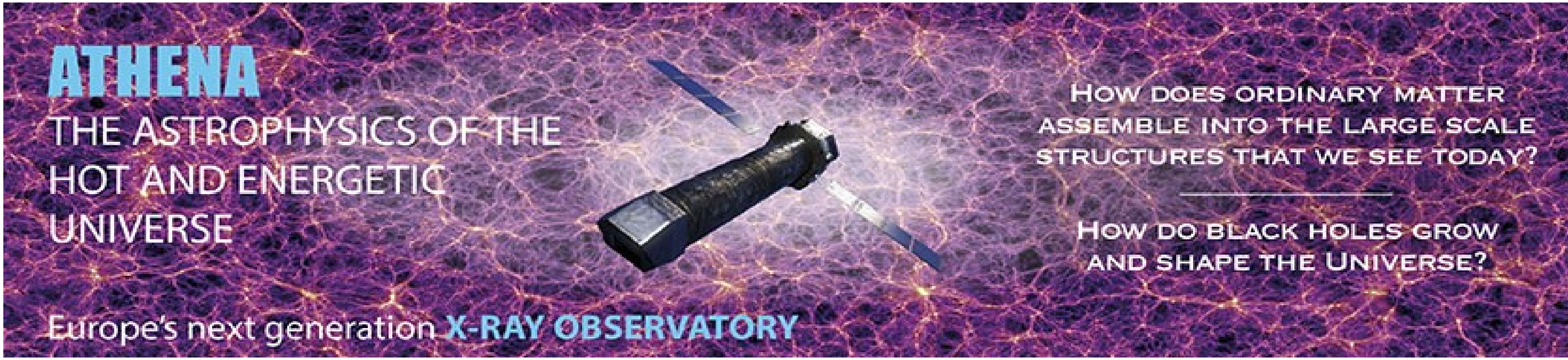


X-ray Universe – In hunt of missing baryons with ATHENA

Agata Różańska, CAMK PAN

POLISH ACADEMY OF SCIENCES
N. COPERNICUS ASTRONOMICAL CENTER

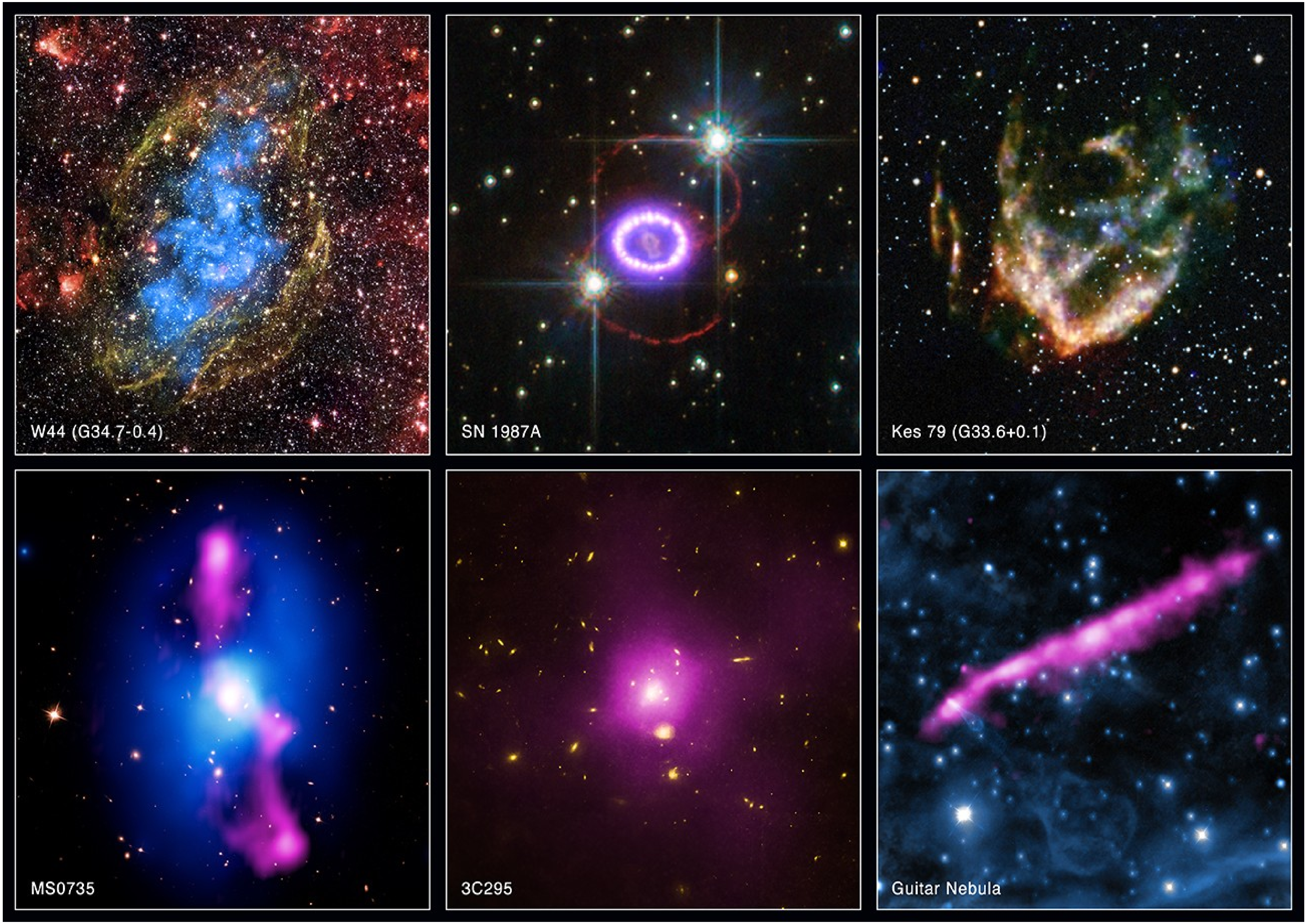
STRONGGRAVITY
EU FP7-SPACE research project 312789 2013 - 2017

Andrzej Sołtan CAMK, Agnieszka Janiuk CFT, Piotr Życki CAMK,
All group members: athena.camk.edu.pl
Piotr Orleański CBK, Mirosław Rataj CBK, Konrad Skup CBK

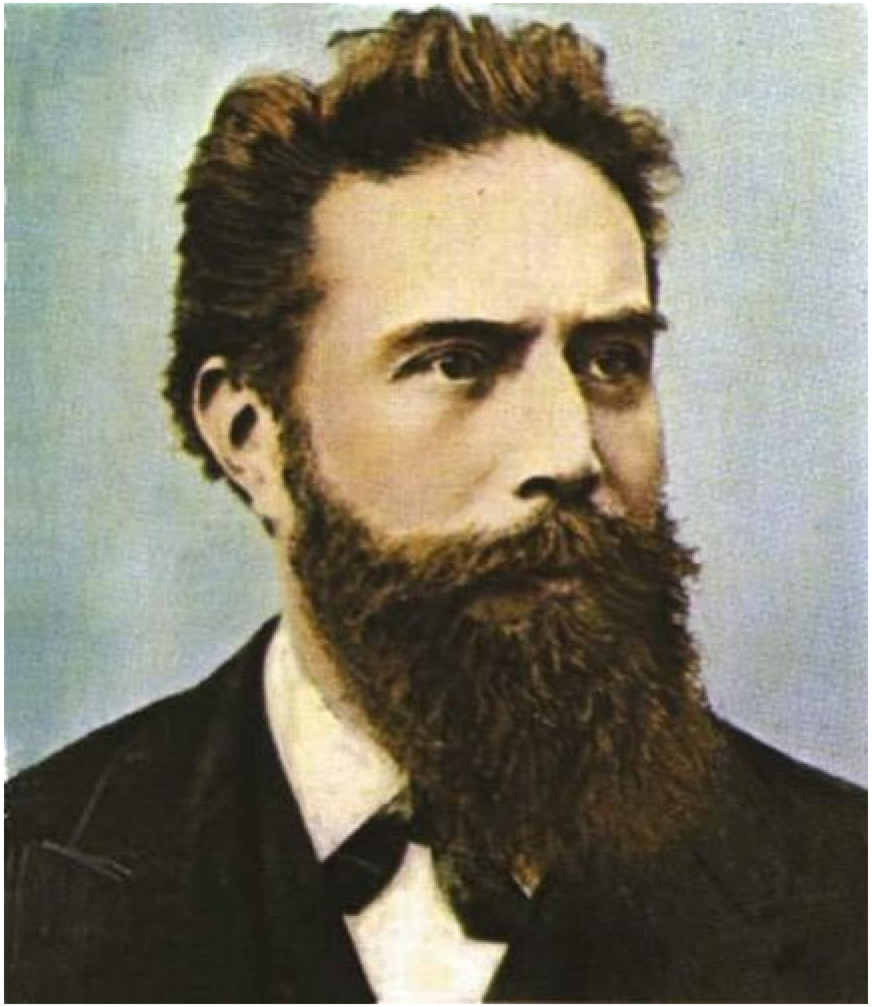
Space Research Centre
Polish Academy of Sciences

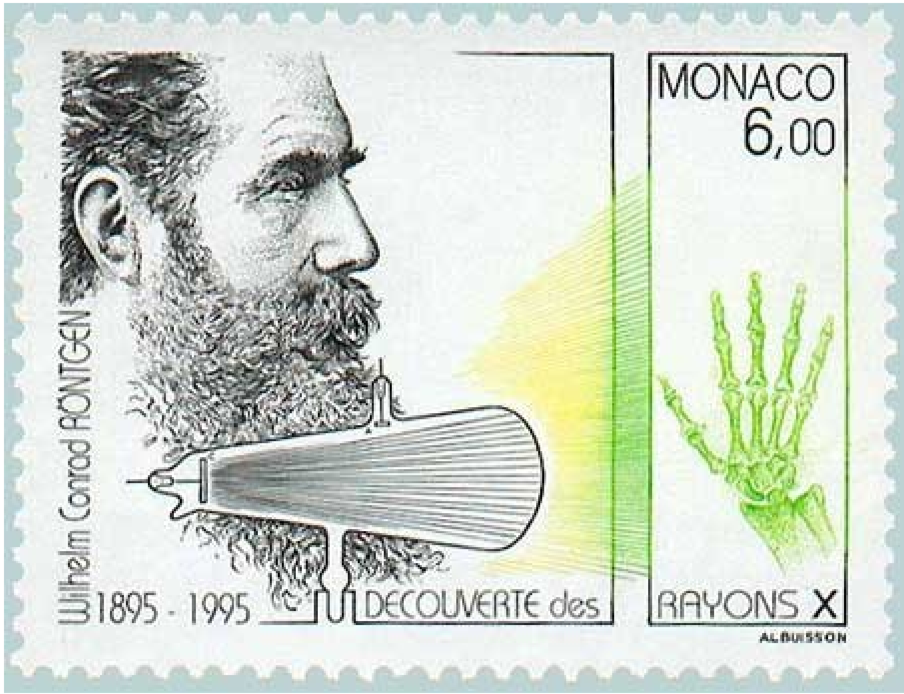
Cosmology school, Kielce, July 13th, 2016

X-ray Astronomy – some history:



1895 – Wilhelm Conrad Roentgen (1845-1923) discovered X-rays.
He had indicated the use of X-rays in medicine.
1901 – Roentgen got the first Nobel Price in physics.





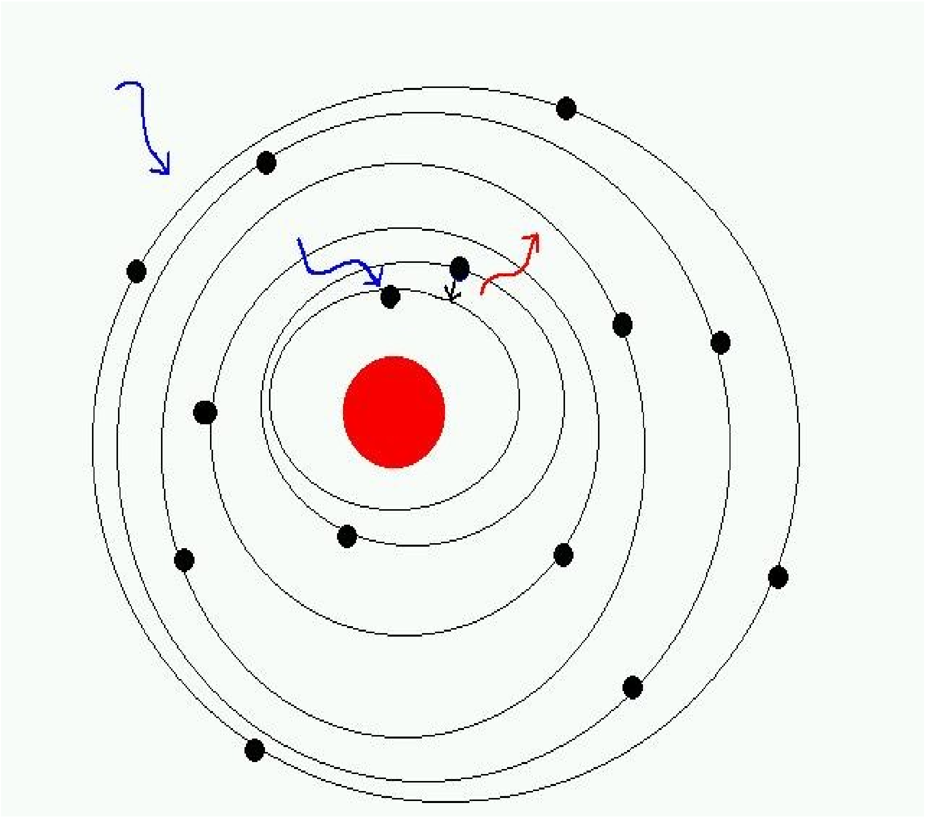
Two most important use of X-rays on the Earth:

1) X-rays transmit through the materials which are not transparent to the optical light.

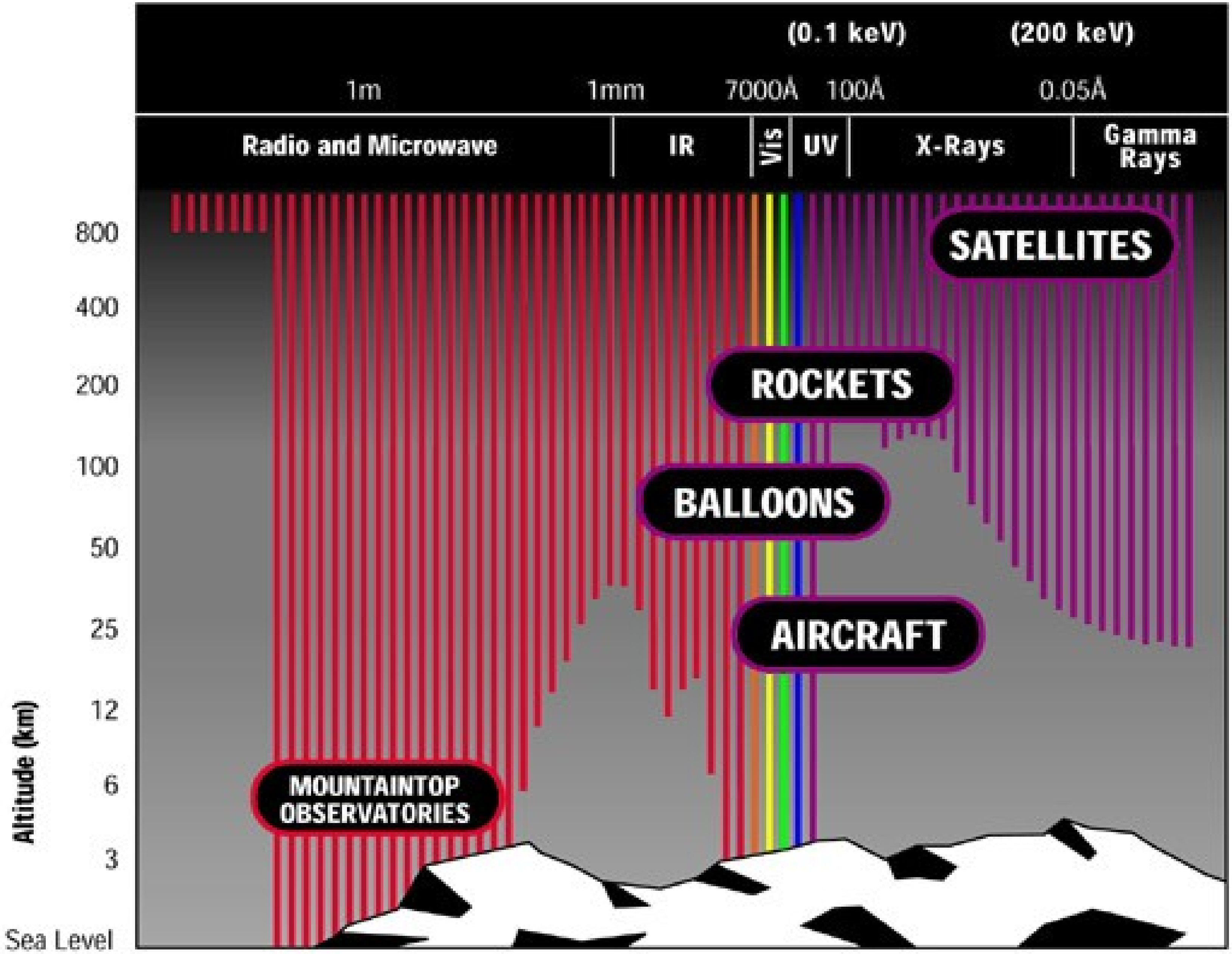
Two most important use of X-rays on the Earth:

1) **X-rays transmit through the materials which are not transparent to the optical light.**

2) **X-rays remove electrons from innermost atomic levels.**



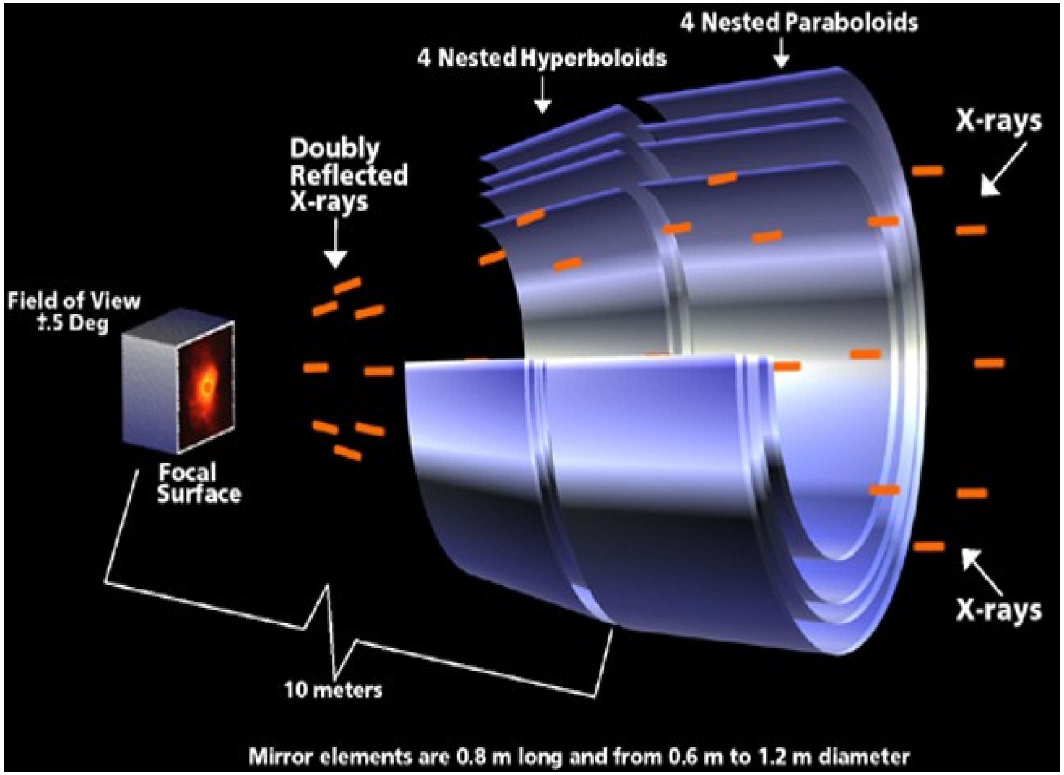
Atmosphere is not transparent to X-rays



1946 – Herbert Fridman had put Geiger-Muller proportional counter on the board of V2 rocket. First weak emission from the SUN was observed.

1946 – Herbert Fridman had put Geiger-Muller proportional counter on the board of V2 rocket. First weak emission from the SUN was observed.

1951 – Hans Wolter proved that X-rays can be focus when reflecting them on hyperbolic and parabolic mirror system – incident grazing mirrors.



0.1 keV - 100 keV
10^6 K - 10^9 K

Wolter mirrors focus photons of energies up to 10-12 keV.

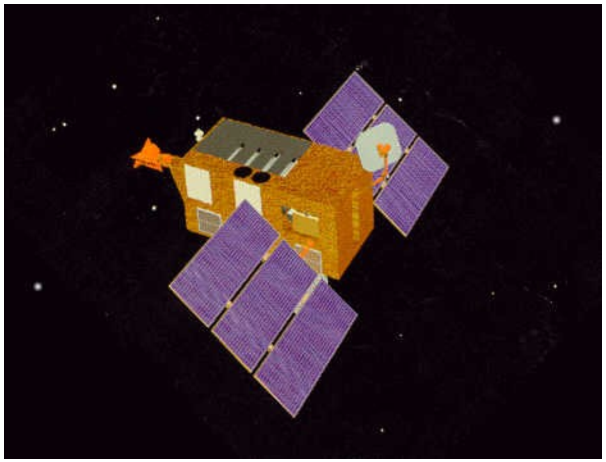
$$E_{max} \propto f$$

1962 – Riccardo Giacconi from Cambridge built proportional counter (2-10 keV) on the board of AEROBEE rocket. the first X-ray source outside Solar System, Scorpius X-1, was detected. In addition, X-ray diffuse radiation from all directions was found.

1962 – Riccardo Giacconi from Cambridge built proportional counter (2-10 keV) on the board of AEROBEE rocket. the first X-ray source outside Solar System, Scorpius X-1, was detected. In addition, X-ray diffuse radiation from all directions was found. Giacconi got the Nobel Price in 2002.

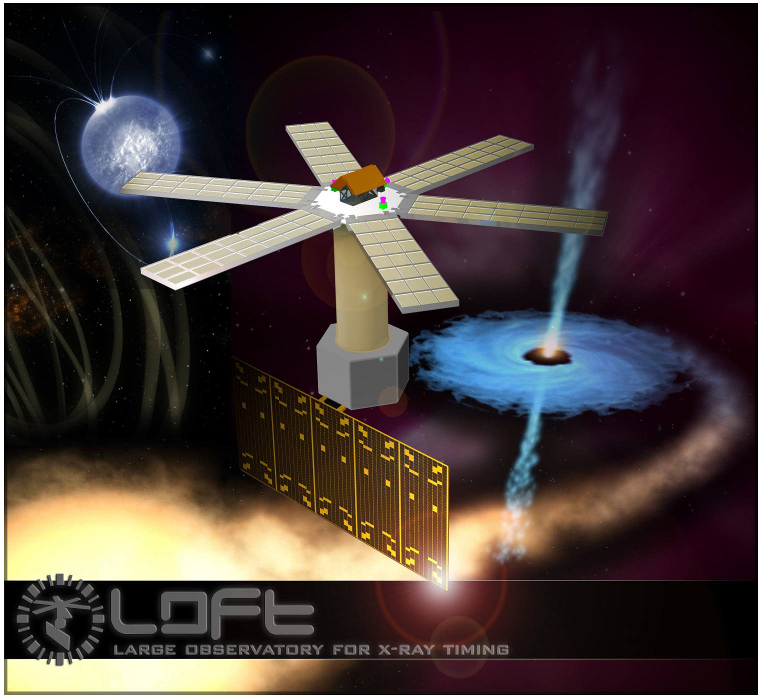
Two types of X-ray satellites:

Type I - detector arrays:



Eff. Area is large:

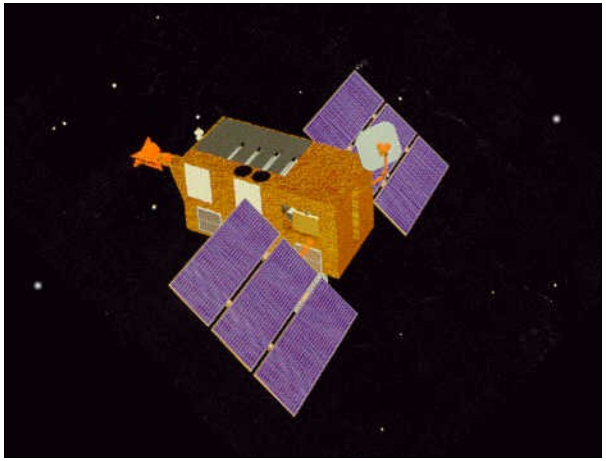
RXTE
0.65 m^2



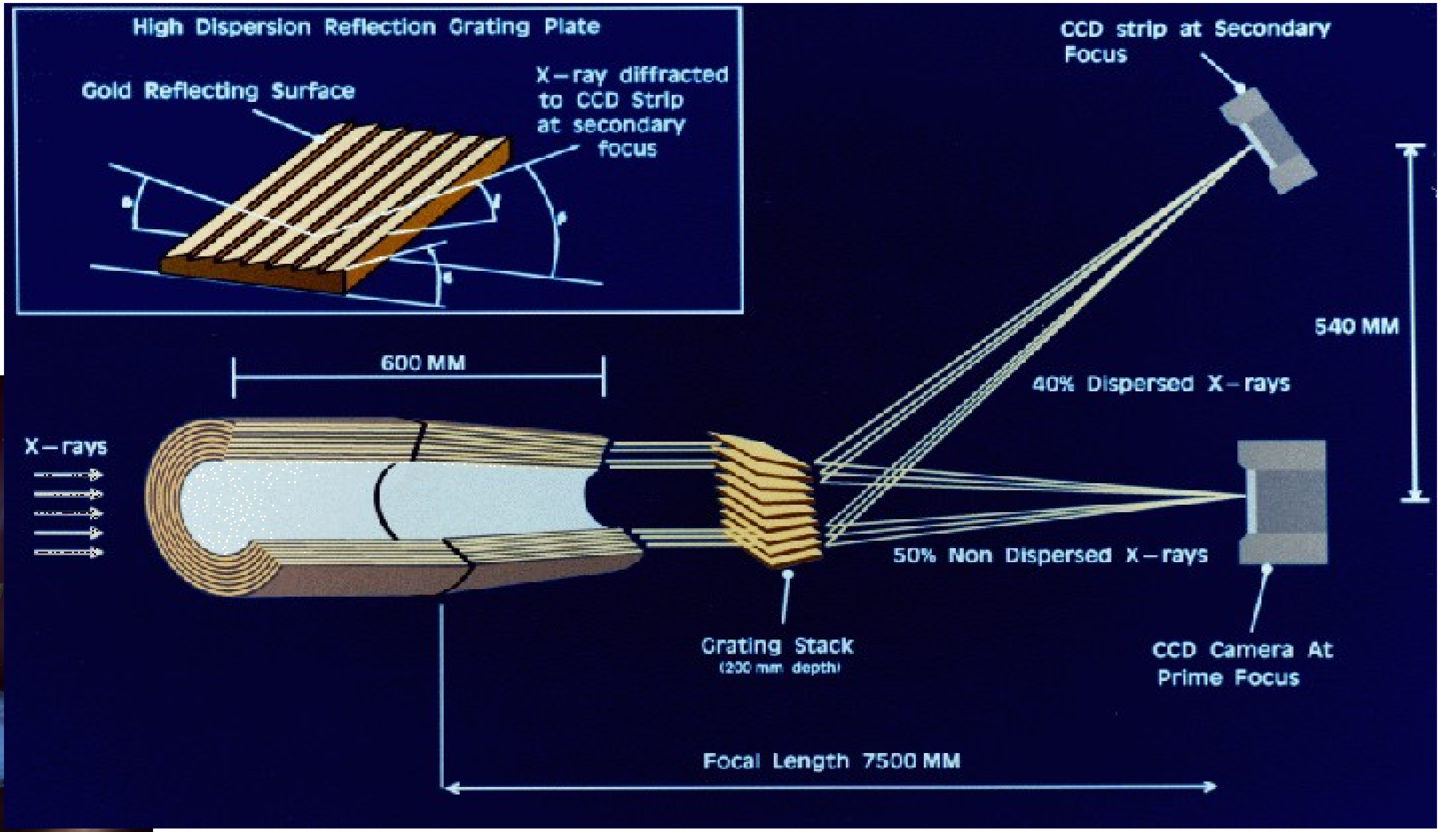
LOFT
8.5 m^2

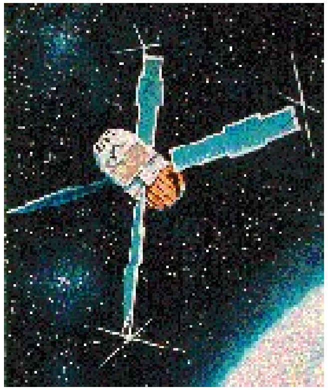
Two types of X-ray satellites:

Type I - detector arrays:



Type II – X-ray telescopes

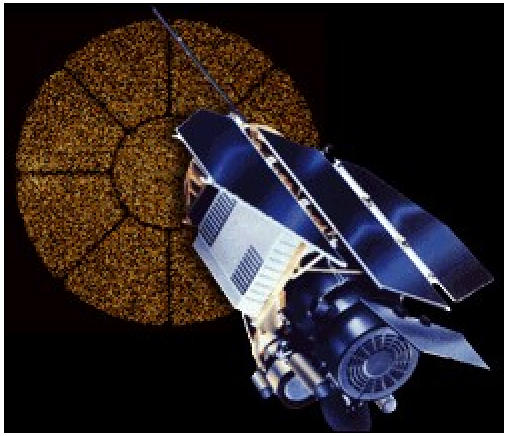




UHURU 1970

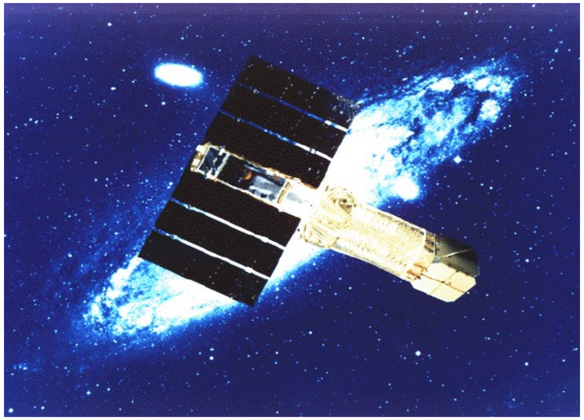
EINSTAIN 1978

EXOSAT 1983



ROSAT 1990-1999

GINGA 1987



ASCA 1993

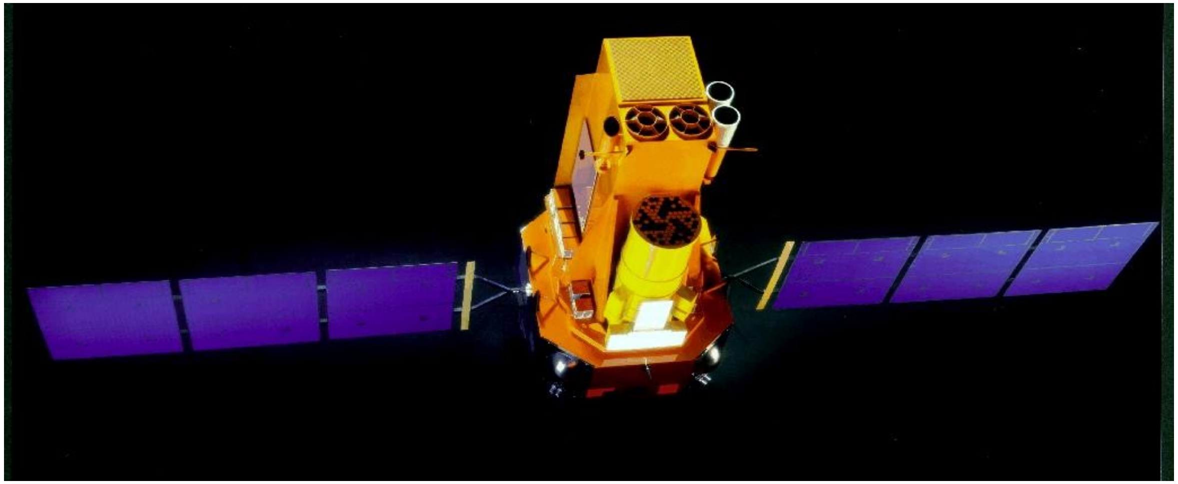
RXTE 1995-2012

Currently, over 10 active X-ray satellites operate in space.

