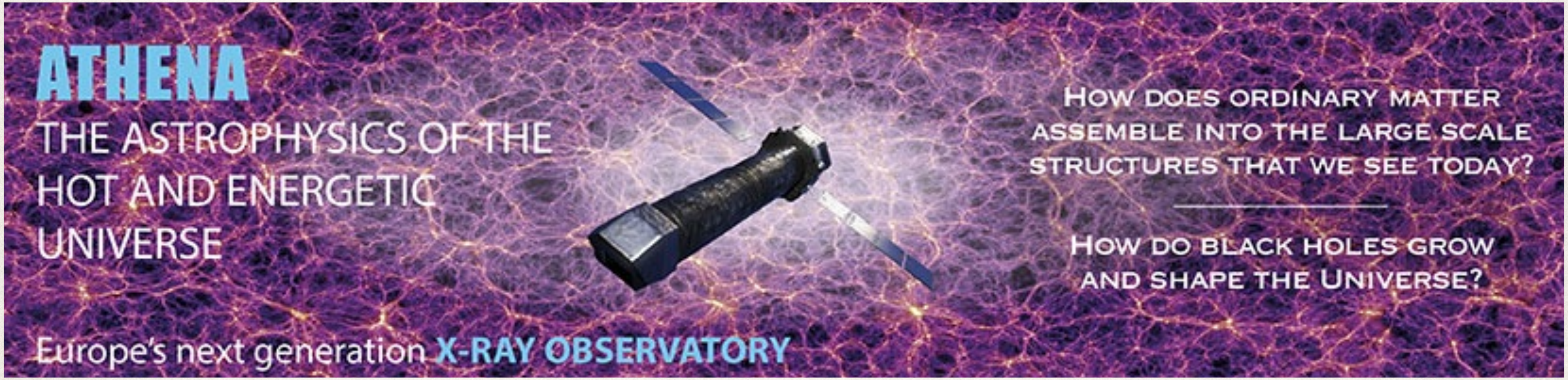


Athena: The first deep Universe X-ray Observatory

François Pajot, IAS, on behalf of the X-IFU collaboration

Date: 11/06/2014 (Colloque LSST France 2014)

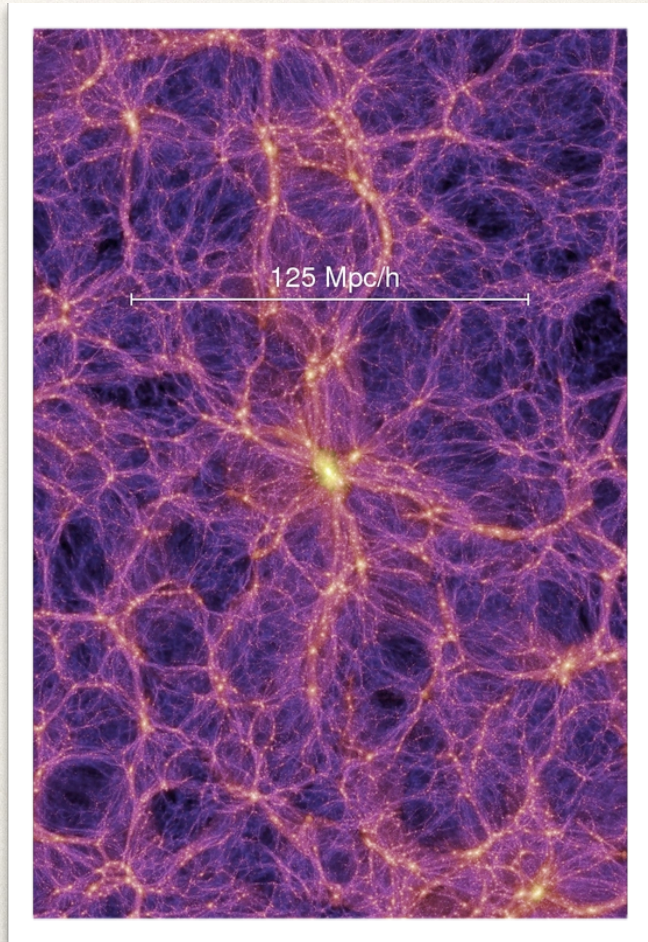
Outline

- The hot and energetic Universe: What is it all about?
- Illustrative breakthrough observations to be performed
- The Athena mission
- The X-ray Integral Field Unit - A revolutionary instrument

The Hot Universe

- How does ordinary matter assemble into the large scale structure that we see today?

  ✓ 85% of the baryons in the local Universe are trapped in the hot gas of clusters

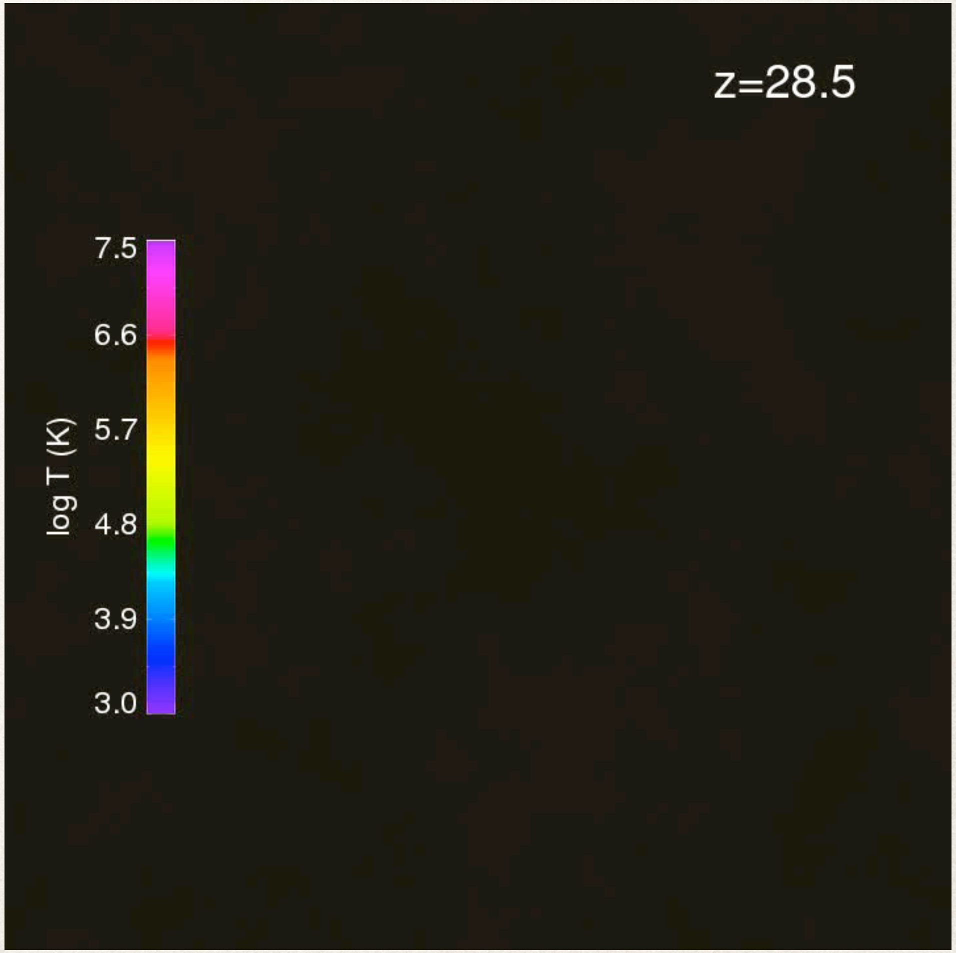


The Hot Universe revealed in X-rays

- To understand the matter assembly in the Universe, one must determine the physical evolution of clusters and groups from their formation epoch at z~2 to today

- These structures grow over cosmic time by accretion of gas from the intergalactic medium, ending up as the massive clusters that we see today

- Hot gas in these structures emits predominantly in X-rays and dominates the baryonic content of the local Universe



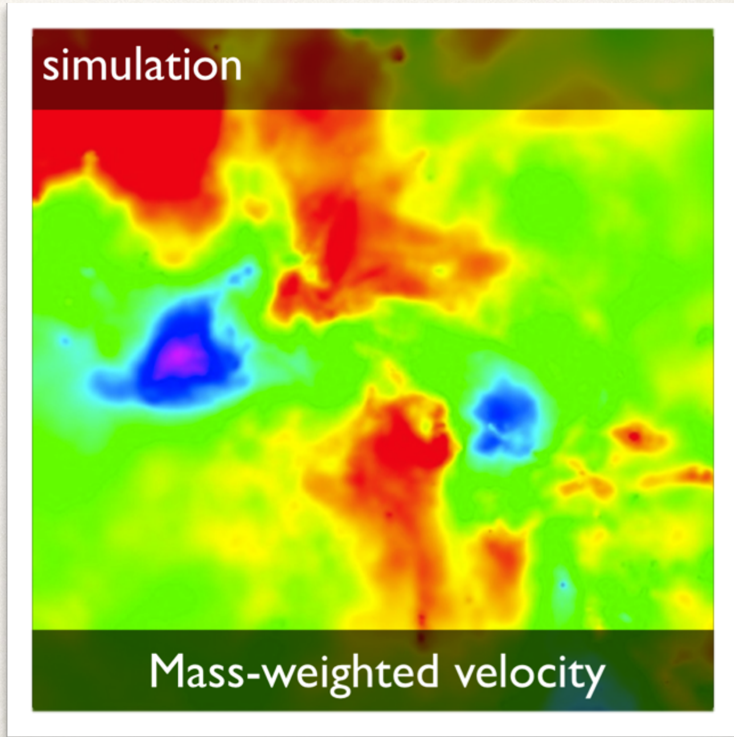
(Oppenheimer, B. D.)

The Hot Universe

- While the growth of structure is set by the large scale dark matter distribution, processes of astrophysical origin have also a major effect

- To understand them, it is necessary to measure velocities, thermodynamics, chemical composition of the gas, to quantify the role of non gravitational heating (AGN feedback, SN driven winds, ..)

  ✓ Spatially resolved high-resolution X-ray spectroscopy enables to map the baryonic structures out to z~1

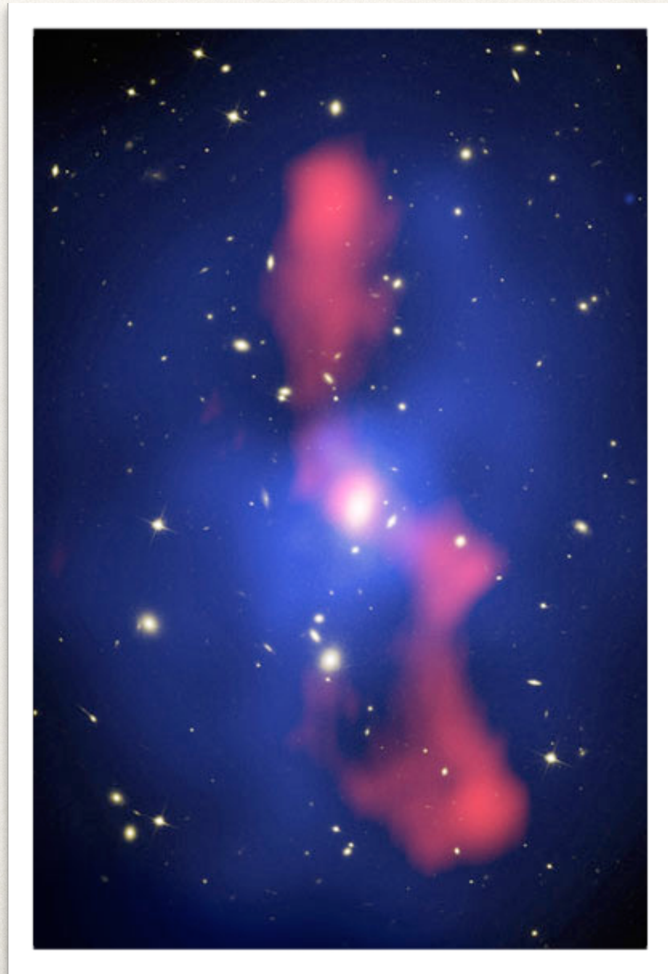


The Hot Universe

- One of the critical processes shaping the baryonic evolution is energy input, also know as feedback from supermassive black holes

  - ✓ Processes originating at the event horizon affecting structures on scales 10 orders of magnitude larger !

