X-ray study of large to small scale structures in the Universe

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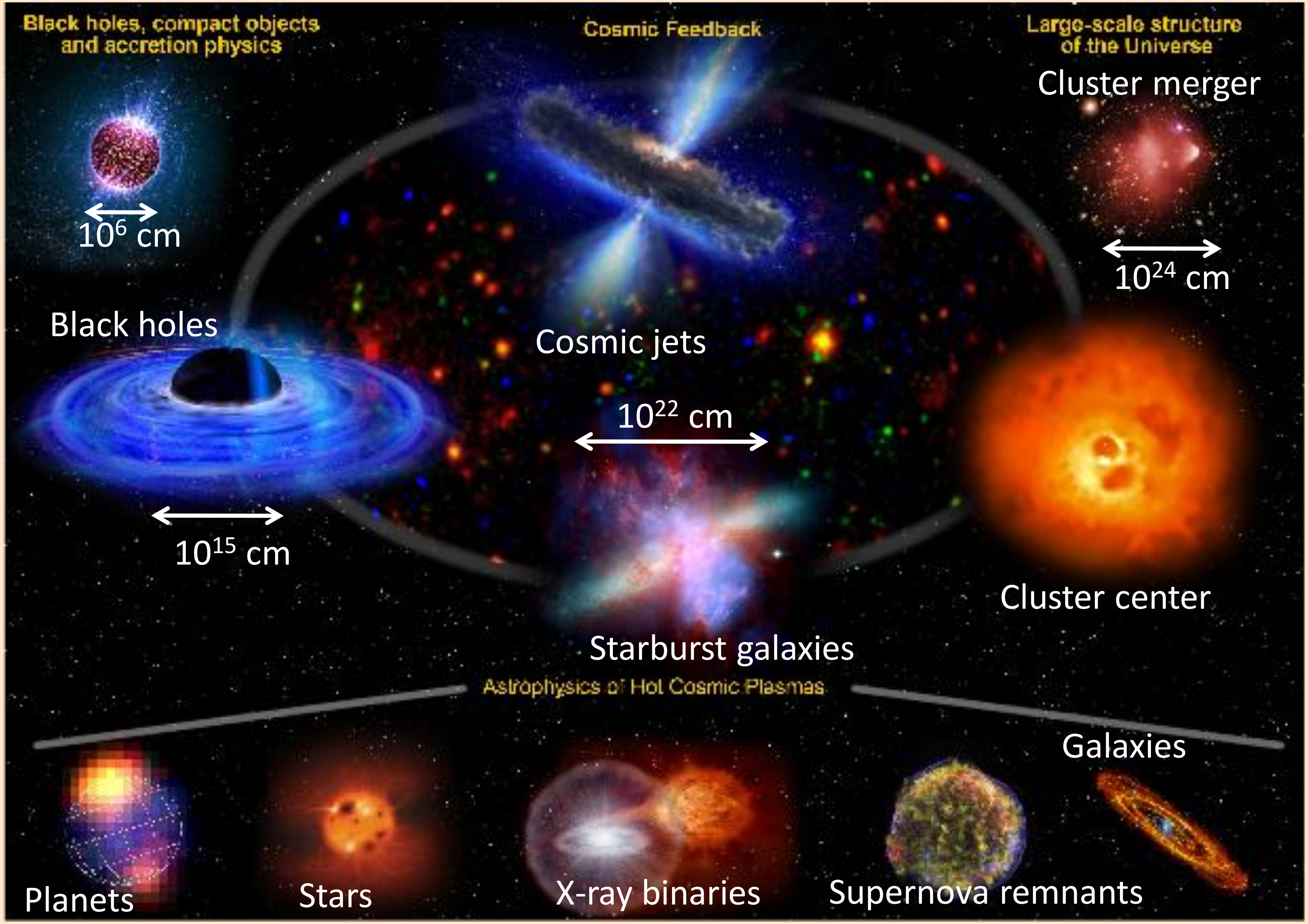
- X-ray astronomy
- Some results on small and large scales
- Future prospects

X-ray view of the Universe

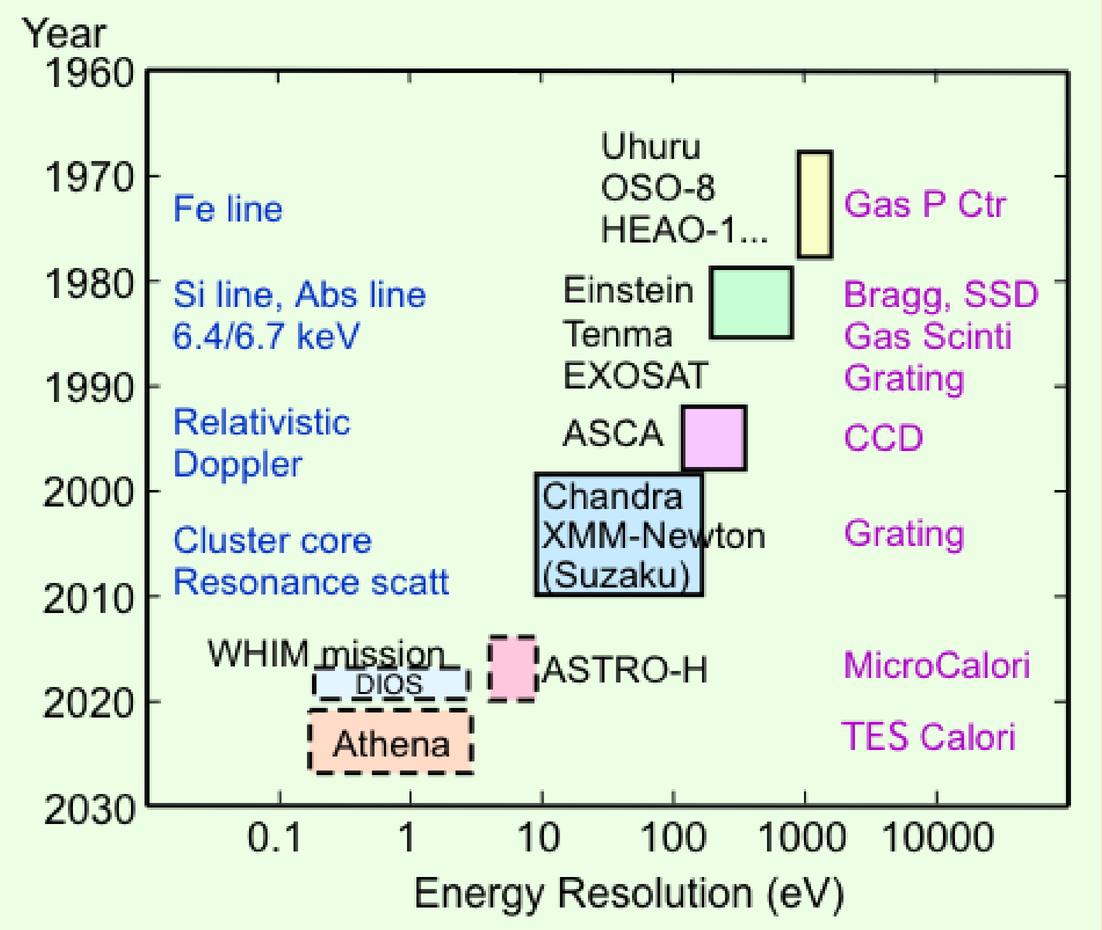
- High-energy photons emitted form very hot matter (T = 10^6 – 10^8 K) such as,
  - Accreting matter near black holes
  - Matter heated by supernova explosions
  - Hot gas confined in dark matter potential in galaxies and clusters of galaxies
  - Dark baryons tracing large-scale structures
- Universe is dynamically evolving in all scales
  - Stellar activity, black hole environments, supernova remnants, dynamics of galaxy clusters
  - All the active features very clearly seen in X-rays