CHANDRA 1999, r < 1''

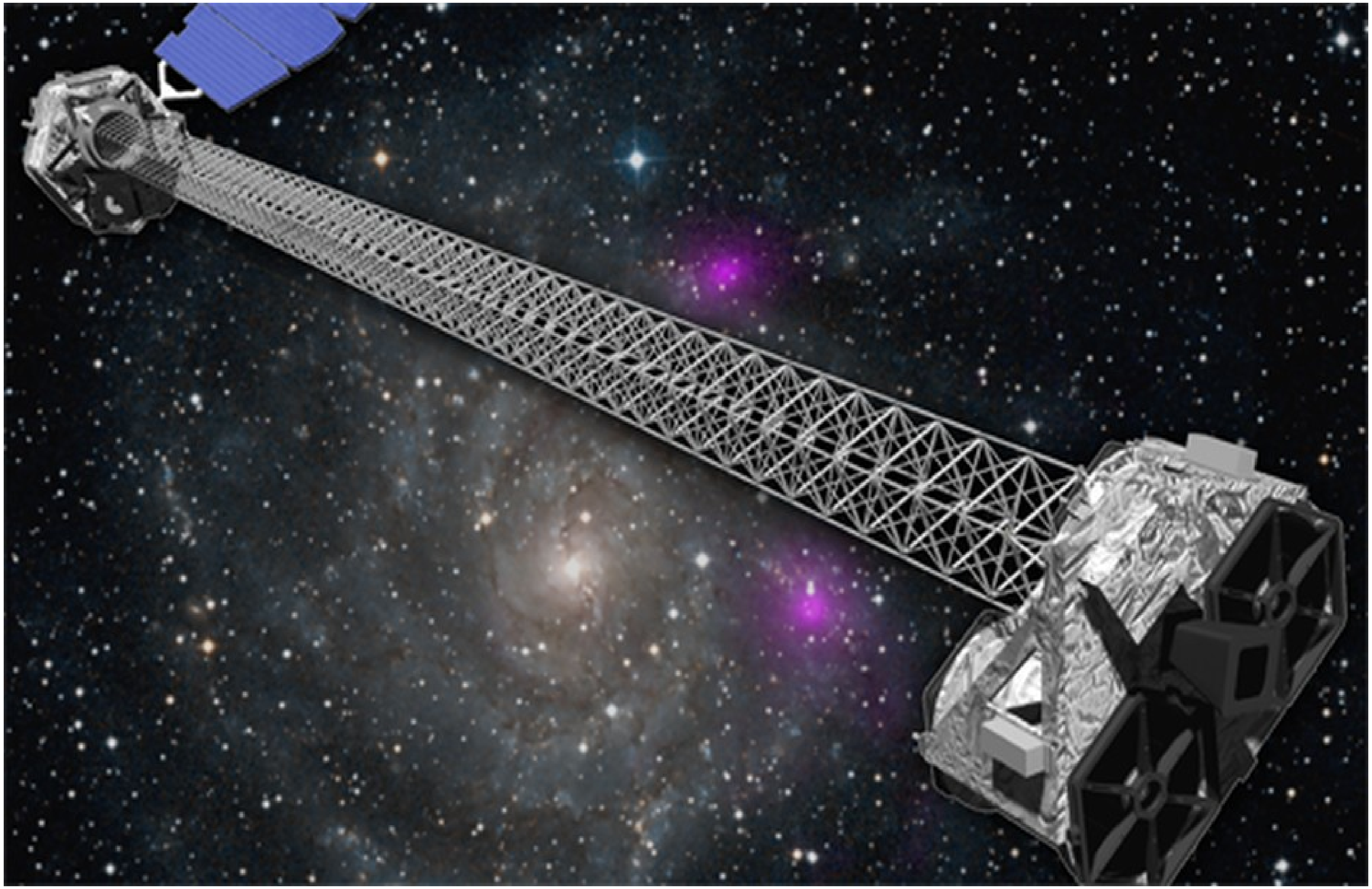
XMM-NEWTON 1999, r<16''

INTEGRAL 2002, r < 22'', up to 10 MeV,

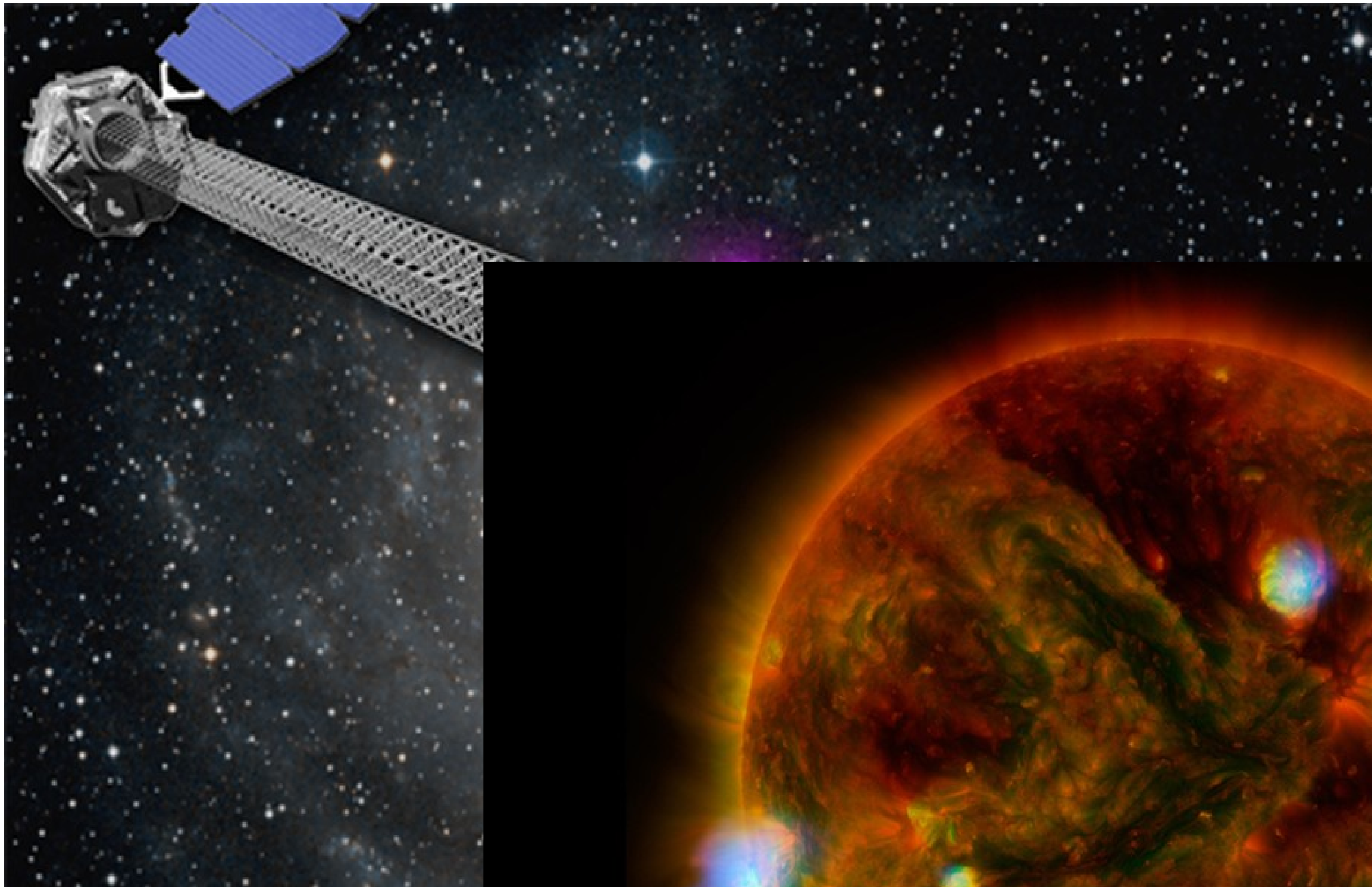


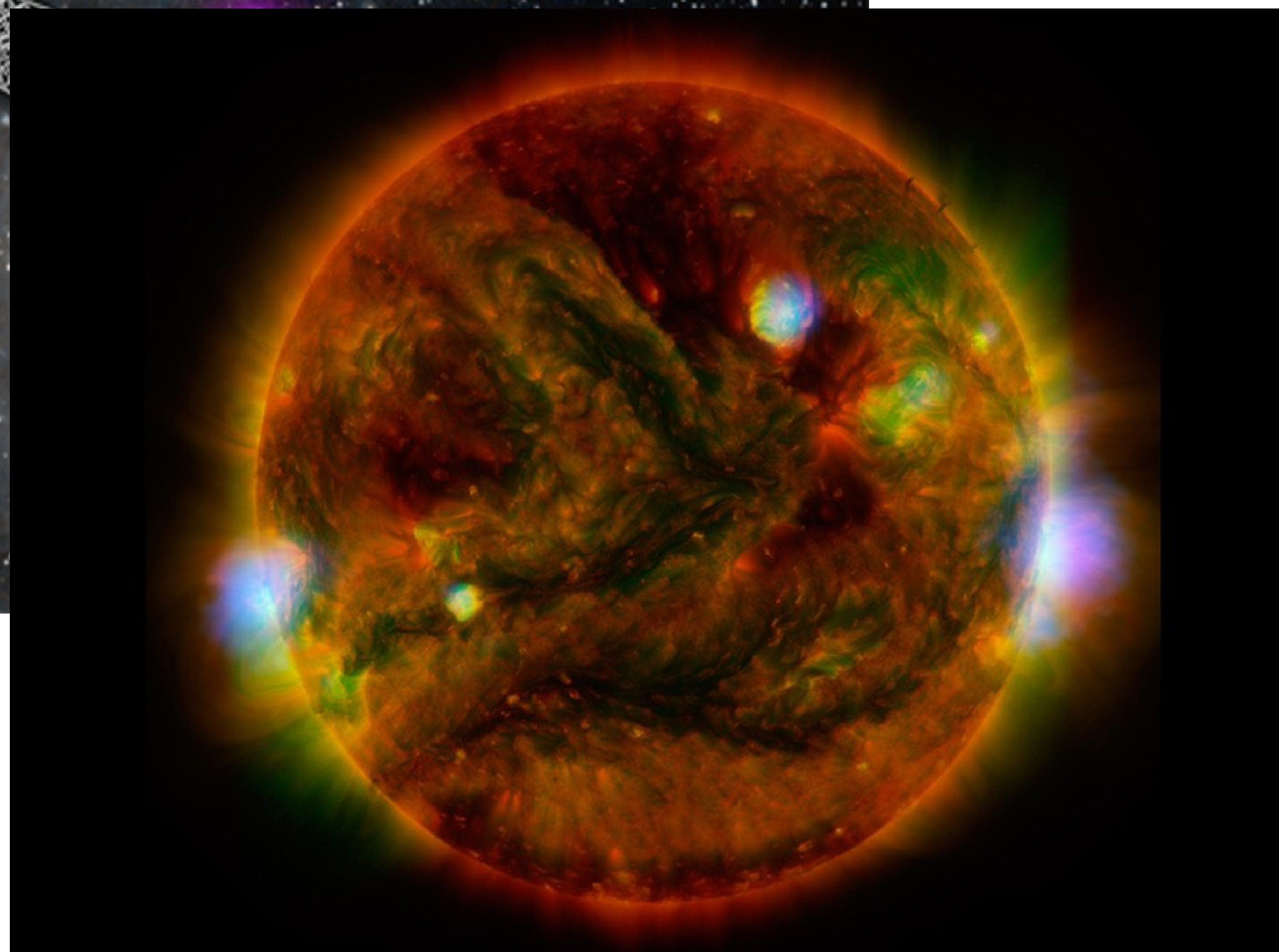
SUZAKU 2005, r < 1.5'

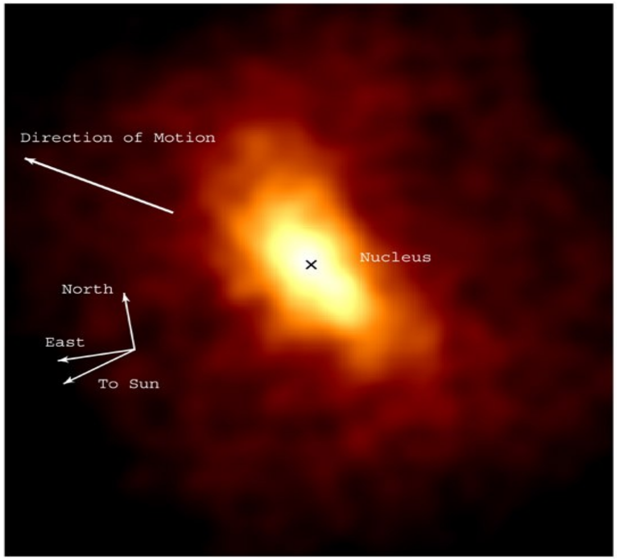
NuSTAR, 3 – 79 keV, f = 12 m



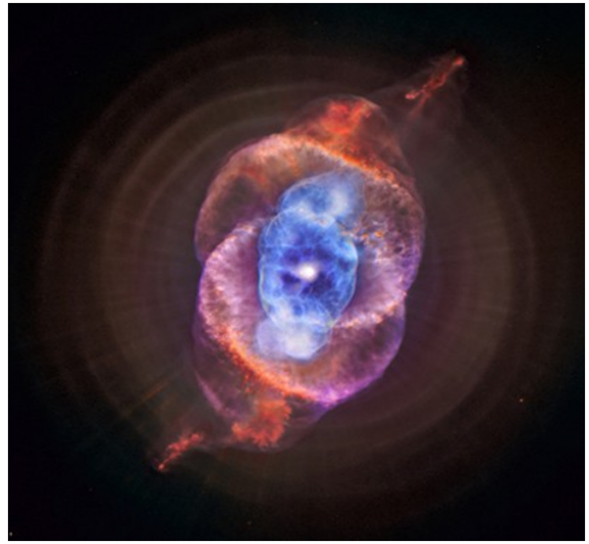
NuSTAR, 3 – 79 keV, f = 12 m. **SUN in hard X-rays.**



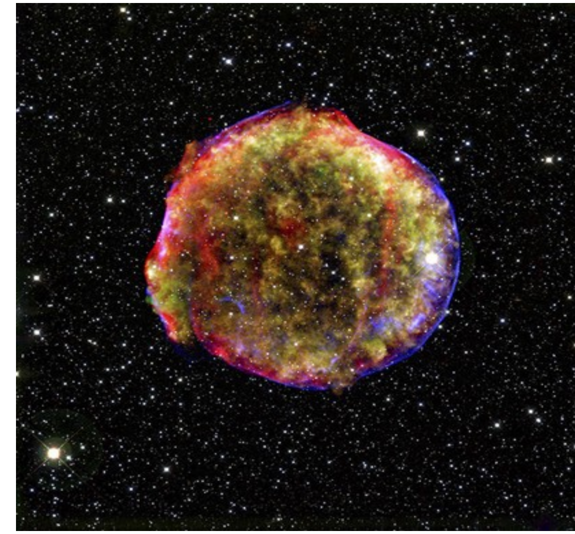




C/1999 S4 LINEAR CHANDRA 2000

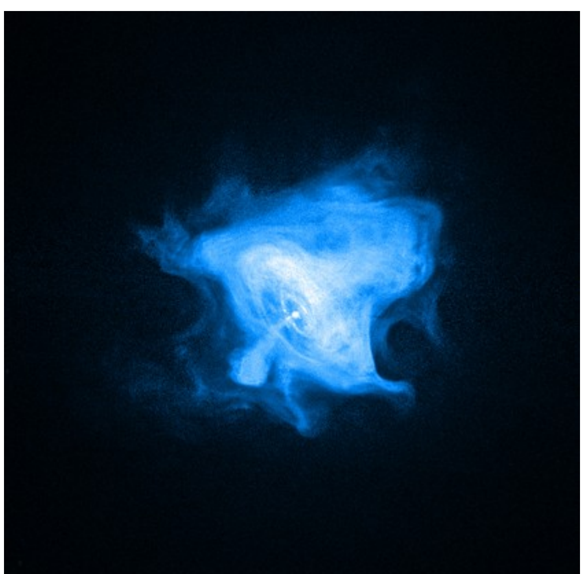


Blue – CHANDRA 2008 Planetary Nebula Cat Eye

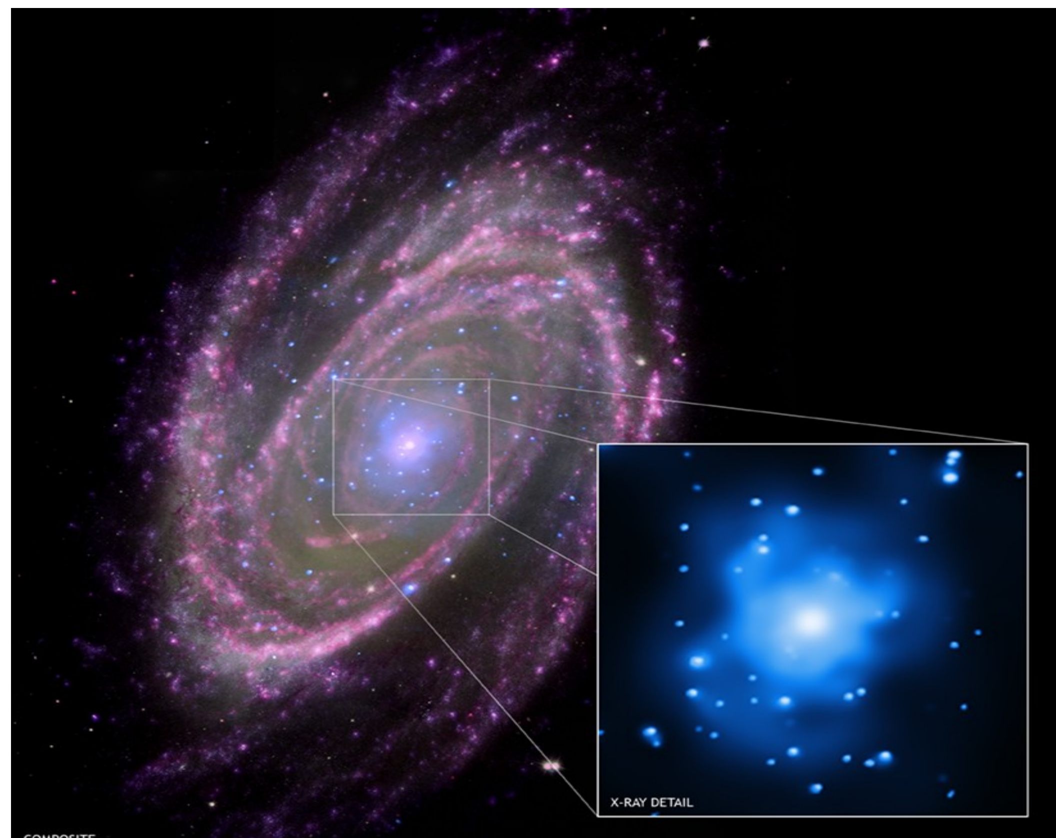


SNR – Tycho, CHANDRA

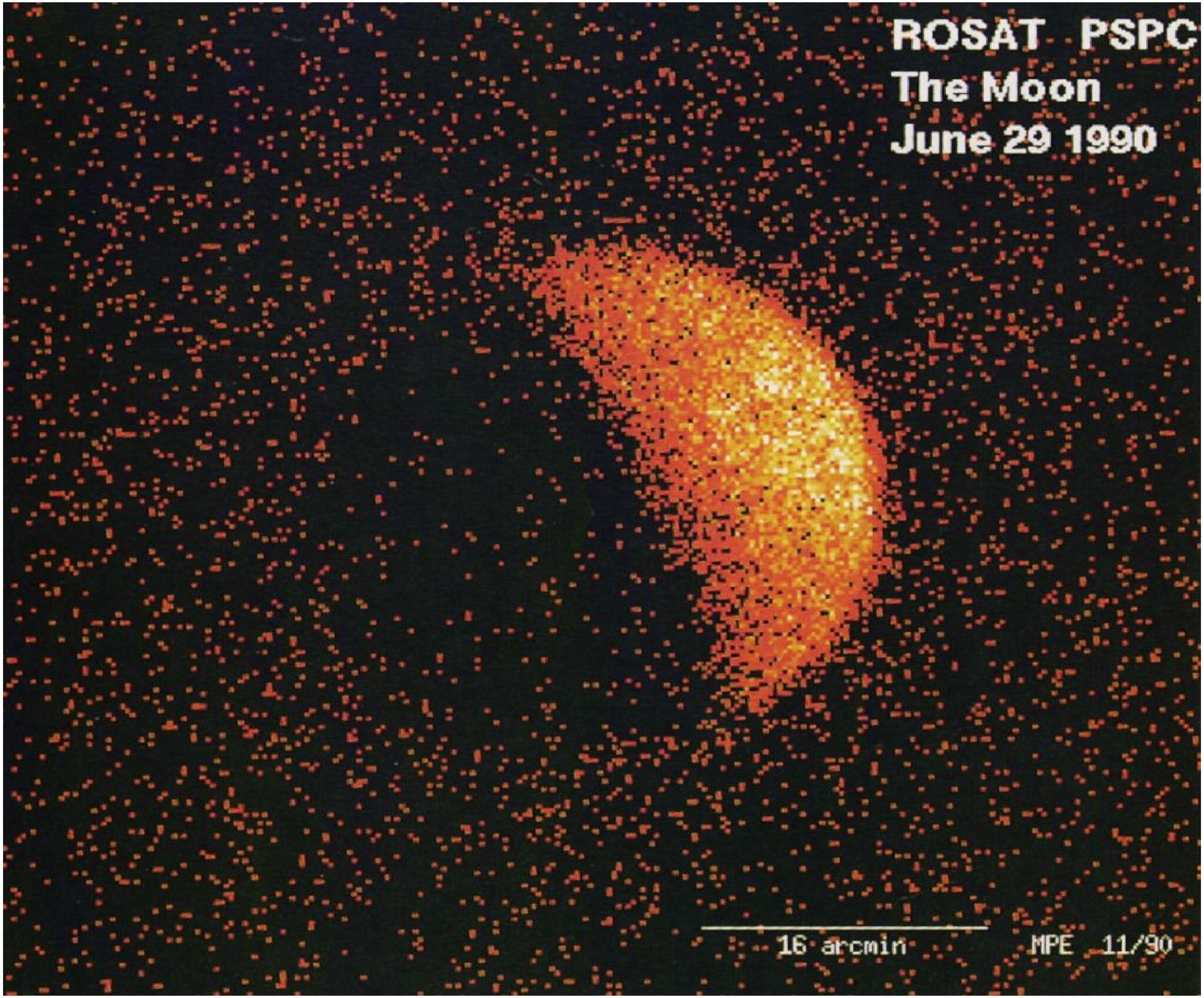
Crab Nebula - CHANDRA

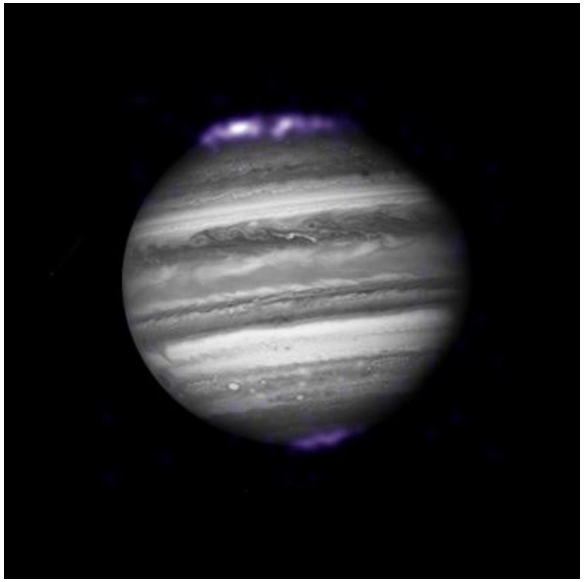


M81

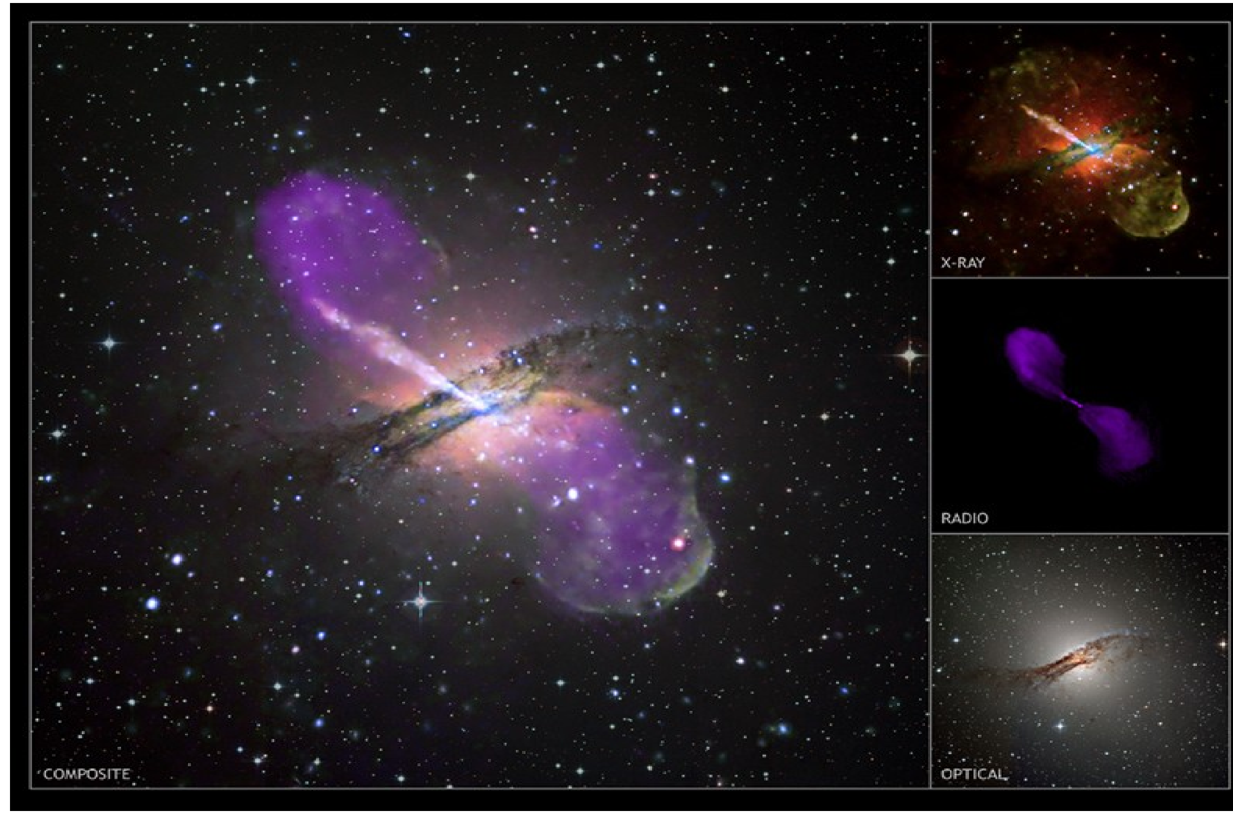


Cosmology starts with X-ray background detected by ROSAT

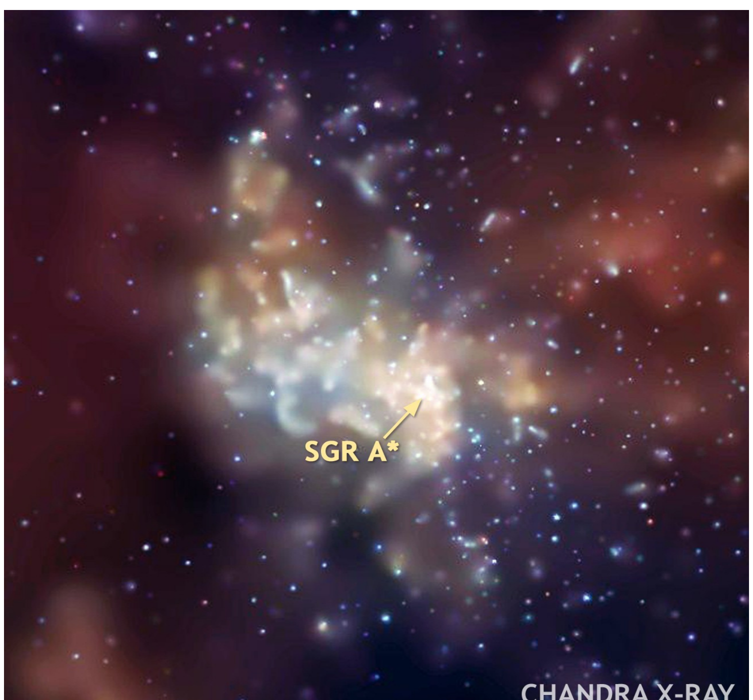


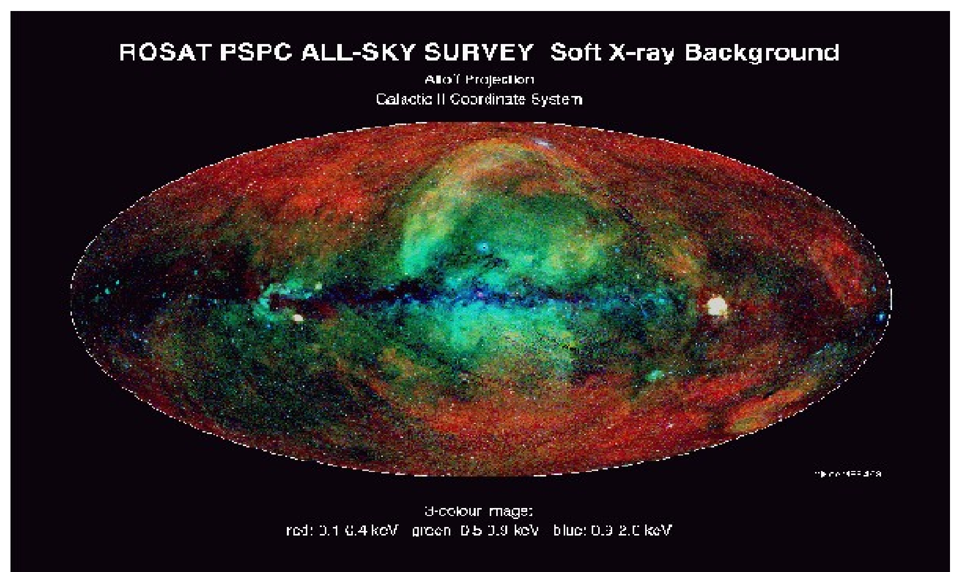


Jupiter – CHANDRA and HST



Centaurus A – active galaxy, CHANDRA 2008

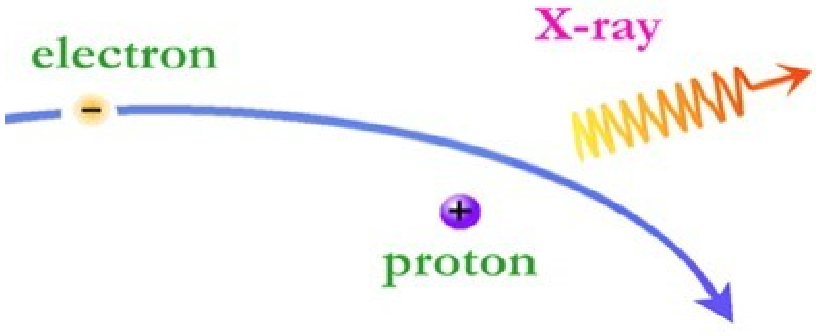




Physics behind X-ray emission from the Universe:

- **Primary emission:**

1) Bremsstrahlung



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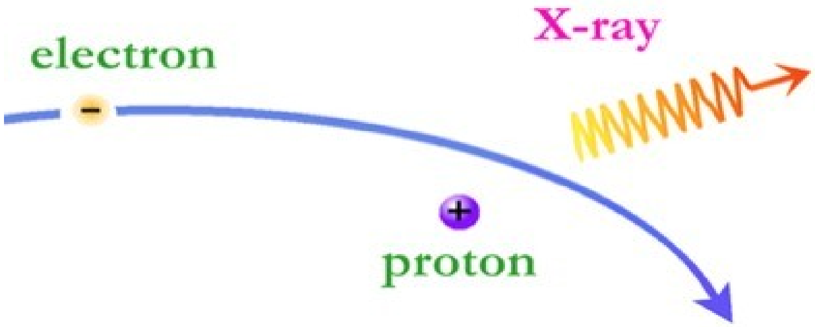
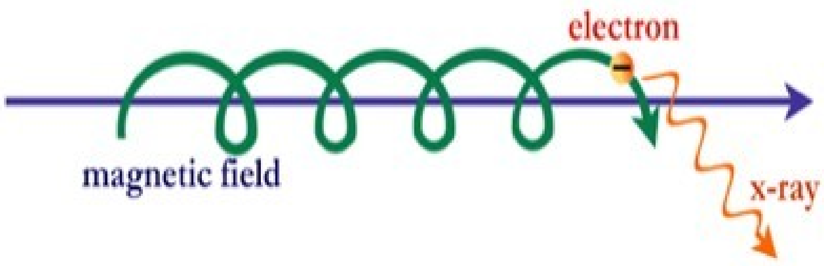


2) Synchrotron radiation



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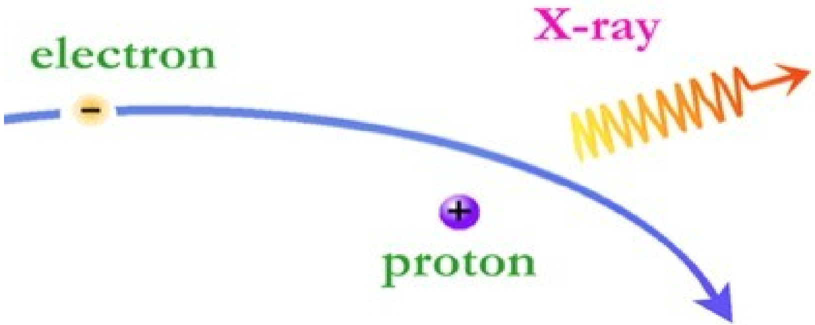

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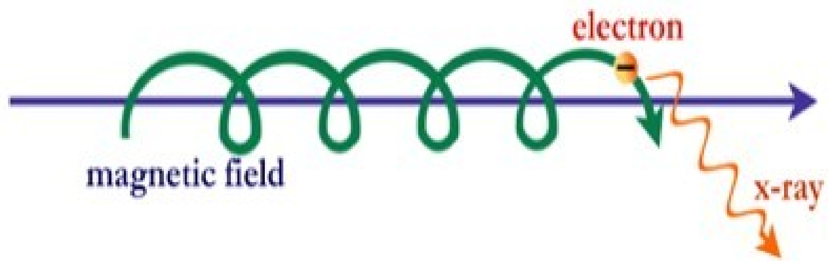
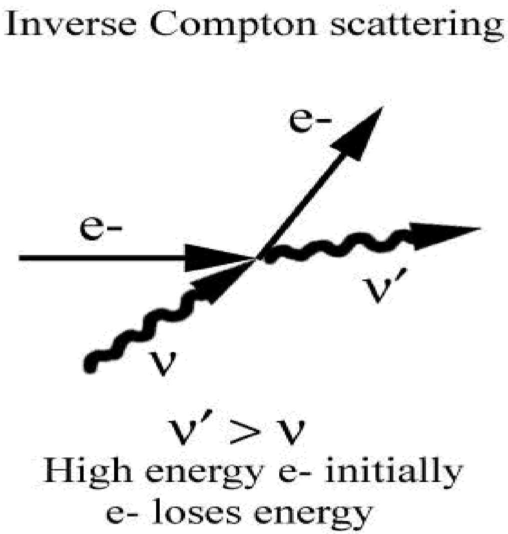


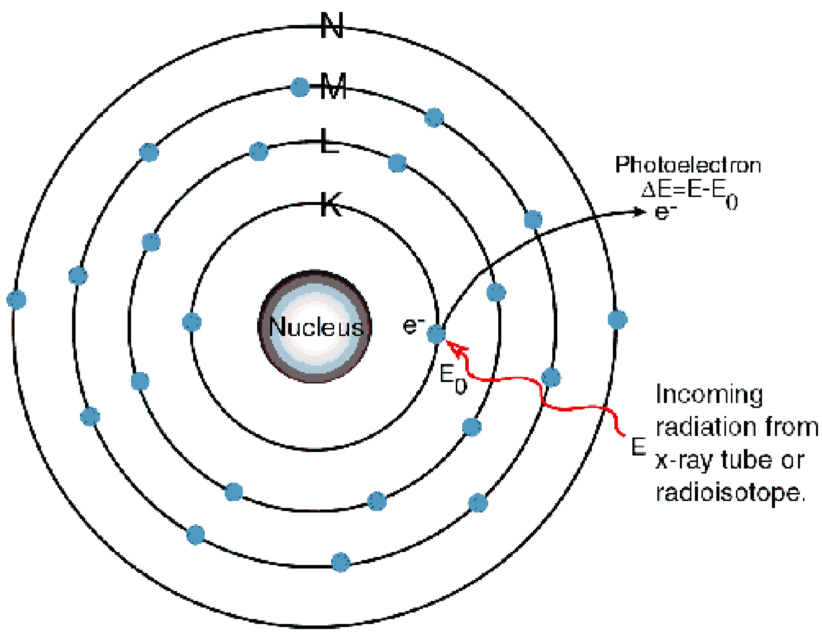


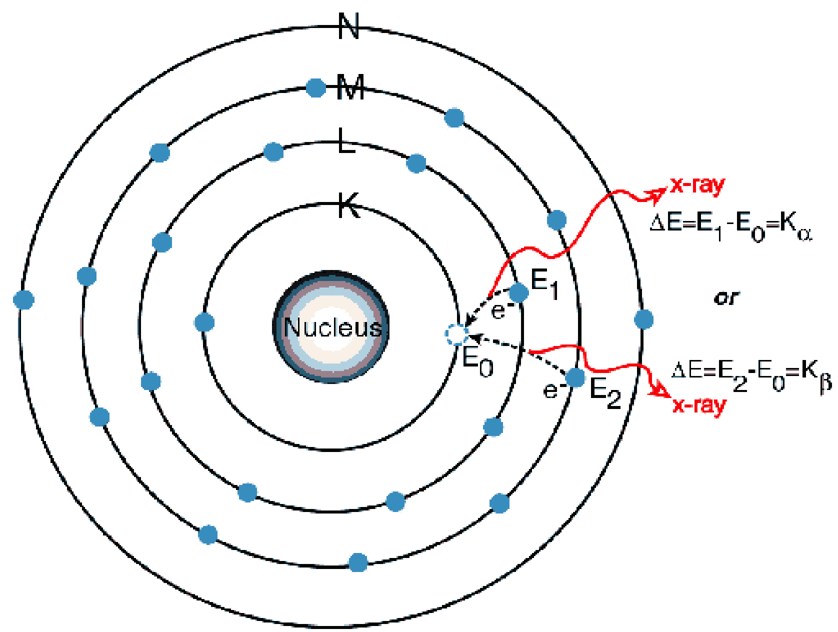
3) Inverse Compton scattering – when soft photons (E < 0.1 keV) scatter with hot electrons (10^7 K) Energy goes from electrons to photons.

Physics behind X-ray emission from the Universe:

- **Secondary emission:**

1) Fluorescent emission – when relatively cold matter is illuminated by hard X-ray source,



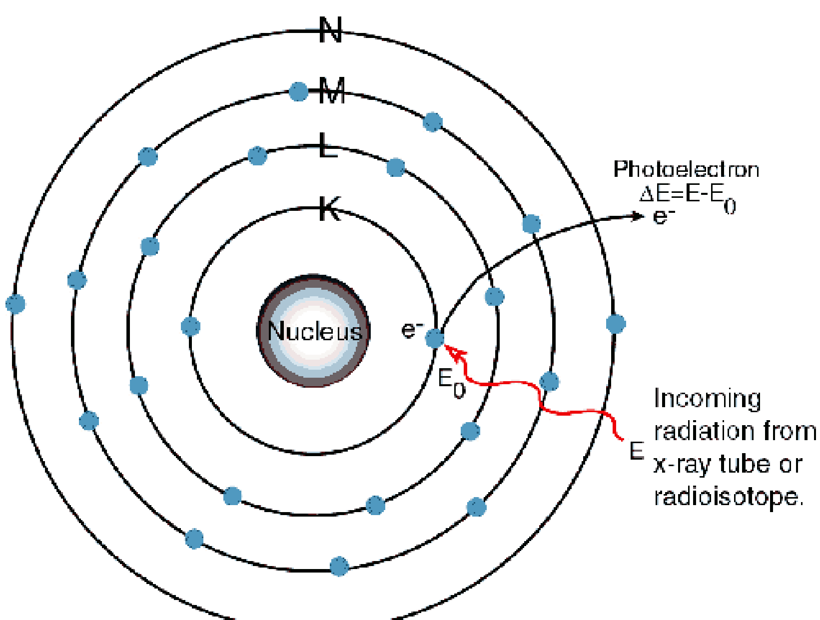


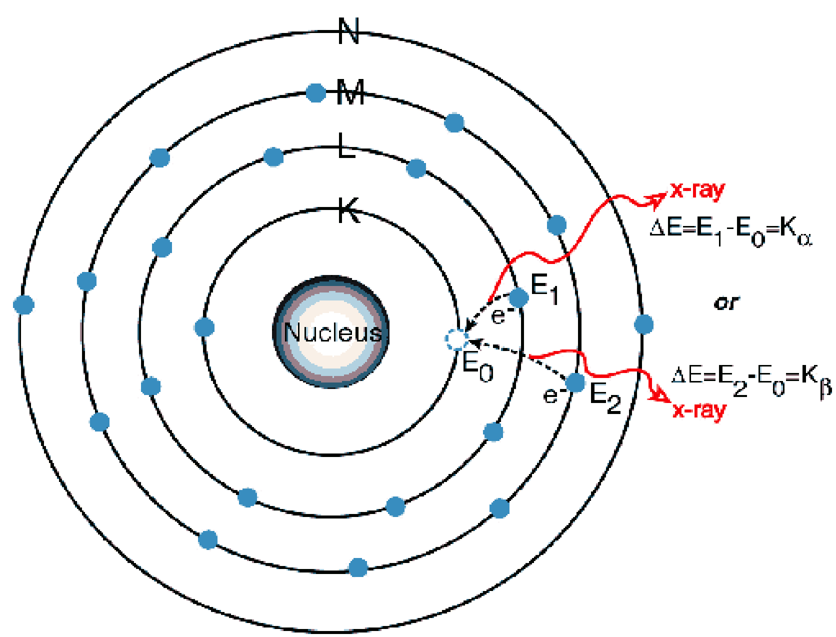
Physics behind X-ray emission from the Universe:

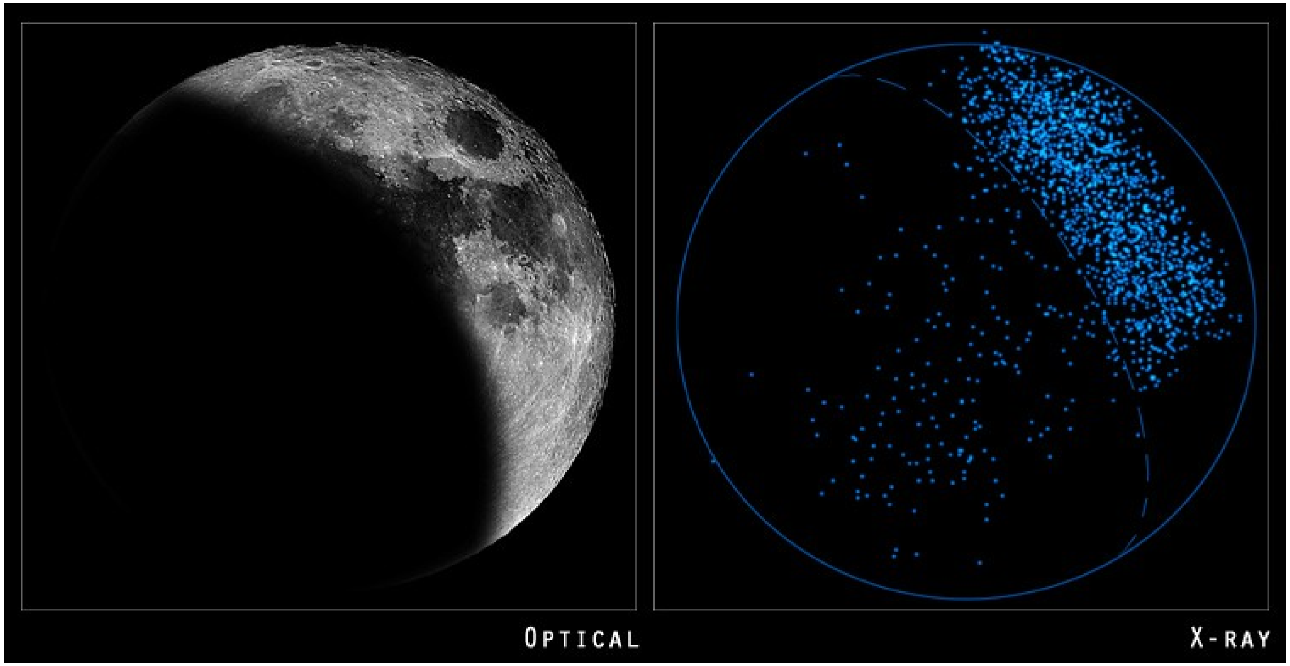
- **Secondary emission:**

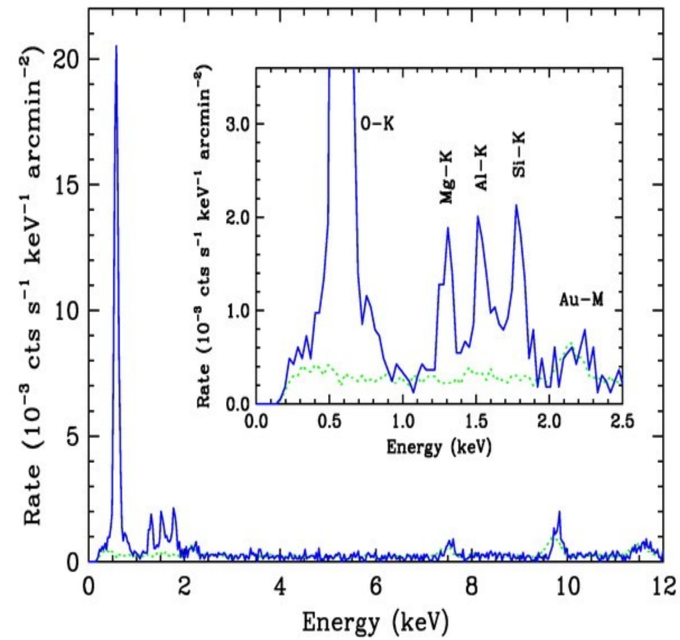
1) Fluorescent emission – when relatively cold matter is illuminated by hard X-ray source,

2) Collisional emission - due to the collisions with fast plasma particles.