- X-ray observations are again key as they probe the mechanisms launching jets and winds from the black hole

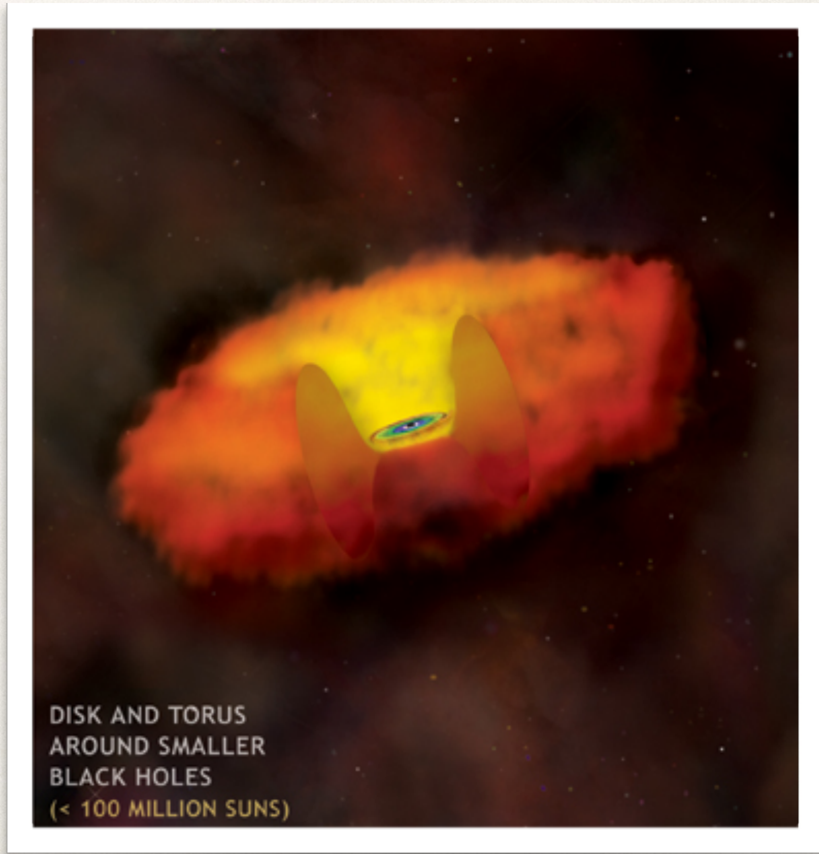


The Energetic Universe

- How do black hole grow and shape the Universe?

  ✓ Building a super massive black hole releases 10-100 times the binding energy of a galaxy

  ✓ 15% of the energy output in the Universe is from accretion onto black holes



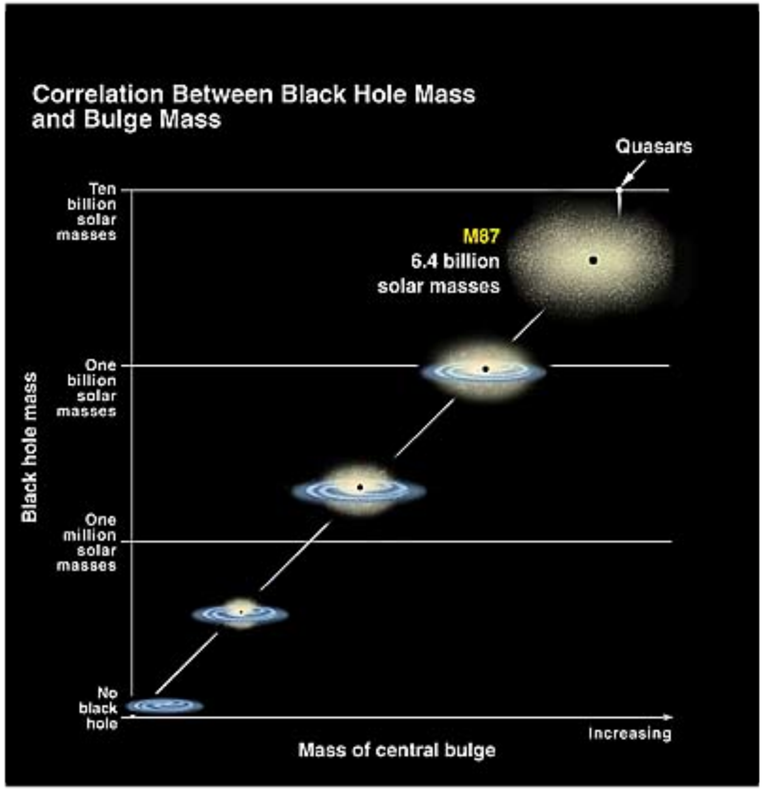
The Energetic Universe

- All massive galaxies, not just those in clusters and groups, host a supermassive black hole (SMBH) at their centre, the mass of which is tightly correlated with the galaxy bulge properties (e.g. via the MBH-σ relation).

  ✓ A self-regulating mechanism connecting the accretion-powered growth of the SMBH to the star-formation powered growth of the galaxy at much larger scales must exist.

  ✓ This process must be probed between z=1-4 when most black holes and stars we see today were put in place

- Determining this feedback mechanism is key to understand the growth and co-evolution of black holes and their host galaxies.



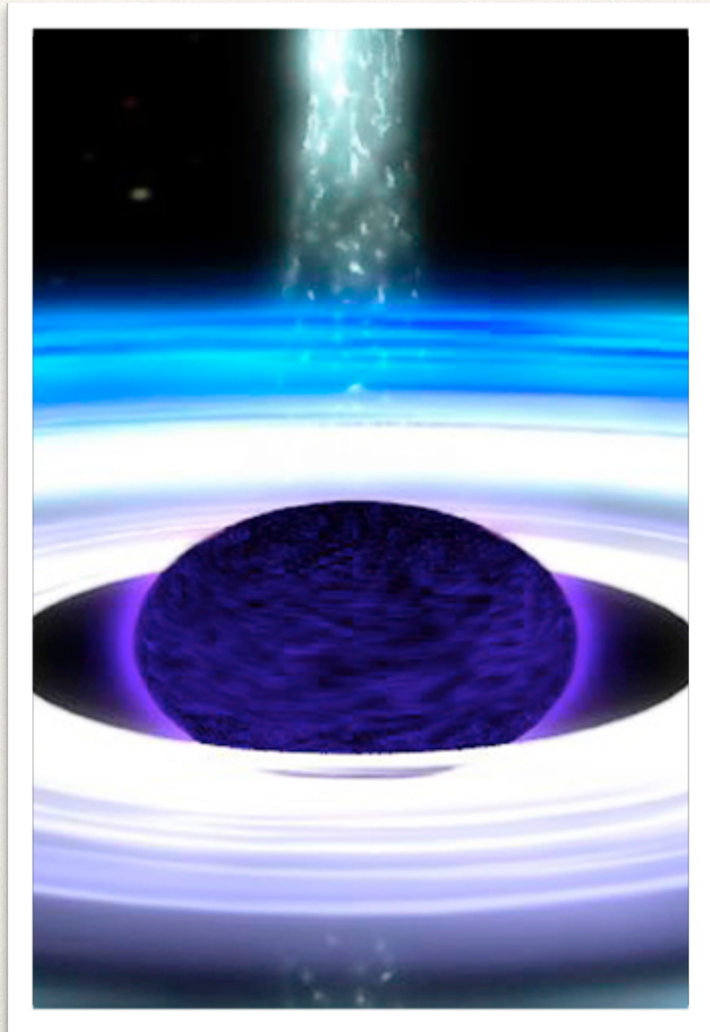
The Energetic Universe

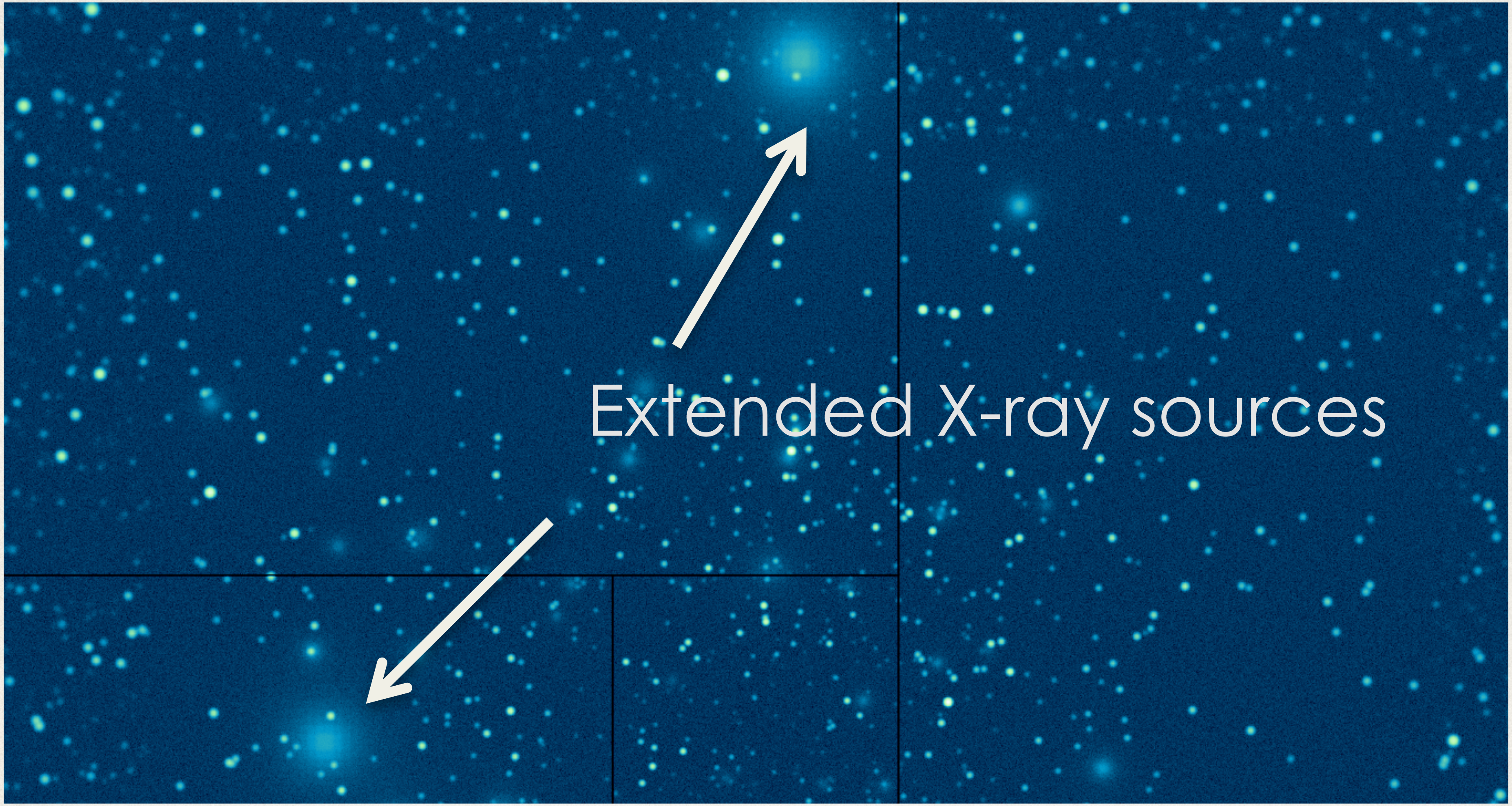
- X-rays provide the clearest and most robust way of performing a census of black hole growth in the Universe, accounting for obscured objects

