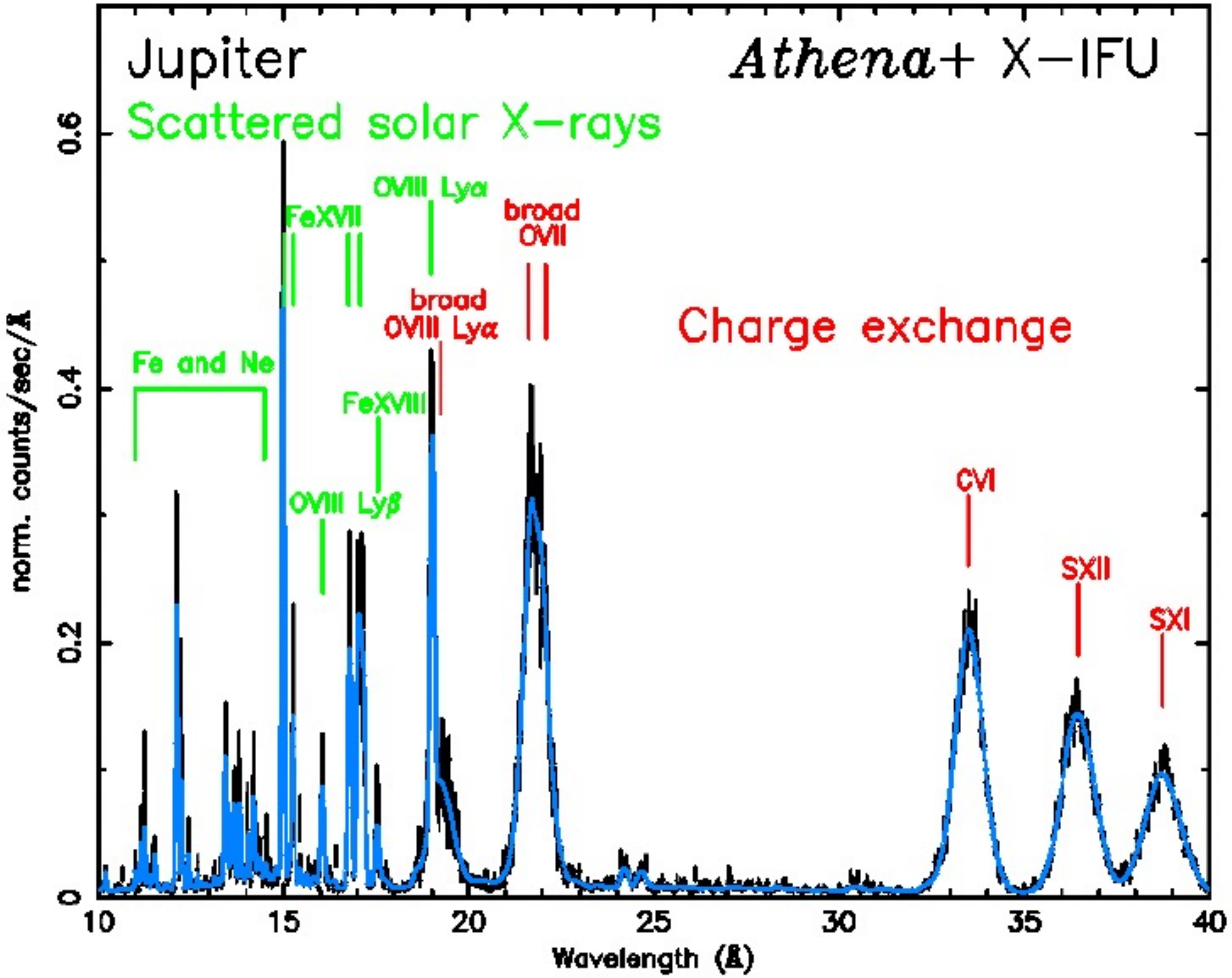
By comparison, the [New]Athena confusion limit is $f_X \sim 2 \times 10^{-16}$ cgs

Detection of Charge Exchange (CX)