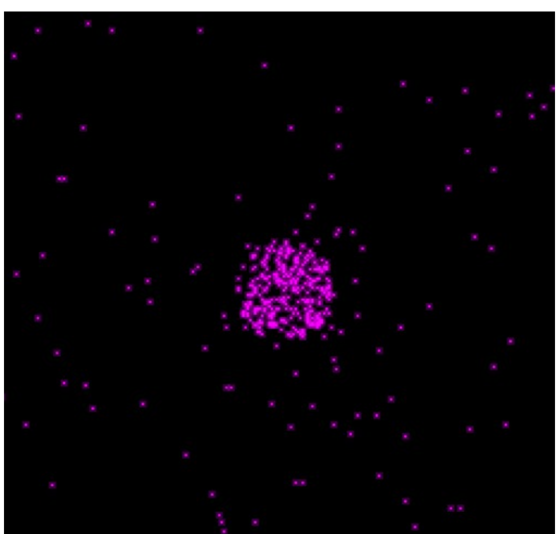




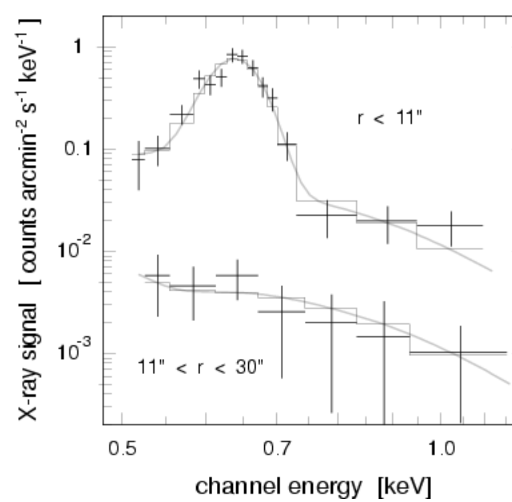




Day side of MOON illuminated by solar wind – CHANDRA 2003



Mars seen in the fluorescent oxygen line CHANDRA 2001

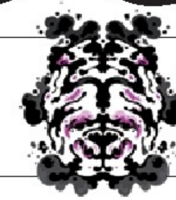


NEWS IN FOCUS

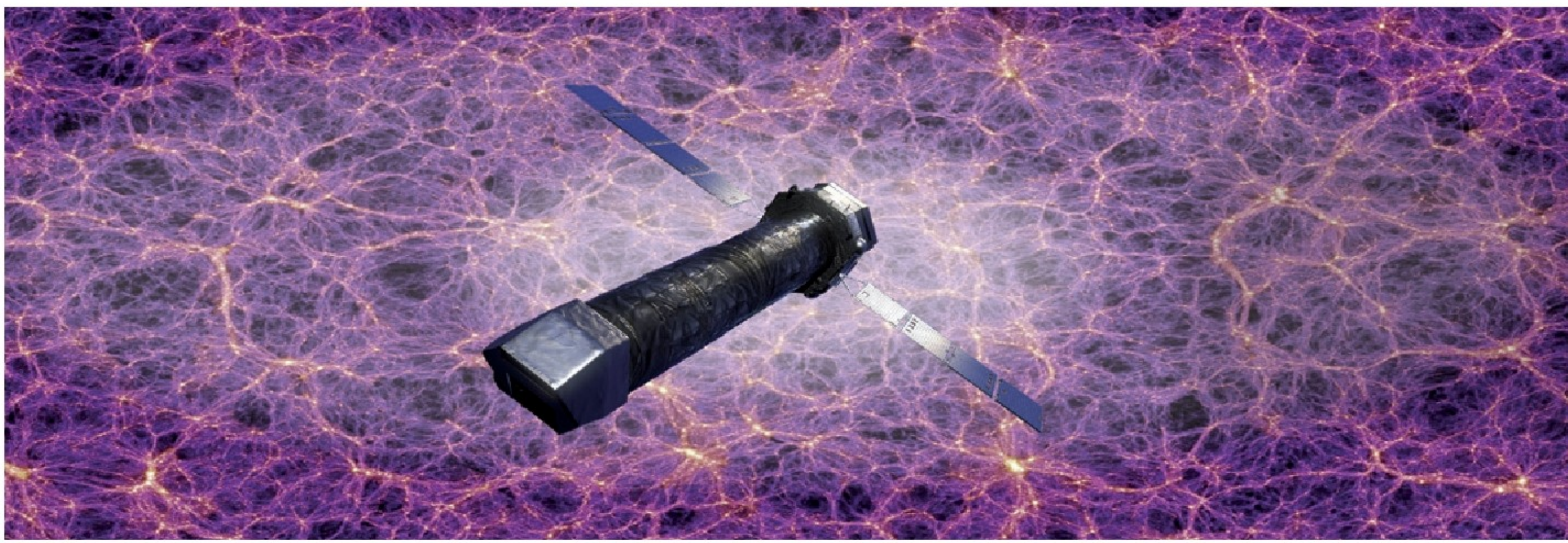
GEOSCIENCE Tremor sensors trundle towards the frozen Alaskan tundra **p.16**

MOLECULAR BIOLOGY Carl Linnaeus had his elephants all mixed up **p.18**

PATHOGENS Virologists challenge rules on export licences **p.19**



NEUROSCIENCE Studies of the brain gain fresh momentum **p.21**



JAVIER GARCIA NOMBELA-ART-ERES.NET/VOLKER SPRINGEL(MPA)/IRAP

Athena+, a planned X-ray observatory that would be the most powerful ever flown, is likely to be launched in 2028.

ASTRONOMY

X-rays top space agenda

European agency selects mission themes, with X-ray telescope the biggest winner.

how black holes grow. Luigi Piro, a member of the Athena+ instrument and optics working group at Italy's National Institute for Astrophysics in Rome, says that half of all visible matter is in this 'hot phase', but is poorly understood. "We will now be able to tackle questions about how the Universe is actually working and what is the role of hot plasma and black holes in shaping the Universe," he explains.

how black holes grow. Luigi Piro, a member of the Athena+ instrument and optics working group at Italy's National Institute for Astrophysics in Ro
is in this
"We will
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to stretch the fabric of space-time. Gravitational waves have not been directly detected at ground-based observatories. eLISA would bounce lasers between three spacecraft at least one million kilometres apart, and spot a passing wave when it alters the precise positioning of one of the spacecraft.

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is in this

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to stretch the fabric of space-time. Gravita- tional waves have not been directly detected at ground-based observatories. eLISA would bounce lasers between three spacecraft

For proponents of eLISA, a launch date of 2034 is frustrating, because a pathfinder mission to test the necessary technology is set to fly in 2015 after several years of delays. Danzmann says that the proposal that the X-ray observatory should be the first to launch reflects a desire to concentrate on the "slightly less risky" of the two projects.

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is in this

"We will

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X-RAY SPECS

The European Space Agency is very close to finalizing the following line-up of large (L-class) missions.

Mission	Name	Launch date	Study targets
L1	JUICE	2022	The magnetic field of Jupiter's moon Ganymede
L2	Athena+	2028	Black holes and galaxy clusters.
L3	eLISA	2034	Gravitational ripples from black-hole mergers.

Danzmann says that the proposal that the X-ray observatory should be the first to launch reflects a desire to concentrate on the "slightly less risky" of the two projects.

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"We will …

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X-RAY SPECS

The European Space Agency is … missions.

Mission	Name	
L1	JUICE	
L2	Athena+	
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STRONGGRAVITY

EU FP7-SPACE research project 312789 **2013 - 2017**

X-RAY SPECS

The European Space Agency is ... missions.

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European Space Agency

Danzmann say... ...osal that the X-ray observator... ...the first to launch reflects a desire to c...centrate on the "slightly less risky" of the two projects.

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esa
European Space Agency

POLISH ACADEMY OF SCIENCES
N. COPERNICUS ASTRONOMICAL CENTER

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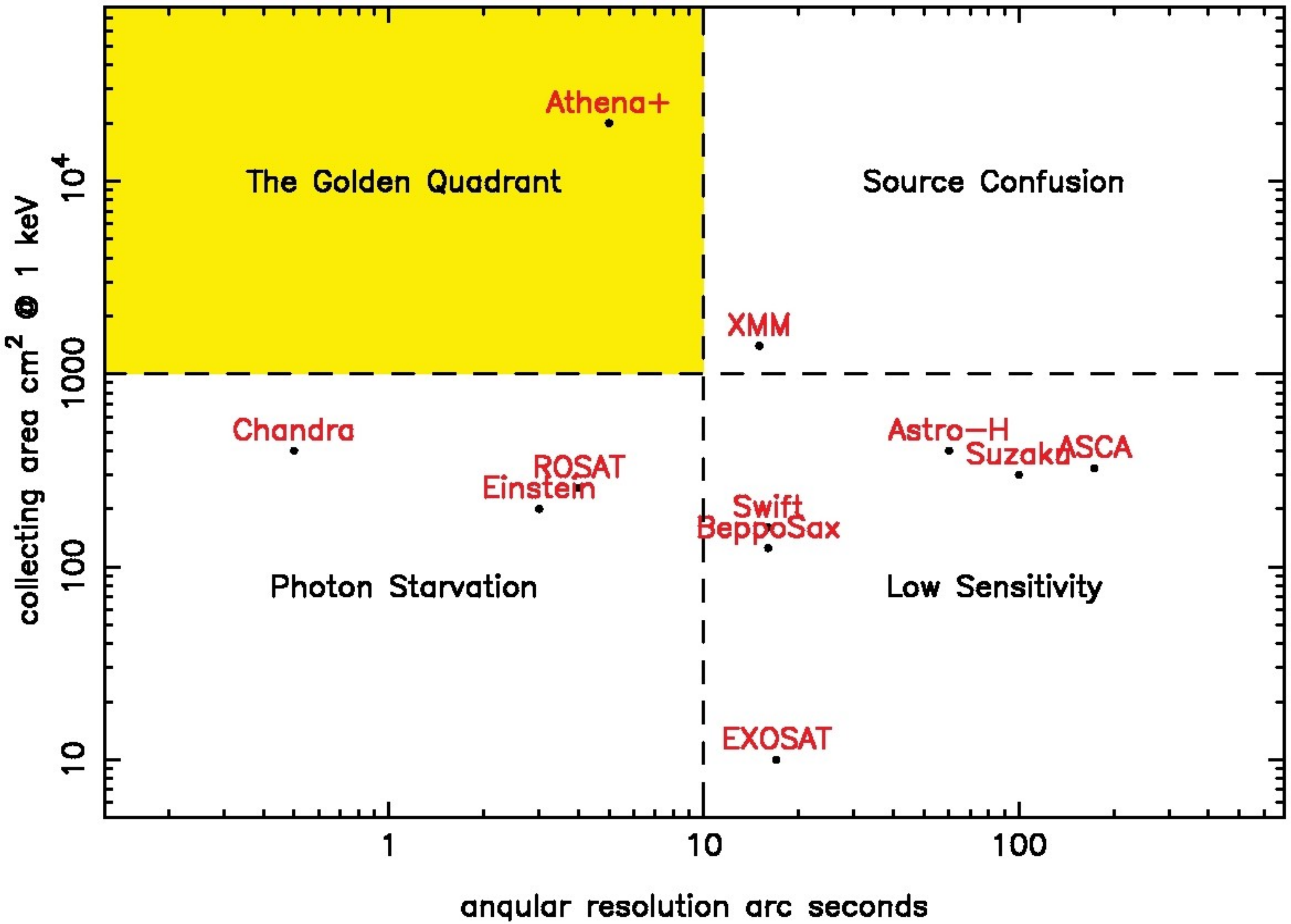
CBK PAN
Space Research Centre
Polish Academy of Sciences
Bartycka 18A, 00-716 Warsaw, phone.: +48 22 4966 200, fax: 022 840 31 31

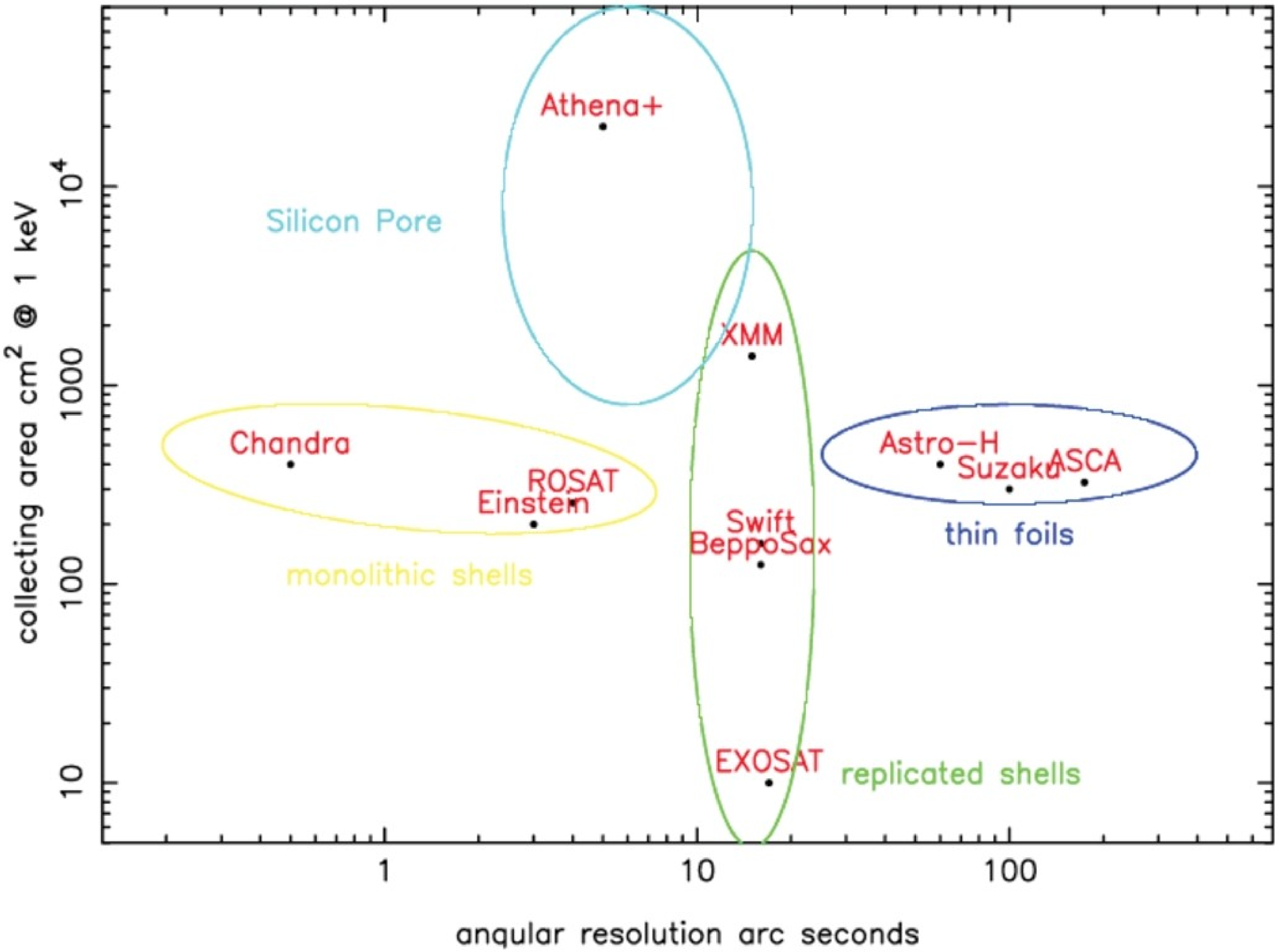
ATHENA is a new generation X-ray Telescope



1 m^2

Willingale et al. 2013, supporting paper

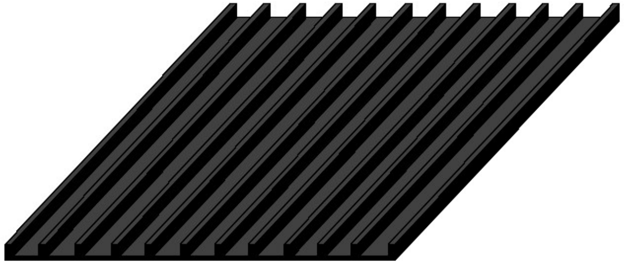
ATHENA is a new generation X-ray Telescope

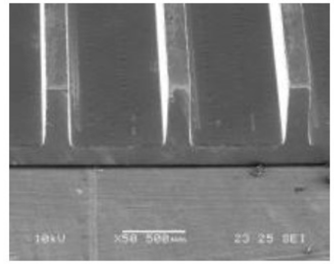


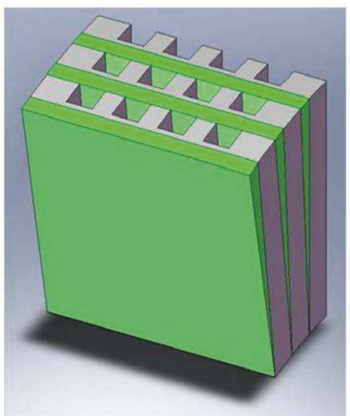
1 m^2

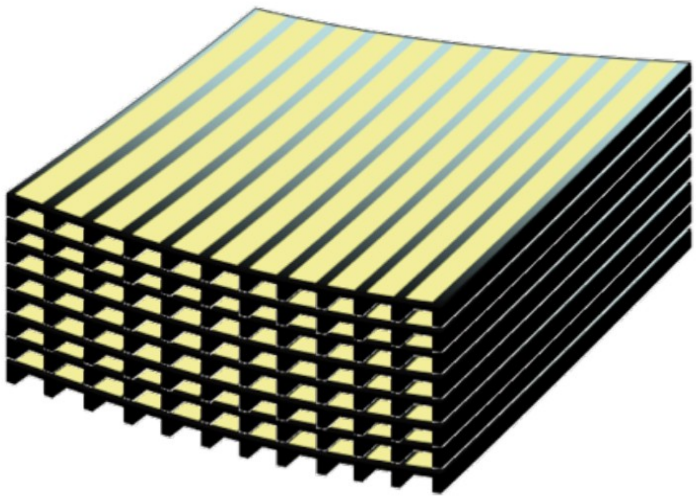
Willingale et al. 2013, supporting paper

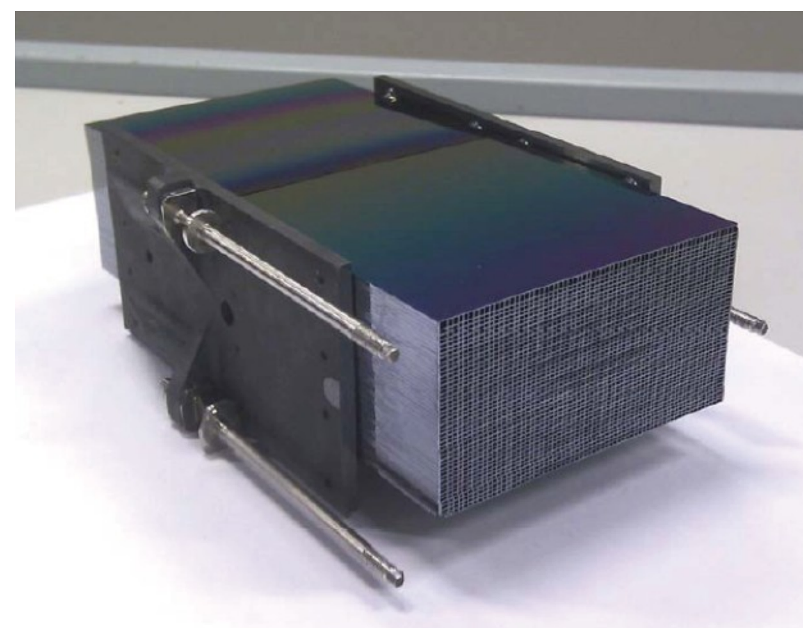
Silicon Pore Optic – SPO   Mirrors on ATHENA





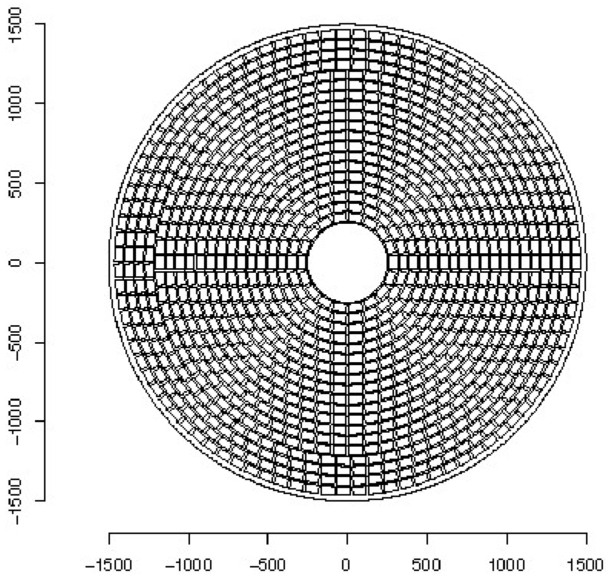


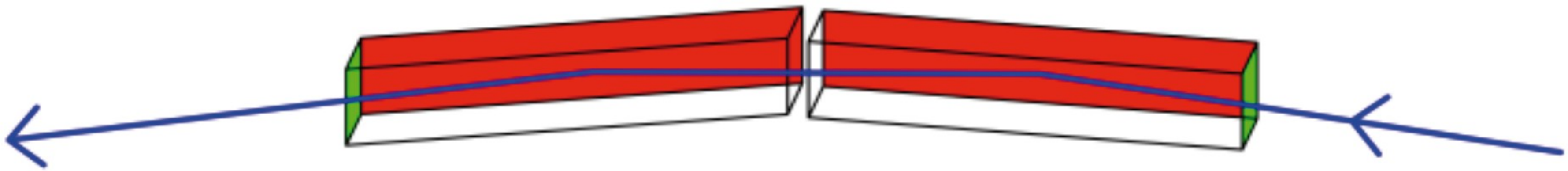




- The large collecting area is achieved using the combination of millions of pores in hundreds of modules.
- The angular resolution is achieved by precise control of the figure and alignment of the reflecting surfaces during the manufacture of the stacks.

Silicon Pore Optic – SPO   Mirrors on ATHENA

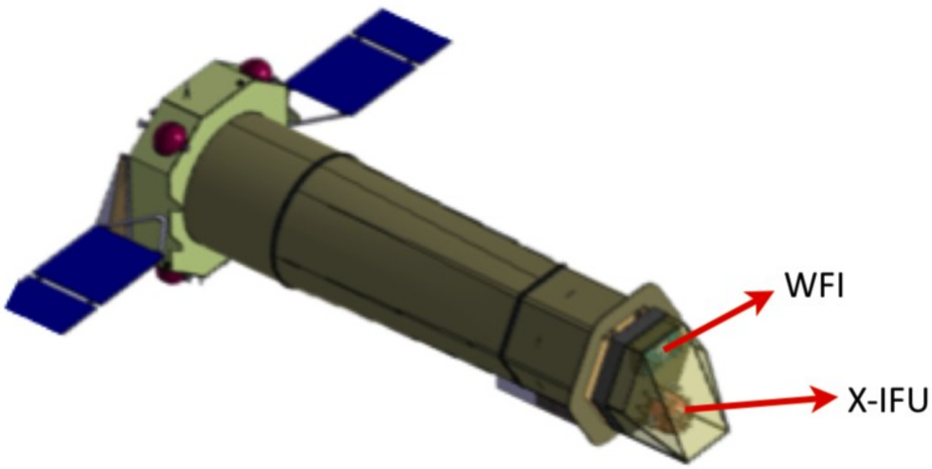


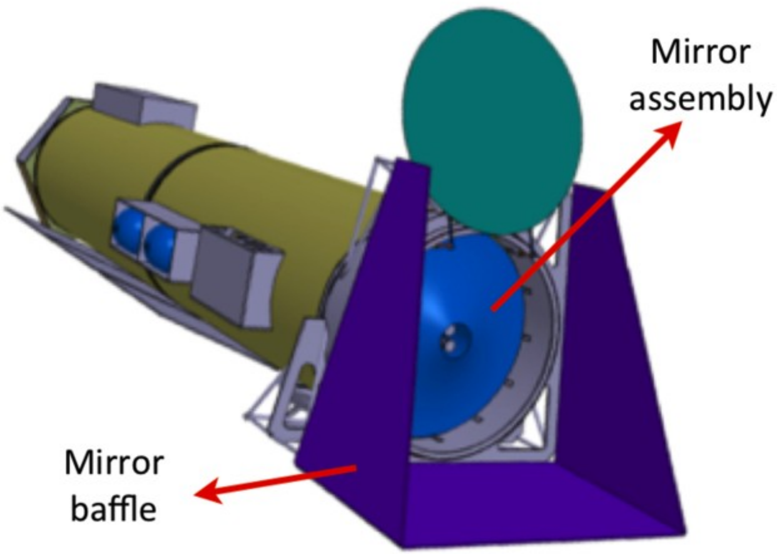


The wide field of view is possible because the rib spacing can be optimized and it is easy to arrange the modules so they approximate the optimum Wolter-Schwartzschild geometry.

ATHENA is a single telescope with fixed 12m focal length using ESA Silicon Pore Optics

5” (3”) resolution

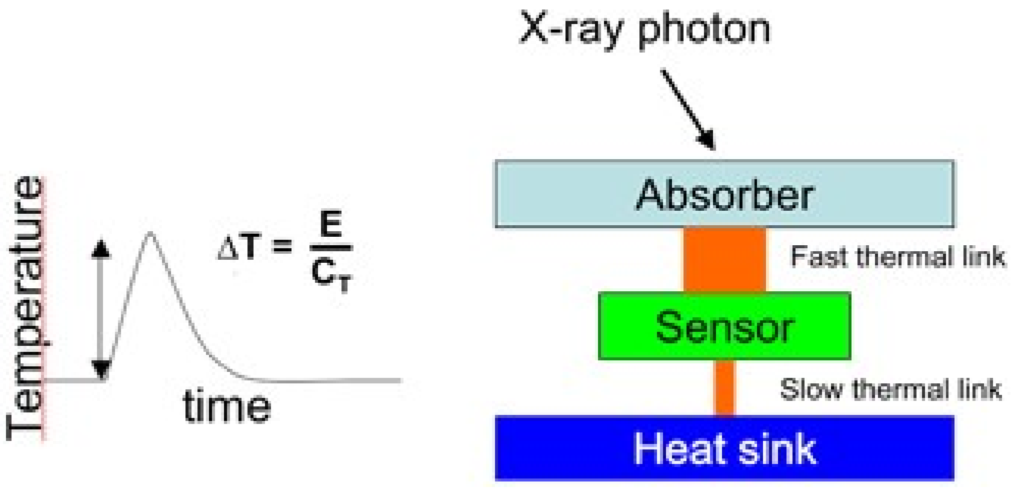




<u>Two X-ray detectors in the focal plane:</u>

1. **X-IFU – X-ray Integral Field Unit 0.3-12. keV**
2. **WFI – Wide Field Monitor 0.1-15. keV**

X-IFU – 0.3-12. keV is an array of
Transition Edge Sensors (TES)
working as micro-calorimeters



The absorption of an X-ray photon heats both the absorber and the sensor. The resulting signal represents the total energy deposited. The system goes back slowly to its original state through a weak thermal link with a heat sink.

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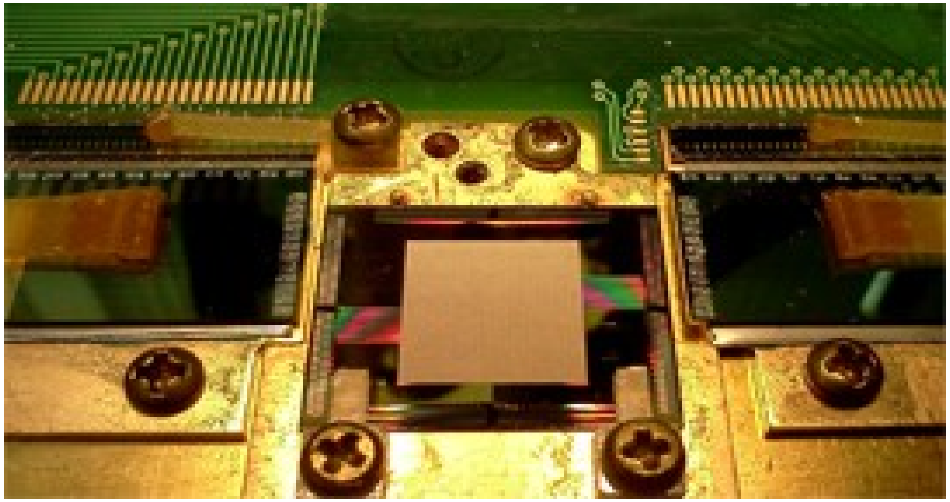
TES Array – X-ray Microcalorimeter Spectrometer (XMS)



The detector consists of an array of 3840 absorbers,
limited FoV - 5' x 5' (goal is 7' x 7')

Count rate capability – 1 mCrab point source
with 90% , high-resolution events

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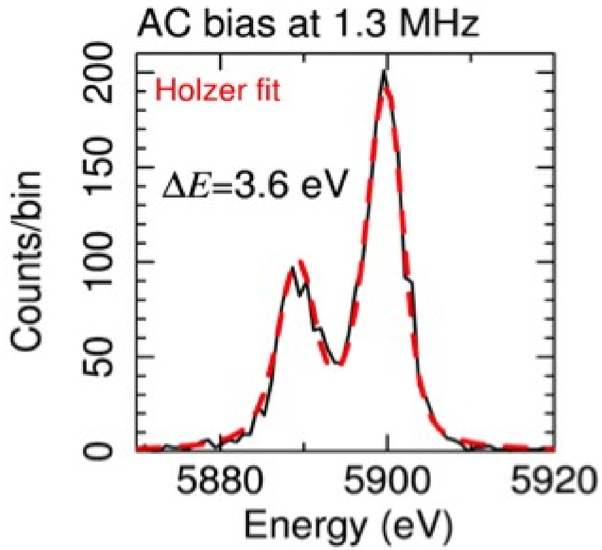

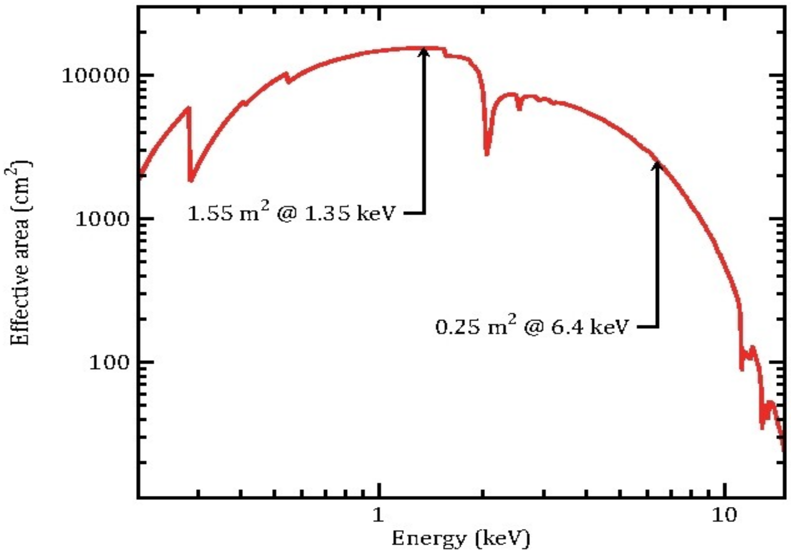

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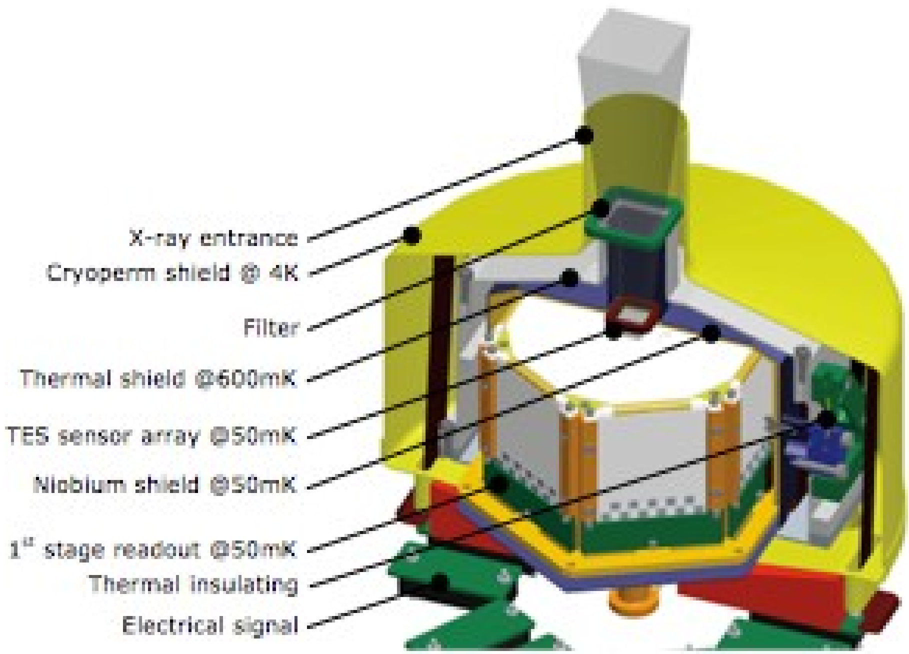

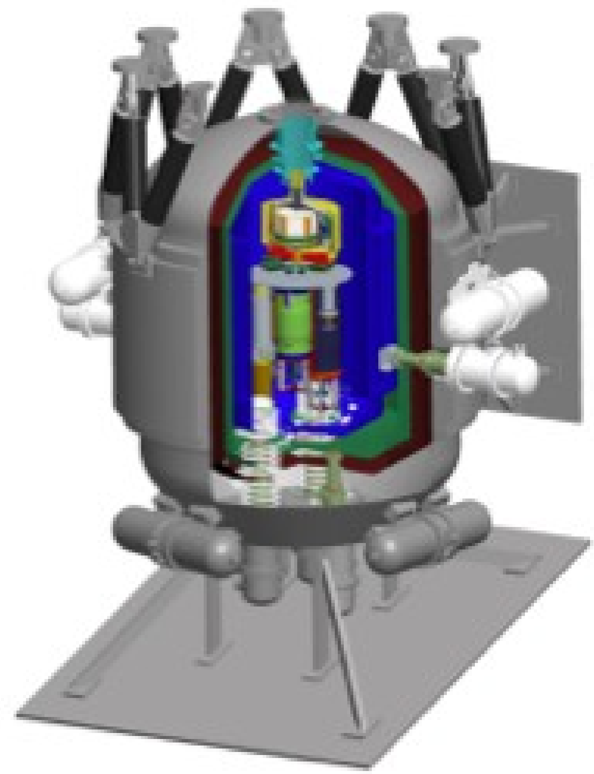

The sensor is coupled to a 50 mK bath. The instrument life time will not be limited by consumables as a combination of different, cryogen free, cooling techniques will be used.

JAXA three times tried to build micro-calorimeter:

2000 – ASTRO-E has been lost in the ocean during launch.