- On smaller scales, X-rays produced by gravitational energy released near the event horizon of black holes diagnose the accretion flow in the strong gravity regime

  ✓ Give insights on jets, winds, and their link to accretion

  ✓ And provide unique information on BH spins and its evolution as it grows





Illustrative breakthrough observations

The Hot Universe

Key questions for the Hot Universe

- A complete understanding of the Hot Universe - the baryonic gas that traces the most massive structures and drives the formation of galaxies within them - can only be achieved via X-ray observations.

- Key questions are:

  ✓ How do baryons in groups and clusters accrete and dynamically evolve in the dark matter haloes?

  ✓ What drives the chemical and thermodynamic evolution of the Universe's largest structures?

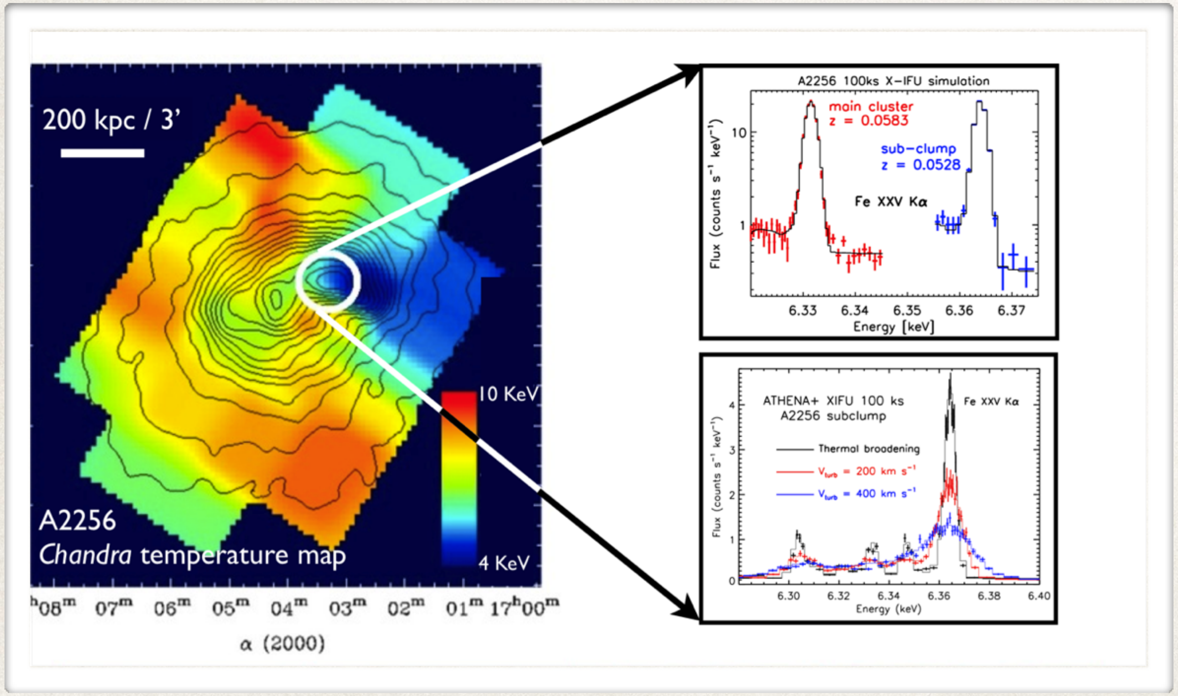
  ✓ What is the interplay of galaxy, supermassive black hole, and intergalactic gas evolution in groups and clusters?

  ✓ Where are the missing baryons at low redshift and what is their physical state?

Cluster astrophysics: baryonic evolution

***Key issue*: Understand how baryons accrete and evolve in the largest dark matter potential wells of groups and clusters.**

***Key measurement*: Measure the gas bulk motions and turbulence through high spectral resolution spatially resolved spectroscopy.**



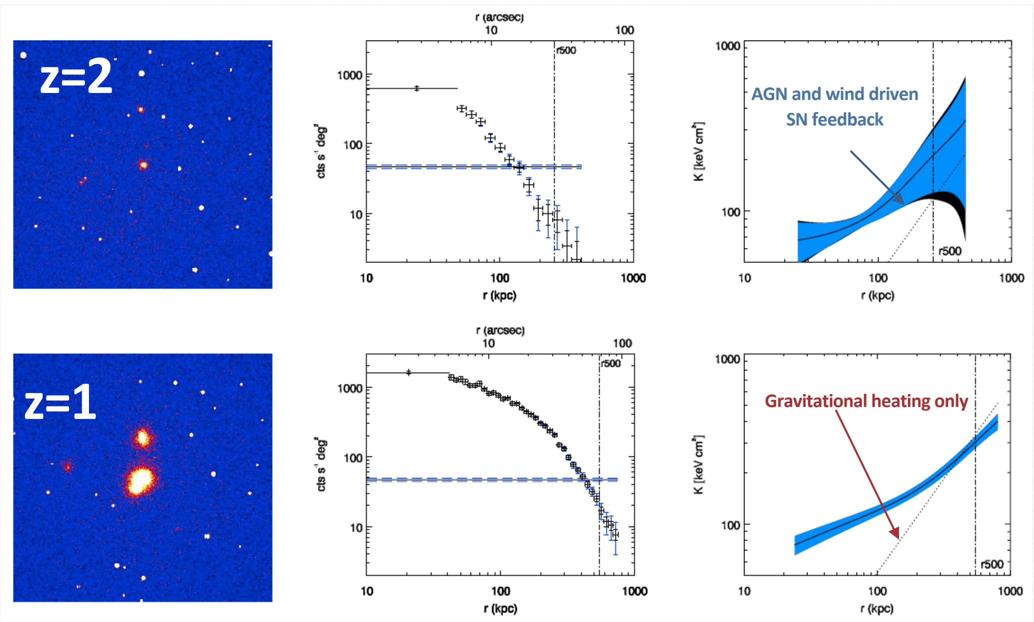
Captions: **Bulk motion and turbulent broadening of the Iron K line centered on the sub-clump accreting onto the main body, opening the way to understand how structures assemble. Coupled with lensing observations will show how gas reacts to an evolving dark matter potential.**

Ettori, Pratt, de Plaa, et al. | The Hot and Energetic Universe: The astrophysics of galaxy groups and clusters | 2013arXiv1306.2322

Cluster astrophysics: energy deposition in the ICM

<u>Key issue</u>: Determine how and when the energy contained in the hot intracluster medium was generated.

<u>*Key measurement*</u>: Map the structure of the hot gas trapped in galaxy clusters at various redshifts out to the virial radius, resolving gas density and temperature.



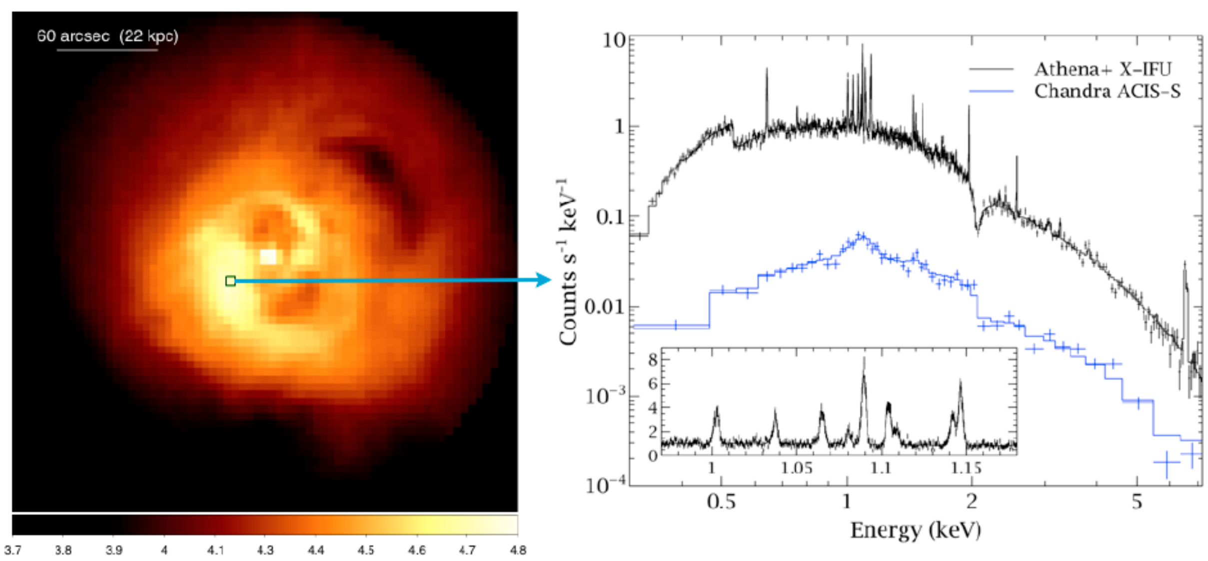
<u>Captions:</u> Left) X-ray images of a cluster at two redshifts. Middle) Surface brightness profile, to recover the gas density profile. Right) Entropy profiles derived the gas density profile and electron temperature. Entropy profile derived from numerical simulations with only gravitational heating processes are shown with a doted line.