X-ray view of the Universe



Power of X-ray spectroscopy

- Chemical and dynamical evolutions working in a closely coupled manner
- X-ray spectroscopy is very powerful in detecting both gas motions and chemical composition

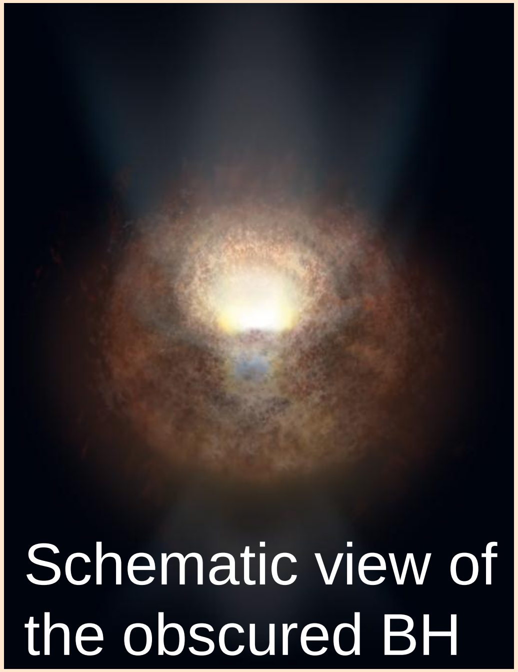


Spectral resolution advanced by an order from gas counter to CCD, and then another order with microcalorimeters on ASTRO-H (2014).

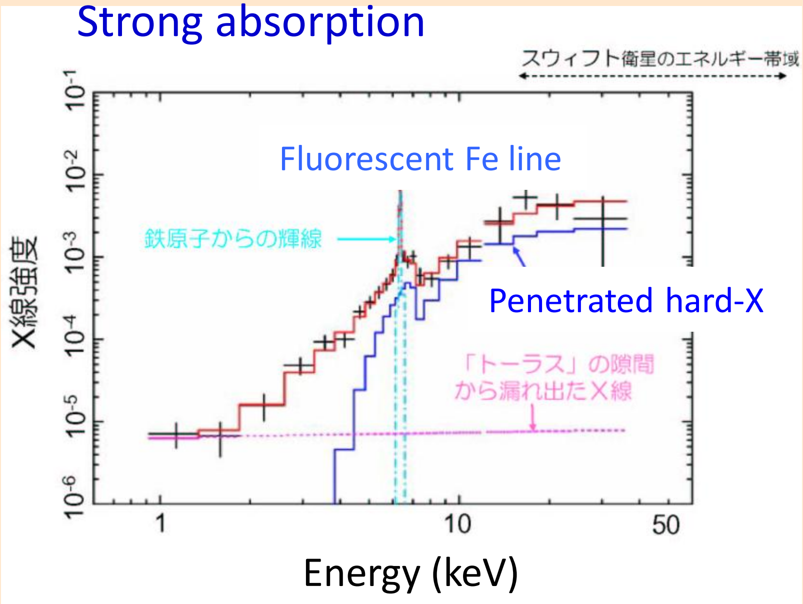
New science revealed with the stepwise advance of energy resolution.

Obscured black holes with Suzaku

- A new type of obscured black hole, surrounded almost completely by matter
- Hard X-ray and strong Fe line are the only signature
- Obscured black holes should be common in the early universe