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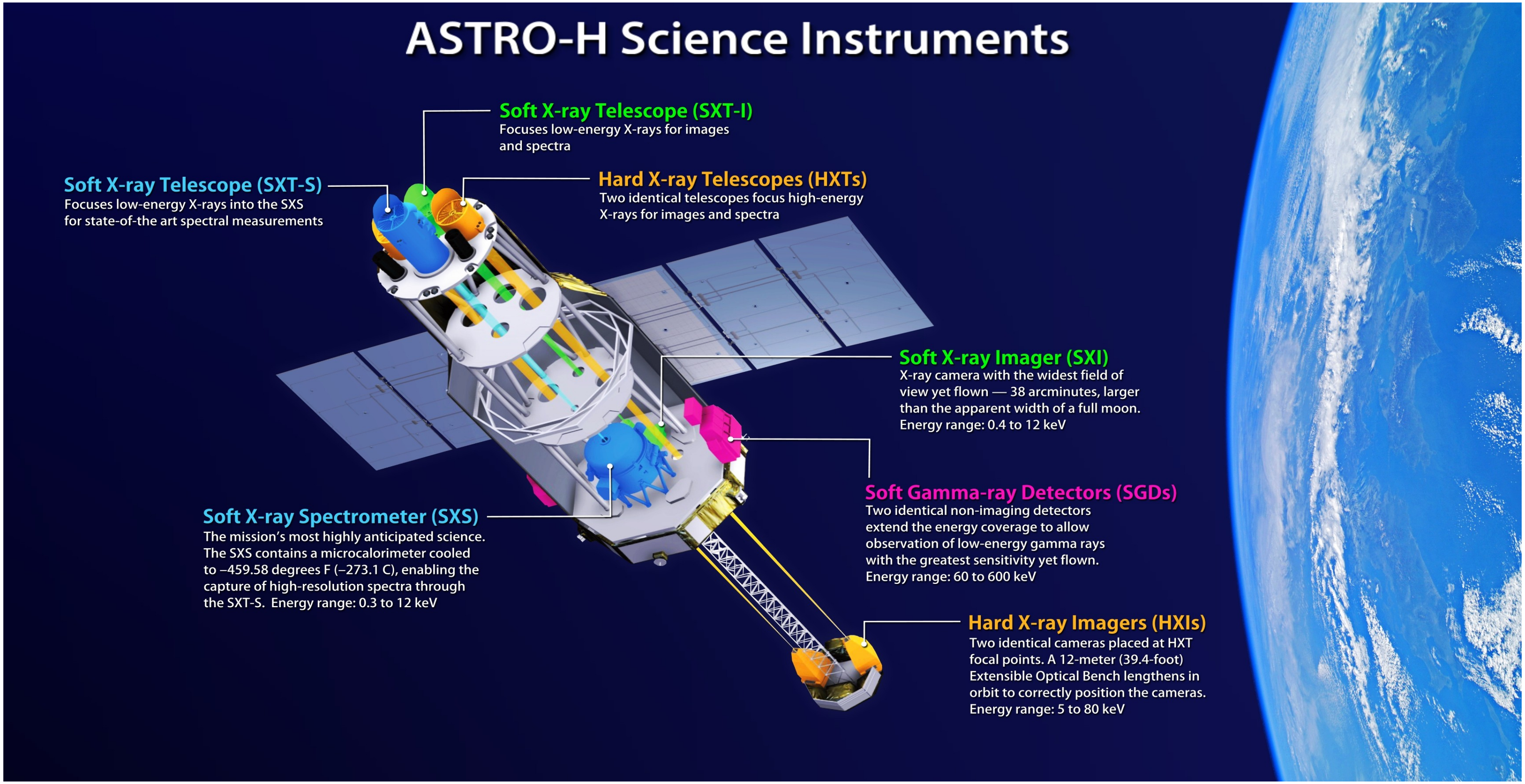
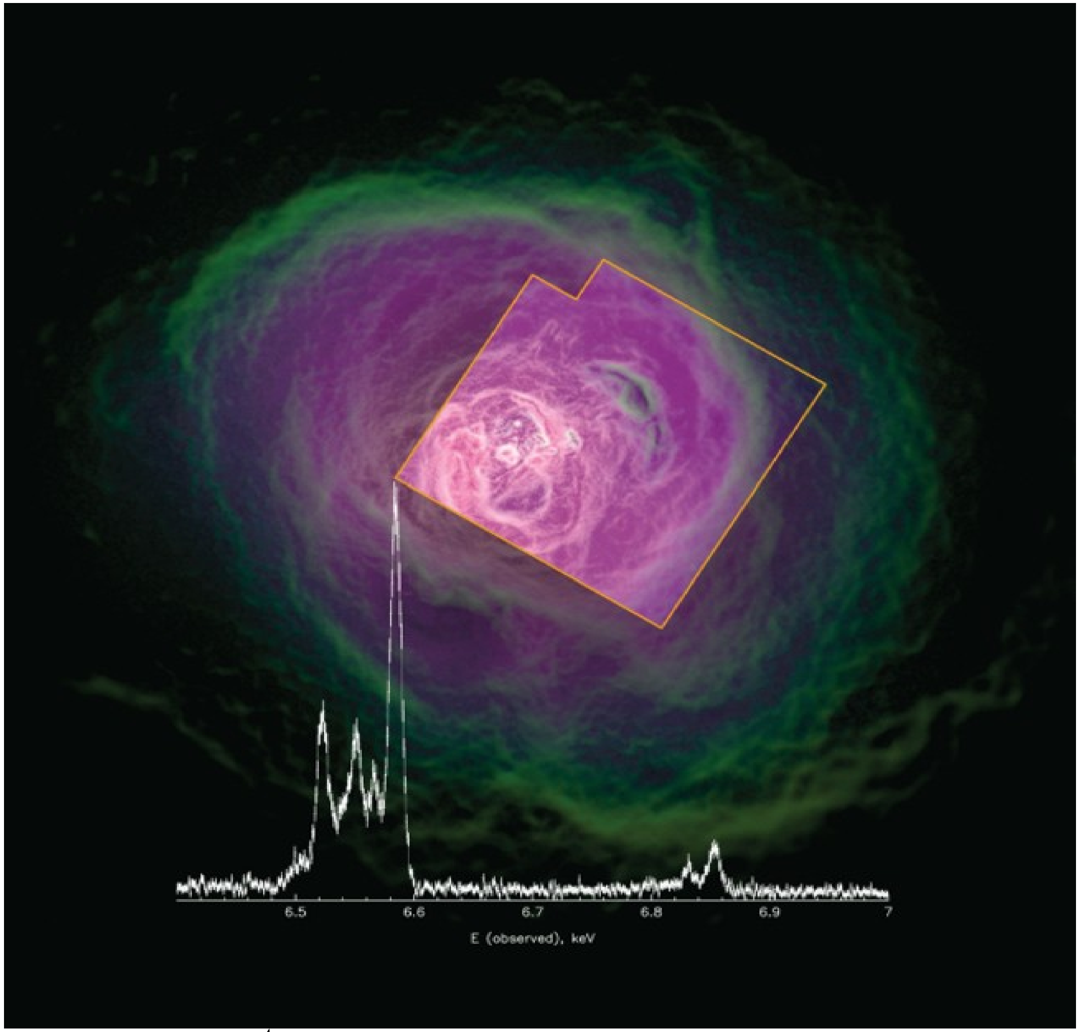
2016 – ASTRO-H, launched on Feb. 2016, renamed as HITOMI, lost on March 2016 due to the software mistake.



HITOMI team NATURE paper issued at July 2016:
- emission from Perseus galaxy cluster with lines !!!



Emission triplet from helium-like Fe ions.

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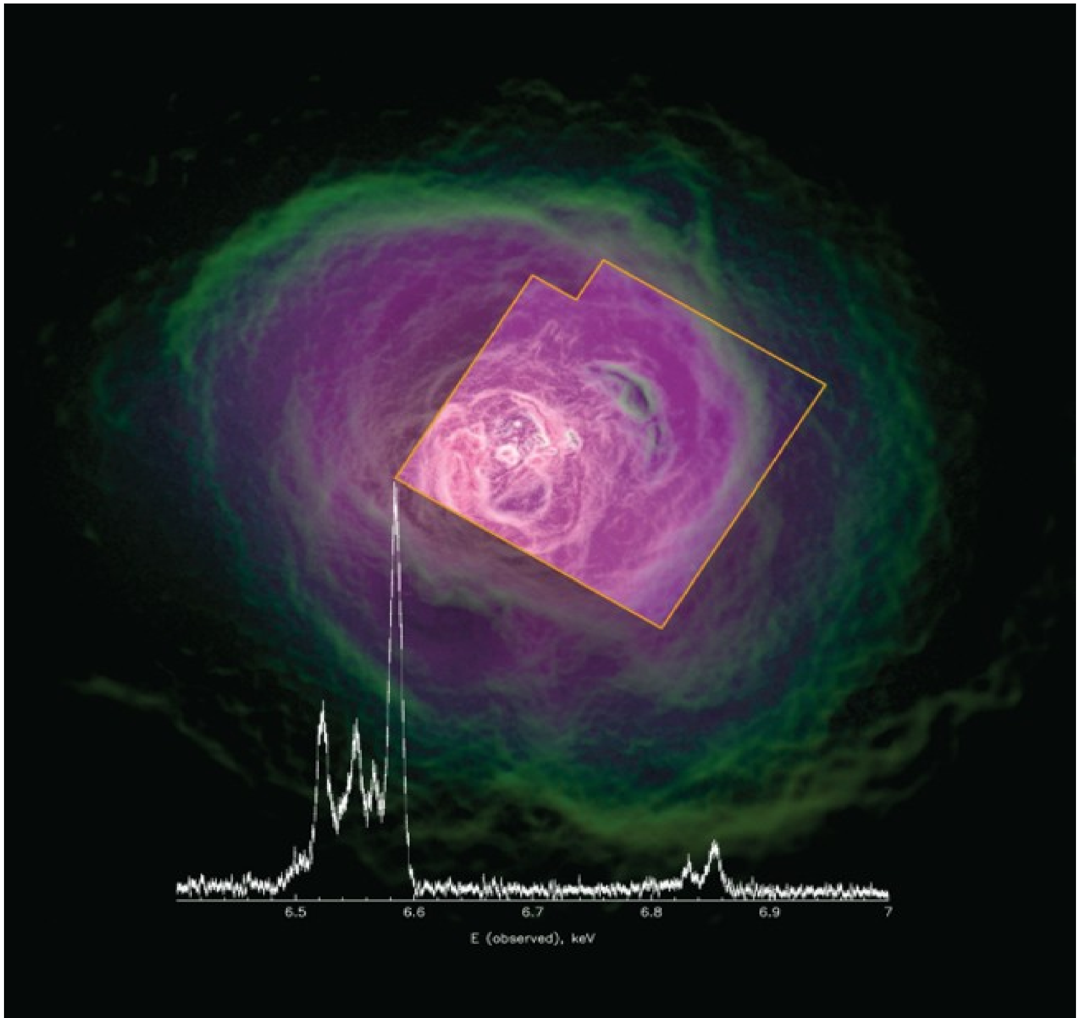
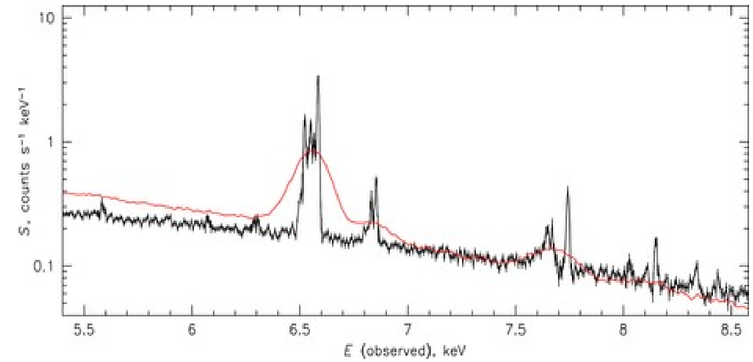
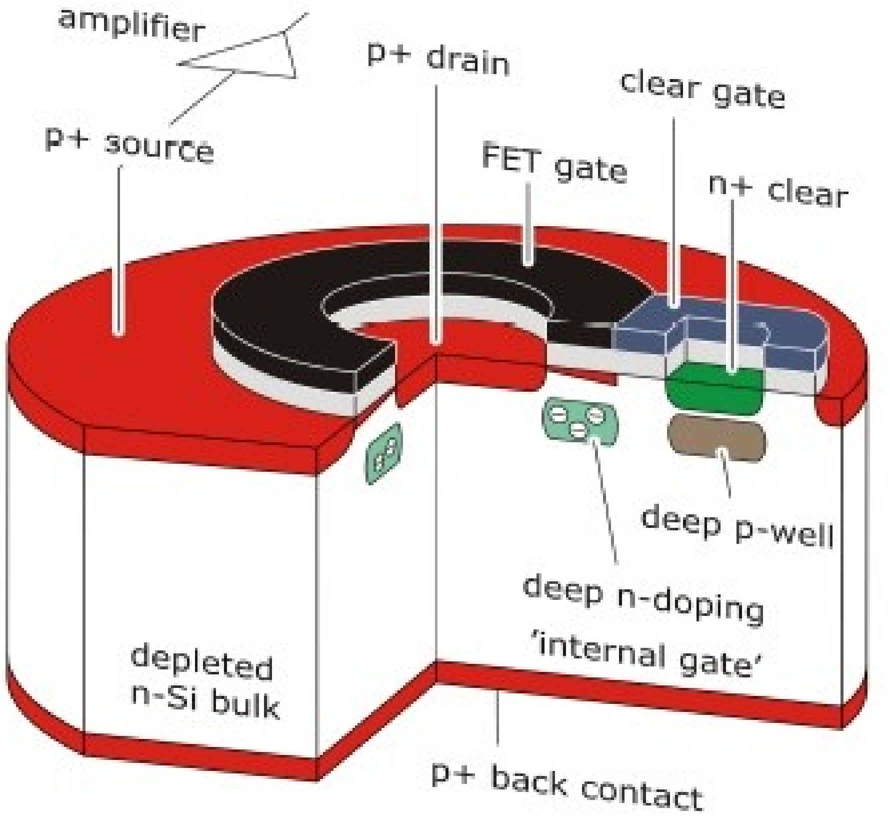




Comparison with SUZAKU

Emission triplet from helium-like Fe ions.

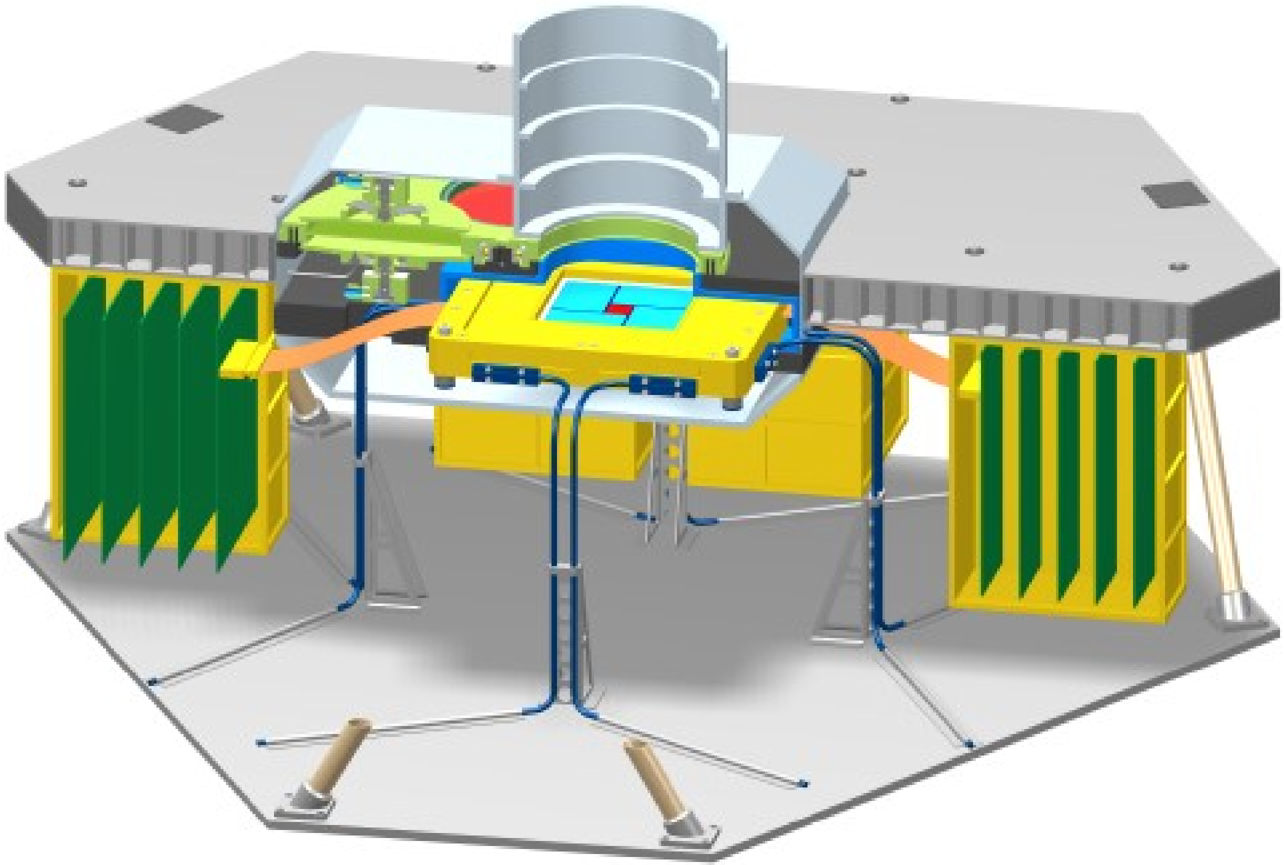
WFI – 0.1-15. keV is an array of Si-based **DePFET** – **De**pleted **P**-channel **F**ield **E**ffect **T**ransistor - **A**ctive **P**ixel **S**ensor (**APS**)



ΔE = 150 @ 6 keV

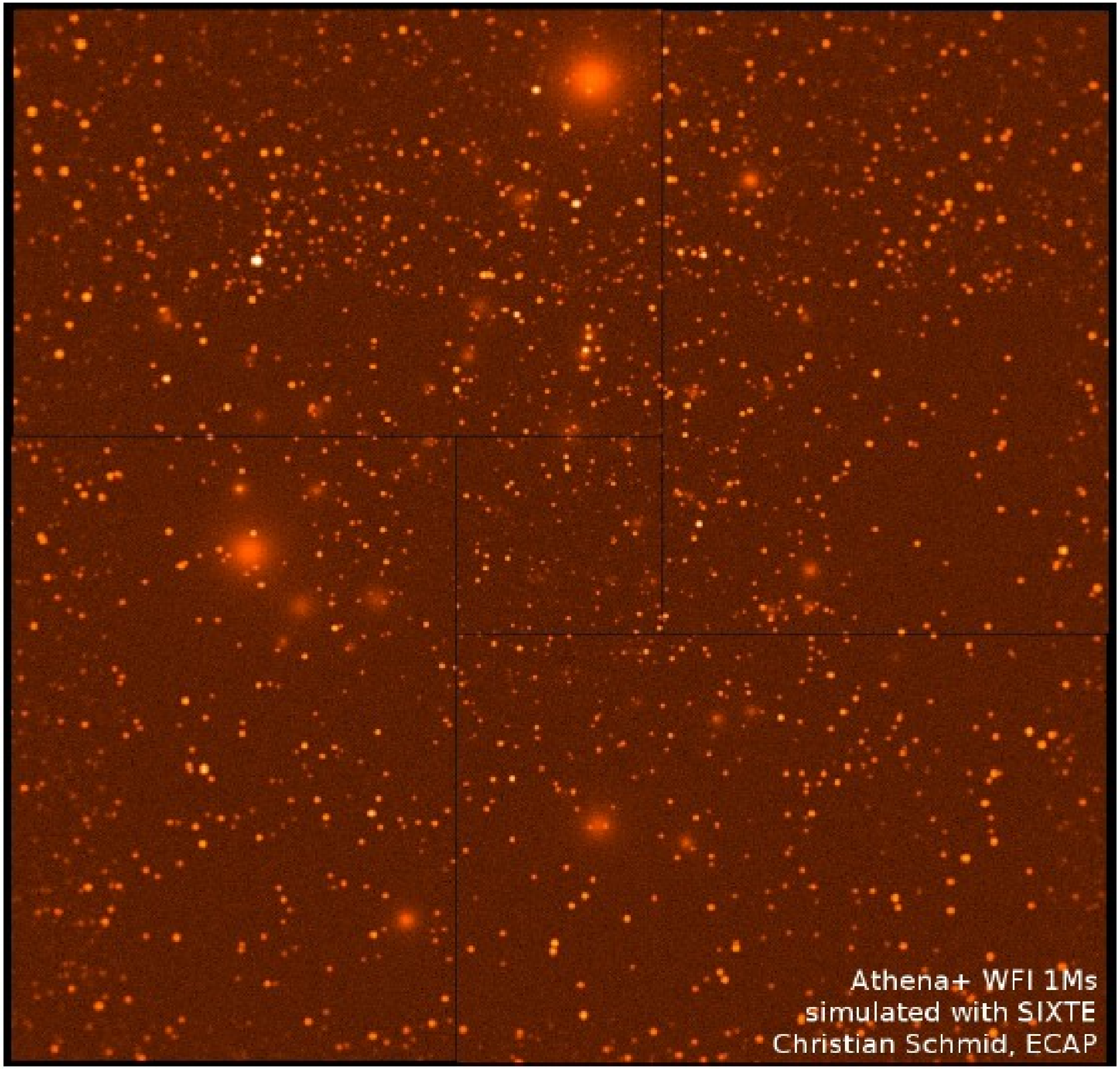
The DePFET is a combined detector-amplifier structure. Here, incident X-ray photons interact with the Si bulk material, and the resulting electron-hole pairs are separated.

WFI – 0.1-15. keV is an array of Si-based DePFET – Depleted P-channel Field Effect Transistor - Active Pixel Sensor (APS)

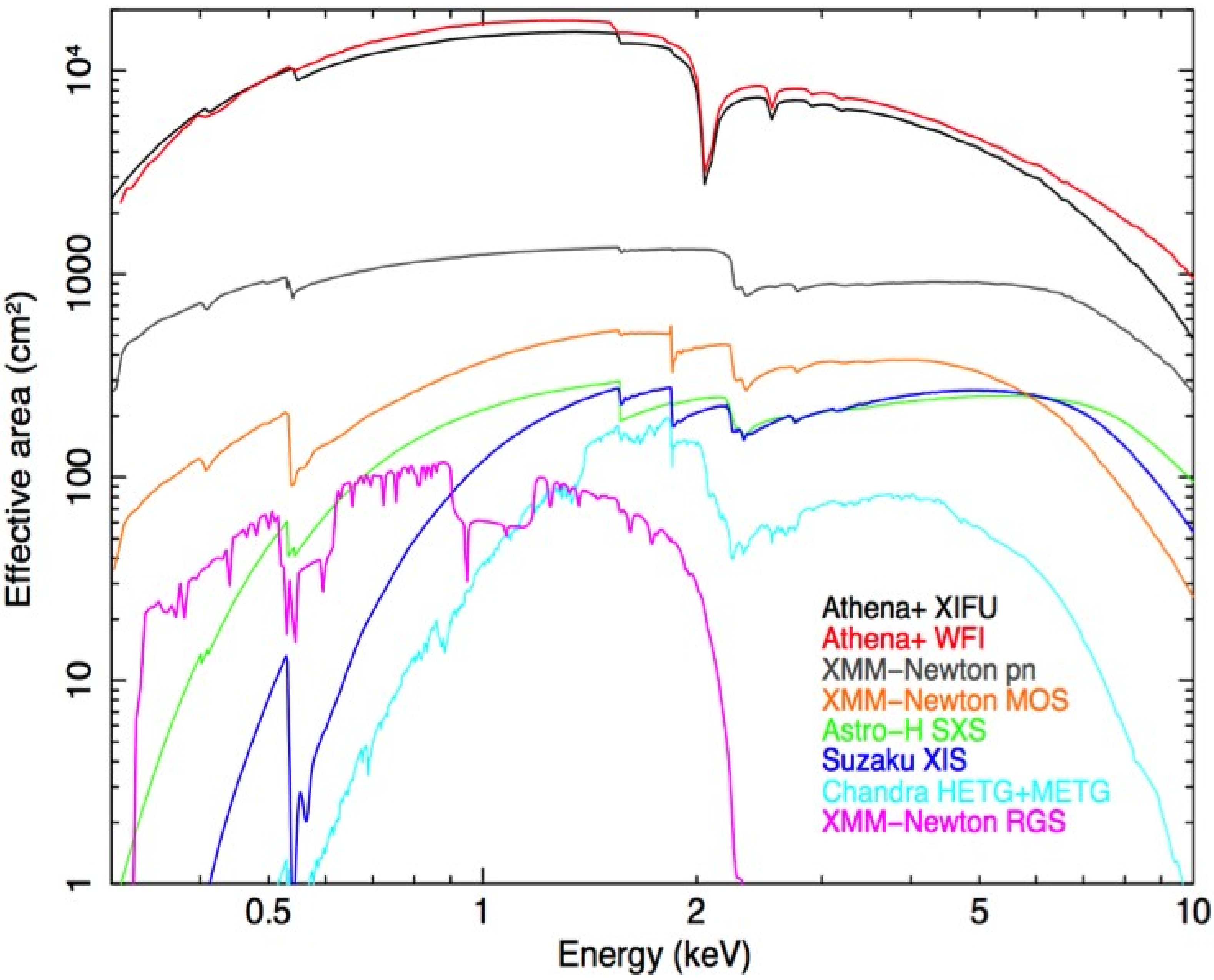


256x256 pixels construct wide FoV 40' x 40' and will in particular allow high-time resolution observations of bright X-ray sources. With a readout time of 8 µs in window mode and a count rate capability of >1 Crab with 80% throughput.

WFI – 0.1-15. keV is an array of Si-based DePFET – Depleted P-channel Field Effect Transistor - Active Pixel Sensor (APS)



Effective area of the ATHENA mission:



Artist's impression of an active galaxy

ATHENA TO STUDY THE HOT AND ENERGETIC UNIVERSE

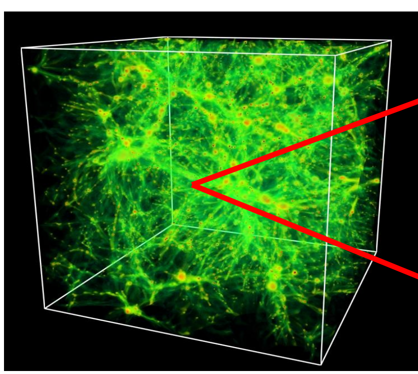
27 June 2014 ESA has selected the Athena advanced telescope for high-energy astrophysics as its second 'Large-class' science mission.

The observatory will study the hot and energetic Universe and takes the 'L2' slot in ESA's Cosmic Vision 2015–25 plan, with a launch foreseen in 2028.

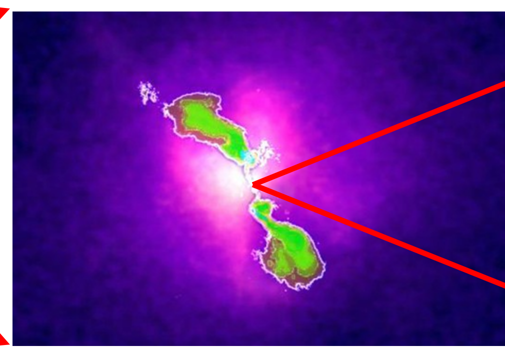
Nandra et al. ESA presentation

Key questions for observational astrophysics in 2028

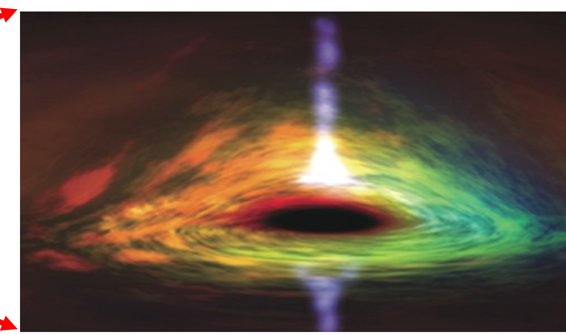
- **How does ordinary matter assembles in large scale structures that we see today ?**
- ***Most of the ordinary matter in the Universe is locked in gas at X-ray temperatures***
- **How do black holes grow and shape the Universe?**
- ***15 % of the (luminous) energy in the Universe is from accretion***



Cosmic Web



Feedback Processes



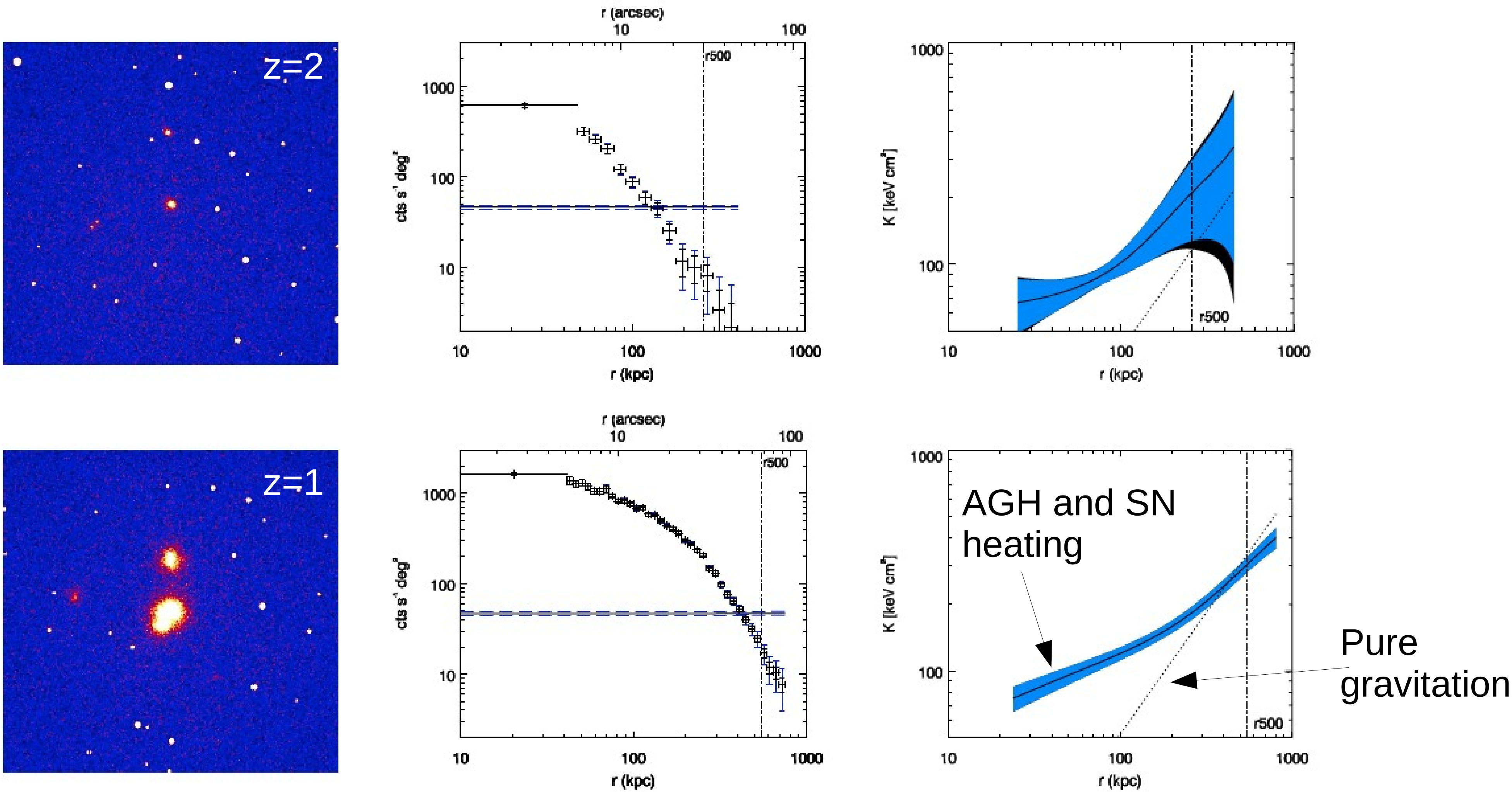
Black Hole Accretion

The formation and evolution of clusters and groups of galaxies, Pointecoutea et al. 2013:

- What is the interplay of galaxy, SBH and, intergalactic gas ?

- What are the processes driving the evolution of chemical enrichment of the hot diffuse gas in large-scale structures?

- How and when did the first galaxy groups form?



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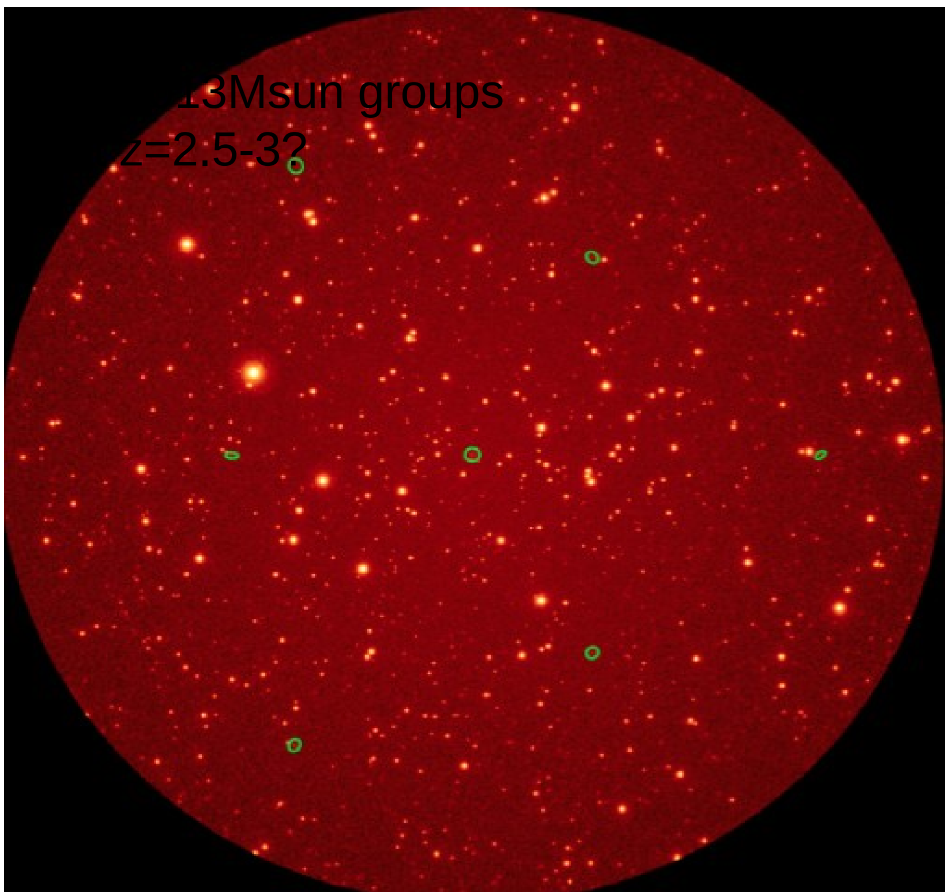
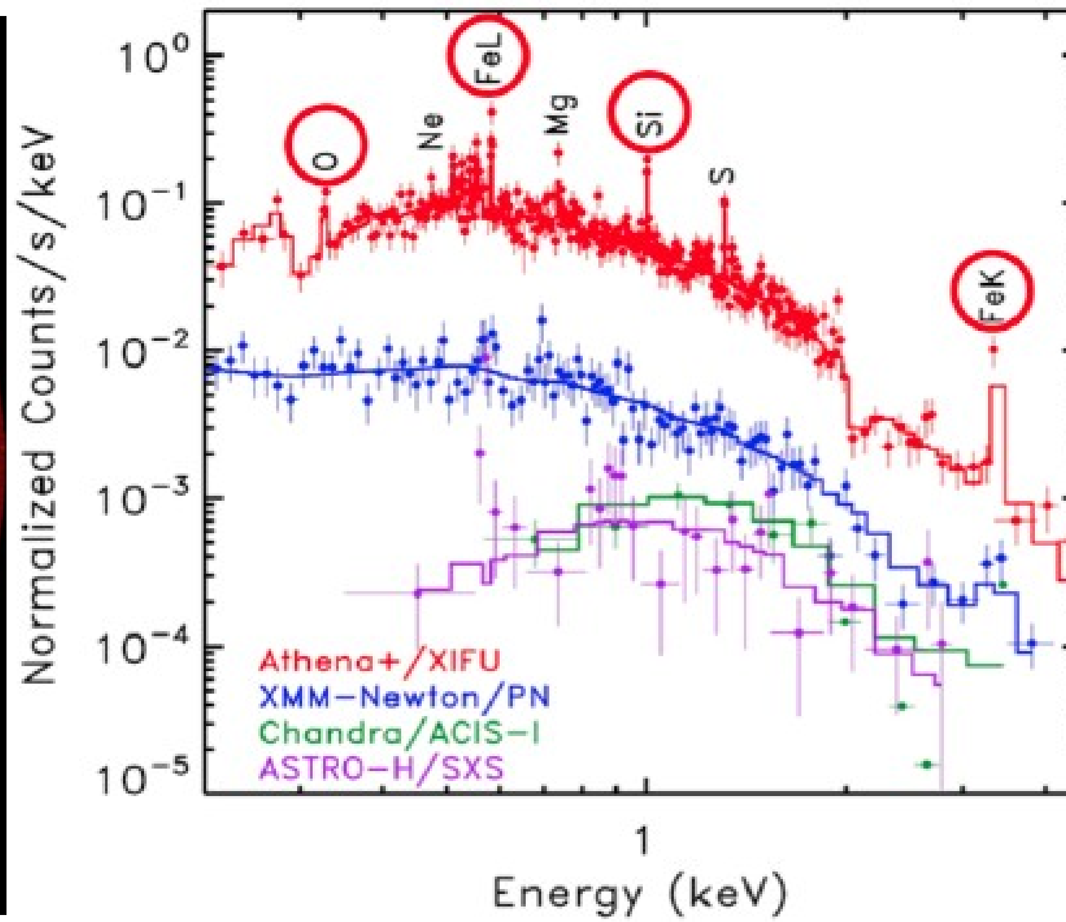
WFI 100 ks 50'x50'

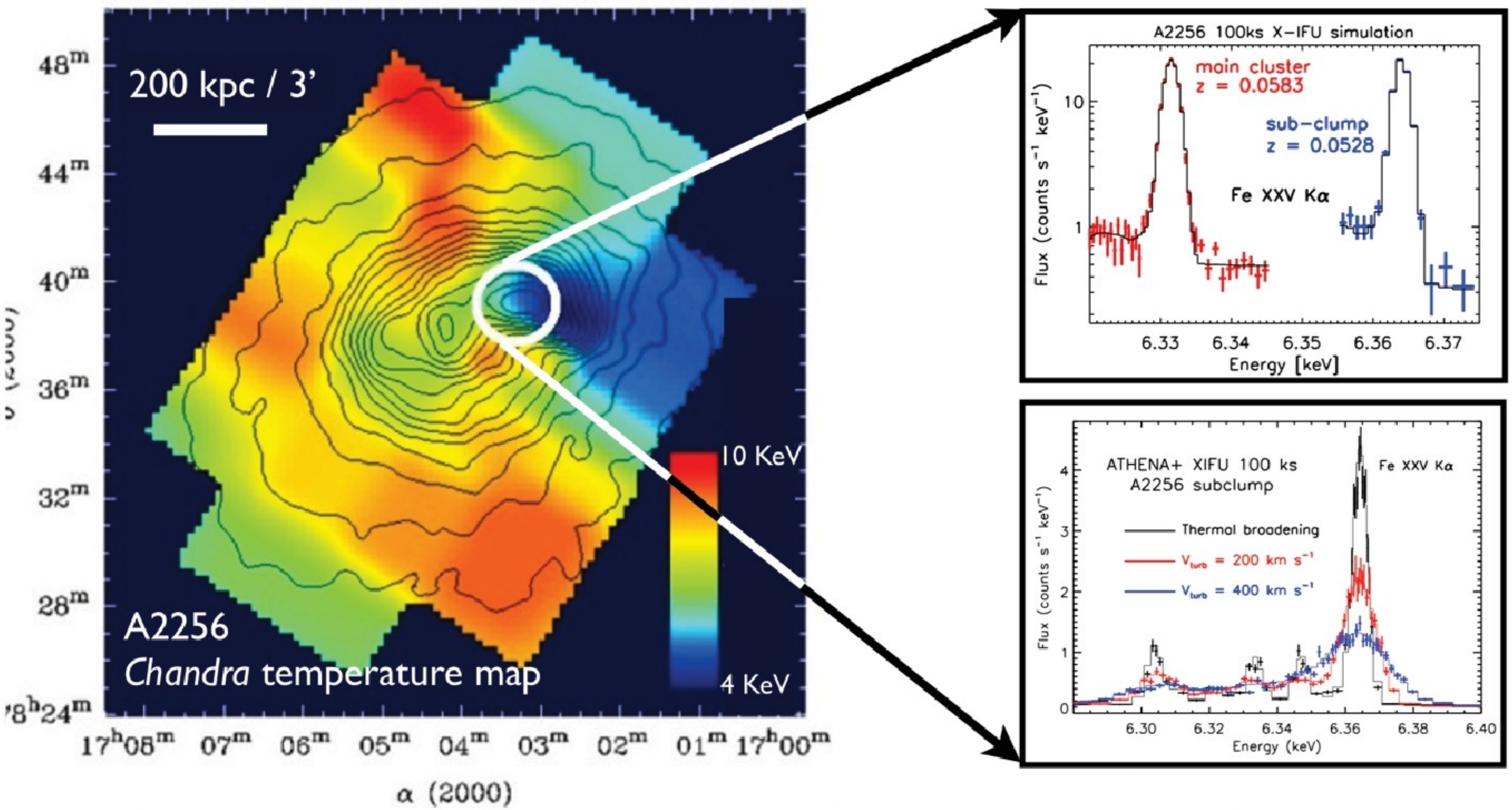


Cluster z=1 kT = 3 keV



The formation and evolution of clusters and groups of galaxies, Ettori, Prat et al. 2013

- How do hot diffuse baryons accrete and dynamically evolve?
- How and when was the energy in the ICM generated?
- Where and when are heavy elements produced?