Pointecouteau, Reiprich, Adami, et al., | The Hot and Energetic Universe: The evolution of galaxy groups and clusters, | 2013arXiv1306.2319P

Cluster astrophysics: jet energy dissipation

***Key issue*: Understand how jets from AGN dissipate their mechanical energy in the intracluster medium, and how this affects the hot gas distribution. Determine whether jets from powerful radio-loud AGN are the dominant non-gravitational process affecting the evolution of hot gas.**

Key measurement: **Measure hot gas bulk motions and energy stored in turbulence directly associated with the expanding radio lobes in the innermost parts of nearby clusters. Map temperatures in radio-loud AGN out to intermediate redshifts and map shock structures.**



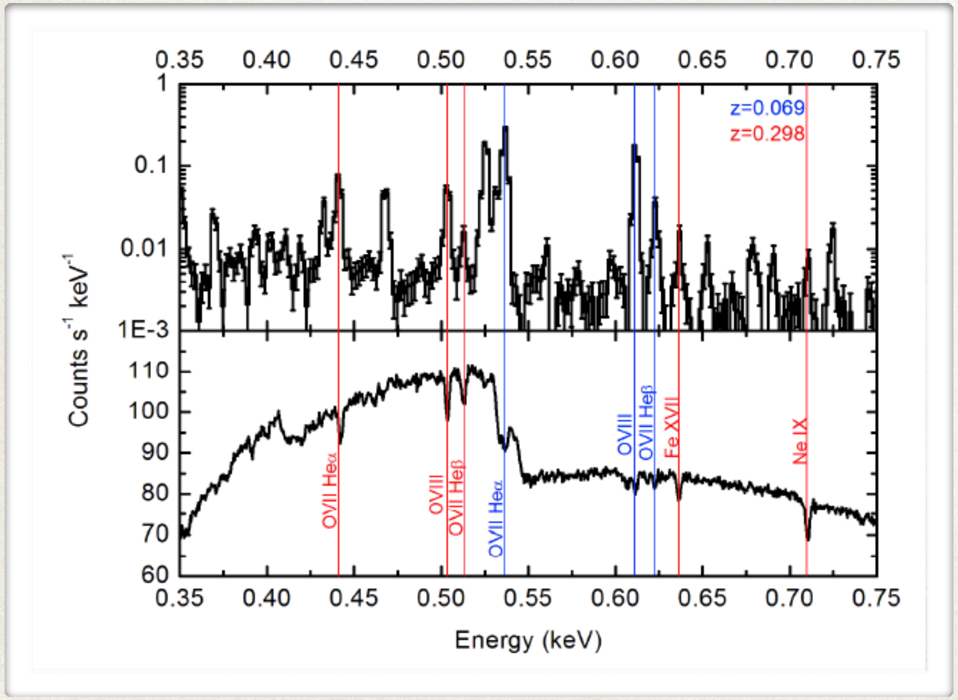
Captions: **Simulated Athena+ observations of the Perseus cluster. The spectrum on the right is from the single 5"×5" region marked by the box, with the existing Chandra ACIS spectrum for comparison. The inset shows the region around the iron L complex.**

Croston, Sanders, Heinz, et al. | The Hot and Energetic Universe: AGN feedback in galaxy clusters and groups | 2013arXiv1306.2323

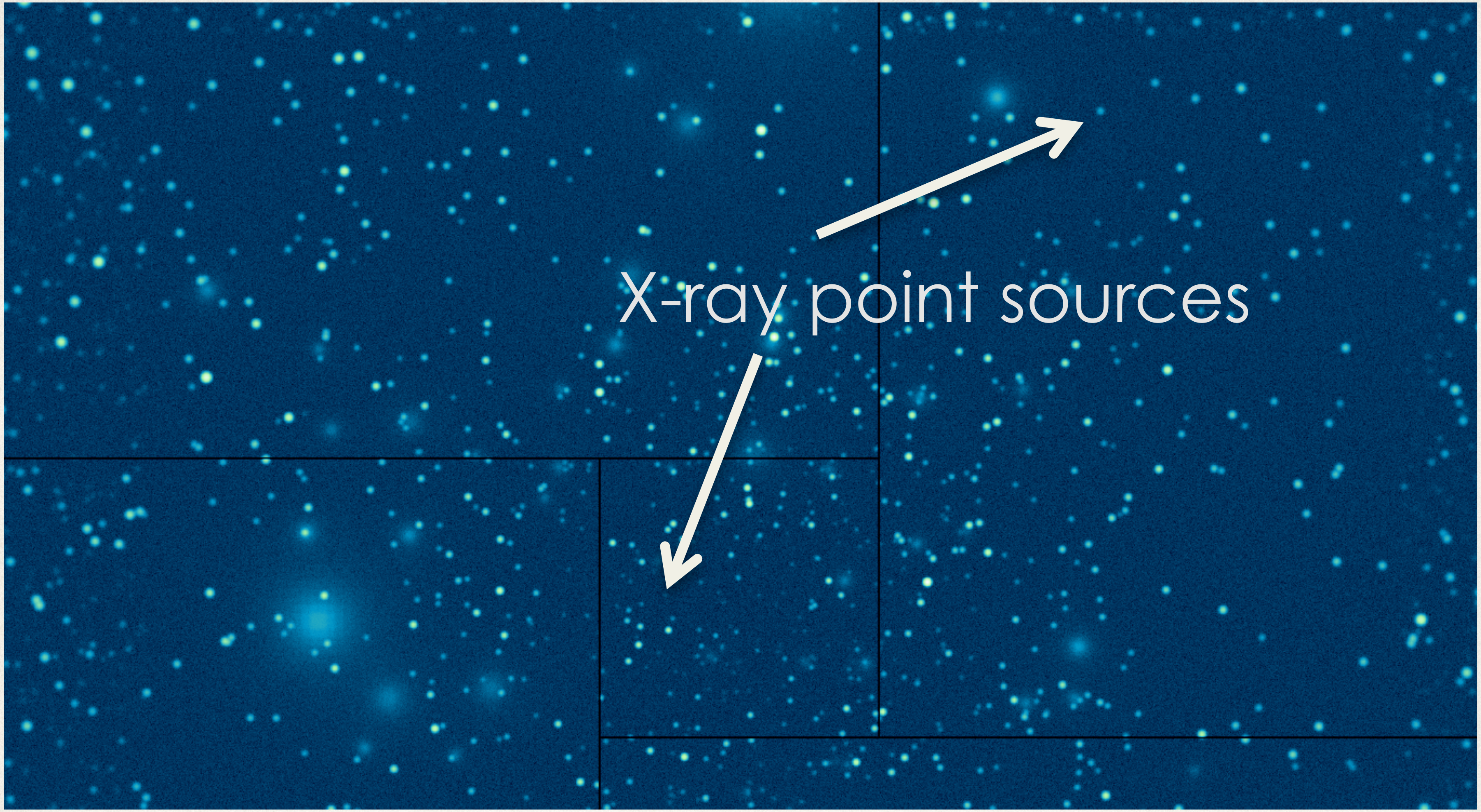
The missing baryons

***Key issue**: As a probe of structure formation and metal enrichment theory, find the missing baryons at low redshifts (z<1), determine their physical state and composition, and identify wether they trace filaments of the Cosmic web, as predicted.*

Key measurement: **Detect highly ionized species (C, N, O, Ne, and Fe) in high resolution X-ray spectra to measure their chemical composition, density, size, temperature, ionization and turbulence.**



Captions: Simulated emission and absorption line spectra for two filaments at two different redshifts. The absorption spectrum is produced by illumination of the filaments by a strong background source (quasar or bright GRB afterglow).



Illustrative breakthrough observations

The Energetic Universe

Key questions for the Energetic Universe

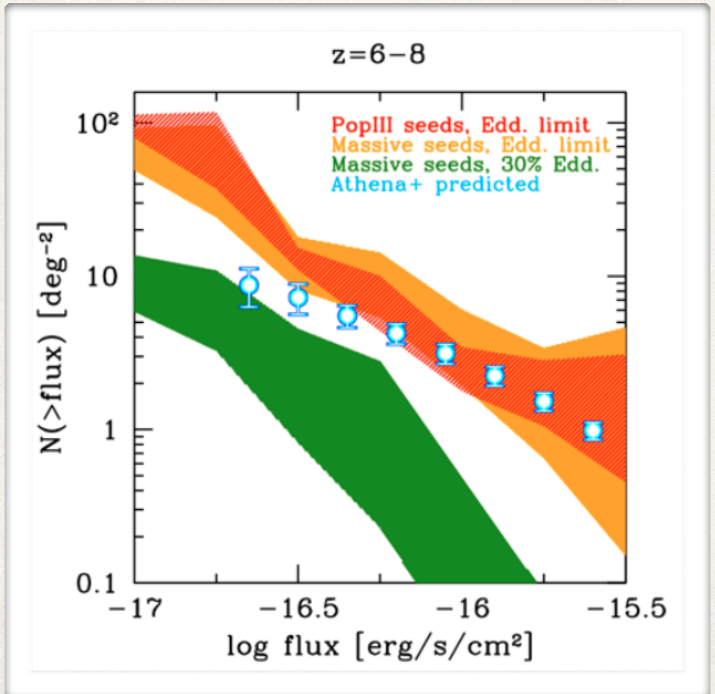
- Pushing the frontiers of black hole evolution at the redshifts when the first galaxies were forming (z>6), performing a complete census of black hole growth, understanding how quasars work and influence their surroundings is best done in X-rays.

- Key questions are:
  - ✓ How do early supermassive black holes form, evolve and affect the distant Universe?
  - ✓ What is the role of (obscured) black hole growth in the evolution of galaxies?
  - ✓ How do accretion-powered outflows affect larger scales via feedback?
  - ✓ How do accretion and ejection processes operate in the near environment of black holes?

Black hole seeds

***Key issue*: Determine the nature of the seeds of high redshift (z>6) SMBH (pop-III seeds versus primordial gas clouds) and which processes dominated their early growth.**

***Key measurement*: Detect low luminosity accreting SMBH, out to the highest redshifts through their X-ray emission in large area X-ray surveys. The most obscured objects will be unveiled by targeted high-res X-ray spectroscopy revealing strong reflected iron lines and follow-up observations.**

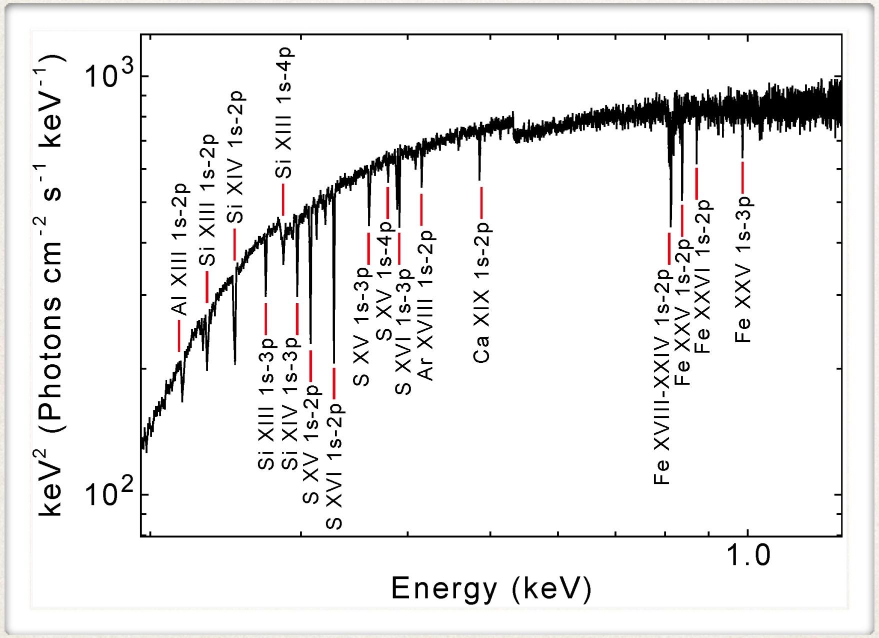


Captions: Expected number counts of z=6-8 AGN from the survey (circles). Note that at present no purely X-ray selected objects have yet been found in this redshift range. The shaded regions show predictions based on theoretical models that differ by black hole formation mechanism and growth rate (Volonteri & Begelman, 2010).