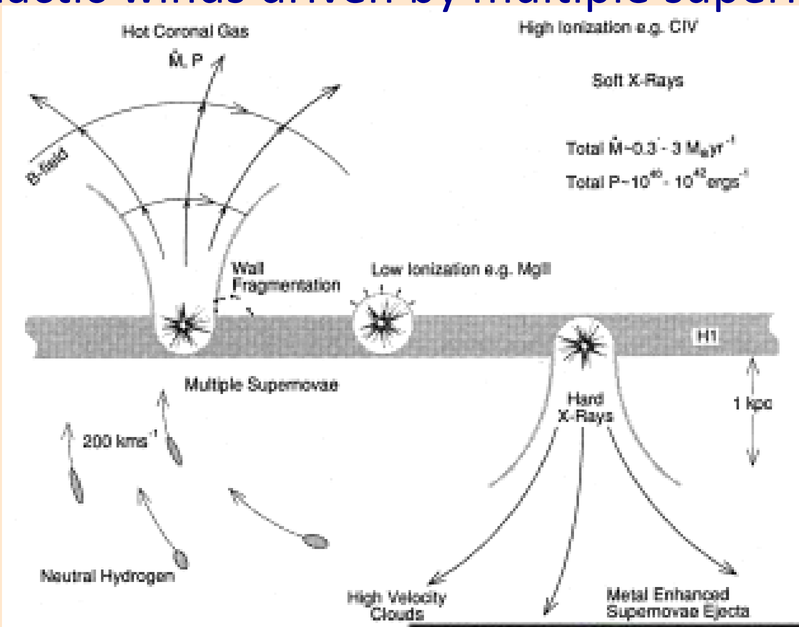
Predicted quasar evolution



Obscured quasar (z = 0.0062): Ueda et al. 2007

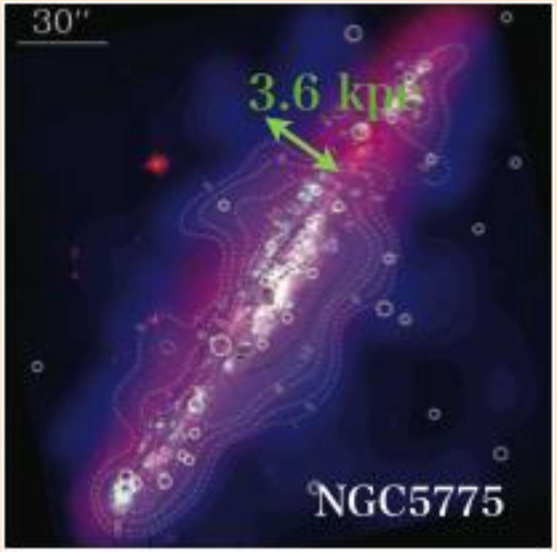
Matter circulation in Galaxy scales

Galactic winds driven by multiple supernovae

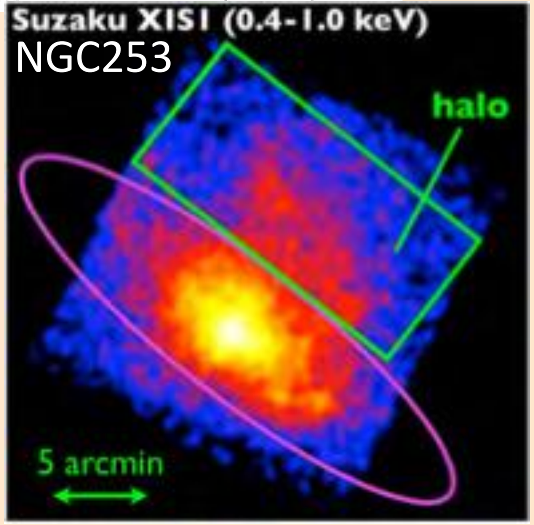


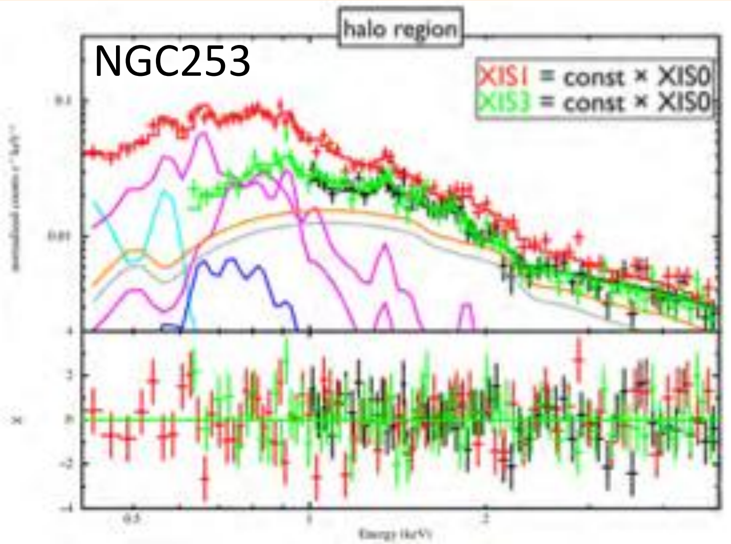
Norman and Ikeuchi 1987

Chandra view of starburst outflow



Mitsuishi 2012

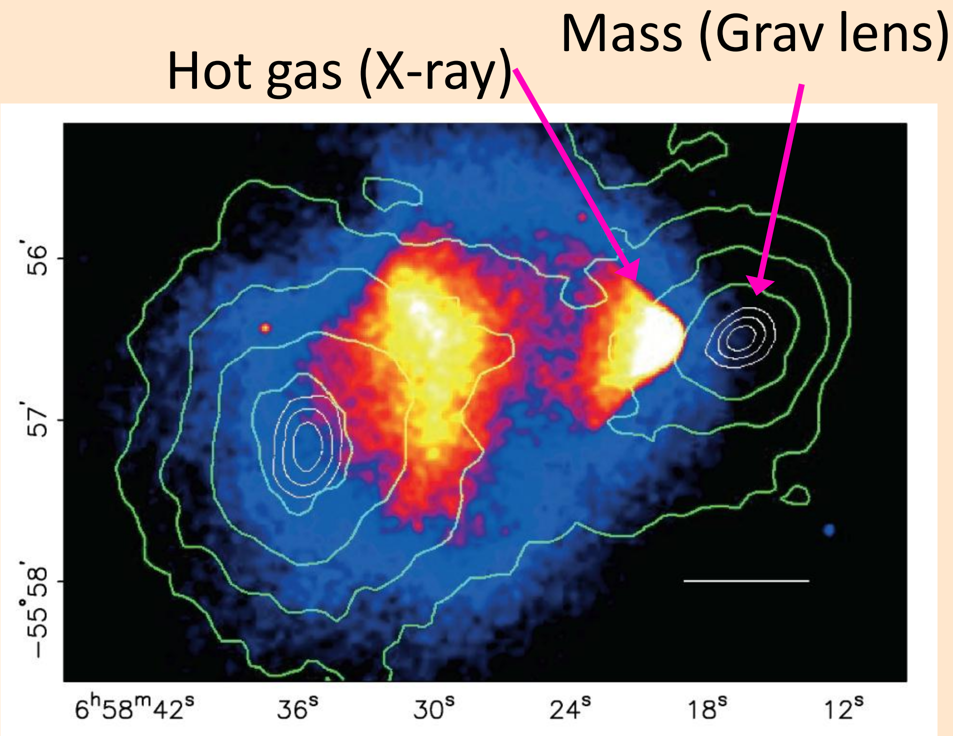




NGC253: metal-rich starburst winds probed with X-ray image and spectra

Dark matter in a merging cluster

- 1E0657-56 (cluster at *z*=0.3) :
  X-ray image shows a bow shock structure with Mach number 2 – 3
- Gravitational lens shows mass concentrations outside of the hot gas
- Dark matter pass through without gas pressure