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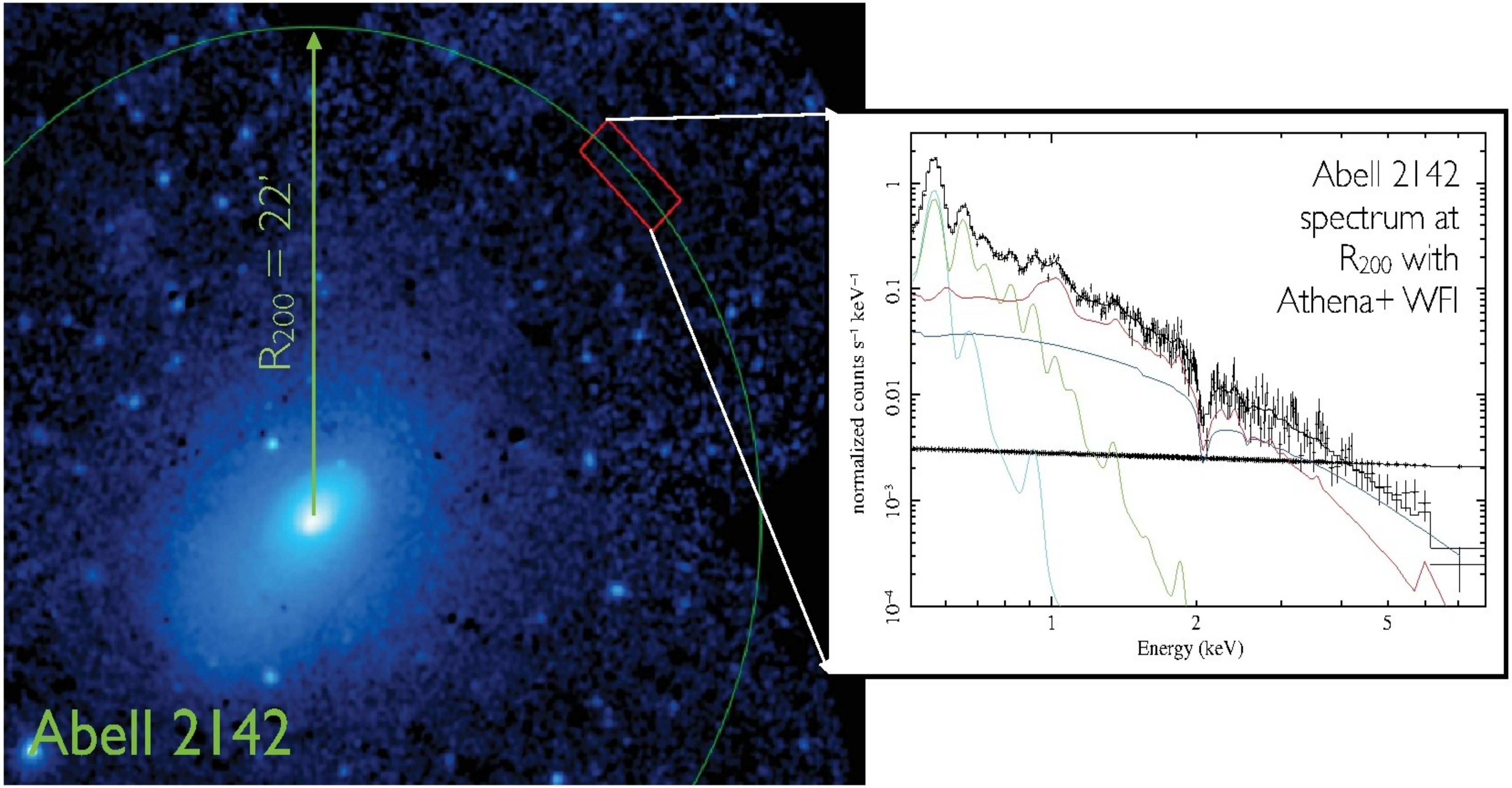
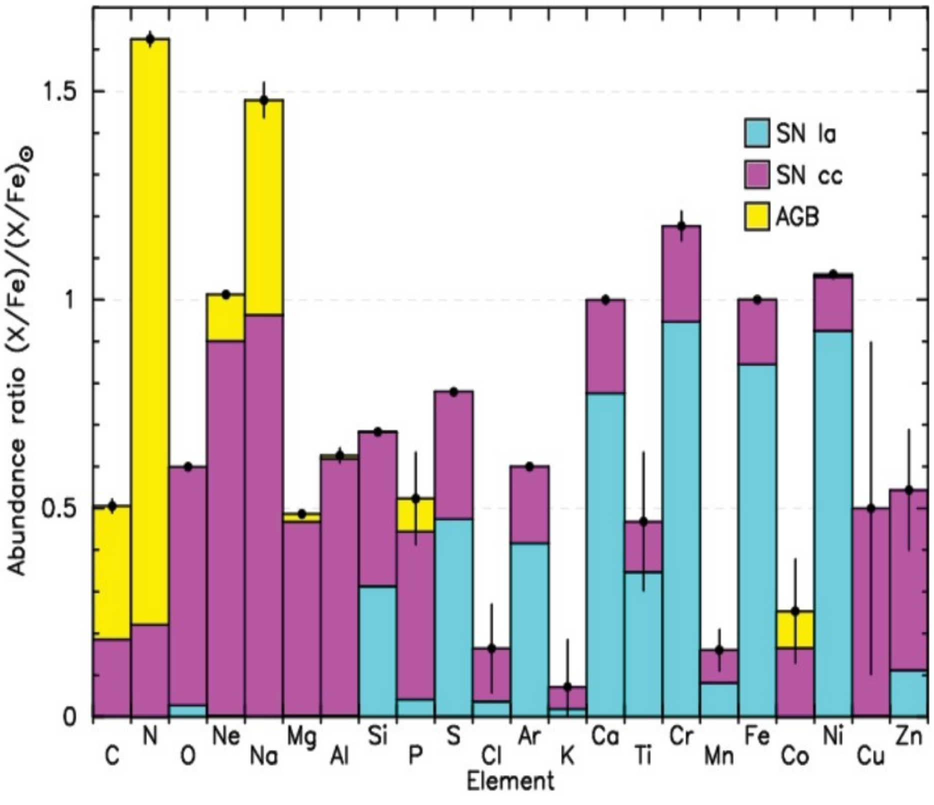
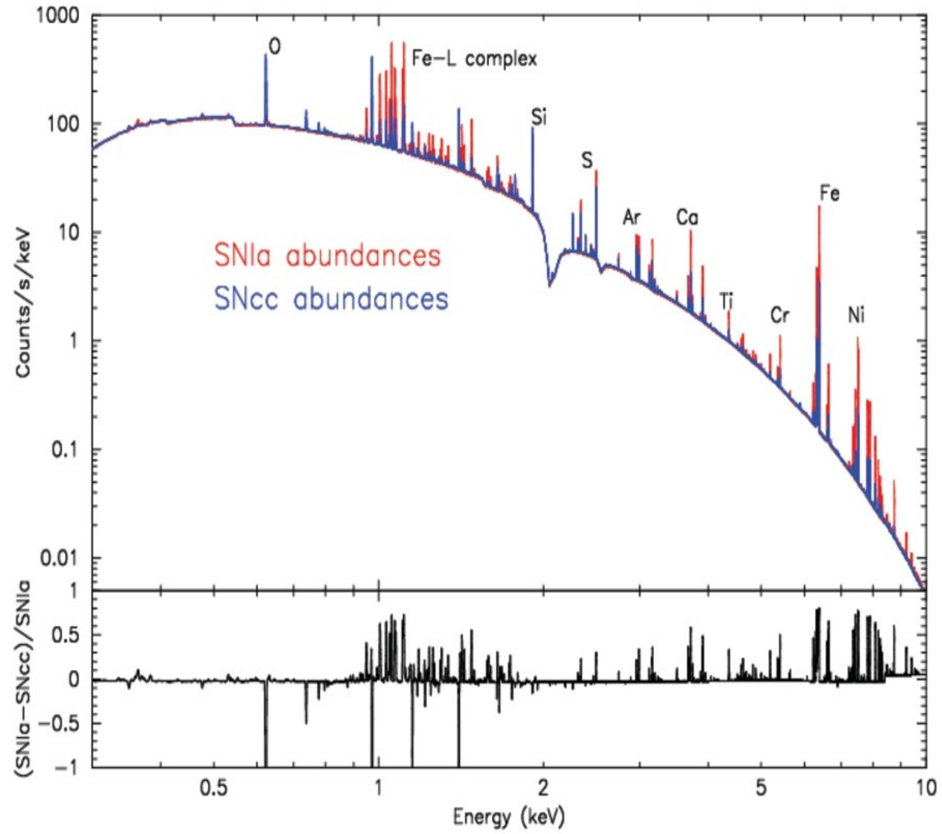


<u>**The chemical evolution of hot baryons, Ettori Prat et al. 2013:**</u>

- Infer the relative contributions of SN types, and the initial stellar mass function in proto-clusters.

- Identify the locations in clusters where the most of the metals are generated, and determine how they are dispersed?





Missing baryons:

- **high resolution X-ray spectroscopy with ATENA X-IFU will characterize the Warm Hot Intergalactic Medium,**
- **and hopefully will find the missing baryons.**

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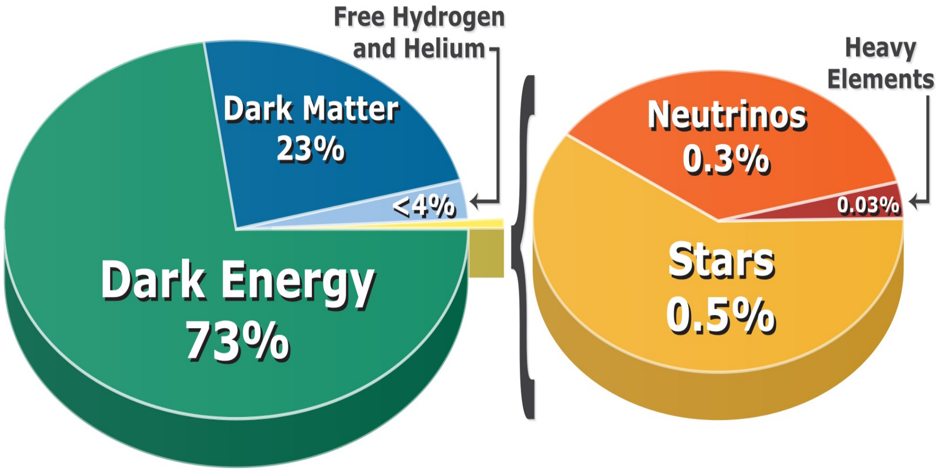
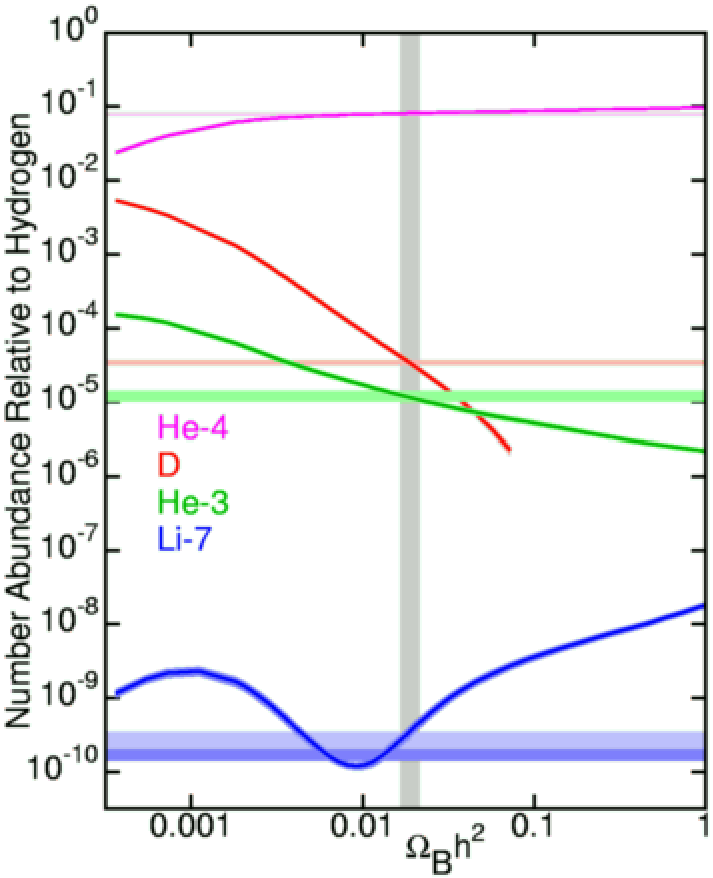
Primary problem with baryons:



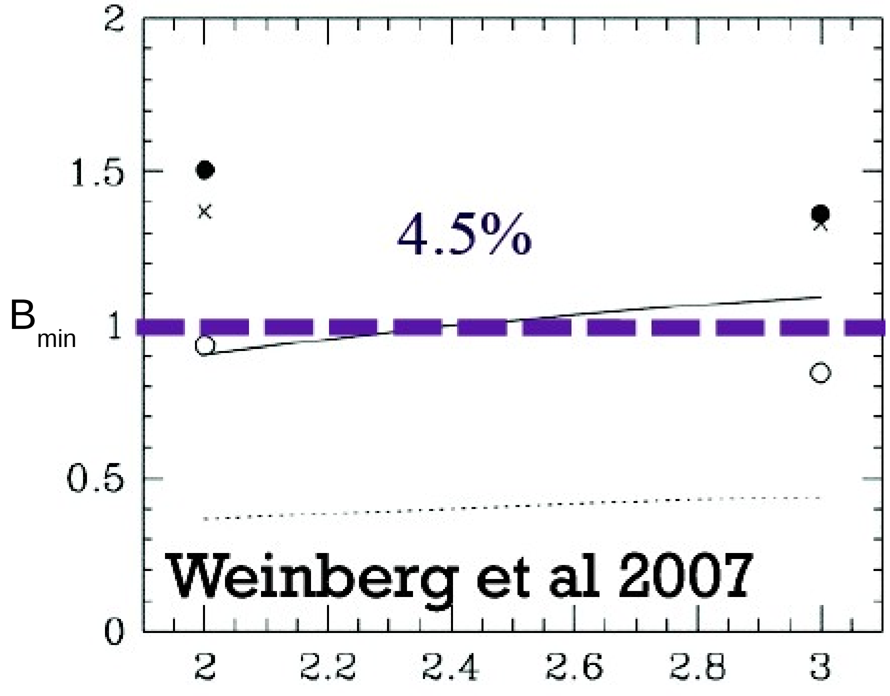


Baryon density from Big-Bang nucl.
Consistent with CMB measurements

Primary problem with baryons: where are they?

Baryon budget at z>2 :

- **most gas mass is accounted for by highly-ionised Ly α absorption systems,**
- **neutral gas at z>2 consistent in mass locked into stars at z=0,**
- **conservative ionization corrections indicate that all baryons are accounted for at z>2.**

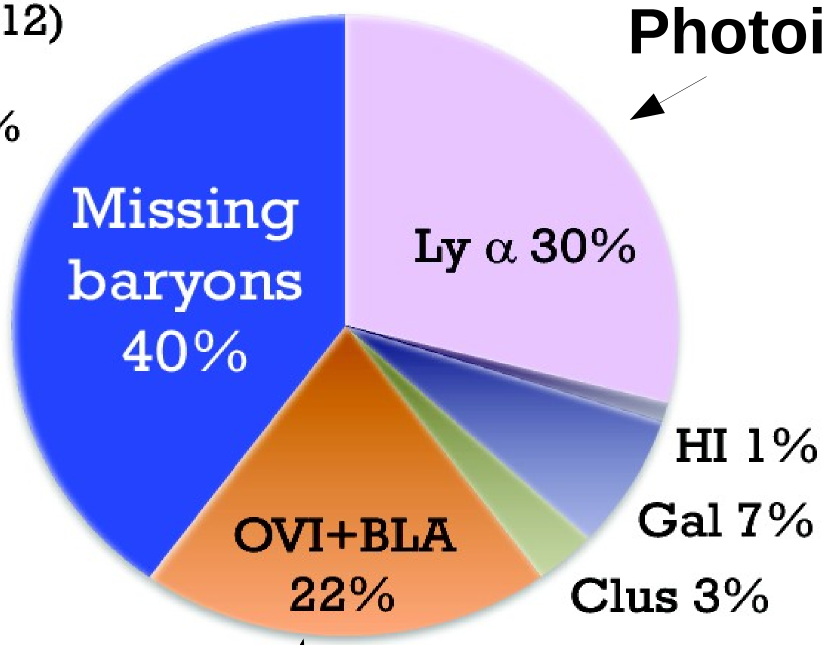


Primary problem with baryons: where are they?

Baryon budget at low z:

Budget from Shull et al (2012)

OVI+BLA uncertain 15-30%



Photoionized forest

Warm (UV) Intergalactic Medium OVI, and Ly α absorbers

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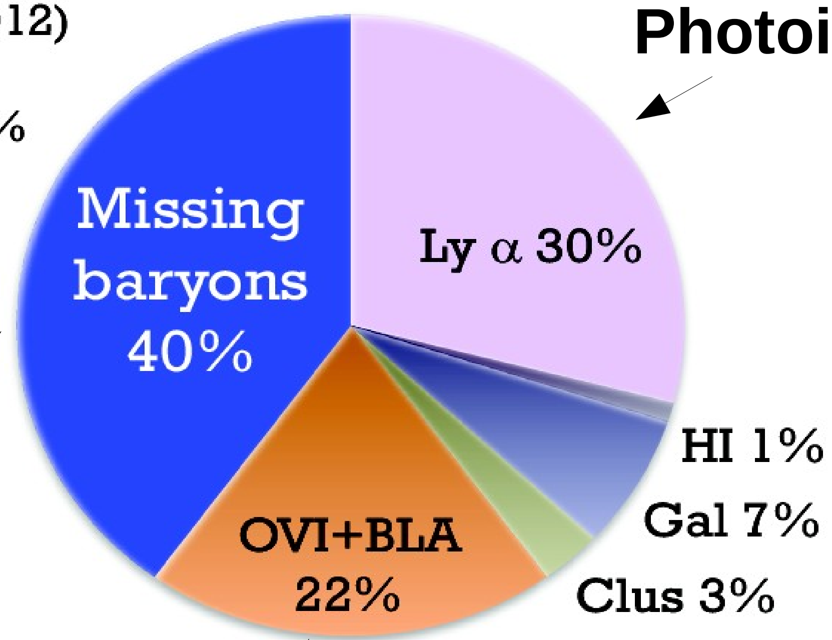
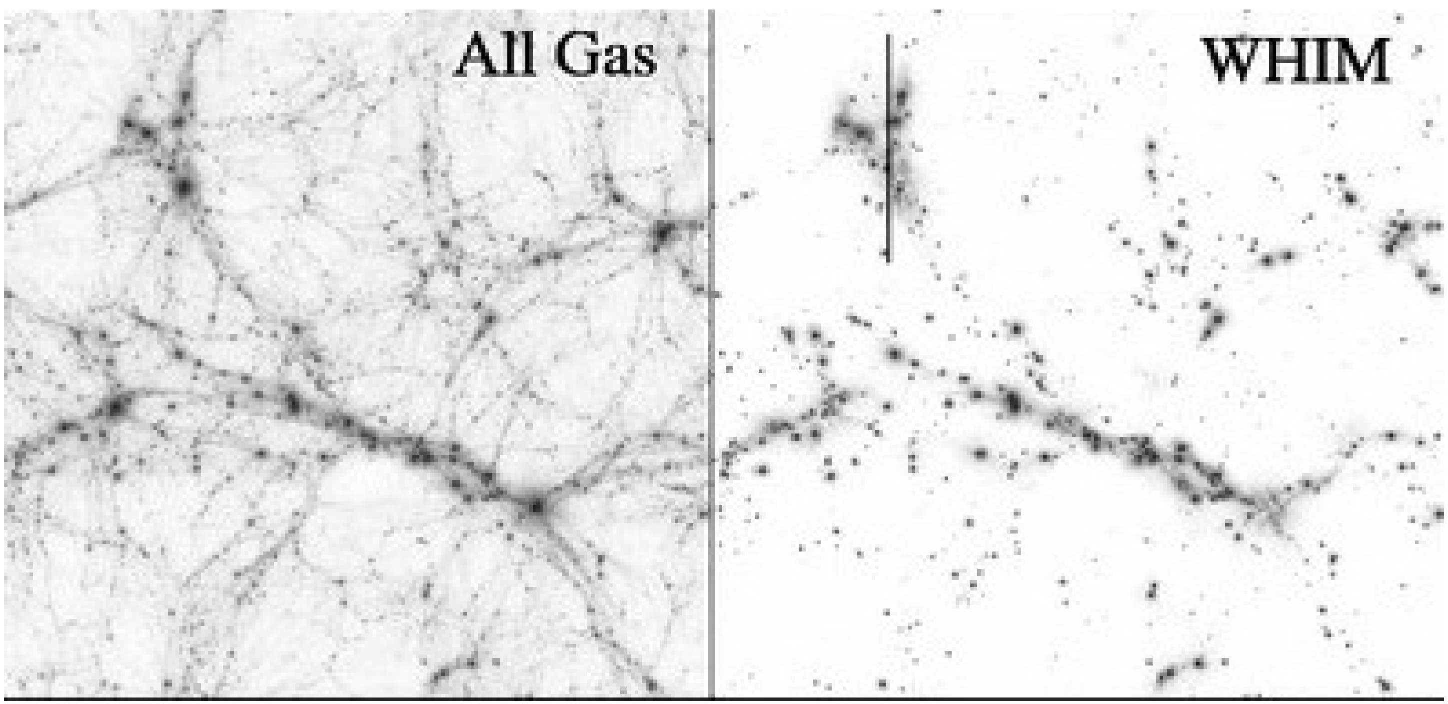


Looked in the Hot diffused X-ray gas OVII, and OVIII Absorbers (WHIM)

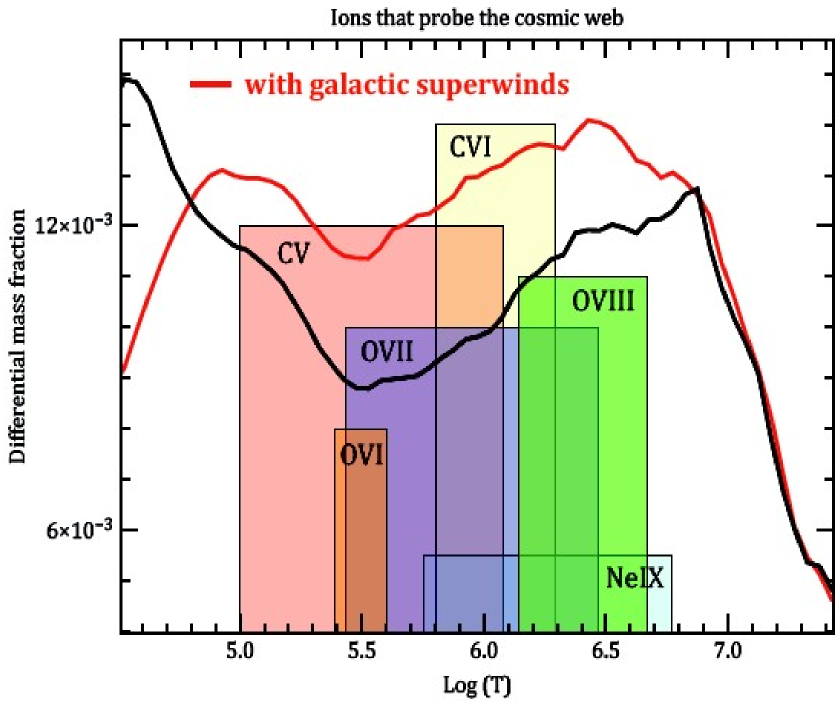
Warm (UV) Intergalactic Medium OVI, and Ly α absorbers

The Warm & Hot IGM gas (WHIM):

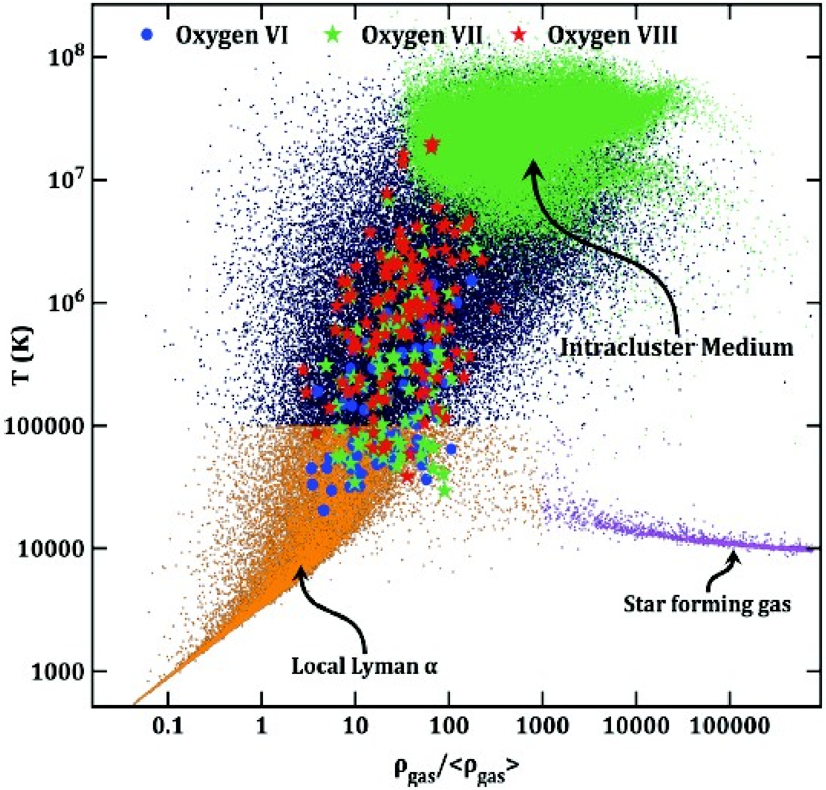
- simulations show that galaxy formation is inefficient In trapping baryons in Dark Matter potential wells.
- Large fraction of baryons at $T=10^{5-7}$ K are:
  i) unvirialized
  ii) filamentary distribution.



WHIM physical state:



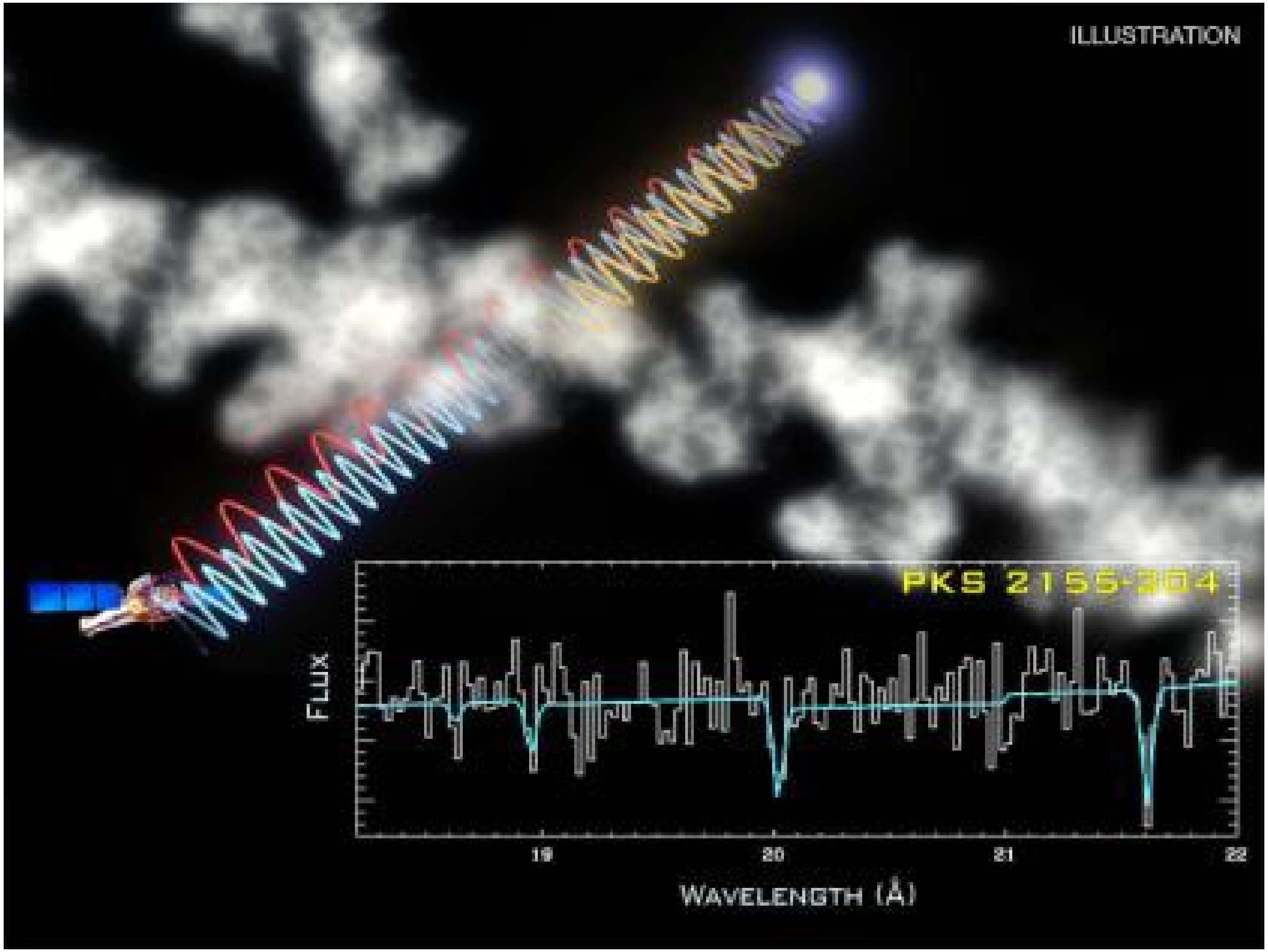
Cen & Ostriker 2006



Branchini et al 2009

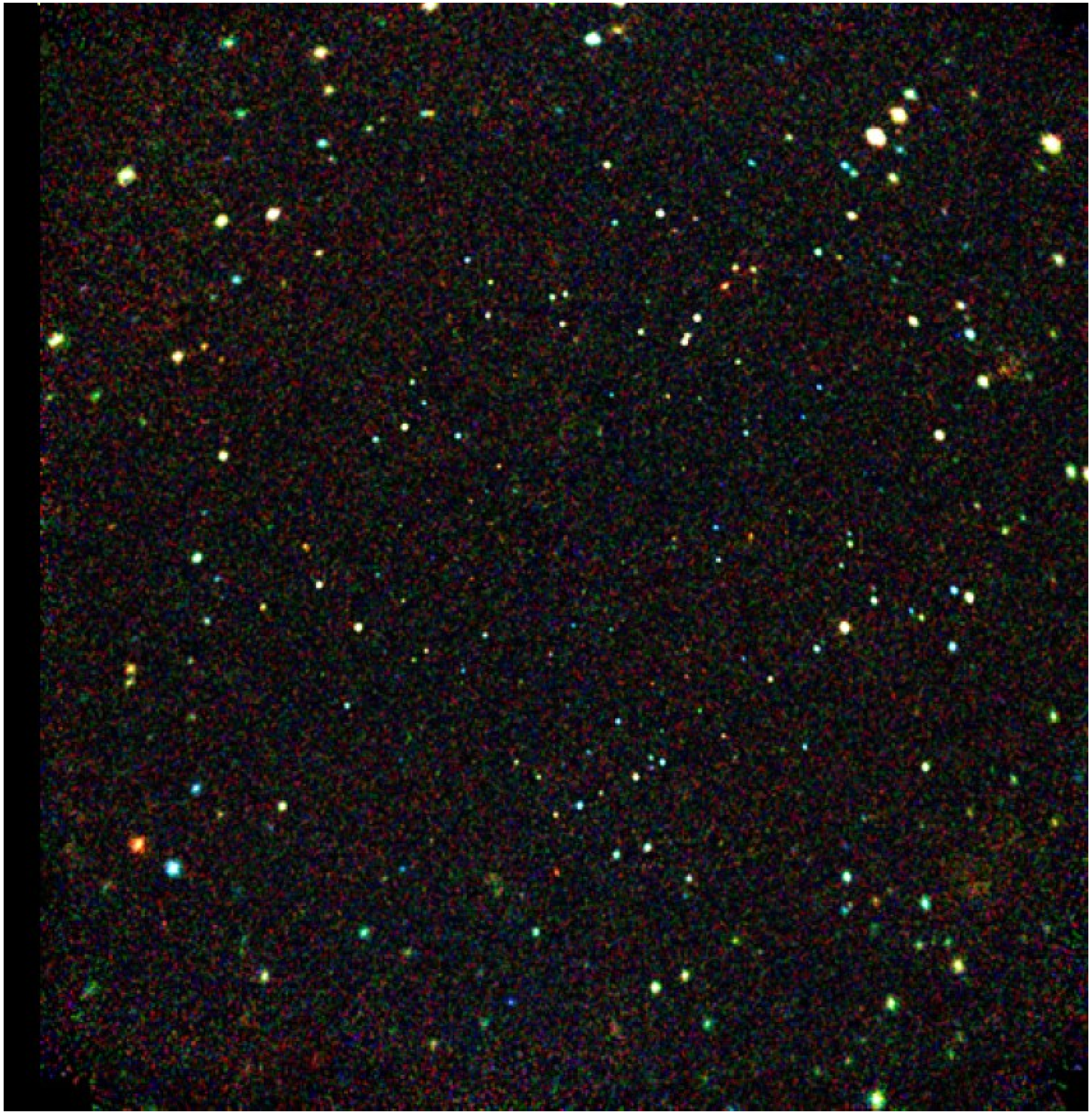
<u>How to detect the WHIM?</u>

- All atomic spectral features are narrow:
need high spectral resolution,
- In absorption – need a bright background source, only along specific lines of sight, geometry difficult to trace,



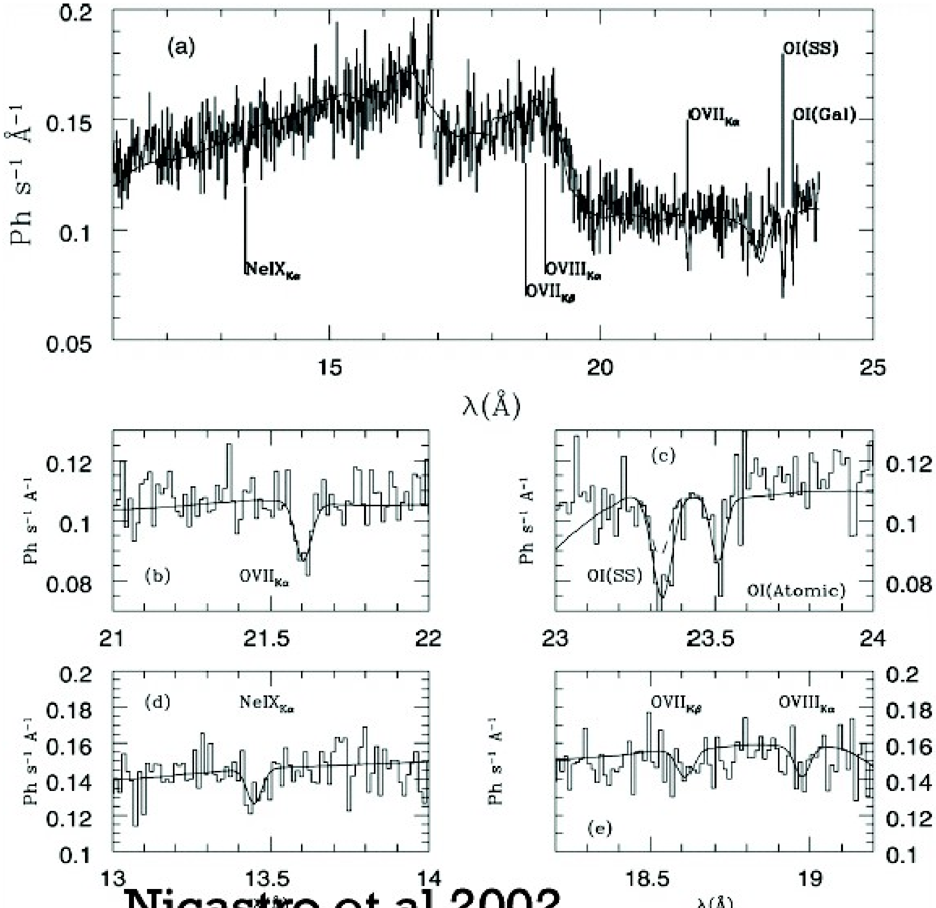
How to detect the WHIM?