Tracing the first generation of stars

***Key issue*: Trace the first generation of stars to understand cosmic re-ionization, the formation of the first seed black holes, and the dissemination of the first metals.**

***Key measurement*: Measure metal abundance patterns for a variety of ions (e.g., S, Si, Fe) in high-z gamma-ray burst X-ray afterglows as a way to distinguish between progenitors.**

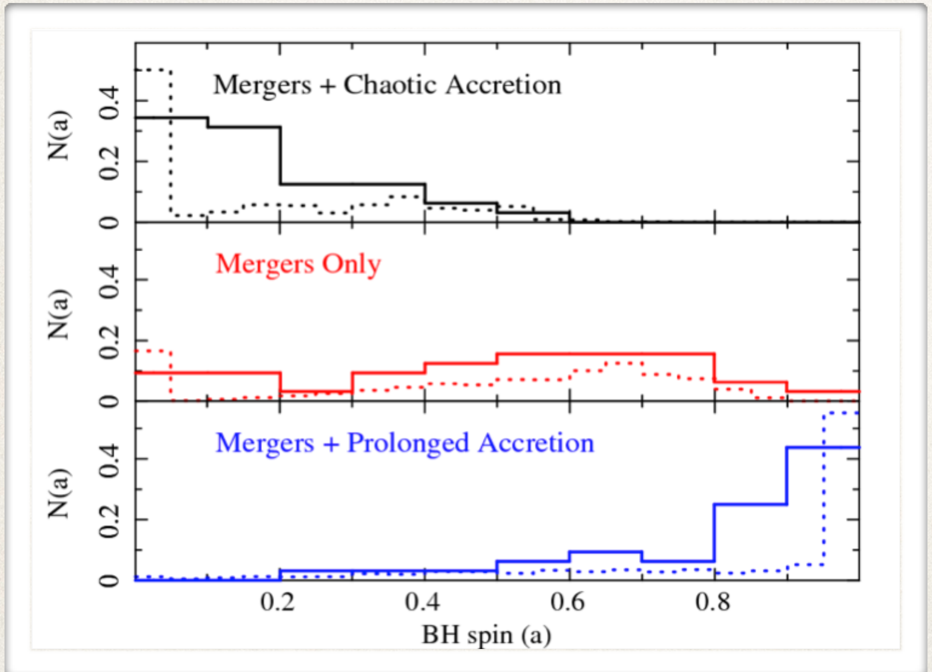


Captions: A simulatedX-ray spectrum of a GRB afterglow at z=7, characterized by deep narrow resonant lines of Fe, Si, S, Ar, Mg, from the ionized gas in the environment of the GRB. The abundance pattern measured by Athena+ can distinguish Population III from Population II star forming regions.

Black hole growth probed by spins

***Key issue*: Infer whether accretion or mergers drive the growth of SMBH across cosmic time.**

***Key measurement*: Measure black hole spins through reverberation, time-resolved X-ray spectroscopy and average spectral methods to perform a survey of SMBH spins out to z~1-2 and compare with predictions from merger and accretion models.**

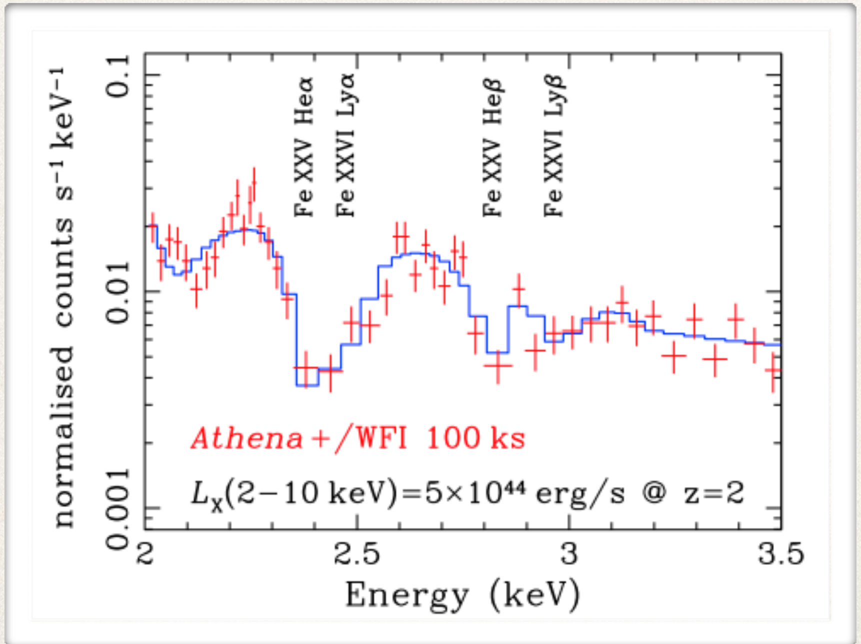


Captions: The theoretical expectations for each SMBH growth scenario (dotted histograms) is shown (Berti & Volonteri 2008) and compared to simulated Athena+ measurements (solid histograms), accounting realistically for all observational errors and spectral complexities.

Blowout phase - feedback in action

***Key issue*: Determine what is the nature of AGN feedback and whether it is key in galaxy evolution.**

***Key measurement*: Determine for a large sample of AGN, the incidence, the nature and the energetics of AGN outflows out to z=4 to test co-evolution scenarios postulating AGN winds for regulating star formation.**

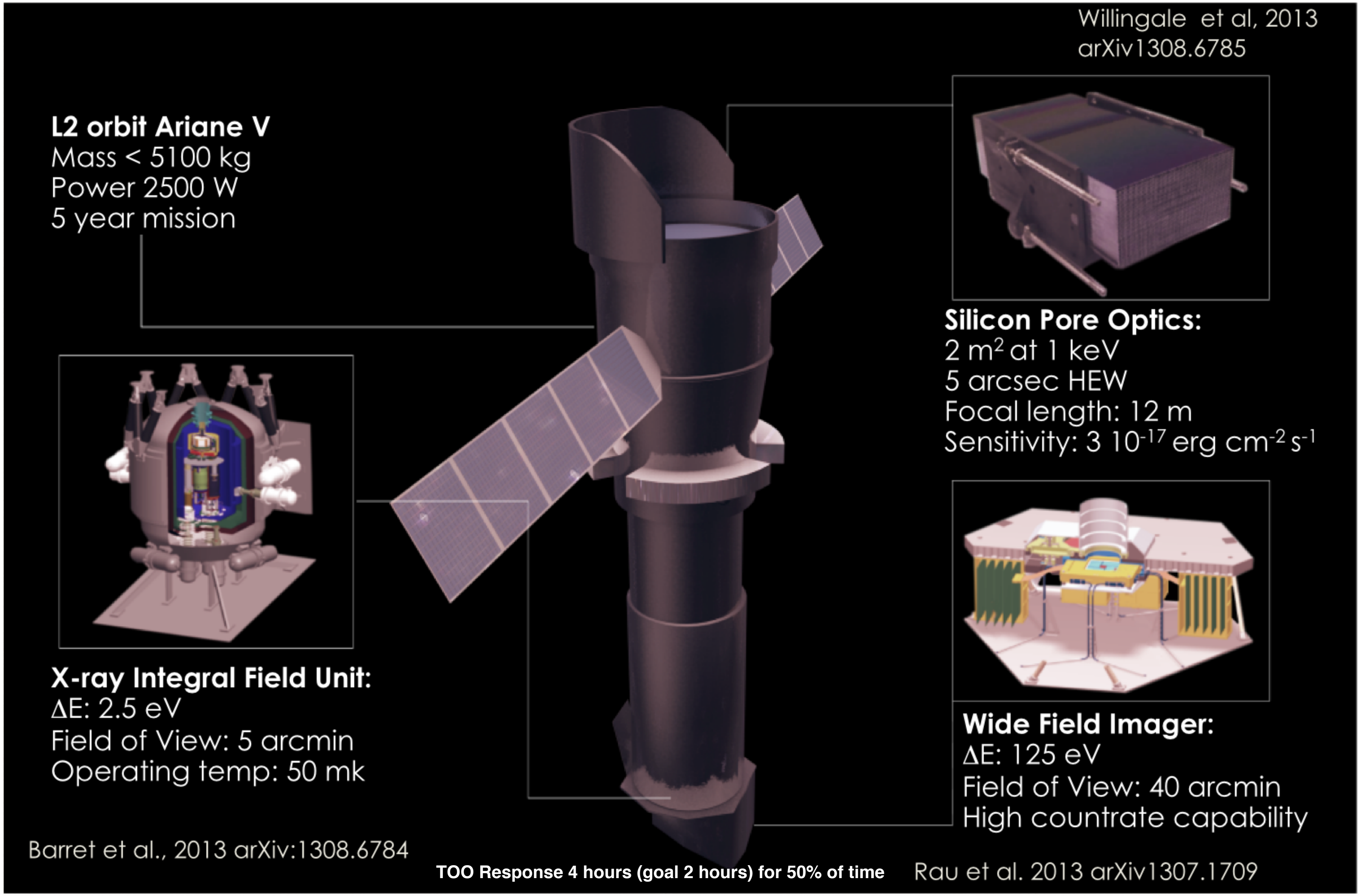


Captions: Simulated Athena 100 ks spectrum of an AGN at z=2 and LX(2-10keV)=5×10^{44}erg/s with a highly ionized (logξ=3.5, NH=10^{24}cm^{-2}, turbulent velocity 1000km/s) ultra-fast (v=0.2c) outflow. The absorption lines imprinted by ionized species enable to estimate the outflow velocity, column density and ultimately energy flux.