⇒ Dark matter exists

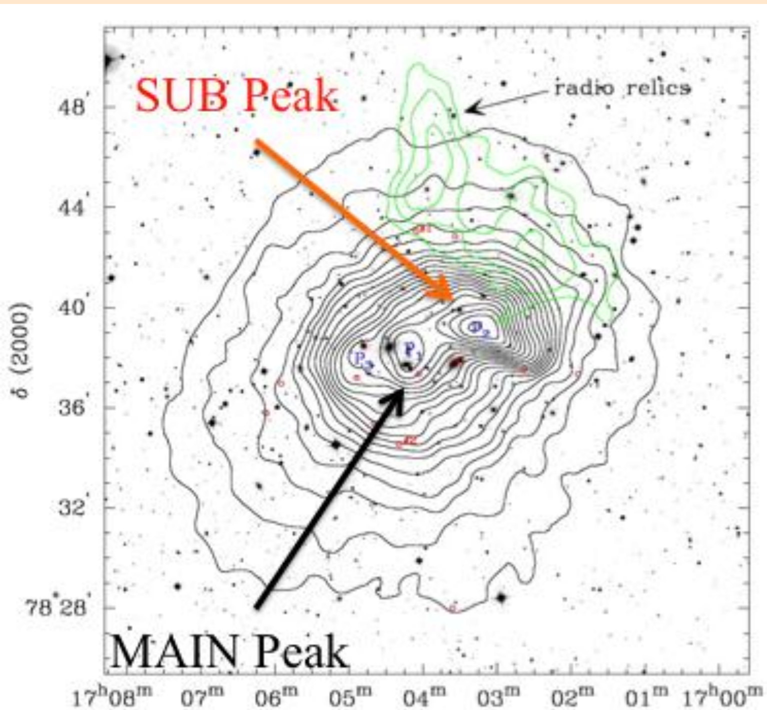
Markevitch et al. 2002,
Clowe et al. 2006

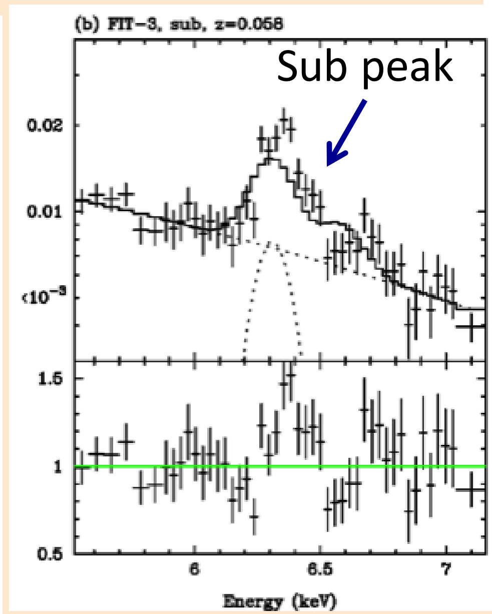
Cluster growth through mergers

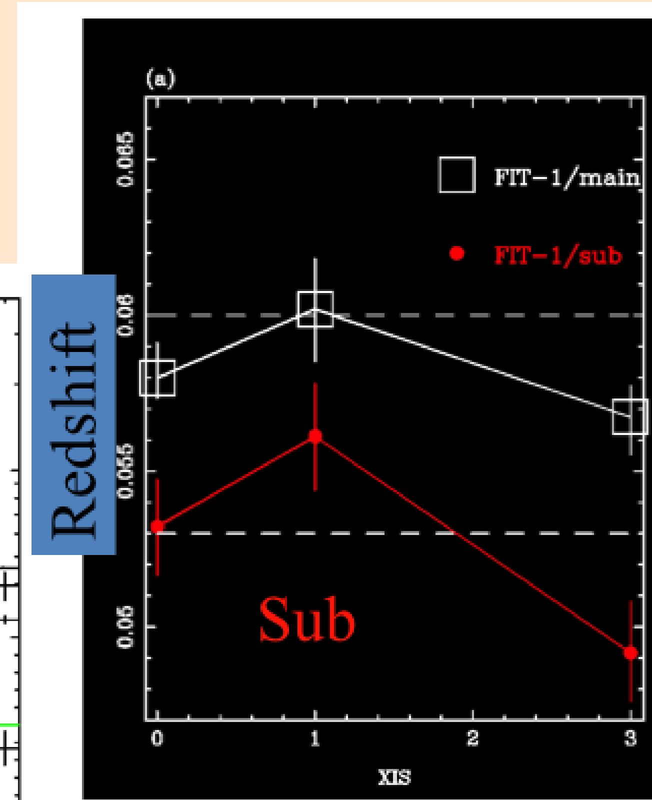
Tamura et al. 2011

A2256: z = 0.058

double core suggests a merger proceeding







The sub peak is relatively approaching us

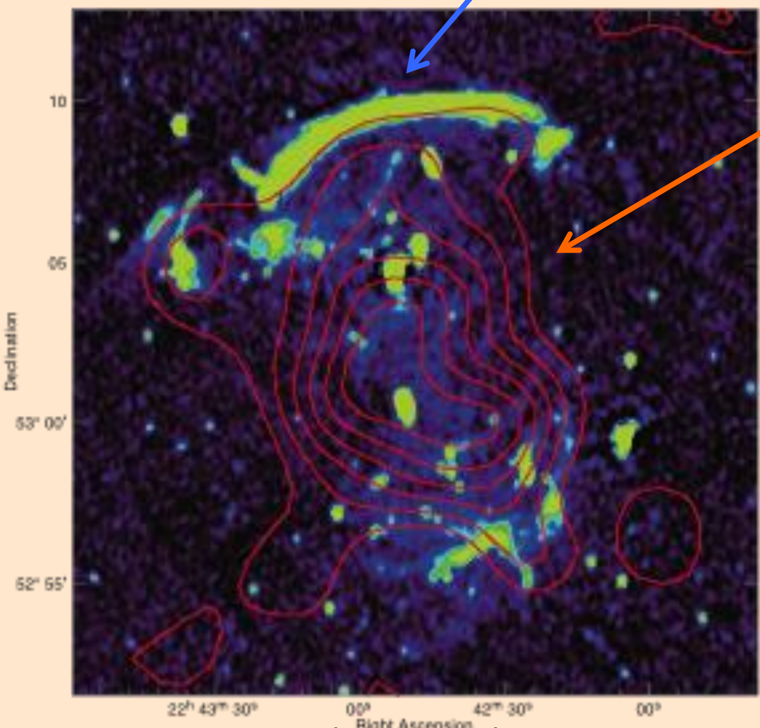
CCD spectra showed significant shifts in the Fe line energy (by 30 eV)