- In emission: tenuous and extended sources,
- need to fight with background,
- large sky area coverage, many papers by Andrzej Sołtan.



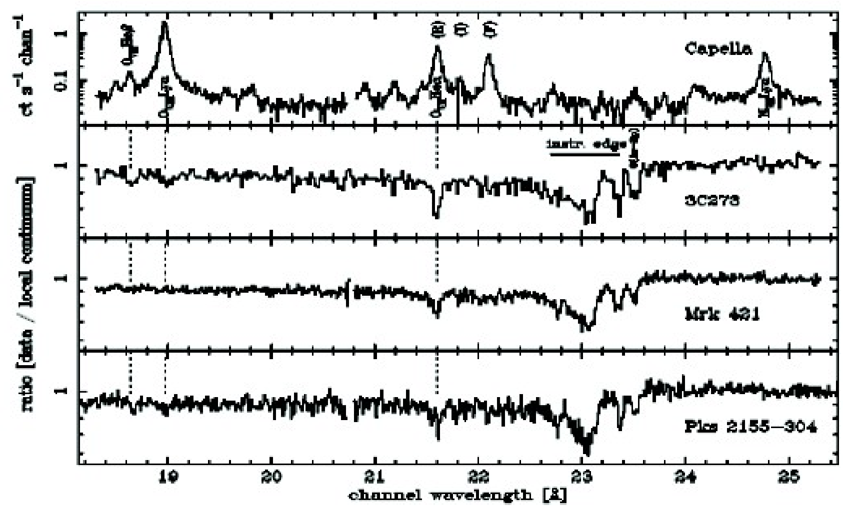
Detection of the "local" X-ray WHIM:

With Chandra



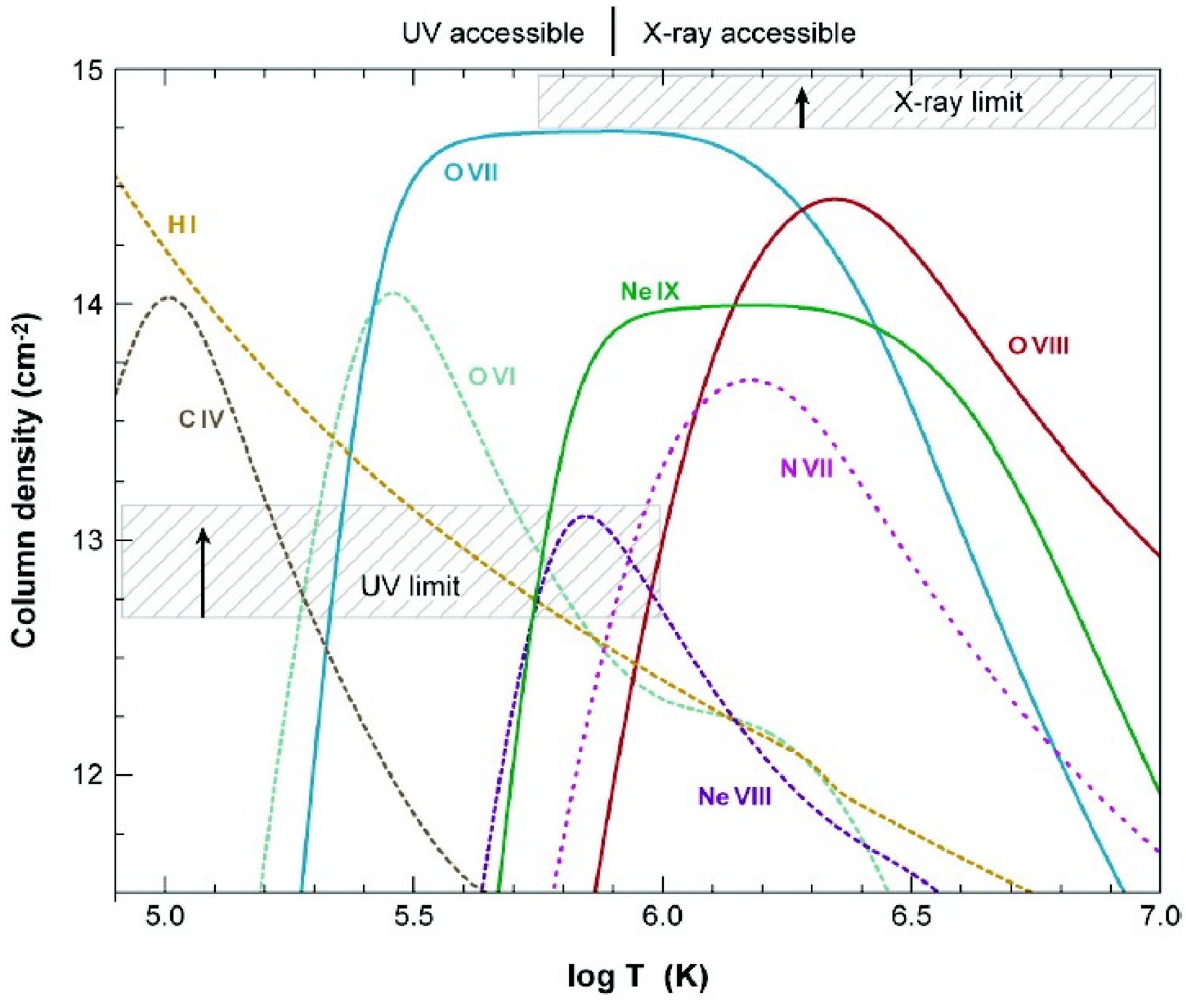
Nicastro et al 2002

With XMM-Newton



Rasmussen et al 2003

Detection of the "local" X-ray WHIM:

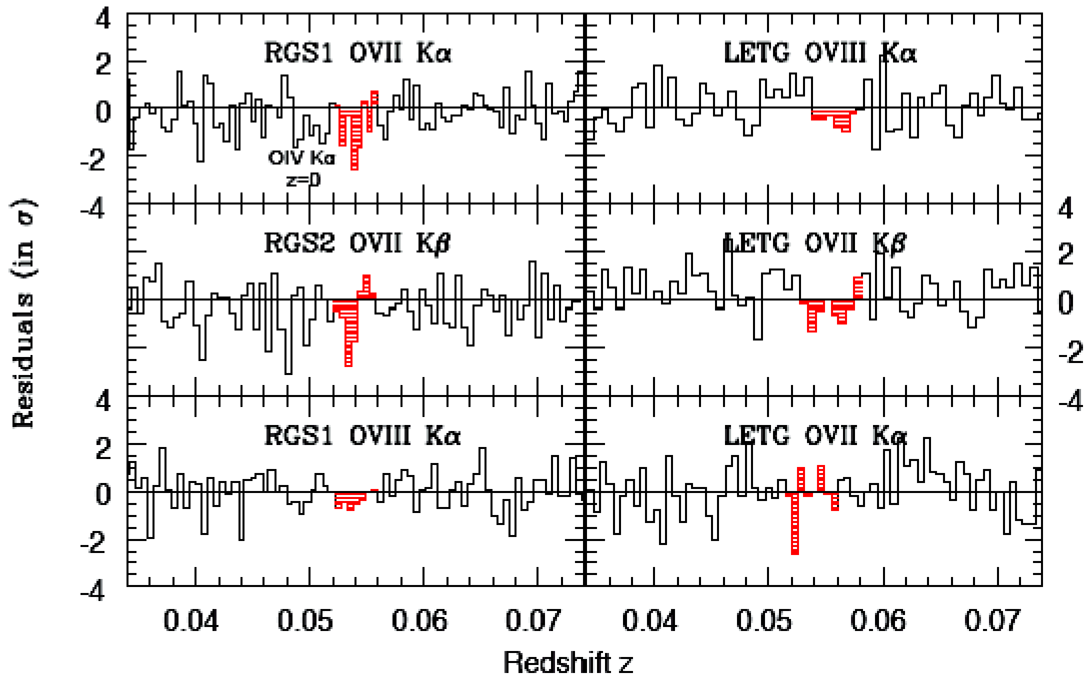


Bregman 2007

Attempts to detect missing baryons:

- Tentative detection of 2 WHIM filaments with CHANDRA against Mrk421 (Nicastro et al. 2005), unconfirmed by XMM-Newton (Williams et al. 2006).

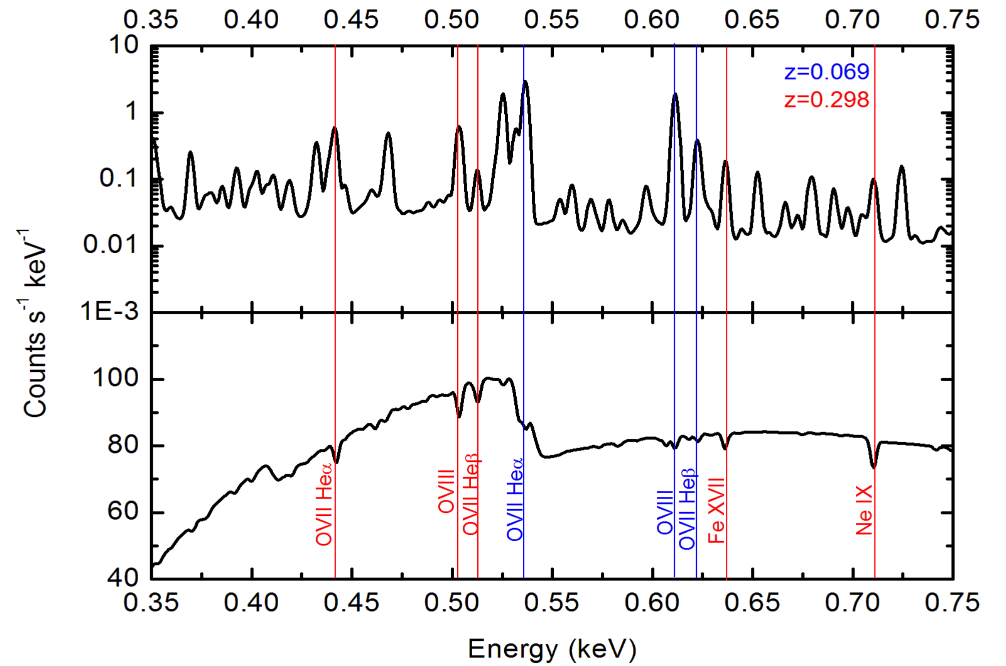
- Observations of the brightest target in the sky 1ES 1553+113 (z>0.3) with Chandra and on-going XMM, Two filaments to 4-6 sigma significance.

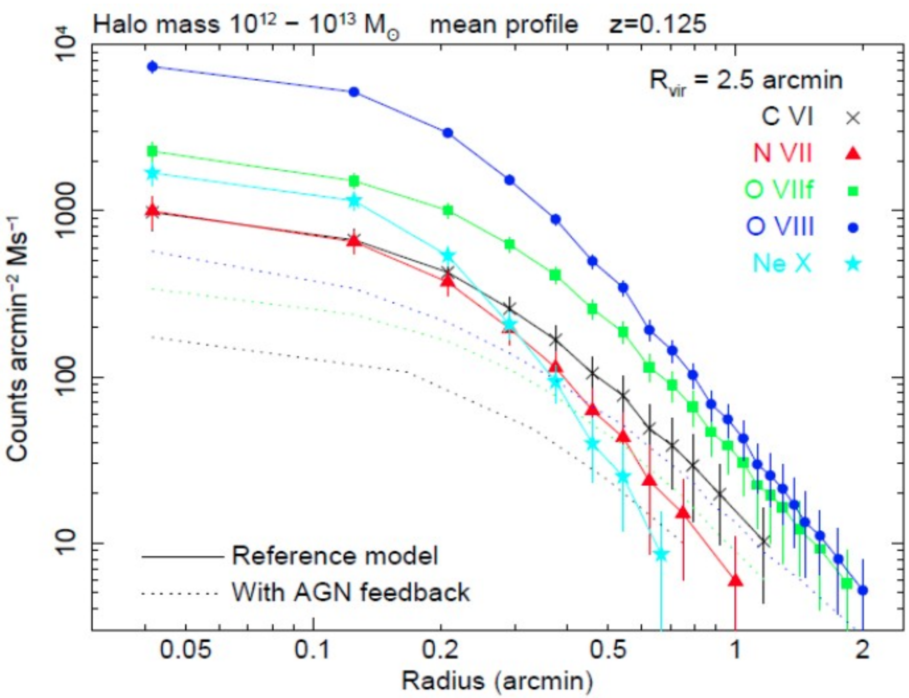


- Not possible to further this with current instrumentation

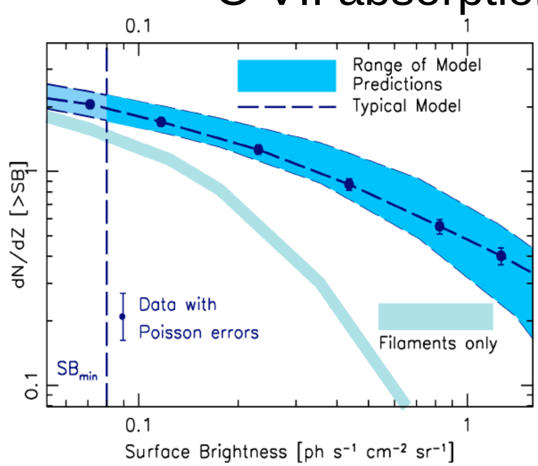
The warm hot intergalactic medium, WHIM, Kaastra et al. 2013:

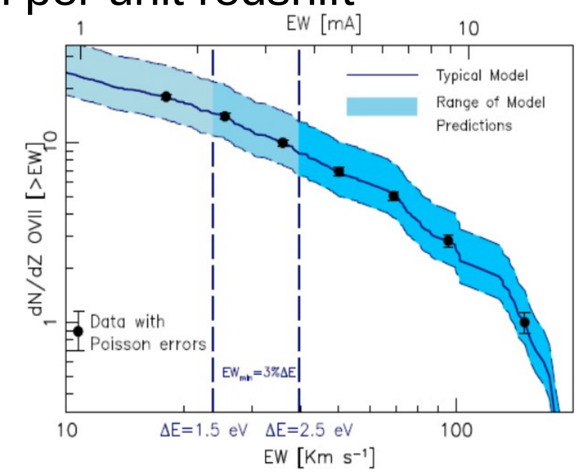
- **Where are the missing baryons in the local Universe?**
- **What is the underlying mechanism determining the distribution of the hot phase of the cosmic web?**





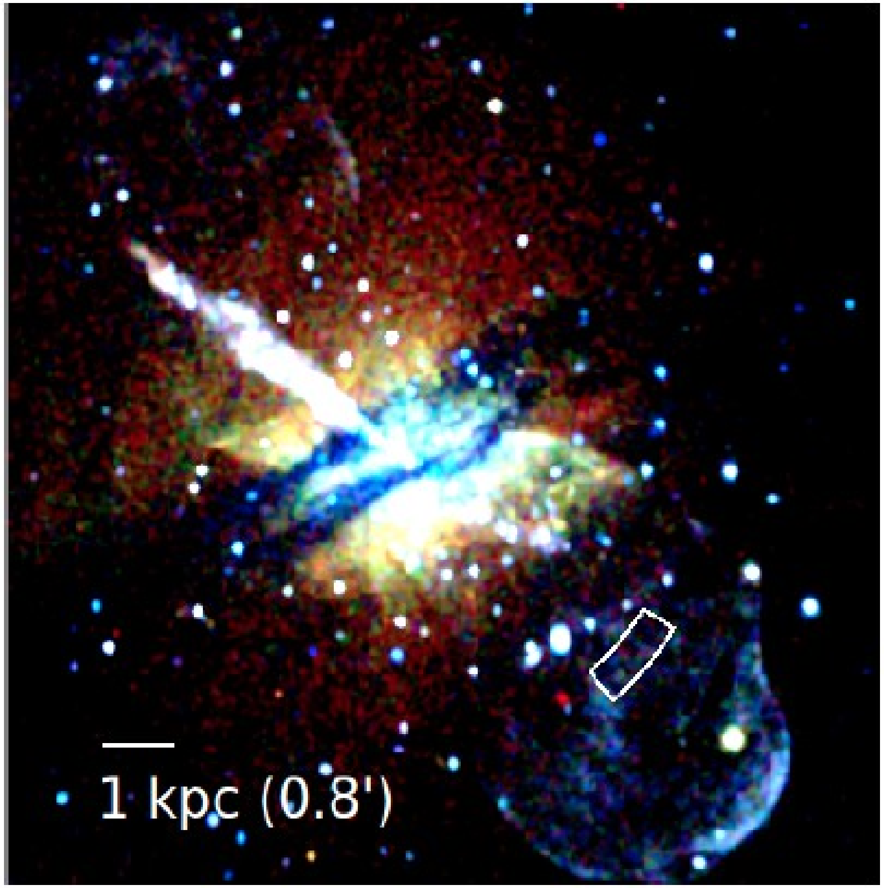
Predicted mean number of
O VII absorption per unit redshift

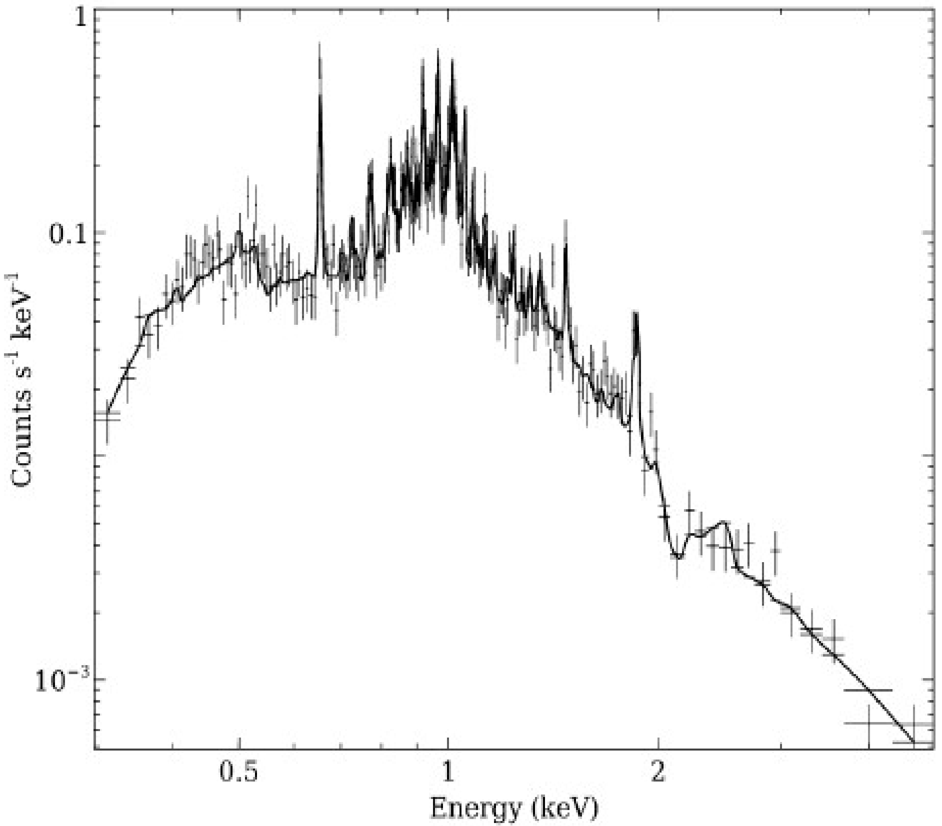




The AGN feedback in cluster of galaxies, Croston et al. 2013:

- **How do jets from AGN dissipate their mechanical energy in hot intracluster medium, how it affects hot gas distribution?**
- **Determine whether jets from powerful radio-loud AGN are the dominant non-gravitational process affecting the evolution of hot gas in galaxy groups and clusters?**





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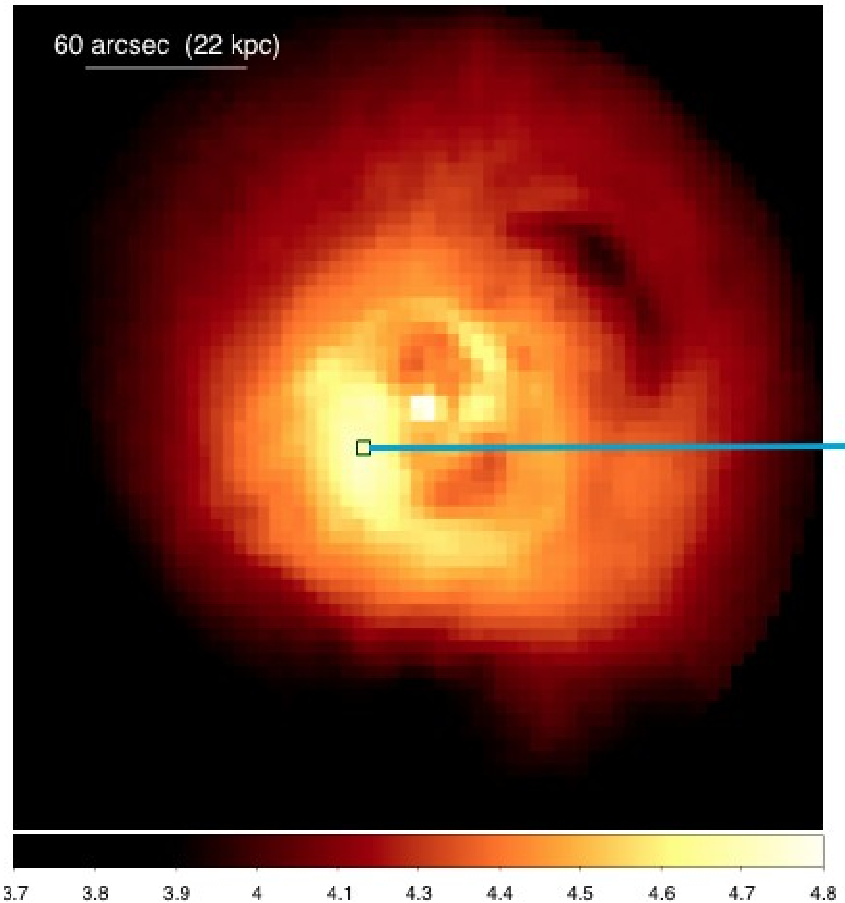
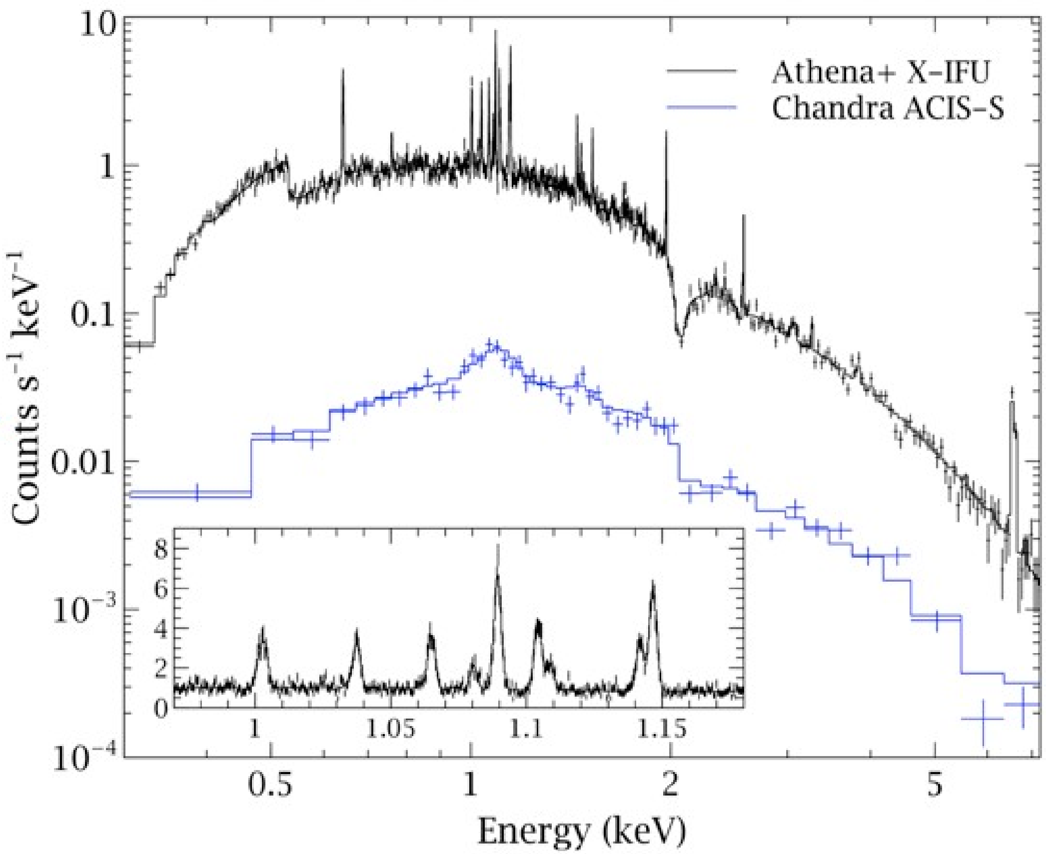
- **How do jets from AGN dissipate their mechanical energy in hot intracluster medium, how it affects hot gas distribution?**

- **Establish how AGN feedback regulates gas cooling in groups and clusters and AGN fuelling?**



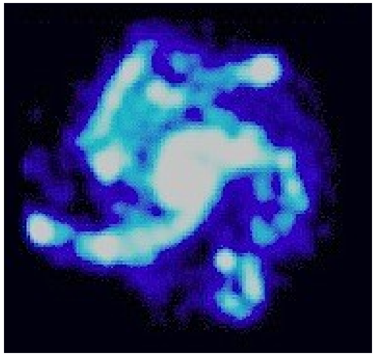


The AGN feedback black hole and galaxy co-evolution, Georgakakis et al. 2013:

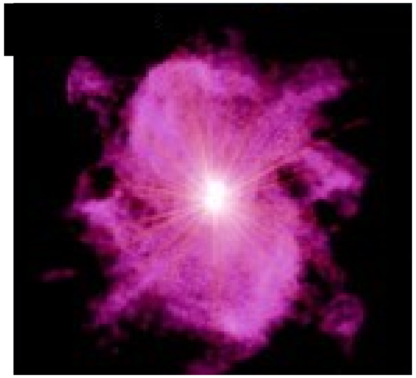
- How much black hole accretion occurs in the most obscured environments ?

- How does this relate to the evolution of the host galaxy?

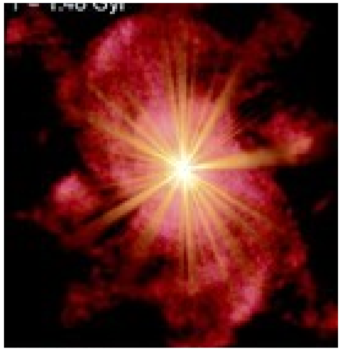
Disk instability



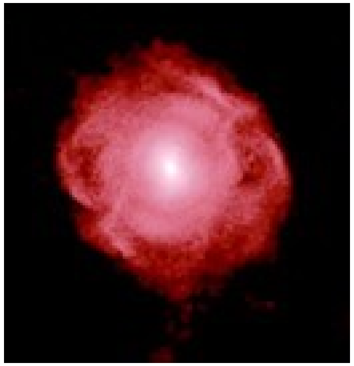
Obscured BH growth

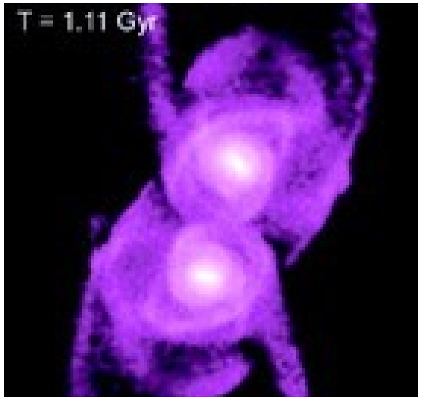


Feedback phase

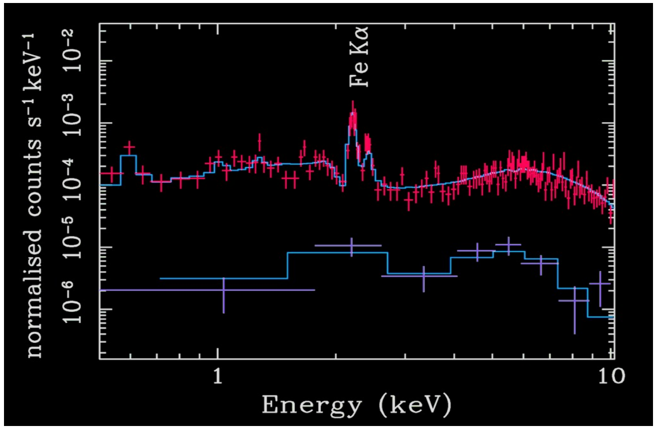


Quiescent reminant

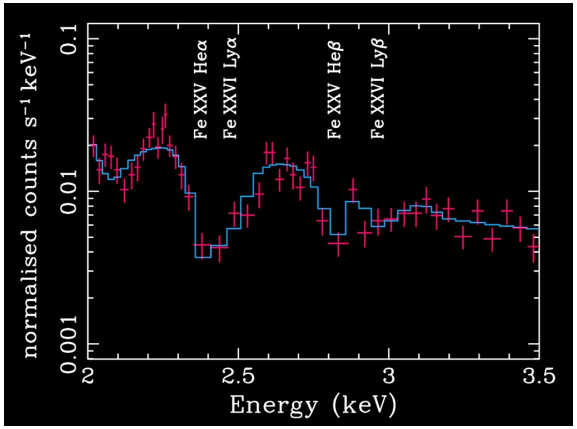




Merger



Compton thick z=2

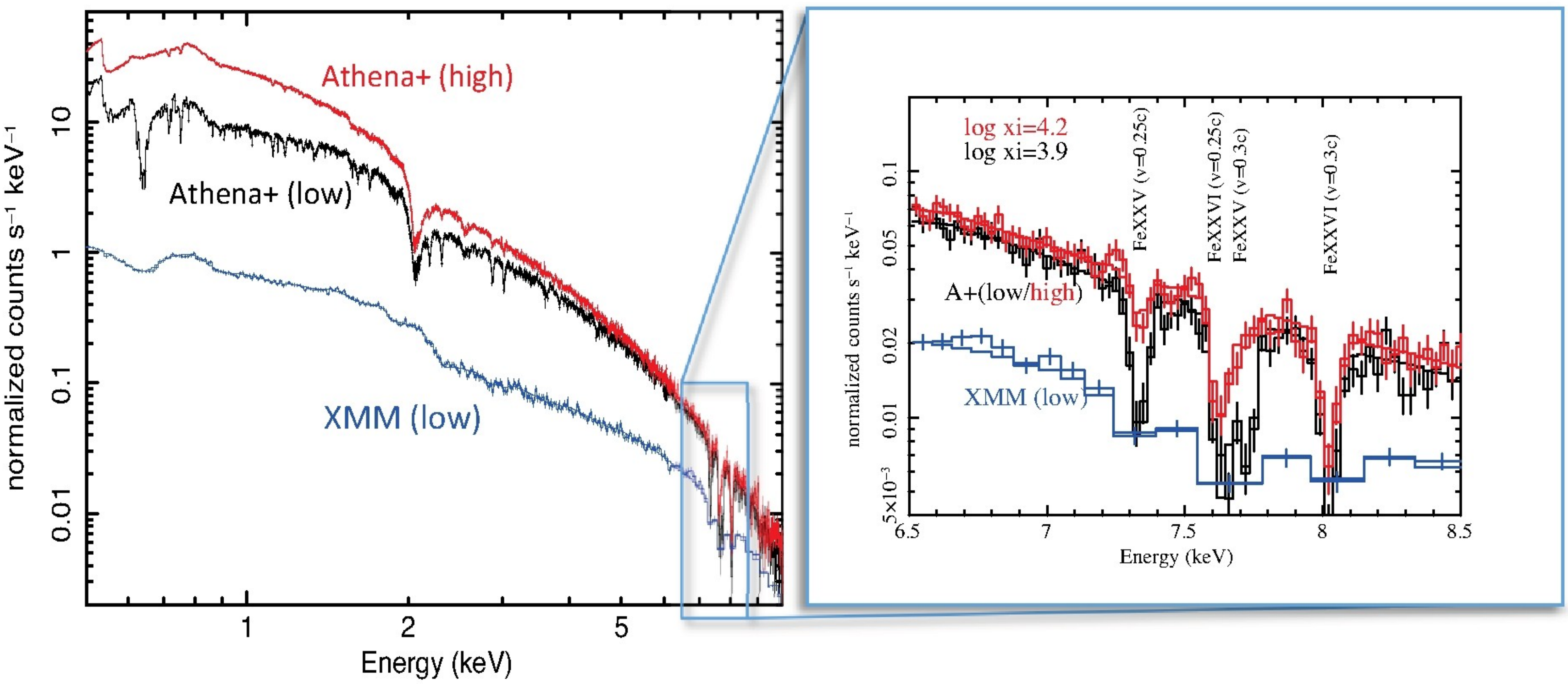


Blowout phase z=2

Astrophysics of feedback, outflows and winds in AGN, Cappi et al. 2013,

- How do accretion disks around black holes launch winds and how much energy do these carry?

- How are the energy and metals transferred into the medium?