The Athena mission

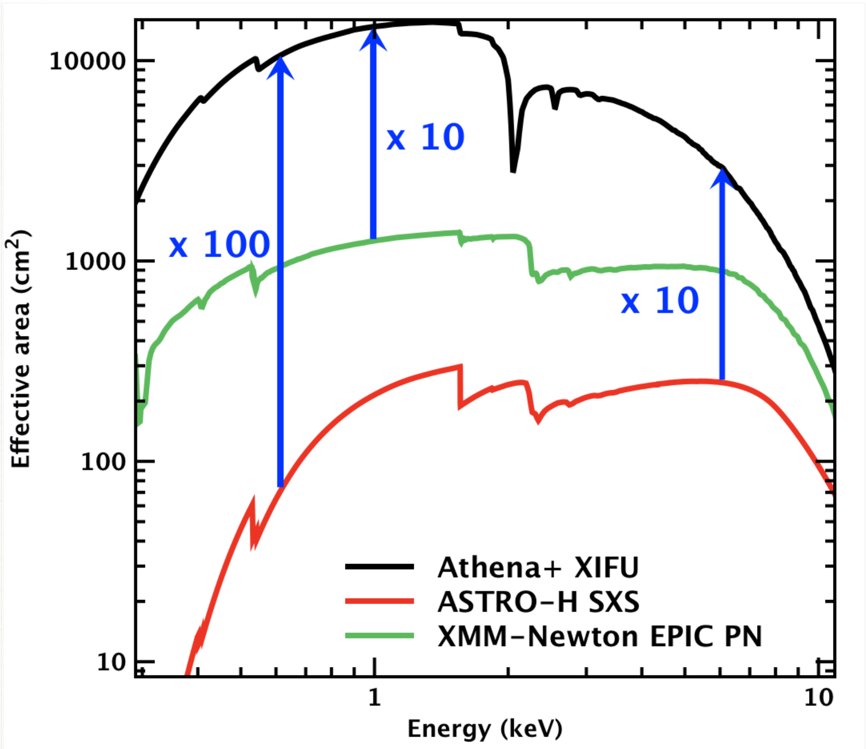
The Hot and Energetic Universe

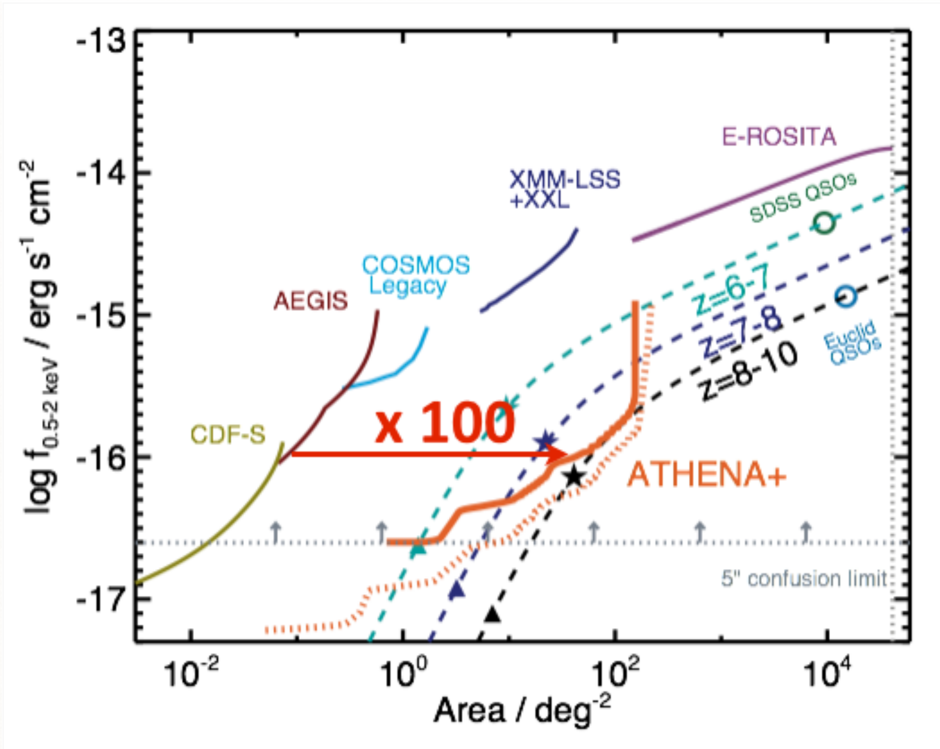
Athena: A large X-ray mirror and two instruments



Comparison with previous X-ray missions

- Huge improvement in effective area and survey capabilities, providing Athena unprecedented capabilities as an observatory





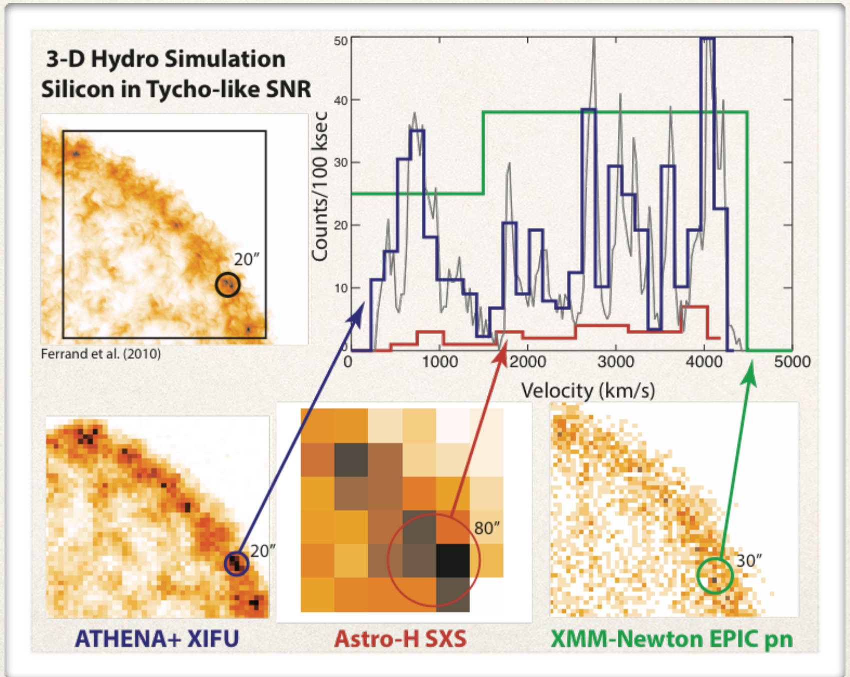
Effective area curve

Survey sensitivity curves

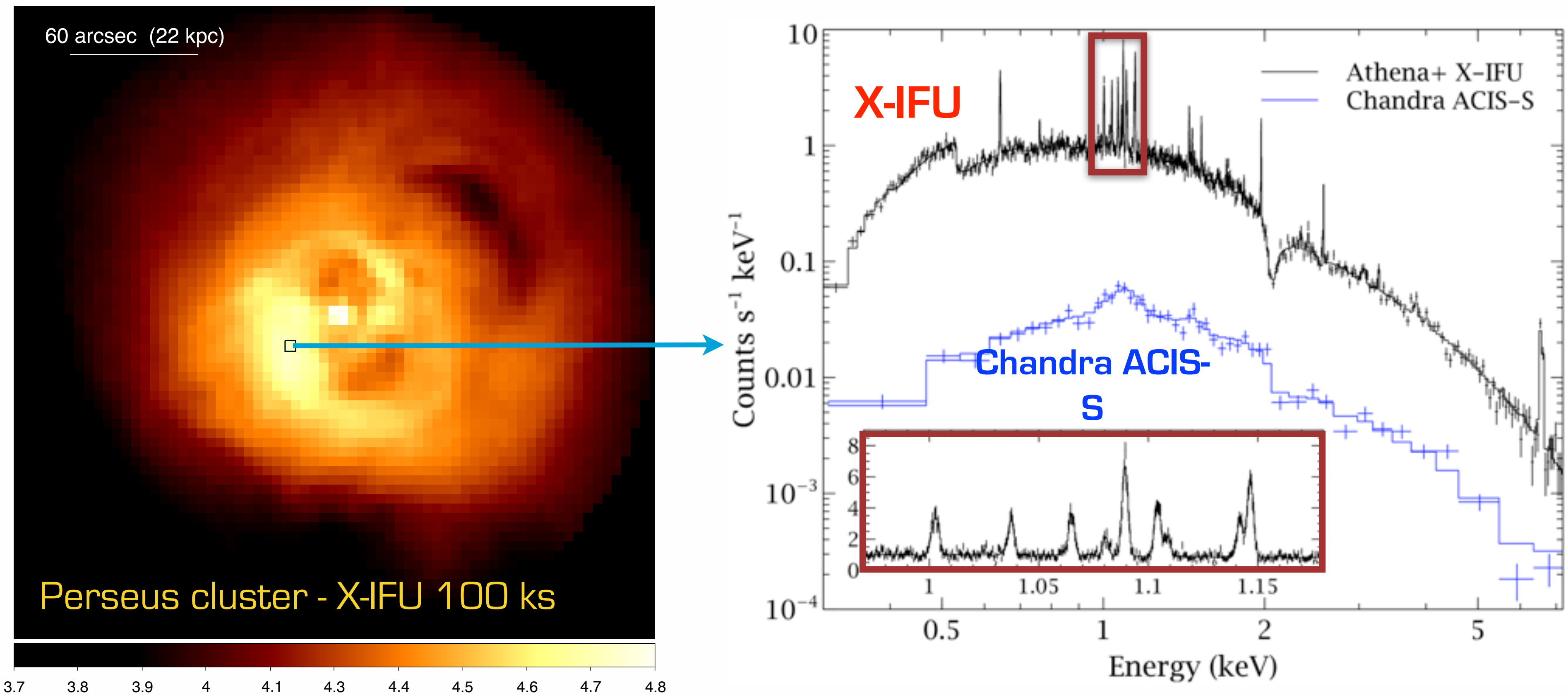
A multi-purpose observatory: An example

<u>Key issue</u>: Understanding the physics of core collapse and type Ia supernova remnants, quantifying the level of asymmetry in the explosion mechanism, the production of heavy elements, and their impact on the galactic environment.

<u>*Key measurement*</u>: First detailed 3D mapping of the hot ejected material in the line of sight (velocity, temperature, ionization state and composition) to determine to the full geometry and properties of the different layers of shocked ejecta.



<u>Captions:</u> Athena+ X-IFU, ASTRO-H, and XMM-Newton images and silicon velocity profiles based on a 3D hydrodynamic simulation of Tycho's supernova remnant (Ferrand et al. 2012, 2010). Only Athena+ X-IFU has sufficient spectral and angular resolution, and sensitivity to isolate the highlighted knot and retrieve the velocity information that will reveal the 3D dynamics of the supernova remnant, providing constraints on the explosion mechanism through the measurements of asymmetries.

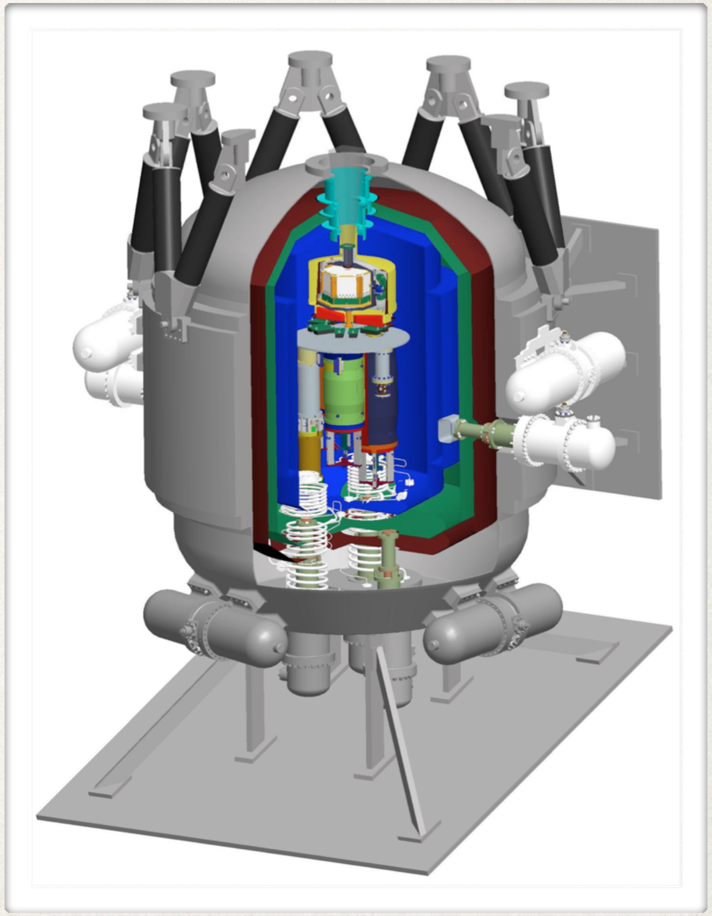


The X-ray Integral Field Unit

A very exciting challenge to be taken up by France (CNES, IRAP, CEA, IAS, LAM, …)