Inferred gas motion (~ 1500 km s^{-1}) is consistent with optical data

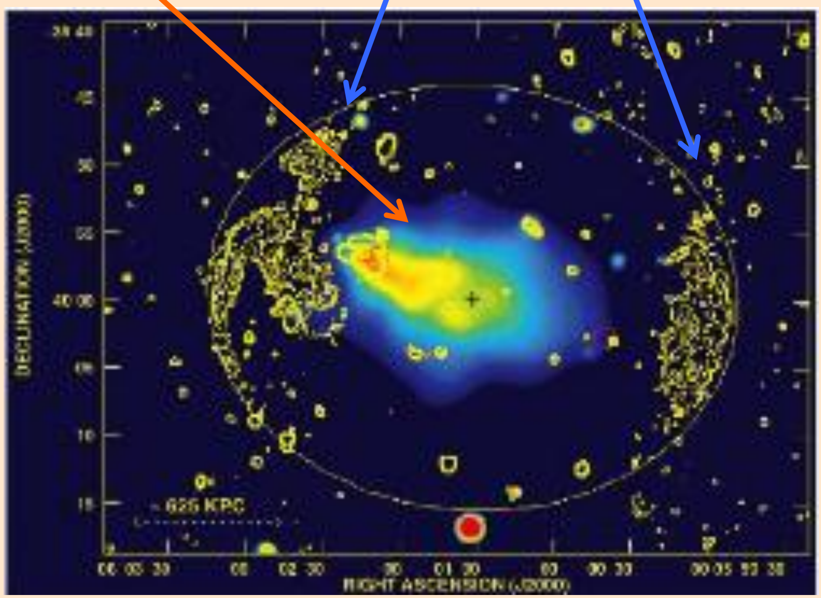
Better energy resolution will detect gas motions in many other clusters

Radio relics: shock fronts?

- Radio relics are synchrotron emission from GeV energy electrons, which must have been accelerated in these regions
- Radio relics are likely to correspond to shock fronts, but no clear evidence so far

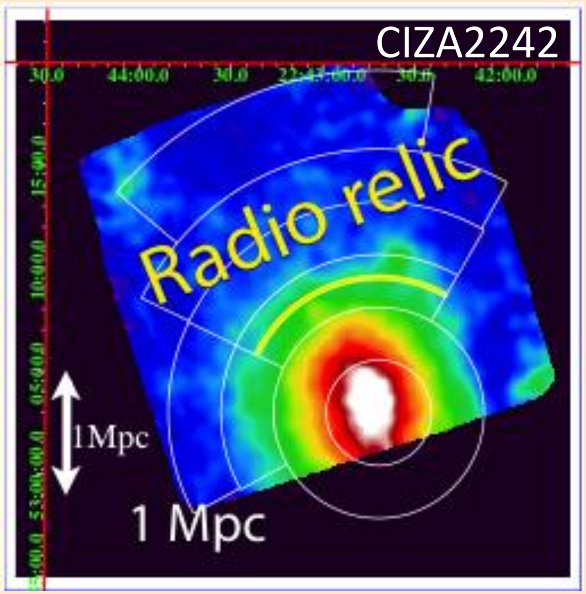


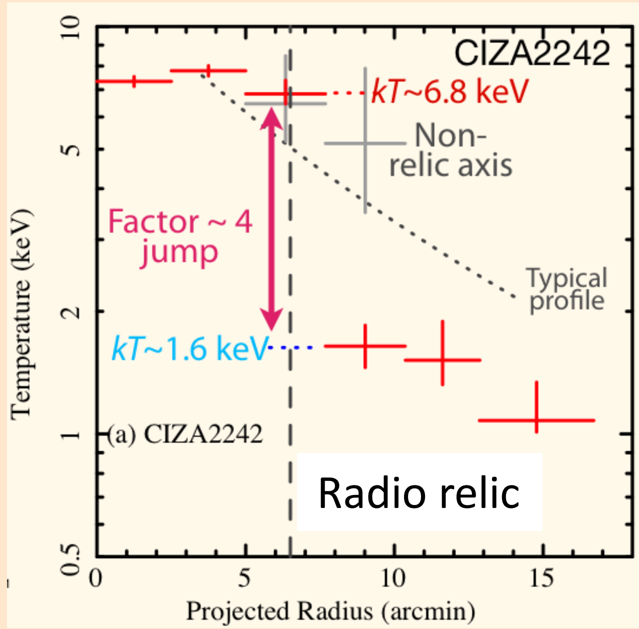
CIZA J2242.8+5301 (z = 0.19) van Weeren et al. 2010



A3376 (z = 0.046) Bagchi et al. 2006

Suzaku evidence of shocks





Akamatsu et al. (2011, 2012, and thesis)

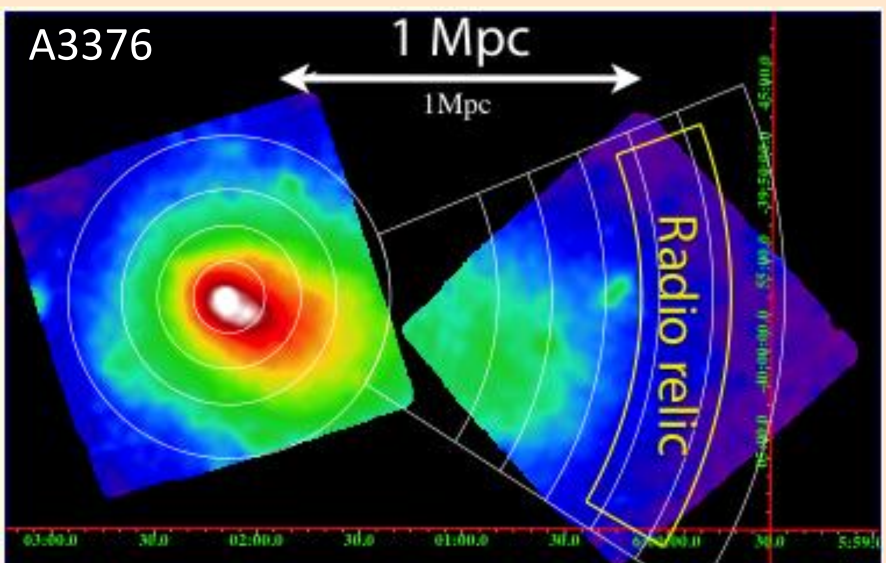
Strong temperature jumps detected from radio relics