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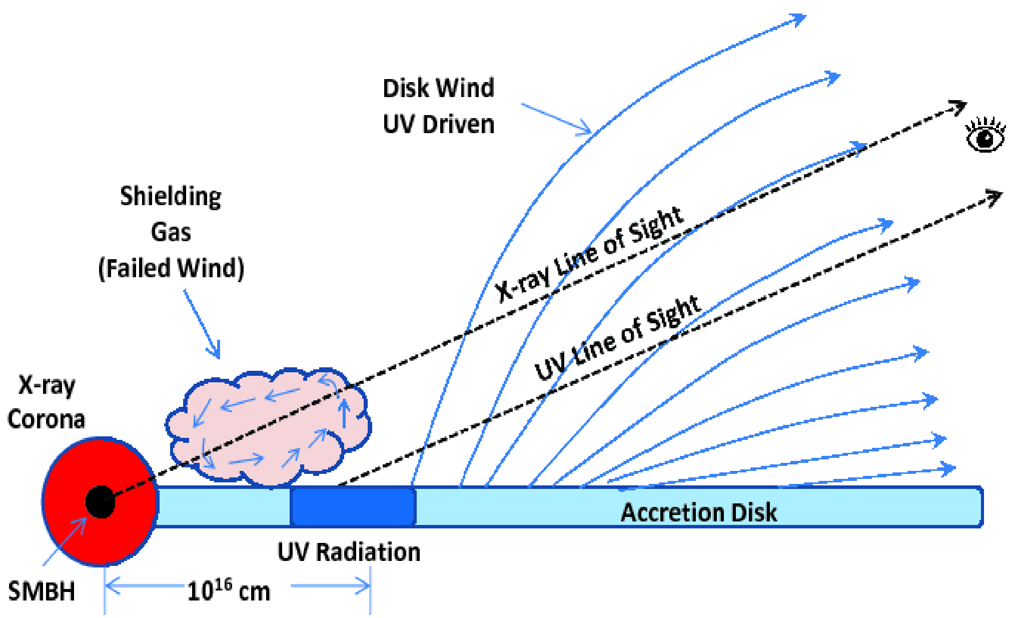

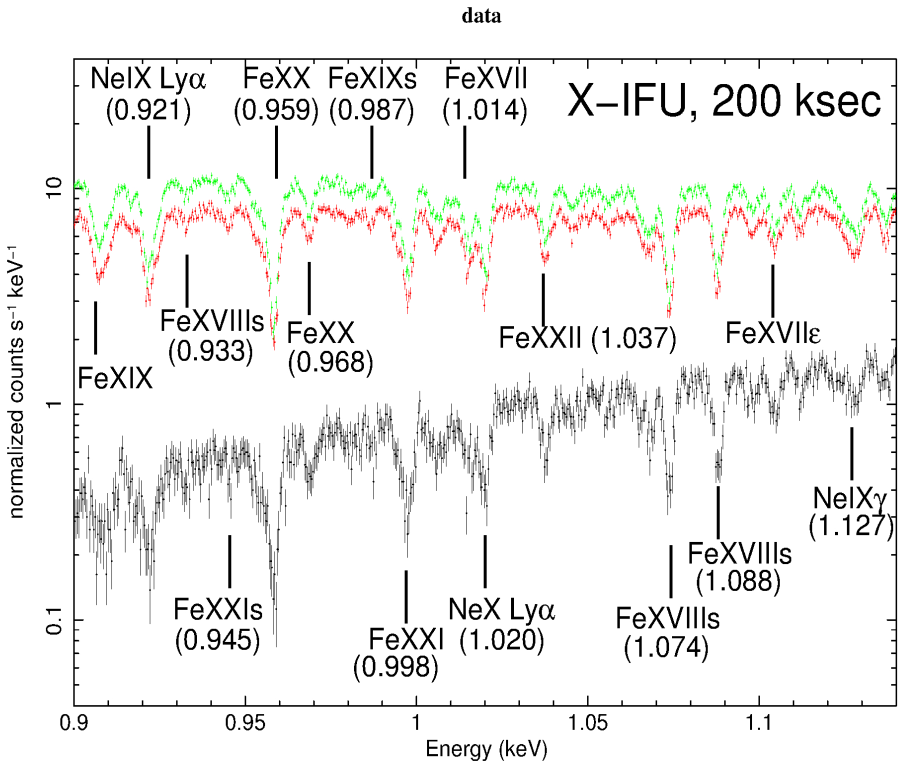

Astrophysics of feedback, outflows and winds in AGN, Cappi et al. 2013,

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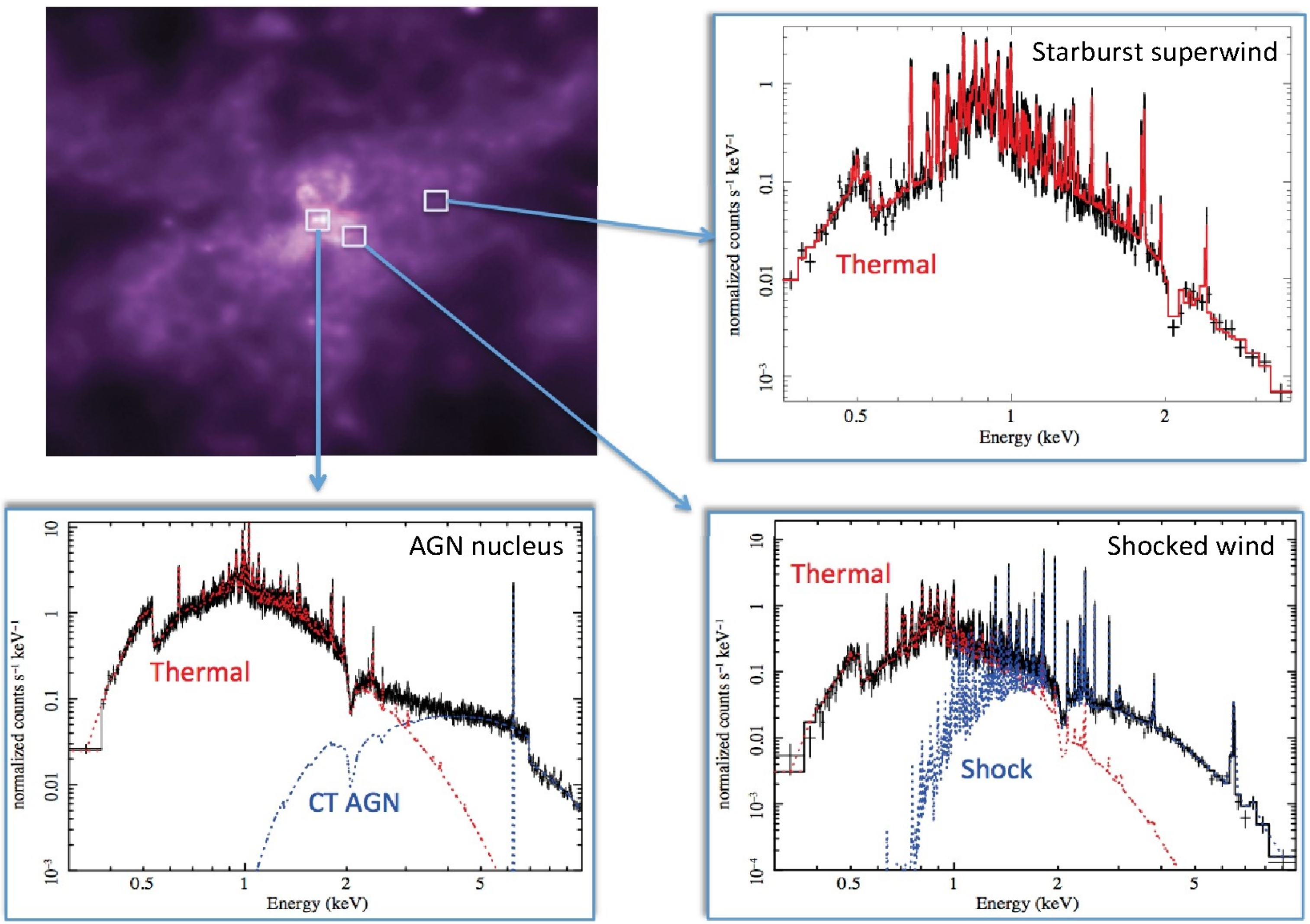

<u>Astrophysics of feedback, outflows and winds in AGN, Cappi et al. 2013,</u>

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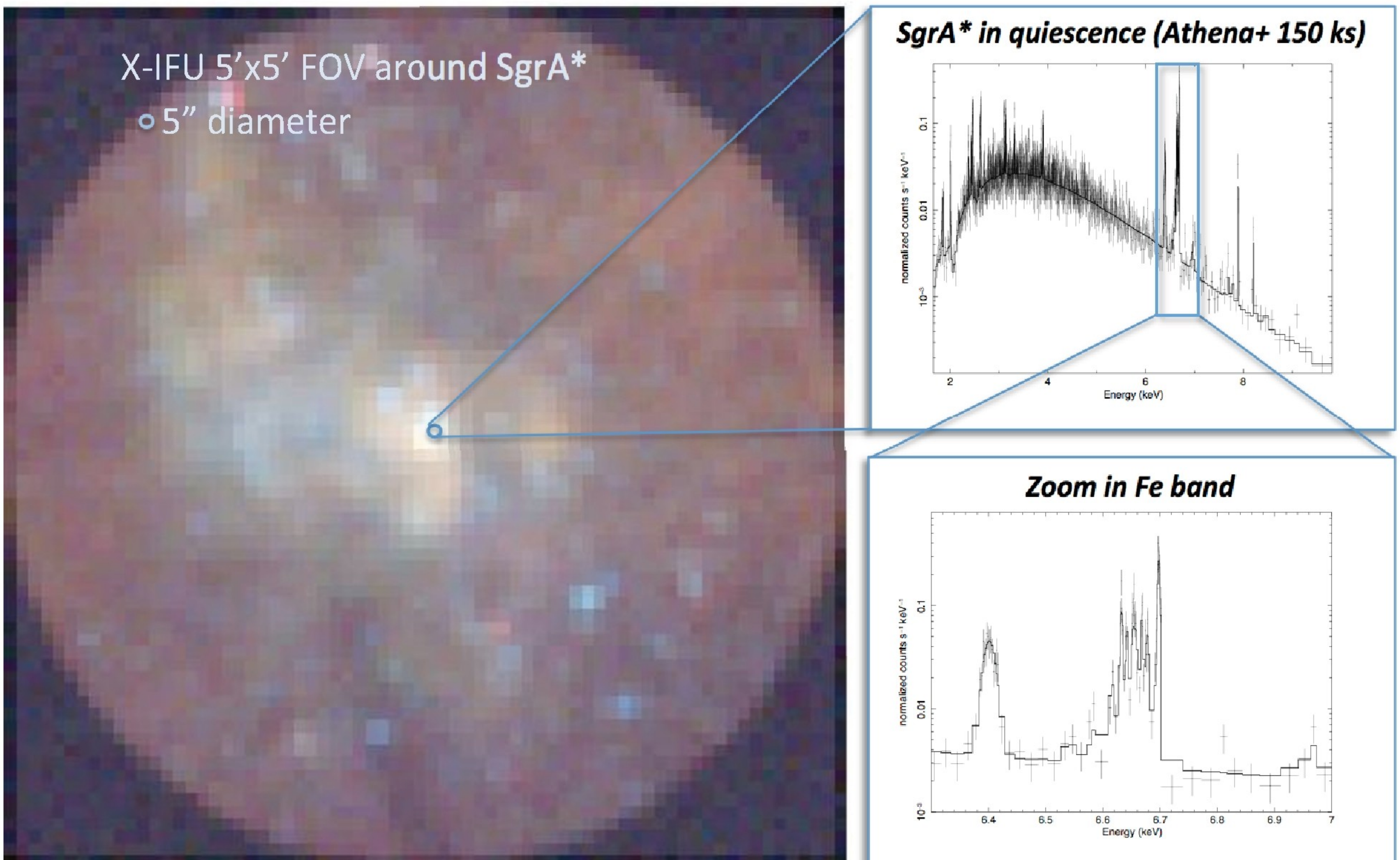
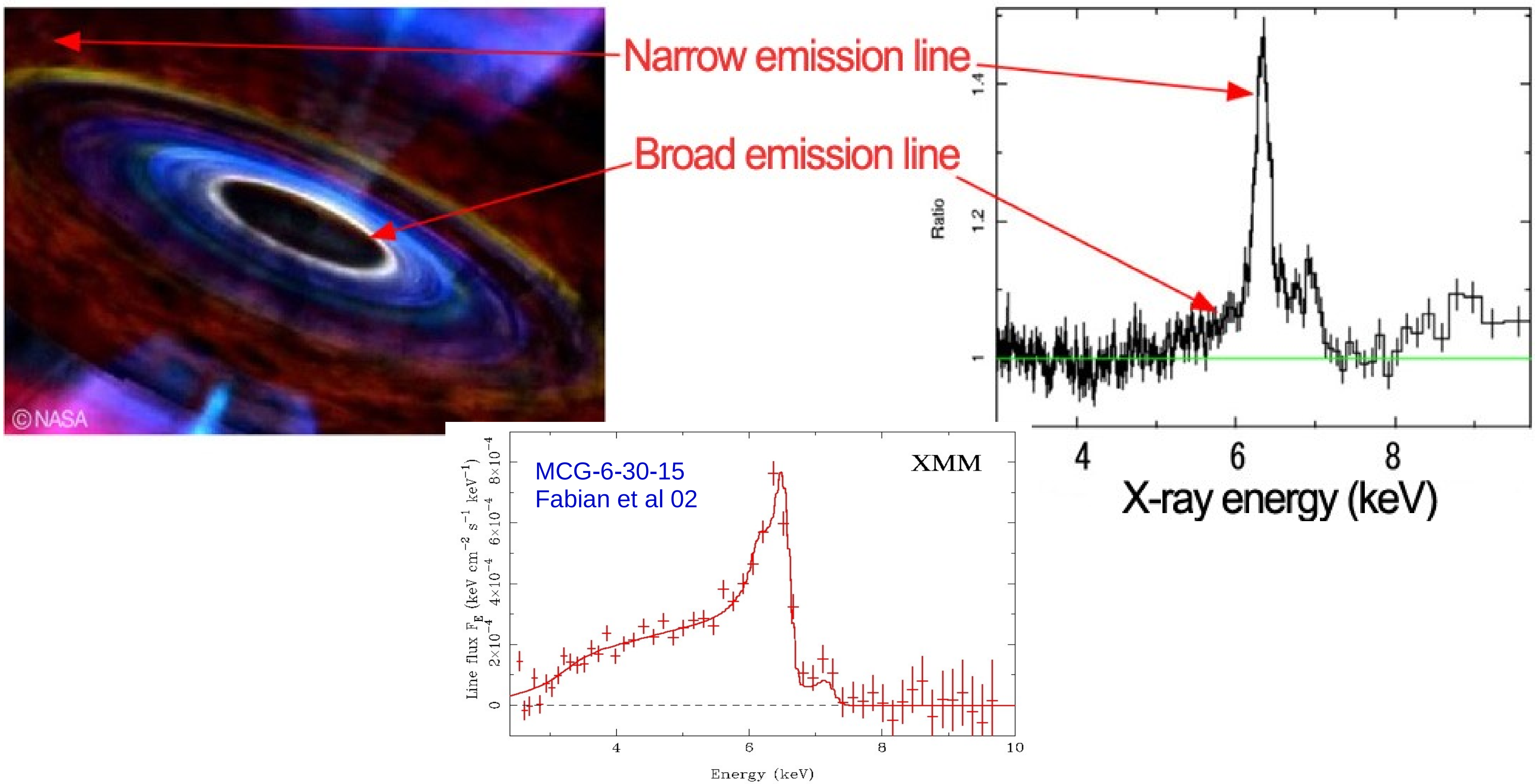


Close environment of supermassive black holes:

Fluorescent iron line profile from accreting black holes.
The profile depends on gravity.



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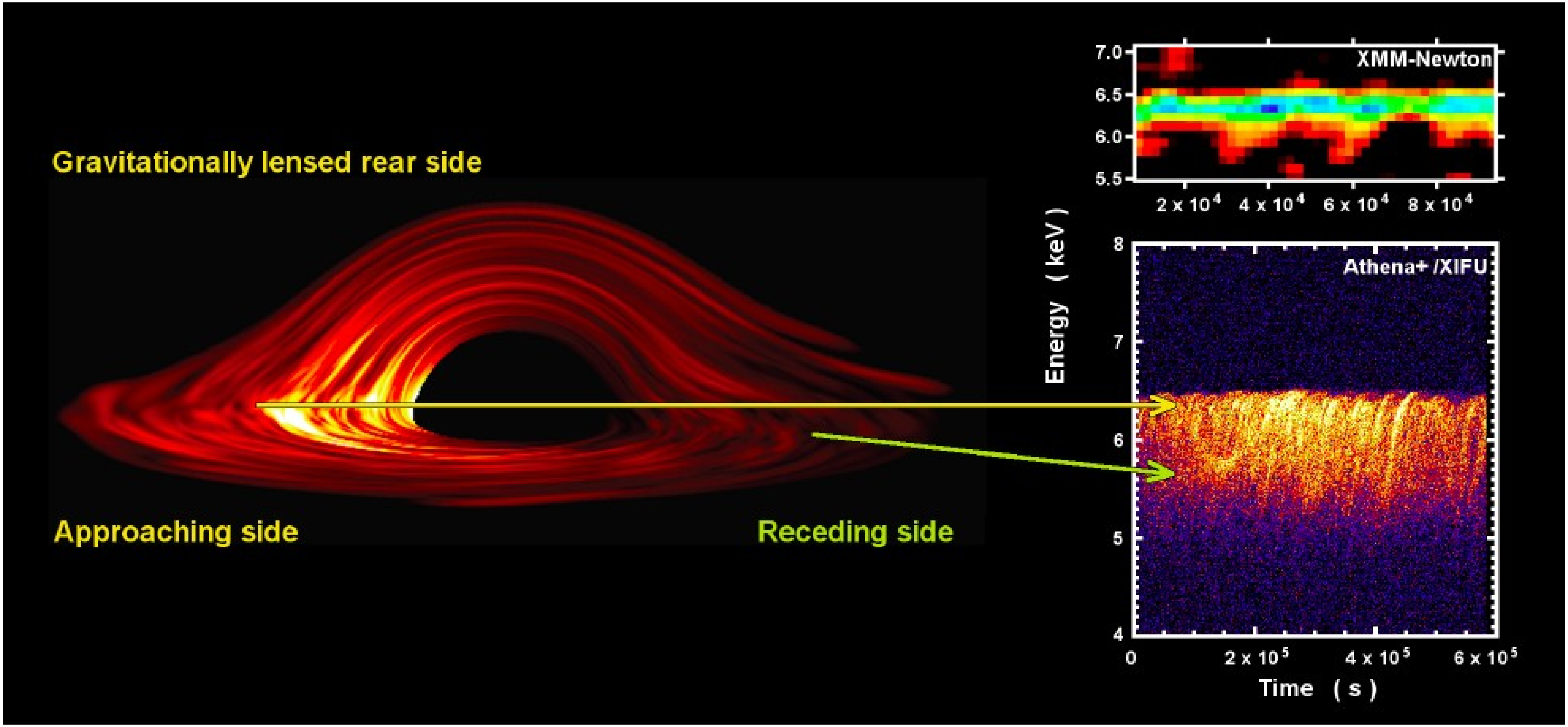
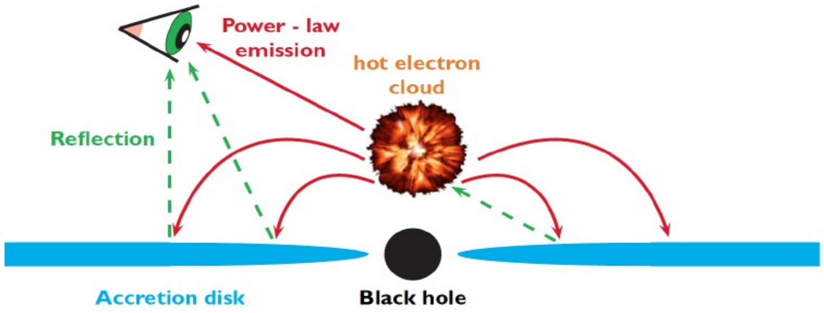
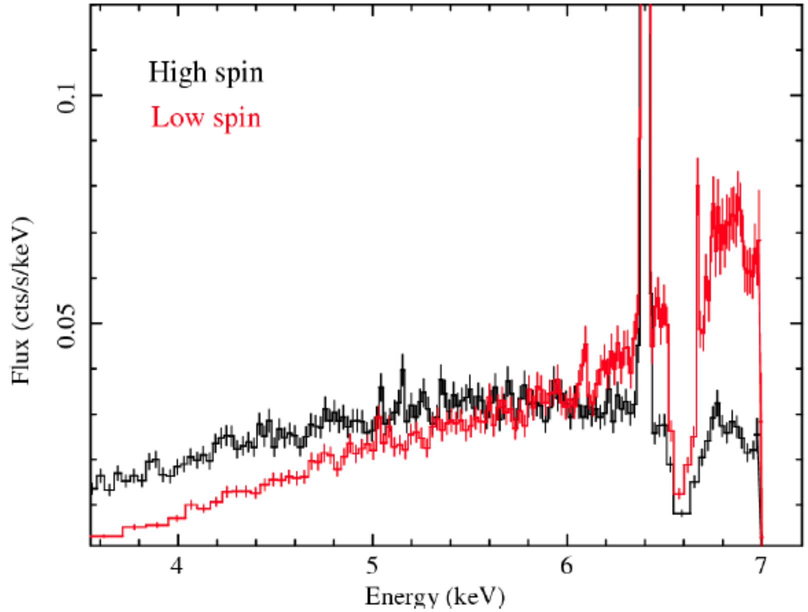


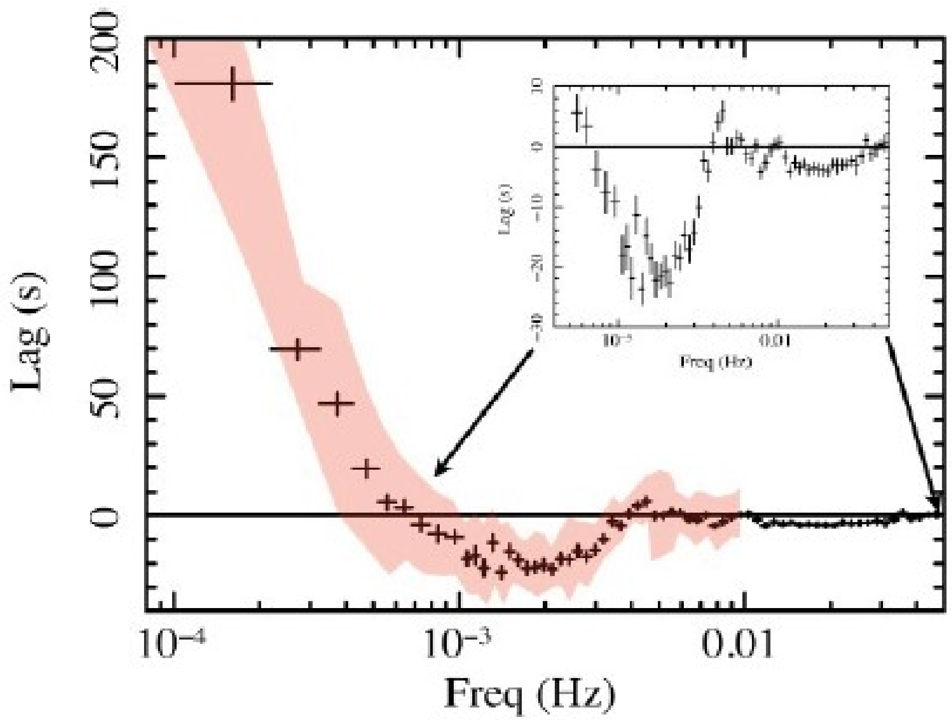
Time resolved spectroscopy puts constrains on
the geometry of disk and corona.

Close environment of supermassive black holes
Dovciak et al. 2013,

- **What is the relationship between the accretion disk and the hot plasma around.**
- **Understand the interplay of the disk/corona system.**

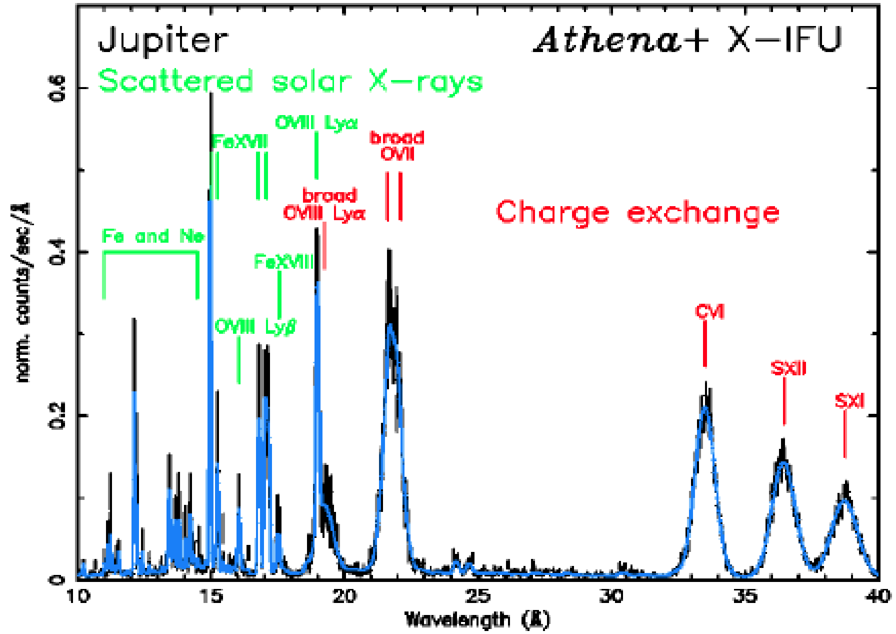






Observatory science questions Branduardi-Raymont, Scortino, Comastri, Decourchelle, Motch et al. 2013,

- Solar system and exoplanets



Observatory science questions Branduardi-Raymont, Scortino, Comastri, Decourchelle, Motch et al. 2013,

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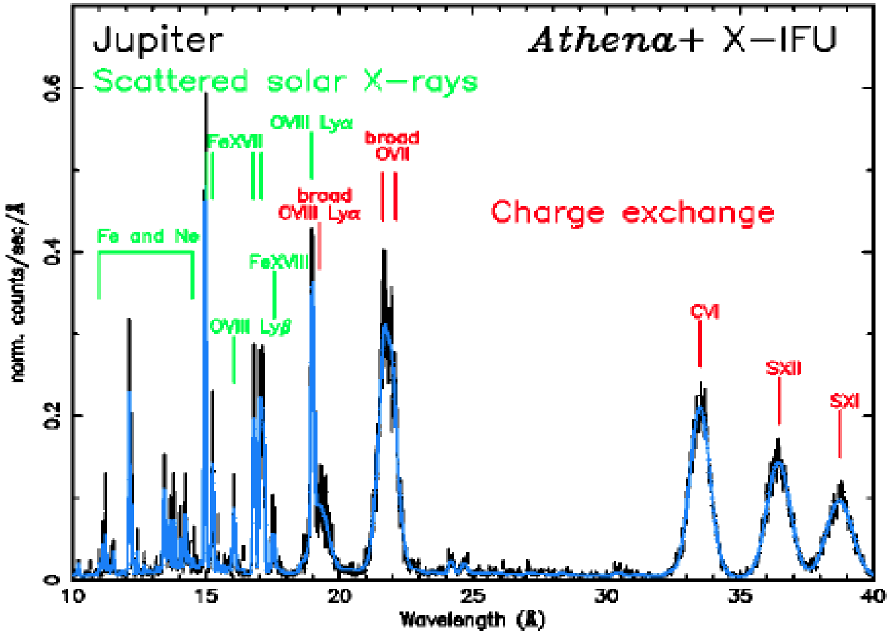
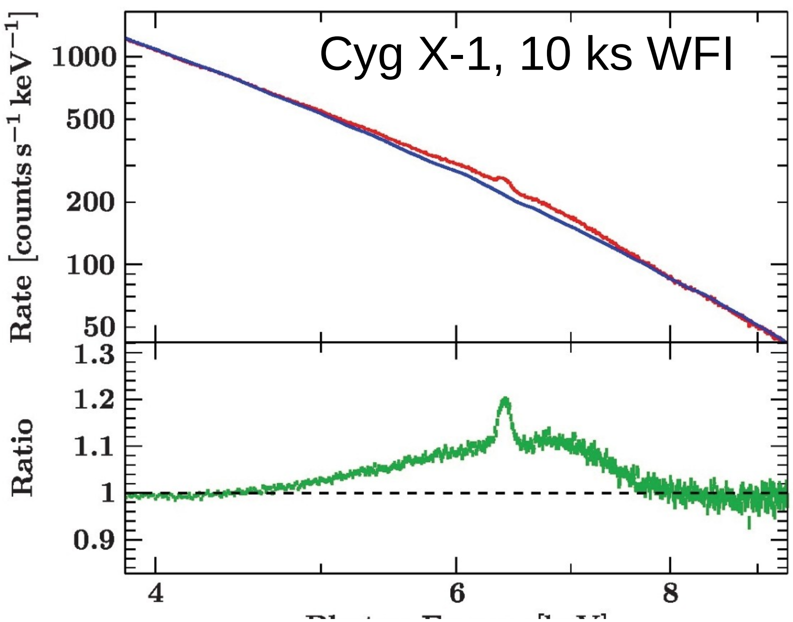
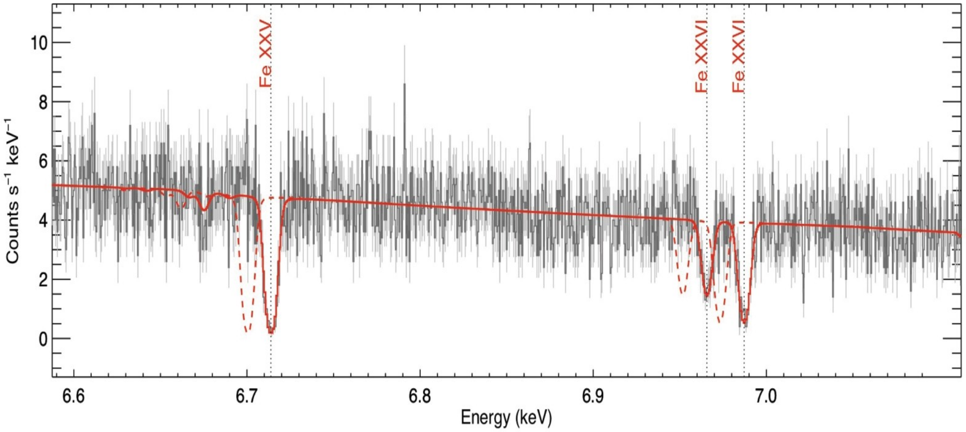
- End point of stellar evolution

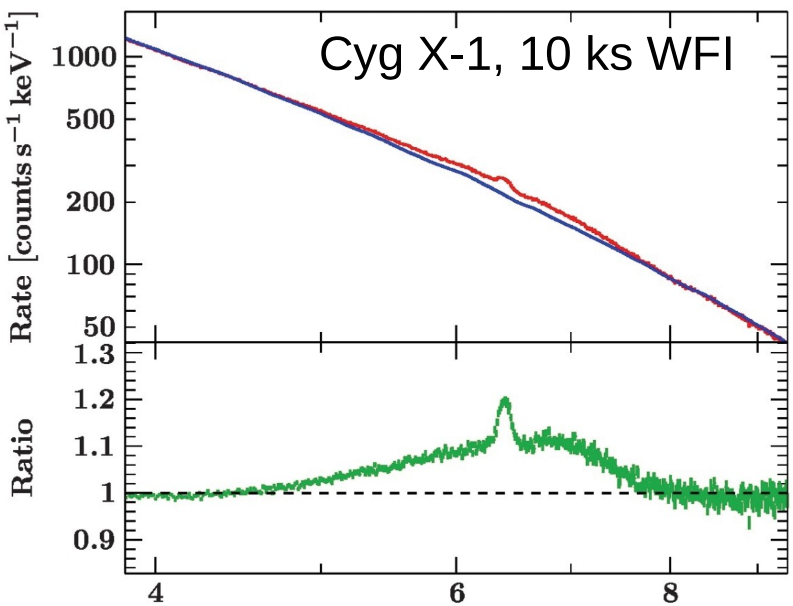


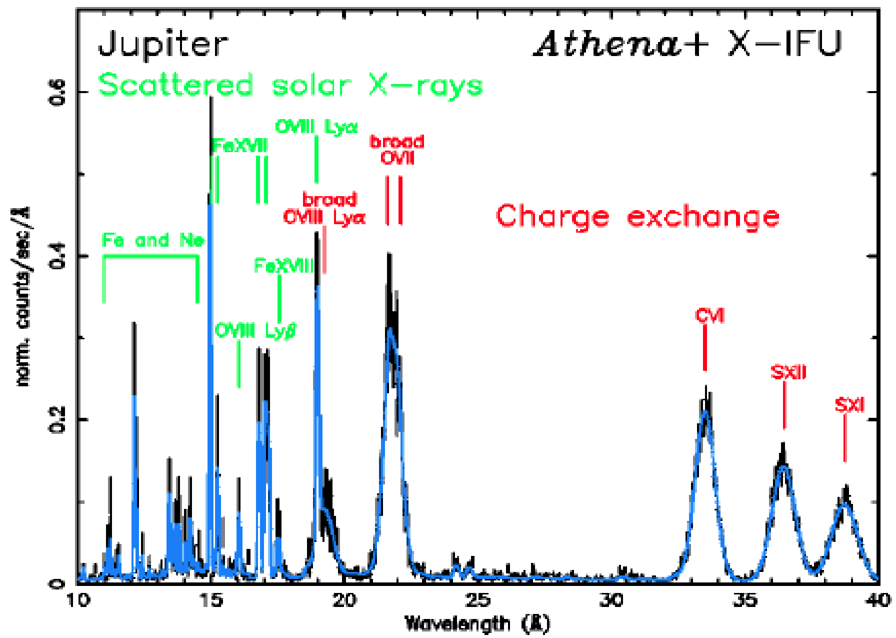


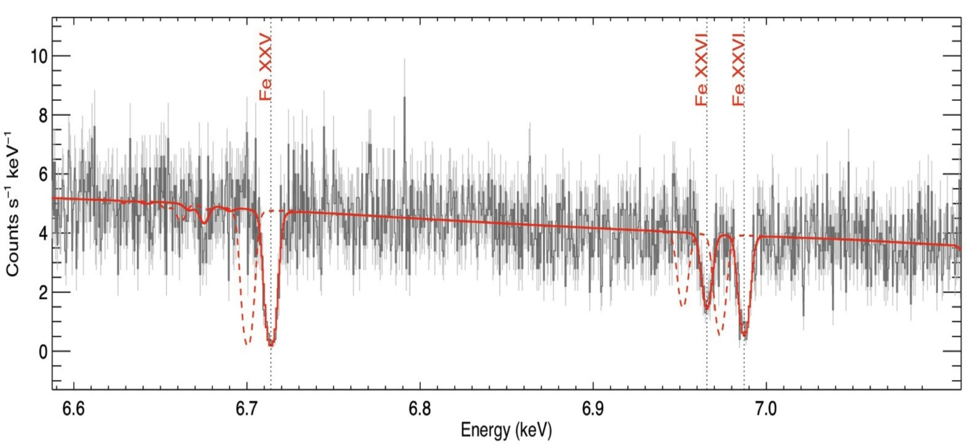


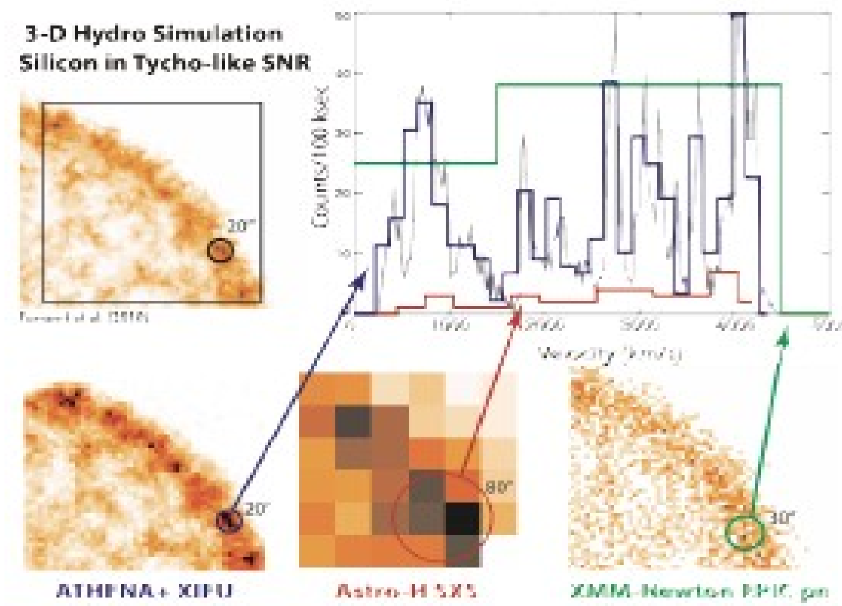
Observatory science questions Branduardi-Raymont, Scortino, Comastri, Decourchelle, Motch et al. 2013,

- Solar system and exoplanets
- End point of stellar evolution
- Supernova remnants









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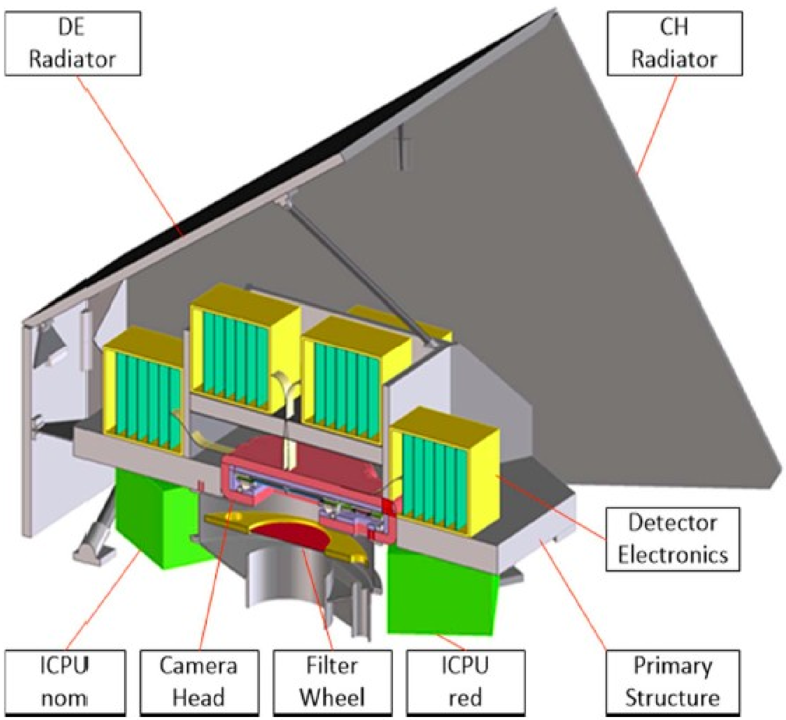
Wide Field Imager