Branduardi-Raymont et al., 2013, arXiv:1306.2332

Recent XMM-Newton results

- Auroral CX in Jupiter probes the plasma dynamics [v~5000 km s^{-1}]
  - Origin: Solar wind? Io's vulcanoes? *Athena* needed to ascertian it
- Solar Wind CX in the Mars exosphere
  - *Athena* can probe it in different seasons and under different wind conditions
- Solar system measurements exploit the non-dispersive nature of X-IFU (not relevant for exoplanets)
- Possible *Athena* stellar targets already identified: εEri, GL876



Other *Athena* topics (list for future reference)

- Reverberation mapping of accretion disks in Young Stellar Objects (fluorescent Fe line)
- Probing X-ray emission (proxy for dynamo mechanism) in Ultra-Cool Dwarfs
- Doppler mapping of magnetically-confined stellar winds in massive stars
- Enebling detection of weak winds in B stars, Wolf-Rayet sraes, Luminous Blue Variables
- Extend stellar studies to the Magellanic Clouds → impact of metallicity on the physics of stellar winds
- Planet transients
  - Differential X-ray vs. optical obscuring radius in a radiation-field expanded atmosphere
- Planetary nebulae (plasma temperature, metallicity, wind interactions with ISM)

To know more, refer to the *Athena* proposal White Papers:

- Sciortino et al., 2013, arXiv:1306.2333 (stars)
- Branduardi-Raymont et al., 2013, arXiv:1306.2332 (planets and exoplanets)

Athena is no more – Long life to NewAthena!

- ***Athena* was terminated in June 2022** – deemed to be too expensive for ESA

- The Science Programme Committee (SPC) mandated ESA to **study a new mission concept (“NewAthena”)**
  - Cost-bounded (to ESA) ≤1.3×10^9 €
  - Retaining science capabilities commensurate to a ”flagship mission”

- In March 2023, ESA announced that **such a new technical concept has been identified**
  - Pending ”programmatic consolidation” by the November 2023 SPC meeting

- In December 2022 ESA appointed a **“Science Redefinition Team”** to advise on NewAthena science:
  - Definition of NewAthena science objectives and requirements (constrained by affordability)
  - Confirmation that NewAthena is a “flagship mission” (TBD) – report scheduled for **June 2024**
  - Full review of the *Athena* science case completed in March 2023
  - Validation of the mission profile on a small number of “Mission-driving science objectives” ongoing

The transition *Athena* to NewAthena

NewAthena will achieve:

- An effective area at 1 keV 70-100% that of *Athena*
- An angular resolution (Half-Energy Width on-axis) between 5″ (*Athena)* and 9″
- An X-IFU 7 keV energy resolution between 3 and 4 eV (2.5 eV in *Athena*)
- An X-IFU Field-of-View (FOV) of 4′ diameter (5′ in *Athena*)
- A WFI FoV between 40′x40′ (*Athena*) and 30′x30′
- A WFI background level between 5 (*Athena*) and 8×10^{-3} cts s^{-1} keV^{-1} cm^{-2}
- A background knowledge ≤5% (≤2% in *Athena*)
- A Field-of-Regard (FoR) between 34% and 40% (50% in *Athena*)
- A Target-of-Opportunity (ToO) response ≤12 hours (≤4 hours in *Athena*)

Most of the *Athena* science objectives remain achievable with NewAthena

Quantitative impact being assessed by the SRDT (until October 2023)

Take-home messages

- Despite the 2022 affordability crisis, an *Athena*-like mission is **still under consideration by ESA**
  - ESA has identified e new technical concept – Phase A could restart in 2024
  - A shorter implementation phase (≤9 years) could (partly) offset the delay induced by the crisis

- *Athena* enabled a wide range of transformational experiments in almost all fields of modern astrophysics
  - Stellar science: origin of soft X-ray emission in YSOs, stellar winds and colliding winds in binaries, stellar flare plasma dynamics, cool dwarfs, population studies in external galaxies
  - Exoplanexts: star/planets interactions, measurements of habitabiliy hazardous events (atmosphere photoevaporation, CMEs), CX

- NewAthena could retain most of the *Athena* original science objectives

- **The SRDT welcomes any studies and/or contributions strenghening/supporting/enhancing the NewAthena science case!**