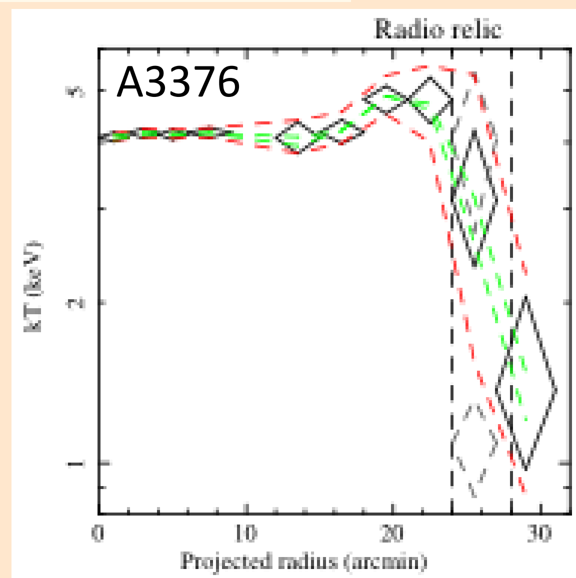
Clear evidence of shock fronts

Inferred Mach numbers:

3.0 ± 0.4 (CIZA2242)

2.9 ± 0.6 (A3376)





Summary of X-ray studies

- X-ray image and spectra jointly reveals formation processes of black holes, galaxies and clusters of galaxies
- Dynamical evolution is very common even in the very large scales (cluster size > 10^{24} cm)
- Suzaku is characterized by good energy resolution and low background, and reveals new features (galaxy outflows and cluster shocks) in the low density "frontier" regions

Further jump in the X-ray spectroscopy expected from ASTRO-H

The ASTRO-H Mission

On behalf of ASTRO-H Team (Project Manager: T. Takahashi at ISAS/JAXA)

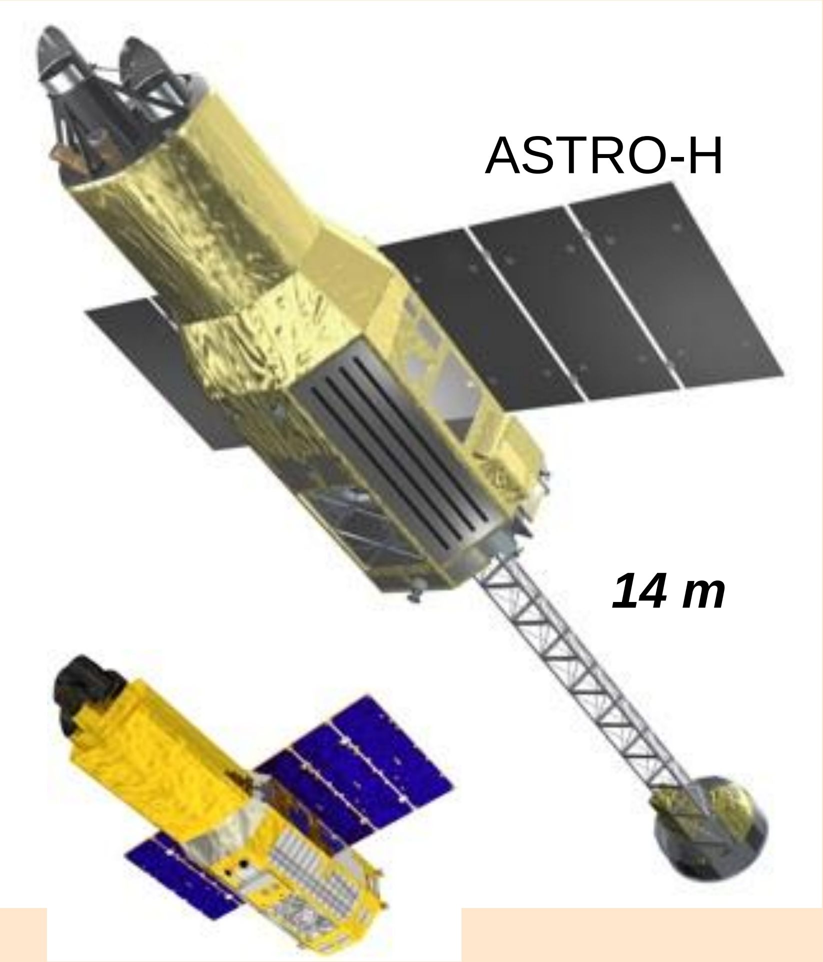
Launch is scheduled in 2014

ASTRO-H Quick Reference: http://astro-h.isas.jaxa.jp/ahqr.pdf

ASTRO-H X-ray Astronomy Satellite

- Launch site:
  Tanegashima Space Center, Japan
- Launch vehicle: JAXA H-IIA rocket
- Orbit Altitude: 550km
- Orbit Type: Approximate circular orbit
- Orbit Inclination: ~31 degrees
- Orbital Period: 96 minutes

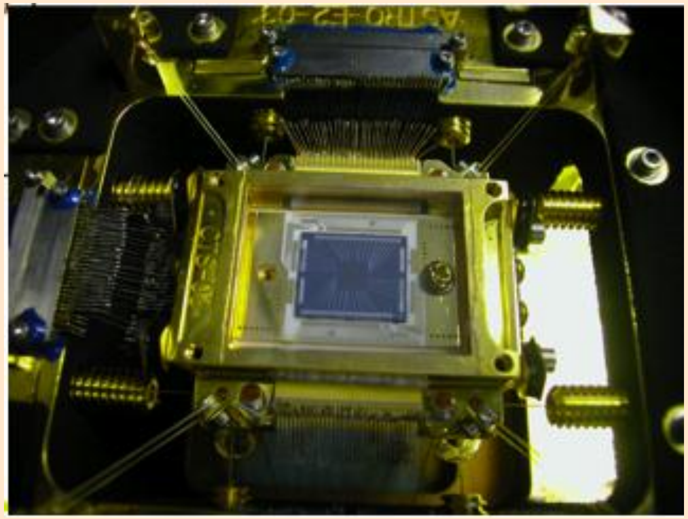
- Total Length: 14m
- Mass: < 2.6 metric ton
- Power: < 3500 W
- Telemetry Rate: > 8 Mbps (X-band)
- Recorder Capacity: > 12 Gbits
- Mission Life : > 3 years