WFI – 3D Overview



PL

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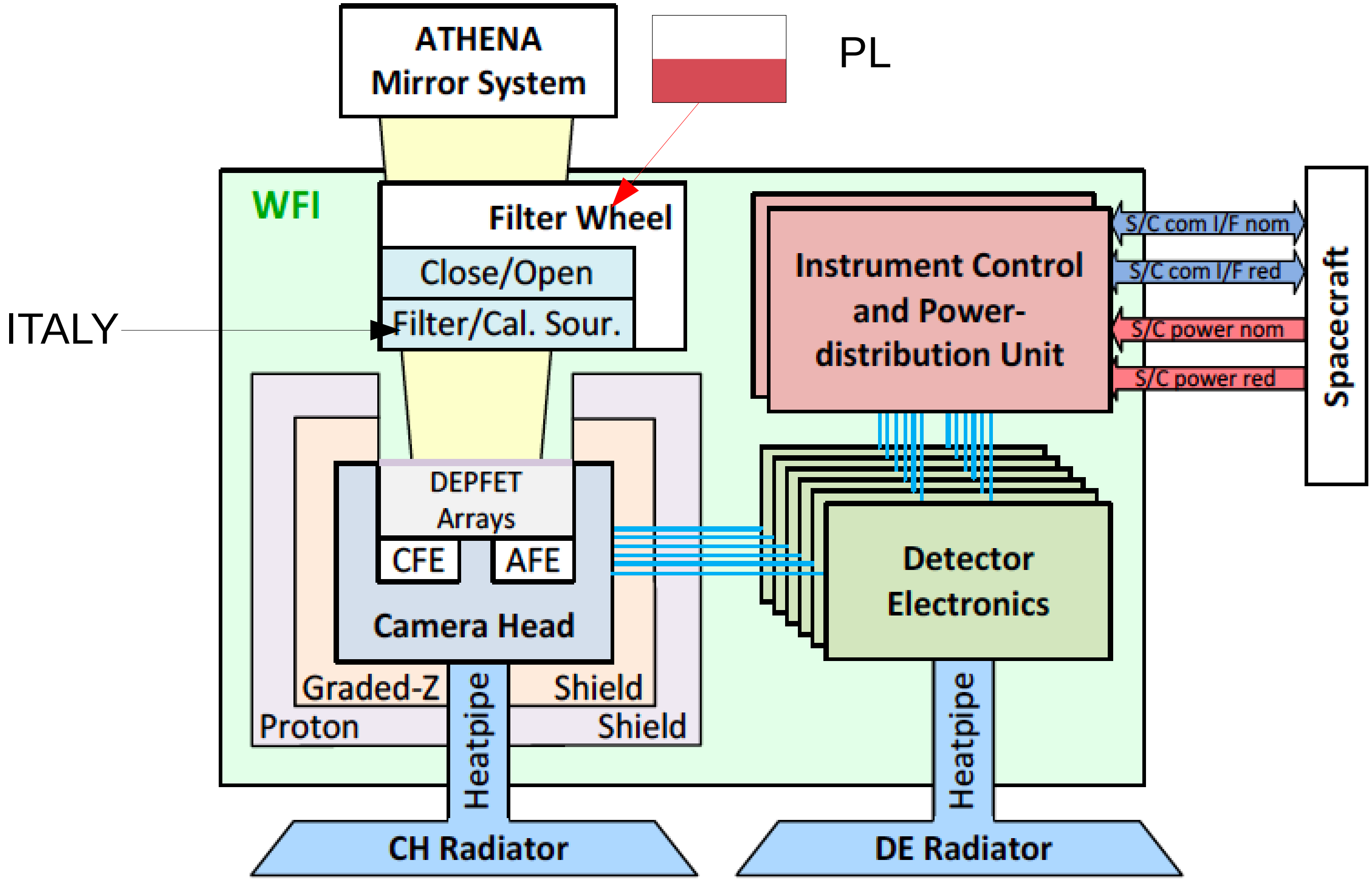
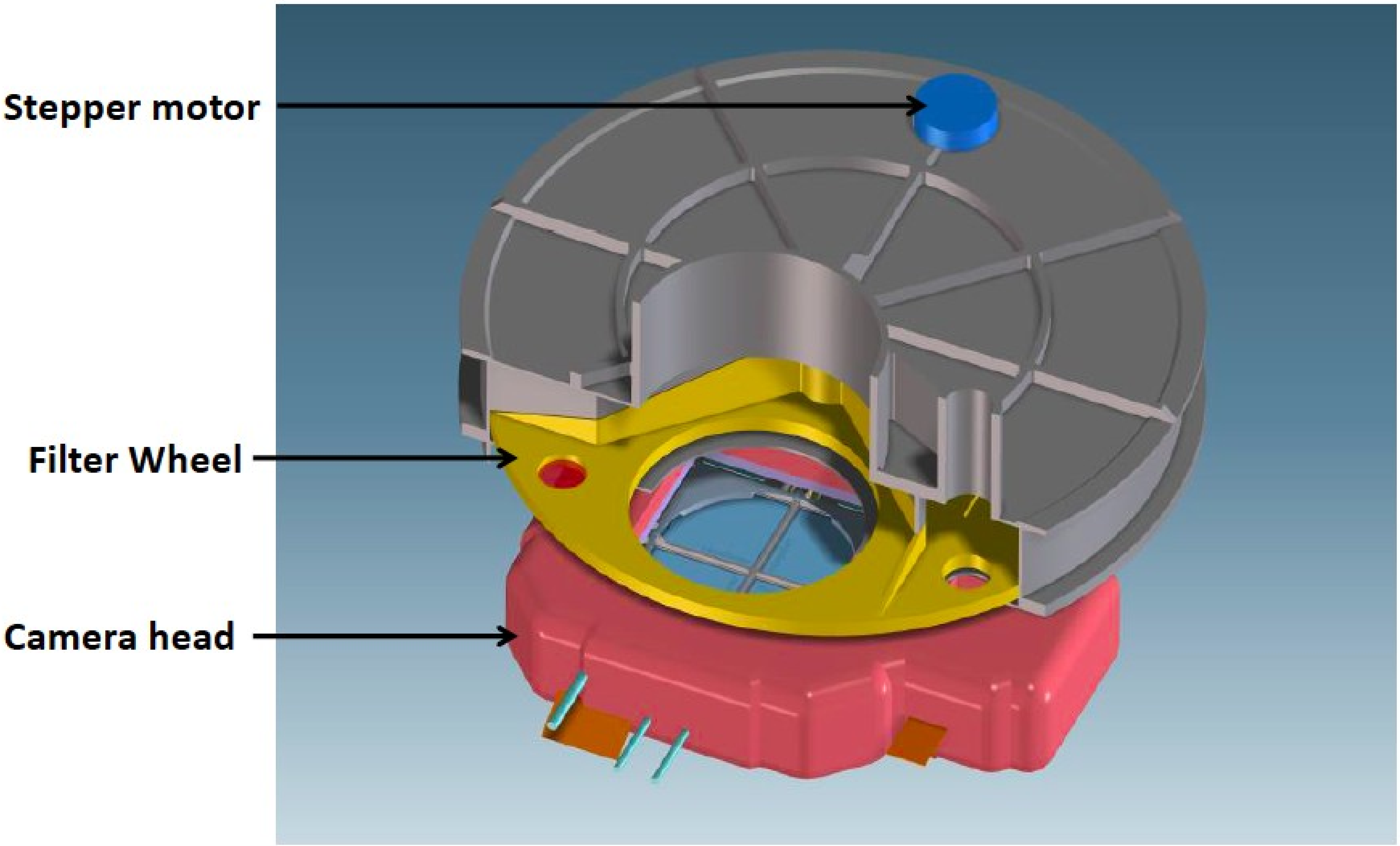
WFI Functional Block Diagram



Filter Wheel Subsystem



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Wide Field Imager

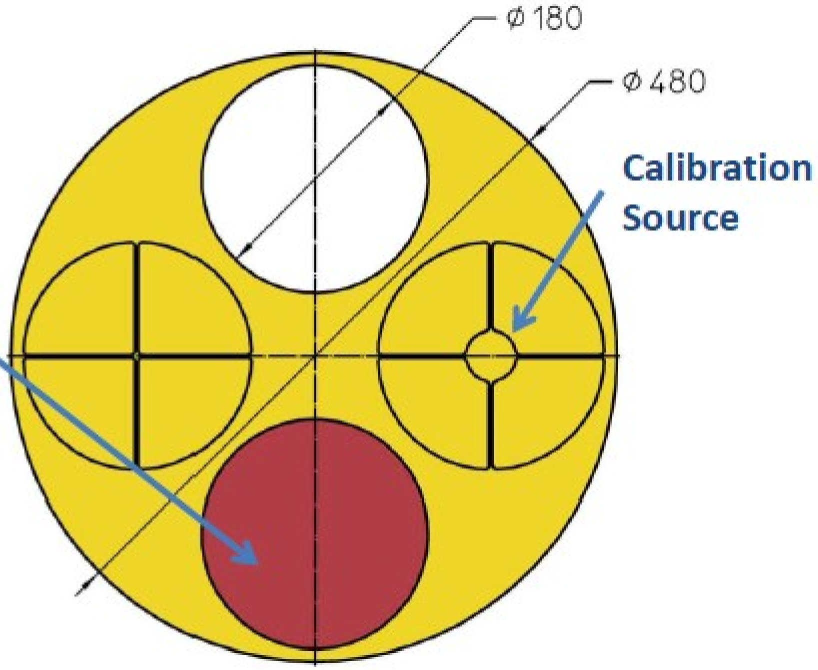
Specification by Mirosław Rataj presented on Proto-Consortium meeting in Rindberg, Germany

Filter Wheel

Functionality and requirements of FW

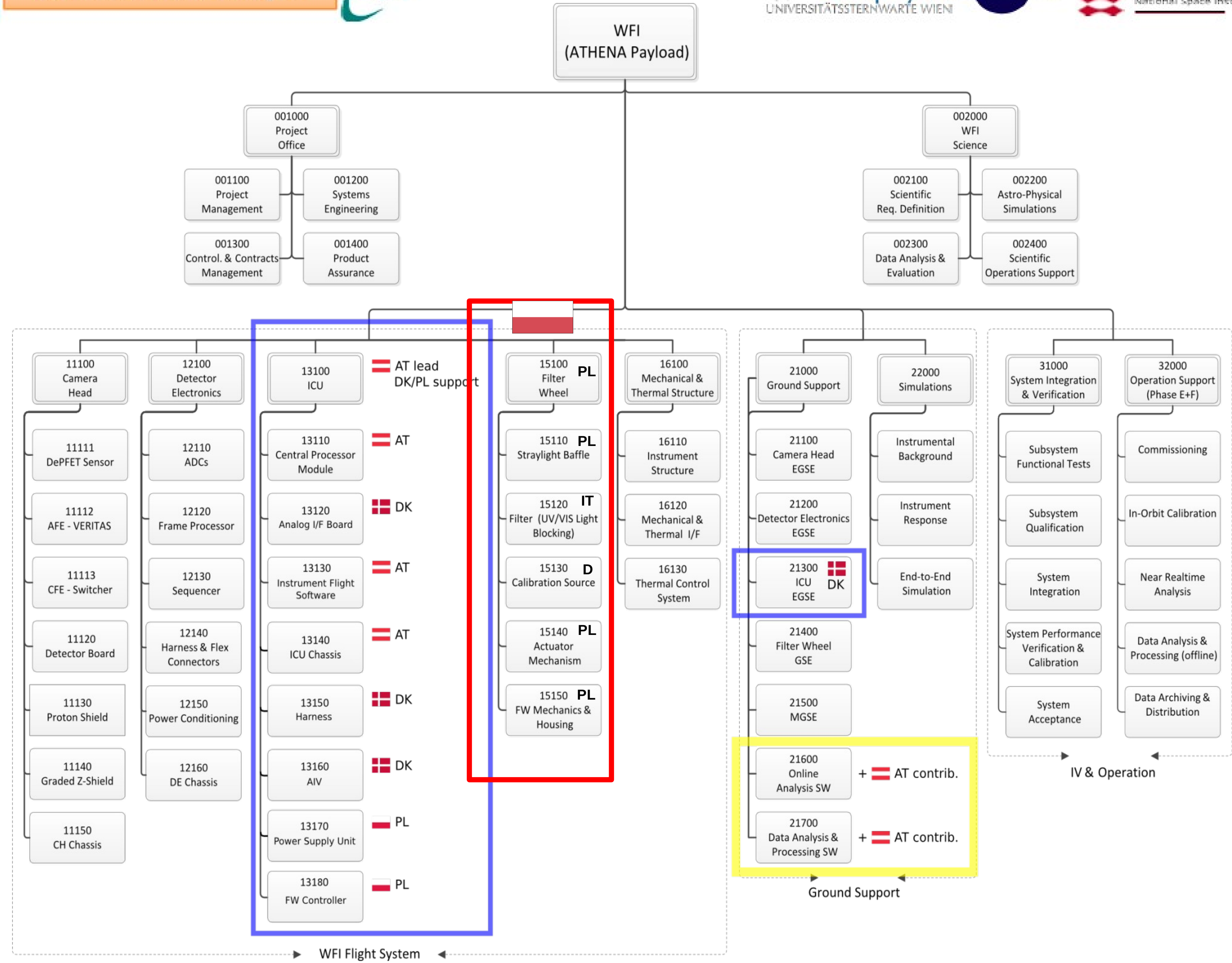
- Open position   Φ 180 mm
- Closed Position min. thickness a few mm Al
- One Filter Φ 180 mm
- Calibration Source (tbd)
- 10 sec. for change position (tbc)
- Alignment between filter mounted on filter wheel and focal plane shall be at least 0.5 mm (tbc)
- Filter size shall match the detector size of 70x70 mm² (tbc) in order to be mounted at filter frame.

Filter size increases with distance from focal plane.



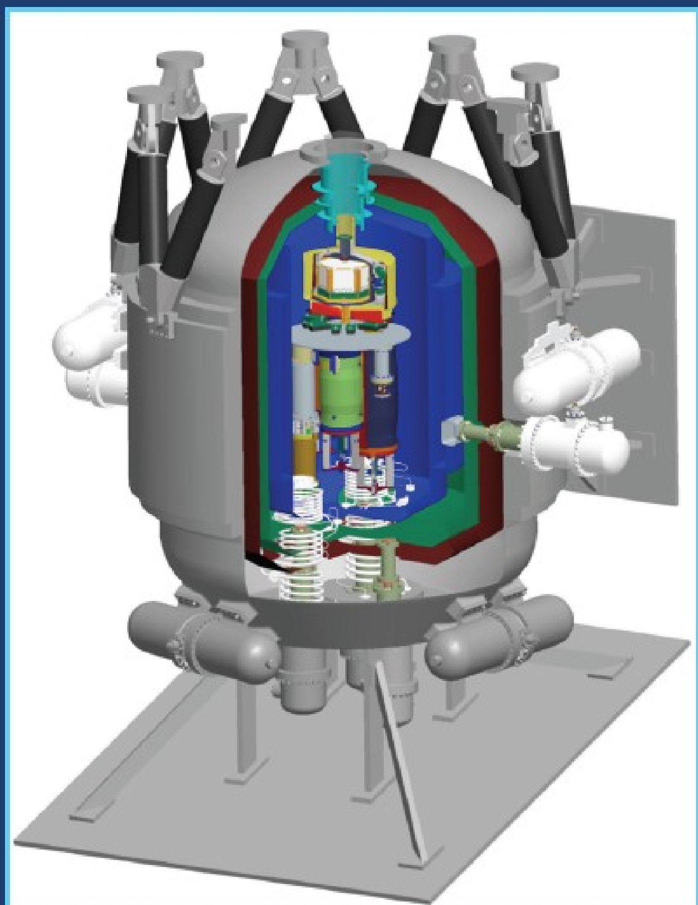
ICPU WBS

Wide Field Imager



X-IFU
X-ray Integral Field Unit

Warsaw meeting, July 2014



X-IFU dewar, cooling chain and a zoom on focal plane assembly

Current best estimates (no system margin)

FOCAL PLANE ASSEMBLY MASS	6 KG
CRYOGENIC CHAIN MASS & POWER	320 KG/900 W
MASS AND POWER OF ELECTRONICS	180 KG/300 W
X-IFU MASS AND POWER BUDGET	506 KG/1.2 KW

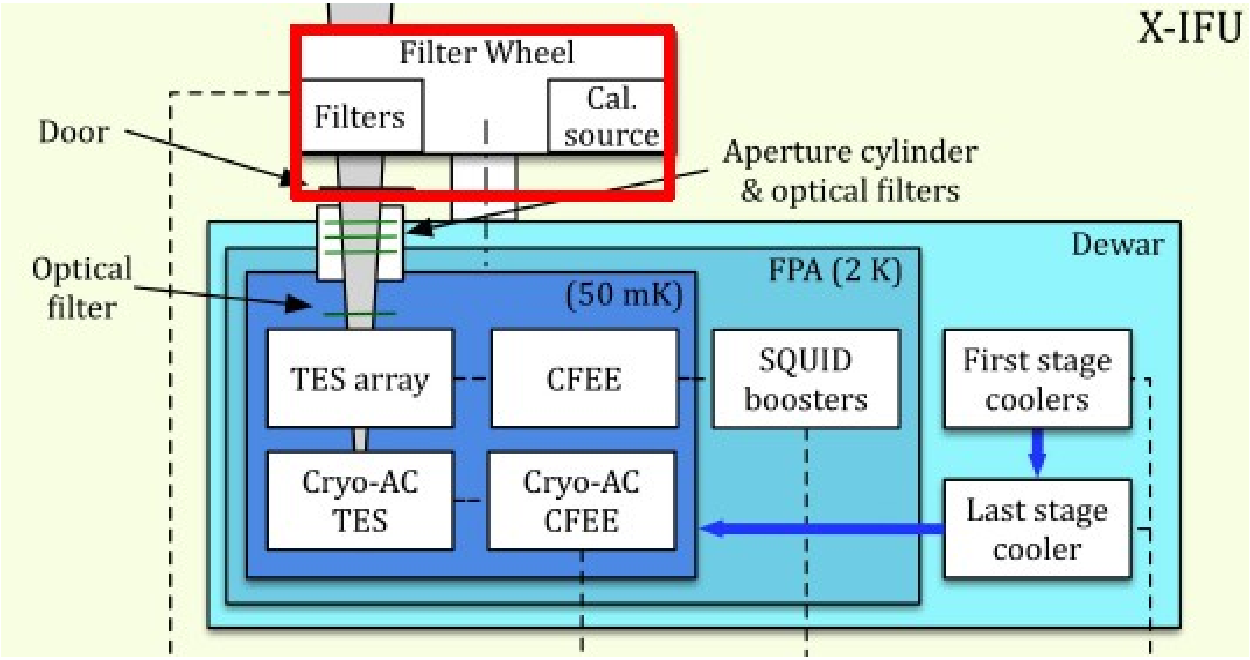
Den Herder et al. (2012), Barret et al. (2013), van Weers et al., Ravera et al., Branco et al., Duband et al. (2014, SPIE)

Space Research Centre, Polish Academy of Sciences

X-IFU
X-ray Integral Field Unit

X-IFU Dewar Door requirements – Mirosław Rataj CBK, Warsaw

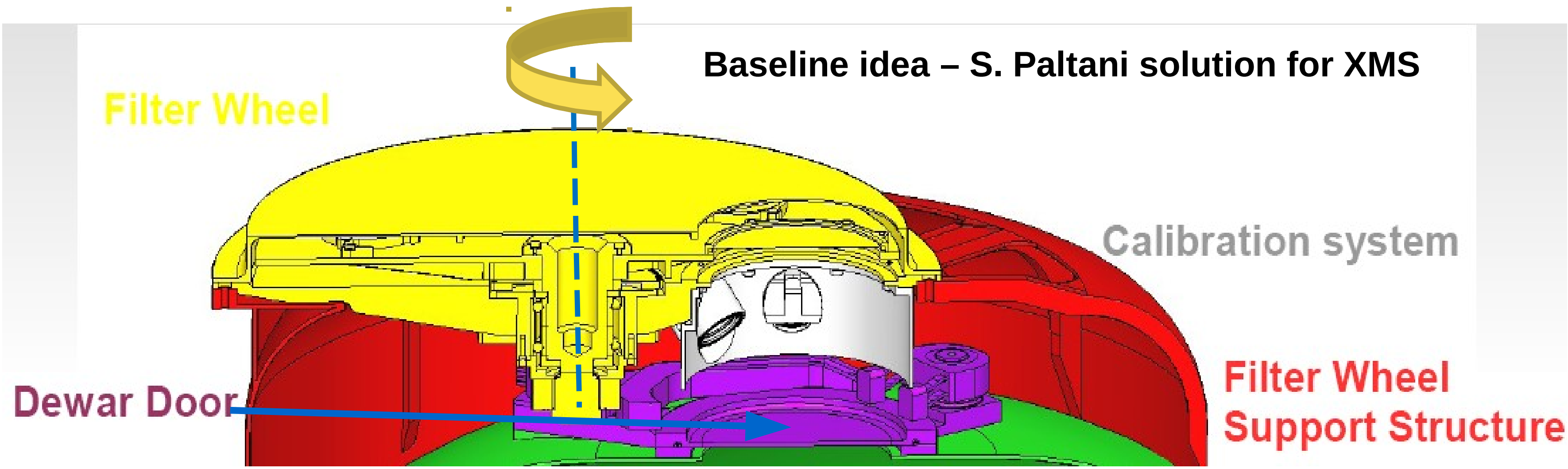
- The X-IFU will be launched with the dewar in vacuum to avoid acustic loads on the optical filters
- The door will be opened and remain open once
- The dewar door will be integrated with the dewar
- Atmosphere pressure outside the dewar



X-IFU dewar door baseline:

1) The dewar door clamping mechanism is based on a coiled spring released by the burn of fiber

2) The dewar door is rotated ???



Astronika company with CBK:

For antennas, MUPUS/Rosetta, MERTIS/Bepi Colombo

Separation mechanism for microsatellites BRITE PL

Space Research Centre, Polish Academy of Sciences

X-IFU
X-ray Integral Field Unit

SRC was proposed to be as a back-up for the PDU/PSU team.

Basic parameter:

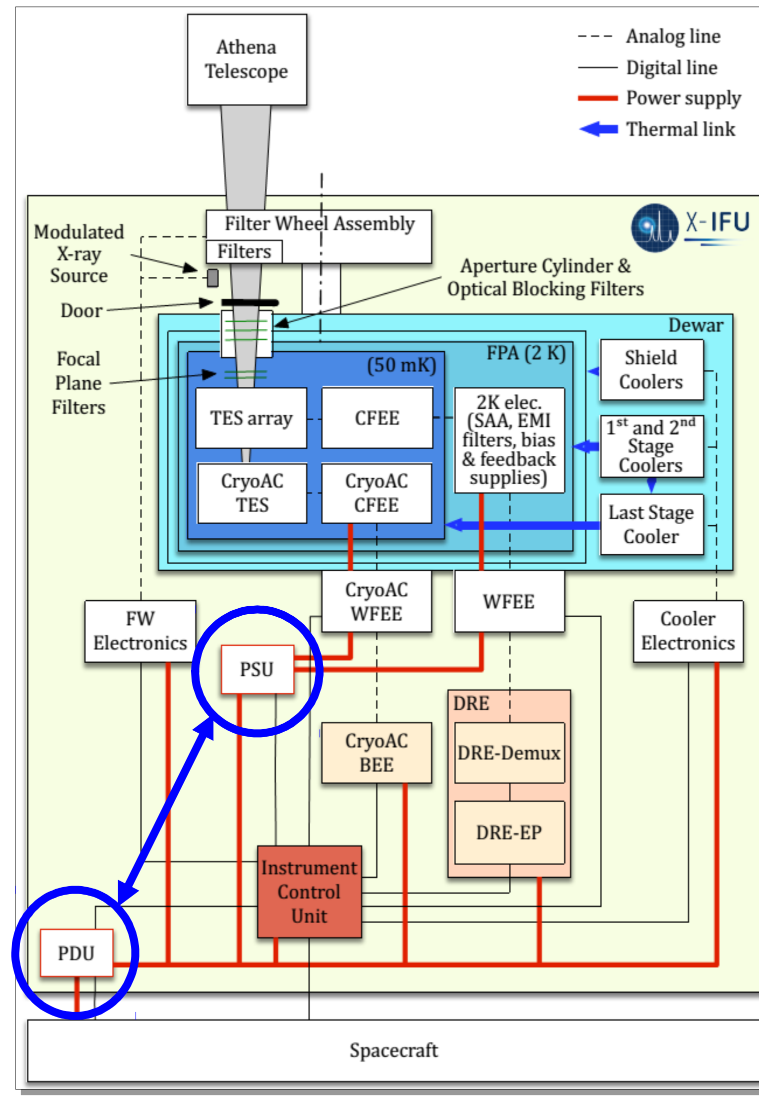
- X-IFU Power consumption : ~1 290 W

Interfaces to spacecraft:

- Power bus: 28-32 V;
- Commanding: on/off;

Design proposals:

- logic: <u>the s/c enables the PDU, then the PDU supplies the ICU</u> => instrument starts to work;
- main and redundant PDU & PSU;
- cold redundancy scheme;
- in separate boxes or frames to suppress noises etc.;
- PDU directly supplies: ICU, FW (electronics & motors), DRE, CryoAC BEE & Cooler;
- PSU directly connected to: CryoAC WFEE & WFEE.



Konrad Skup, CBK, Warsaw

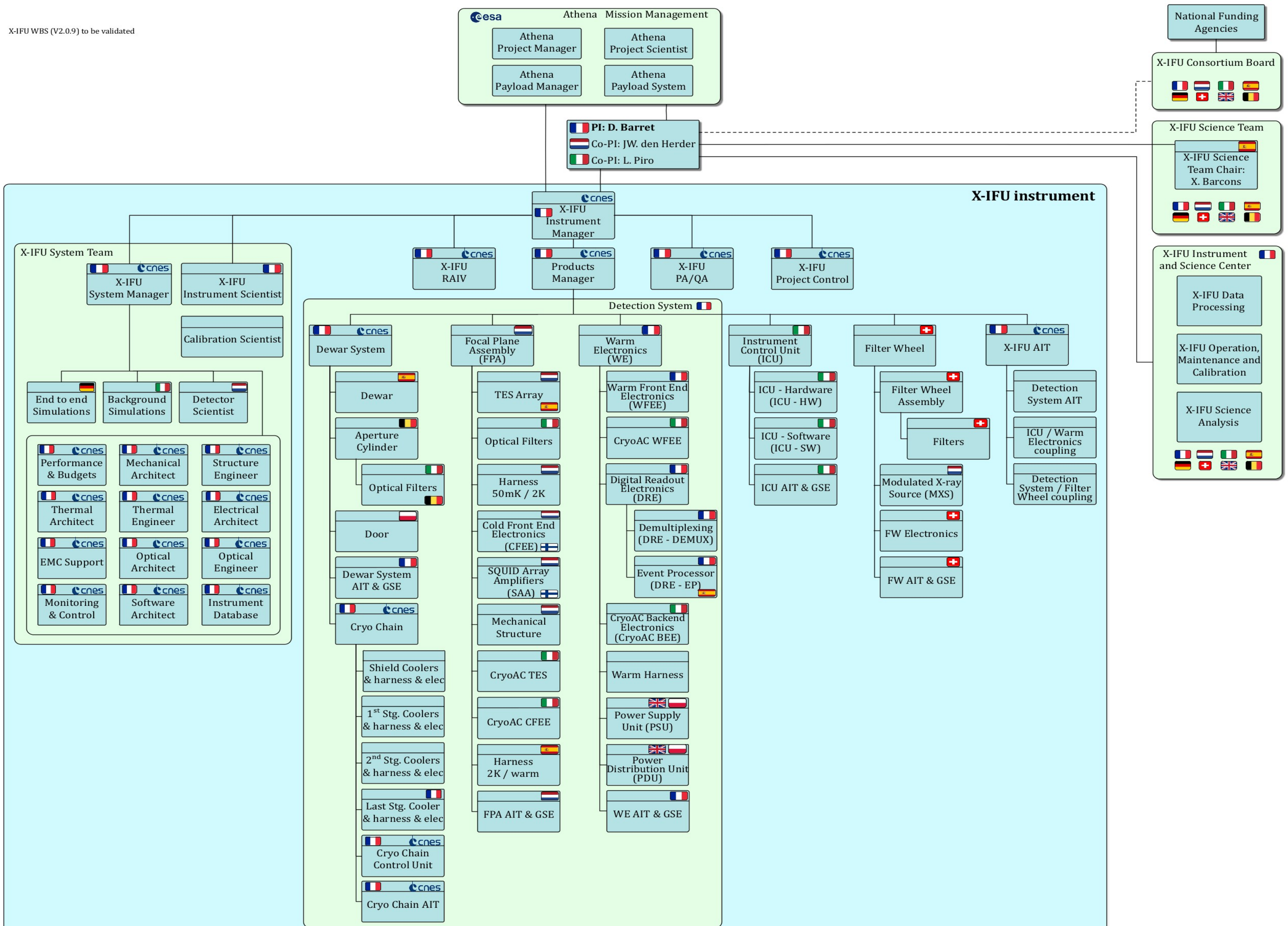
Space Research Centre, Polish Academy of Sciences

X-IFU
X-ray Integral Field Unit

Feb. 2015 – Toulouse Consortium meeting

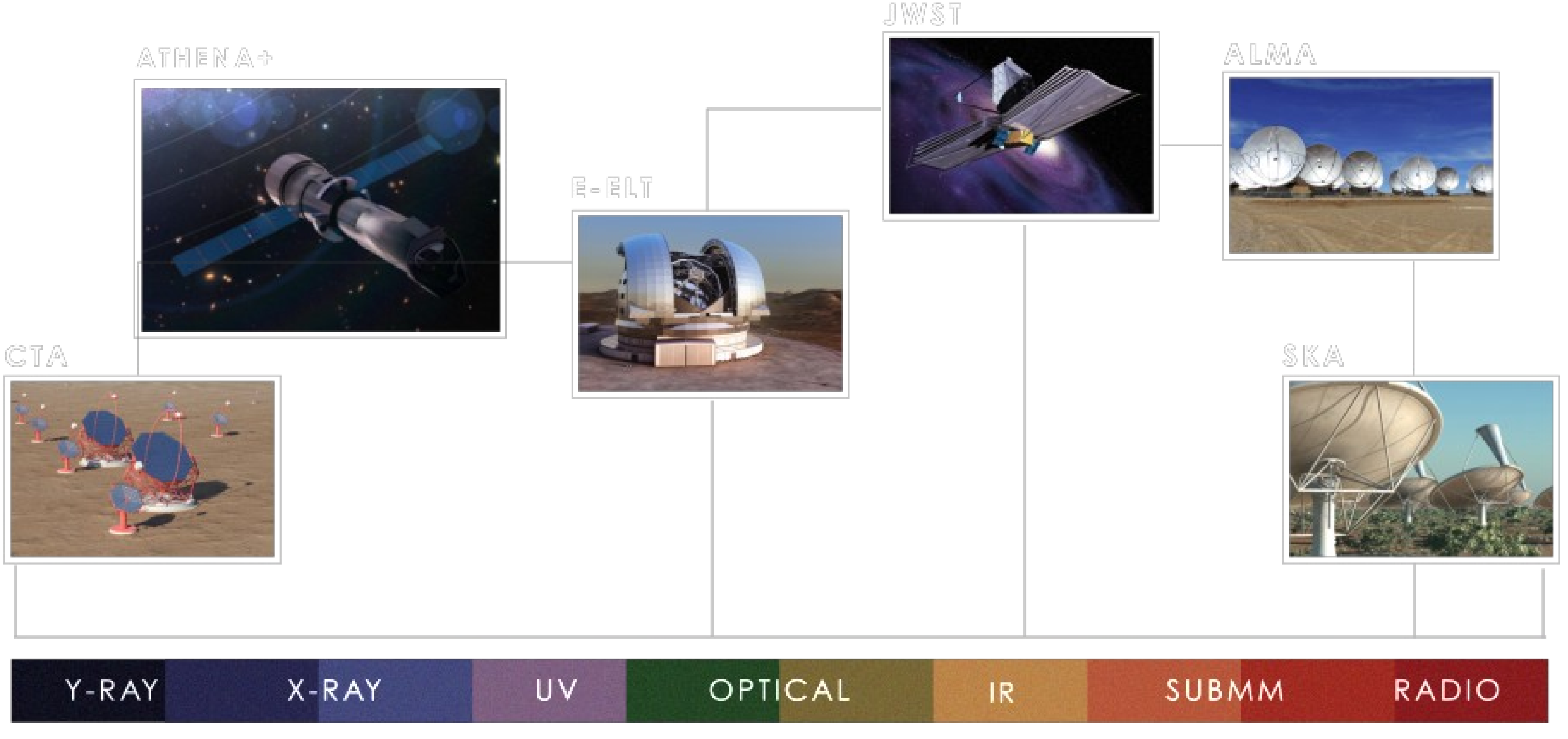
Agata Różańska – Consortium Board Member
Agnieszka Janiuk – Science Team Member

X-IFU WBS (V2.0.9) to be validated



Conclusions:

ATHENA presents great science with modern technology



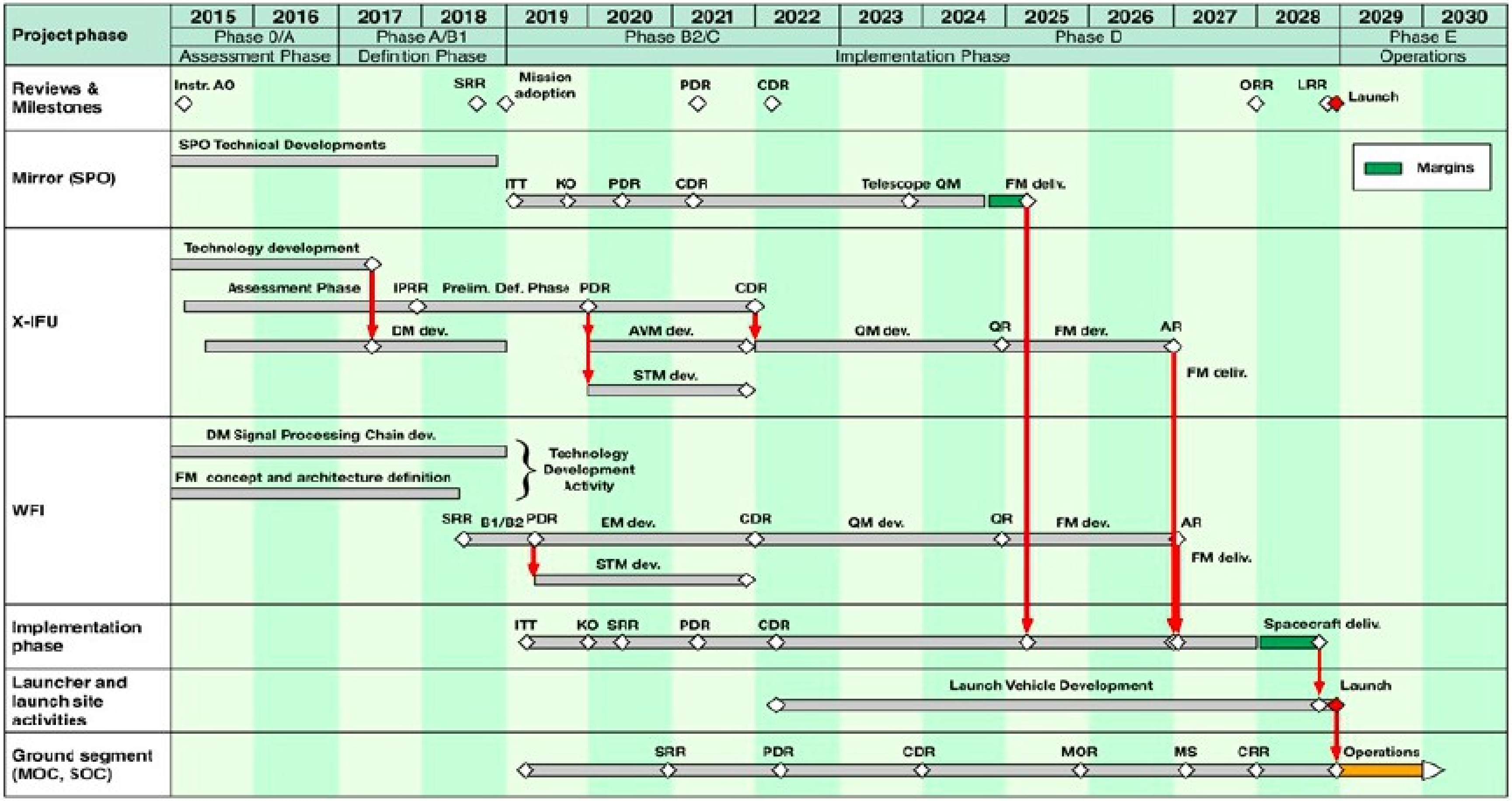
Athena is a crucial part of the suite of large observatories needed to reach the science objectives of astronomy in the coming decades

Conclusions:

ATHENA is a real ESA mission, and PRODEX can help very much to build this telescope

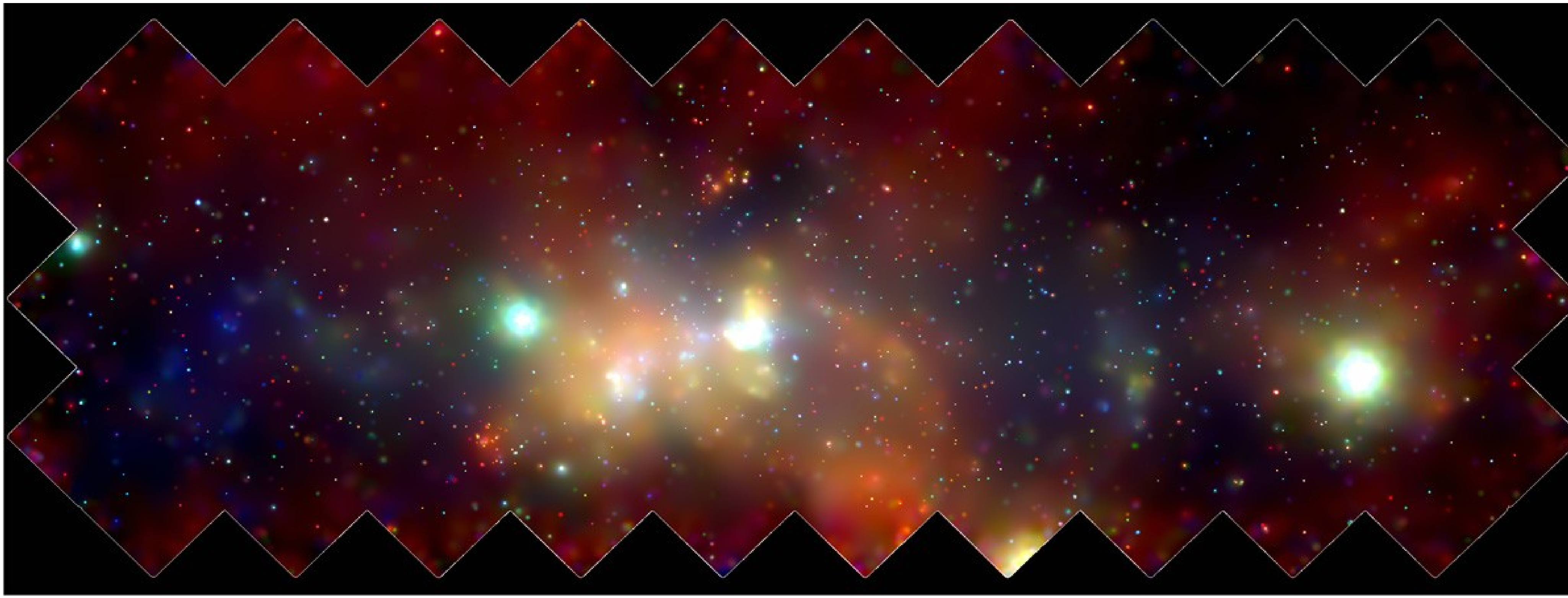
WFI: BB EM + STM QM FM FS

Athena Schedule



ATHENA will hunt for missing baryons,

THANK YOU FOR YOUR ATTANTION



Cosmology school, Kielce, July 13th, 2016