The X-ray Integral Field Unit (X-IFU)

Parameter	Value	Comment
Field of view	5 arcmin (diameter)	3480 Transition Edge Sensors
Spectral resolution	2.5 eV	(250 x 250 μm TES cooled at 50 mK)
Energy range	0.3-12 keV	Bi/Au absorbers
Time resolution	10 μs	Digital pulse selection

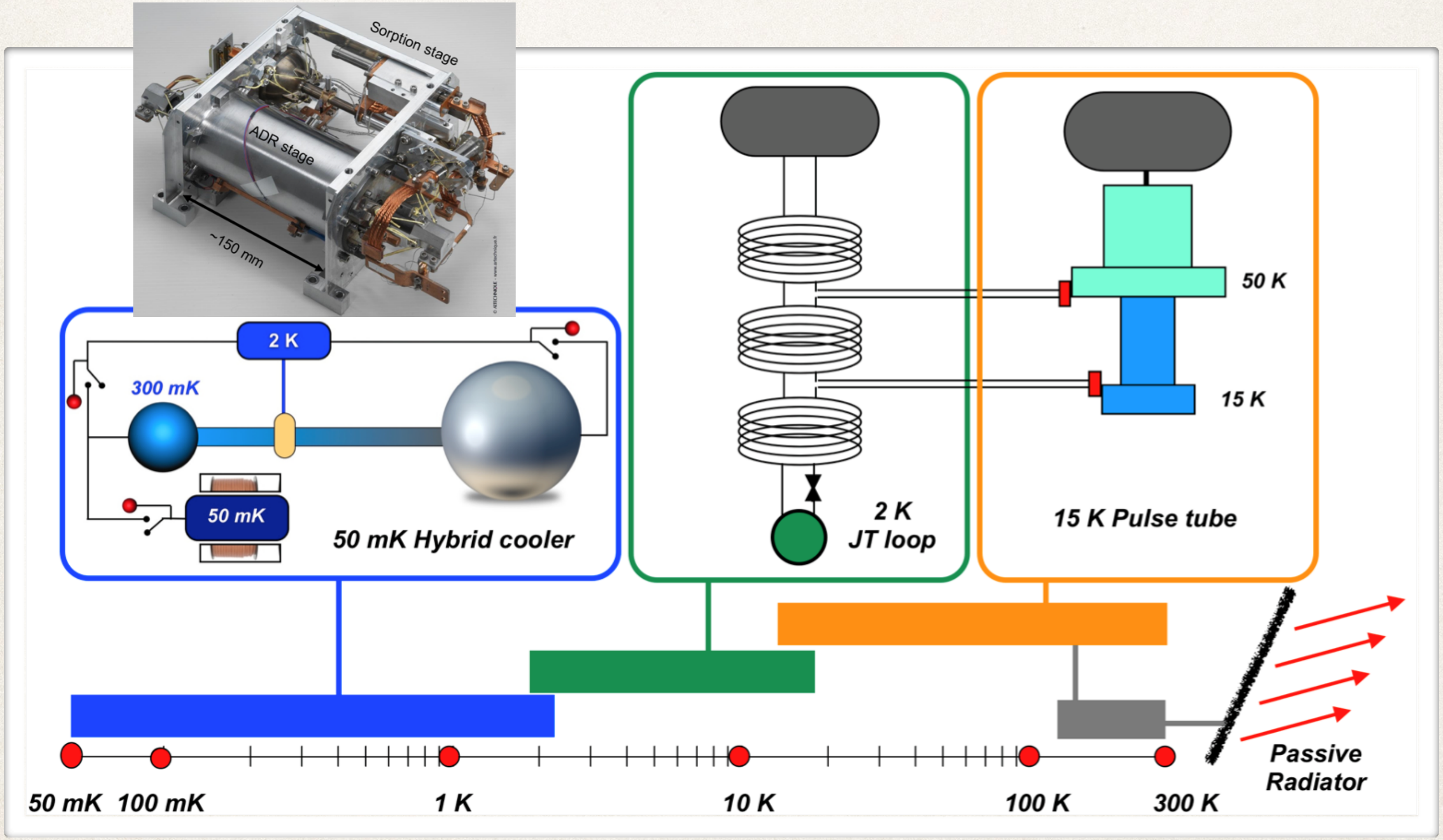


Parameter	Value
Focal plane assembly mass	6 kg
Mass/power of electronics	180 kg/300 W
Cooling chain mass	320 kg
Overall mass and power	514 kg/1.2 kW

The X-IFU organisation

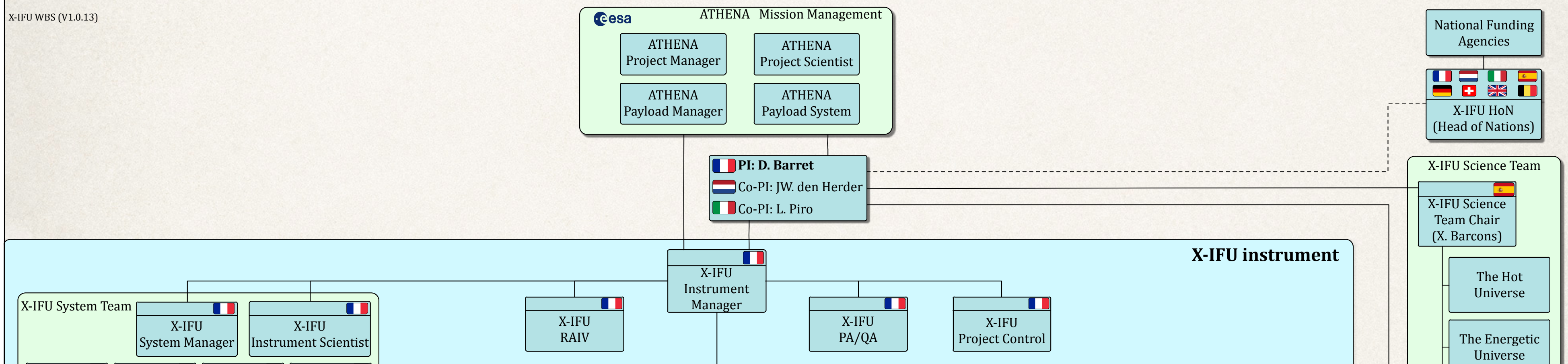
Role	Name(s)
PI	**D. Barret (FR, IRAP)**
Co-PIs	J.W. den Herder (SRON, NL) L. Piro (INAF, IT)
X-IFU Science team Chair	X. Barcons (CSIC, ES)
XIFU Science Team	G. Branduardi-Raymont (GB) , M. Dadina (IT), **A. Decourchelle (FR, CEA)**, P. Jonker (NL), Y. Nazé (BE), F. Nicastro (IT), S. Paltani (CH), **E. Pointcouteau (FR, IRAP)**, **D. Porquet (FR, Strasbourg)**, **G. Pratt (FR, CEA)**, J. Schaye (NL), S. Sciortino (IT), P. Uttley (NL), J. Wilms (DE)
X-IFU Head of Nation Committee	**D. Barret (Chair, FR)**, J.W. den Herder (NL), L. Piro (IT), M. Mas-Hesse (ES), M. Page (UK), S. Paltani (CH), G. Rauw (BE), J. Wilms (DE)
IRAP project manager	**L. Ravera**
Instrument scientist	**F. Pajot**
End-to-end performance	**Ph. Peille**
Electronics responsible	**E. Pointecouteau**
Ground segment responsible	**N. Webb**
Project management & Prime	**CNES**
System team	**CNES + X-IFU consortium partners**

Cooling chain with ADR as a baseline



The X-IFU European consortium

- The European consortium for the X-IFU has been set-up and is being ready to answer the AO call for instrument consortia



Barret, D., den Herder, J., Piro L. et al	The Hot and Energetic Universe: The X-ray Integral Field Unit for Athena+	2013arXiv:1308.6784

Conclusions

- The Hot and Energetic Universe science theme was selected by ESA for its L2 mission.
  - ✓ Very strong support from the broad astronomical community, behind the X-ray community
- This science theme could be implemented by an observatory like Athena
  - ✓ Athena provides the necessary angular resolution, spectral resolution, throughput, detection sensitivity, and survey grasp needed to revolutionize our understanding of the Hot and Energetic Universe
- Athena will open up a vast discovery space leading to completely new areas of scientific investigation
  - ✓ The implementation of Athena for launch in 2028 will establish European leadership in high energy astrophysics for the foreseeable future.
- France played a key role in the theme selection and is now ideally placed to have a leadership in the main element of payload of the next large astronomy mission
  - ✓ I hope you will join us in building the great instrument that is the X-ray Integral Field Unit

Acknowledgments

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Bold Face Denotes Working Group Chairs

Athena+ Coordination Group:
K. Nandra, D. Barret, X. Barcons, J.-W. den Herder, A. Fabian, L. Piro, M. Watson

Athena+ Working Groups
(~250 people)

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Special thanks to the review team:
M. Arnaud, J. Bregman, F. Combes, R. Kennicutt, R. Maiolino, R. Mushotzky, T. Ohashi, K. Pounds, C. Reynolds, H. Röttgering, M. Rowan-Robinson, C. Turon, G. Zamorani