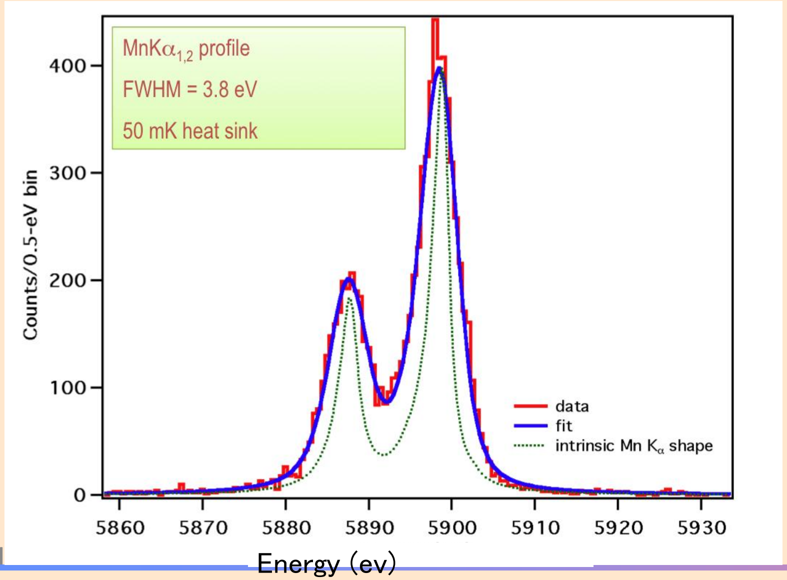


Suzaku (6m, 1.7t)

Soft X-ray Spectrometer (SXS/XCS)

ISAS/Kanazawa/Metro U./Saitama U./Rikkyo U./Riken/GSFC/Wisconsin U./Yale U./SRON/Geneva U and more

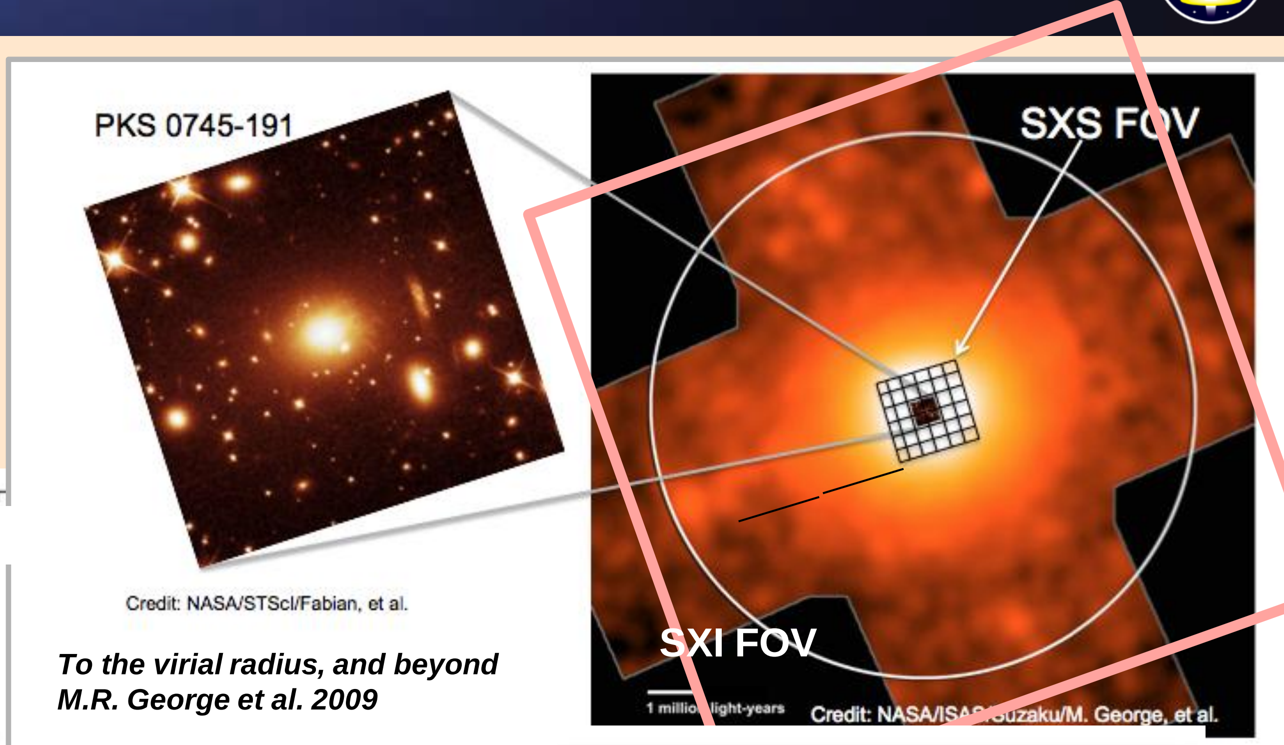




	Requirements (/Goal)
Energy resolution	7 eV (FWHM) (4 eV(FWHM) Goal)
Energy range	0.3 - 12 keV
Field of view	2.9 x 2.9 arcmin
Detector array	6 x 6
Absorber size	800 µm
Effective area	160 / 210 cm^2 (at 1 / 6 keV)