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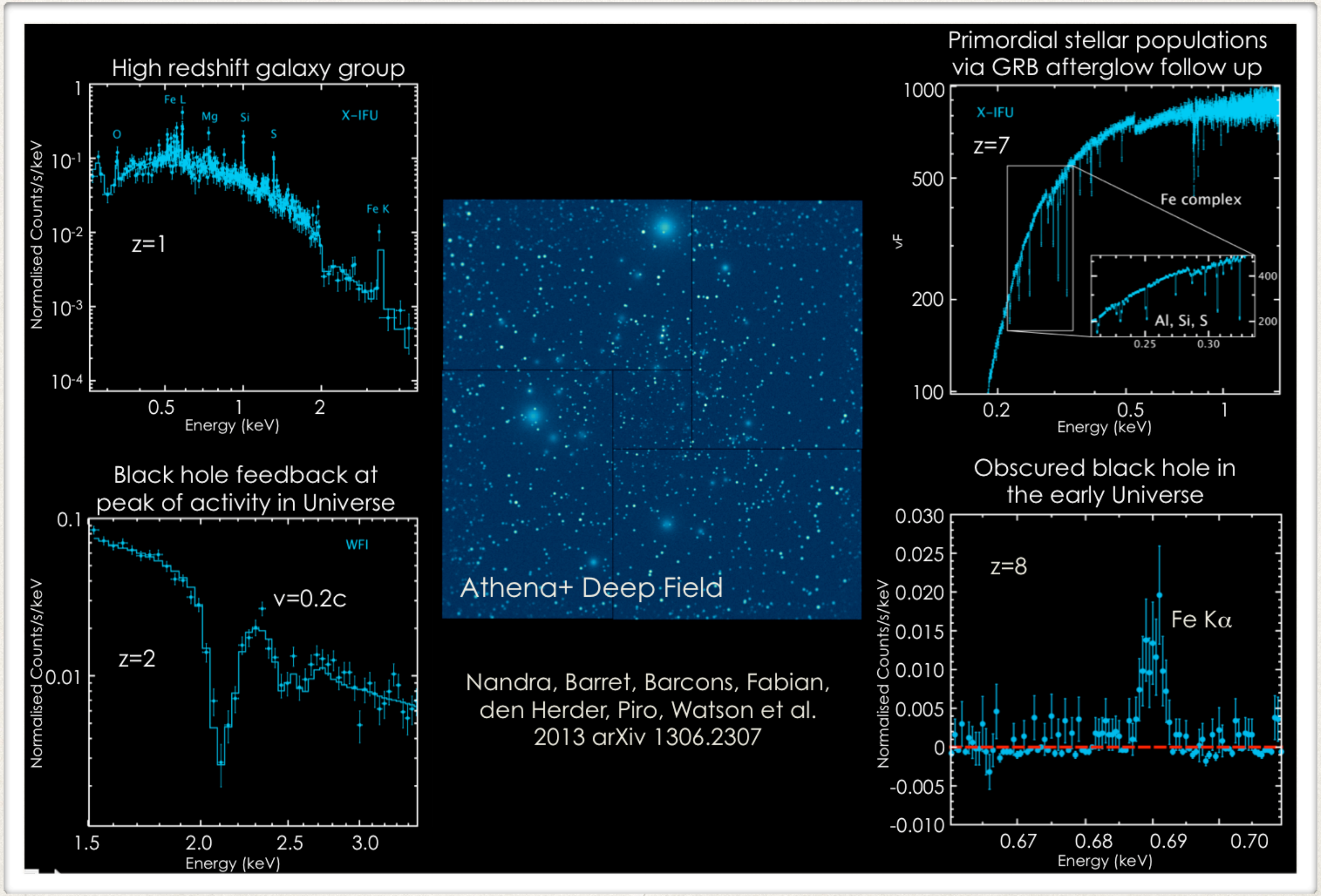
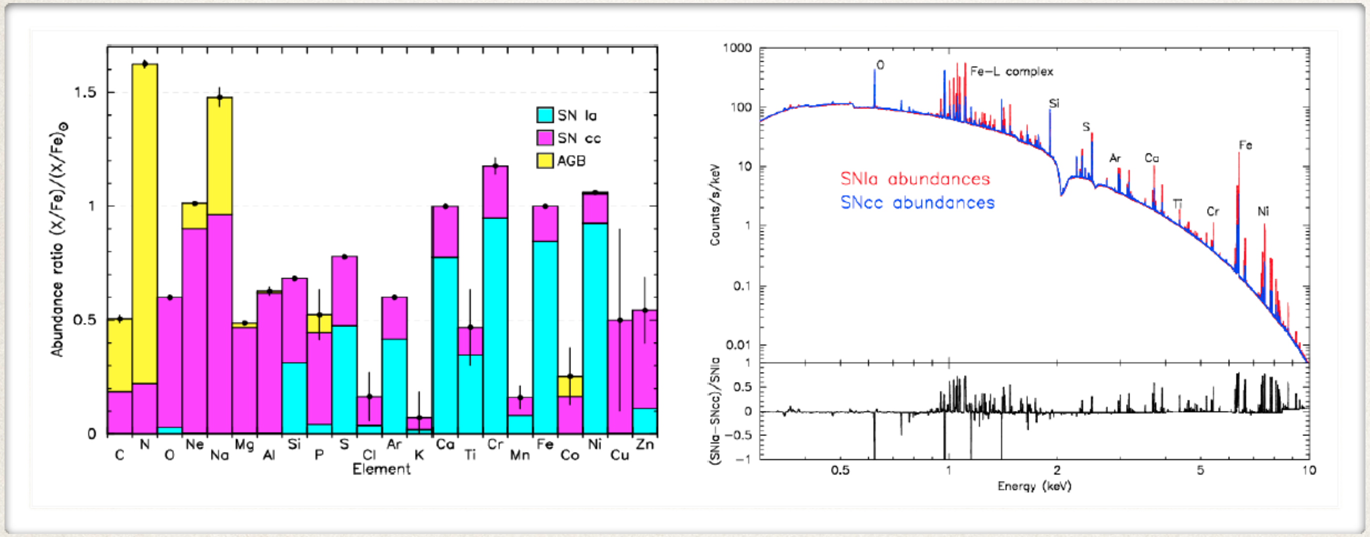


Cluster astrophysics: chemical enrichment

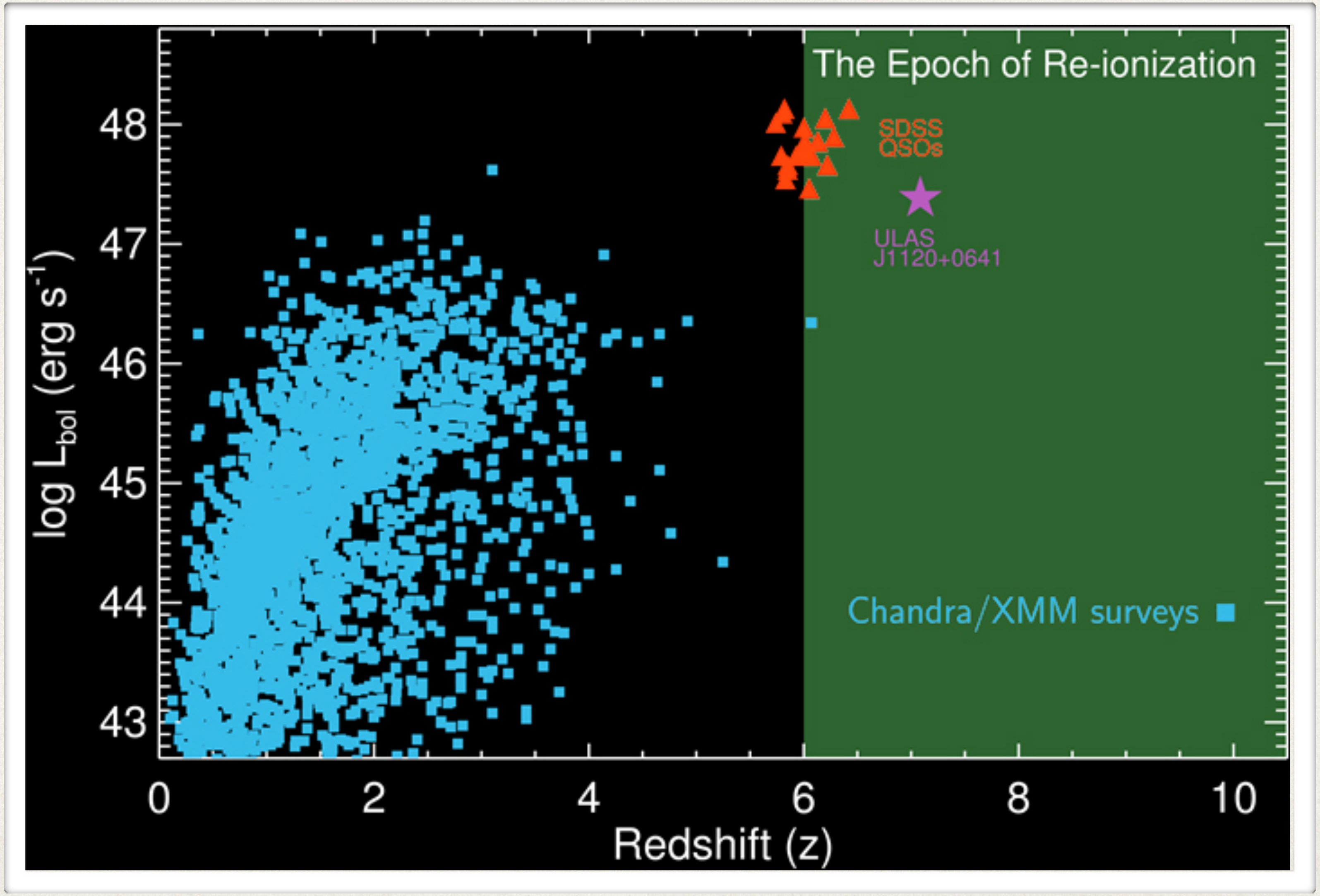
<u>Key issue</u>: Determine when the largest baryon reservoirs in galaxy clusters were chemically enriched and by which processes. Constrain the cluster IMF and the SN 1a explosion mechanisms.

<u>*Key measurement*</u>: Measure abundances of heavy elements from O to Fe in clusters at different redshifts. Invert the abundances using yields of various SN types and AGB stars to constrain the IMF and SN1a explosion mechanism. Determine where metals are produced in nearby objects in nearby clusters.



<u>Captions:</u> Left) Abundance ratios predicted from different contributions of SN types and AGB stars. Right) X-ray spectrum of a typical 3 keV cluster at z=0.02 showing the products of two different types of SN, 1a and CC.

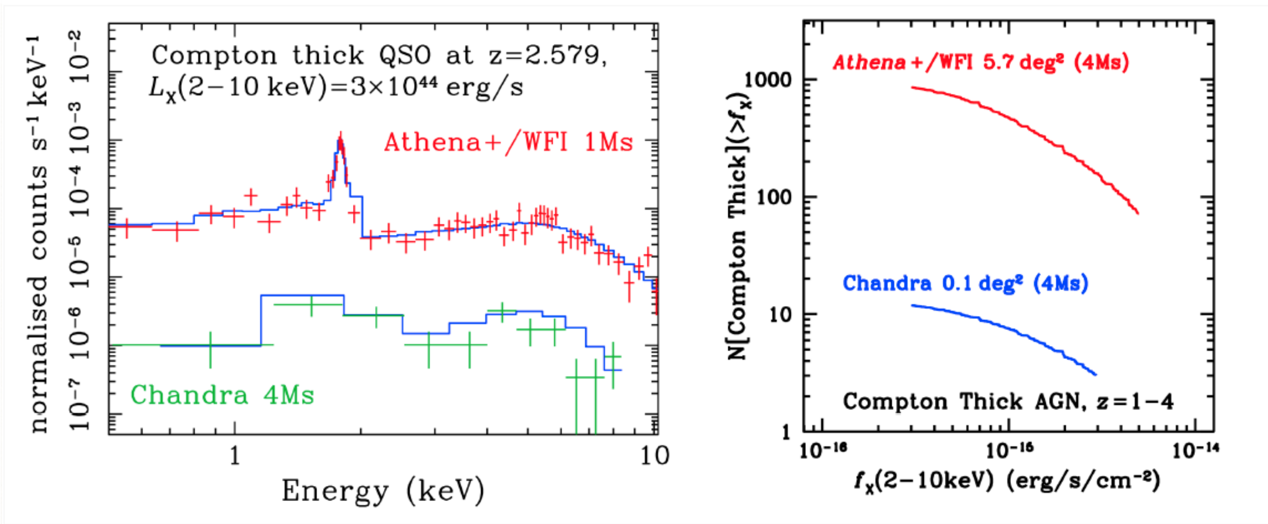
Pushing the frontiers



Obscured accretion

<u>Key issue</u>: Find the physical conditions (fueling mode, outburst triggering mechanism) under which SMBH grew at the epoch when most of the accretion and star formation in the Universe occurred (z~1-4)

<u>*Key measurement*</u>: Perform through wide field imaging a complete census of AGN out to z~3, including those that reside inside a Compton-thick environment. Search for strong iron line dominated spectral as the signposts of heavily obscured AGN.



<u>Captions:</u> Right) Simulated Compton thick QSO spectrum in comparison with the Chandra one. Left) Log N/Log S curves for Athena and Chandra, showing that Athena will deliver 100 times more objects than achieved today.