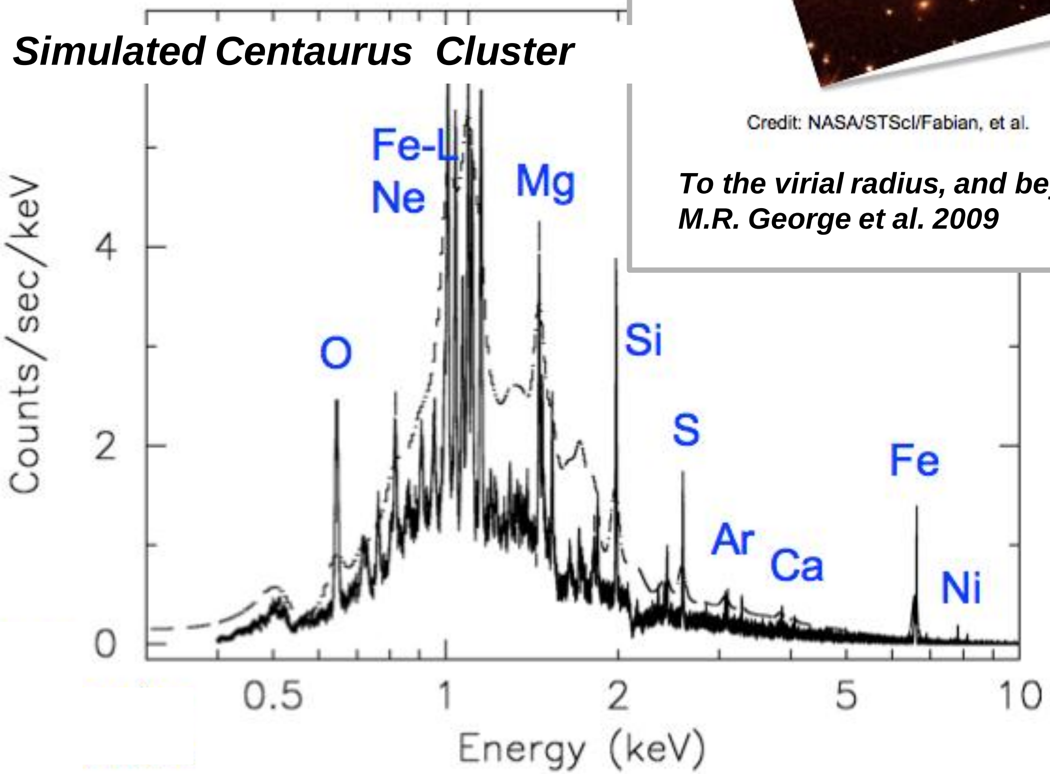
Clusters of Galaxies

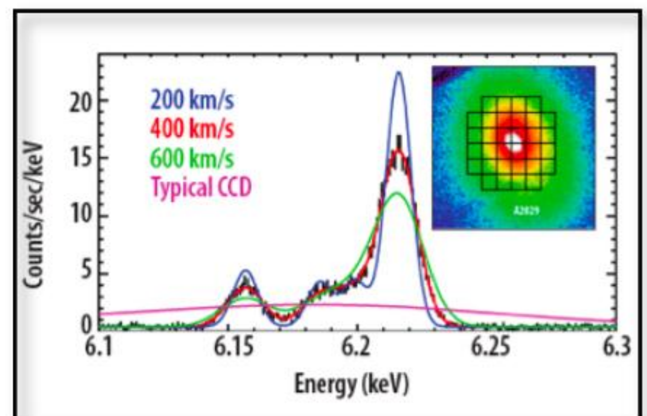
Dynamics
(Turbulence, Collisions)
Non-thermal Emission
Cluster Outskirts
(Site of Structure Formation)
Temperature Map
Heavy Metal Distribution



To the virial radius, and beyond
M.R. George et al. 2009

Simulated Centaurus Cluster



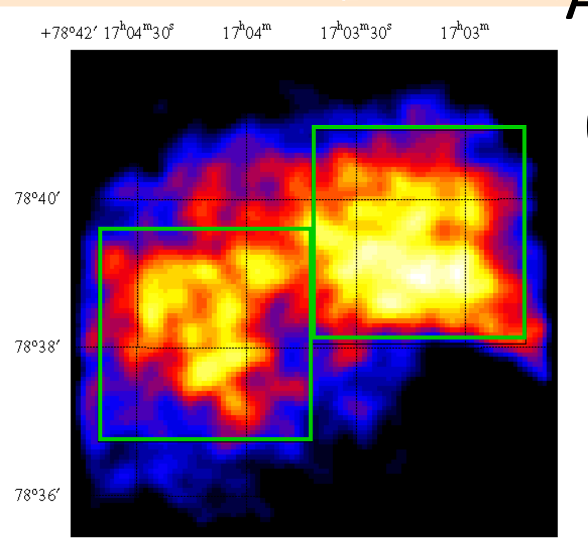


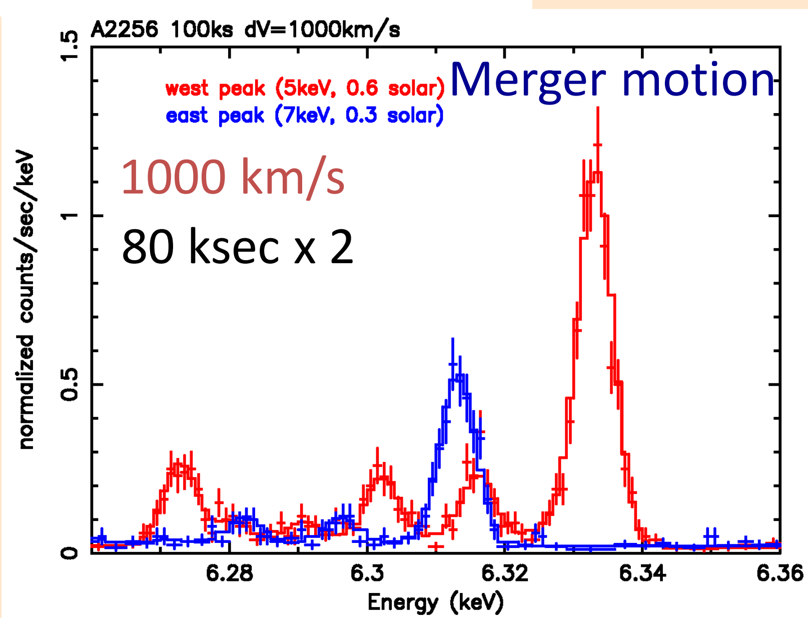
Astro-H will detect bulk velocity flow as small as 300 km/s in the brightest 30 clusters with T > 60 x 10^6 K (kT > 5 keV.)

Merging Clusters

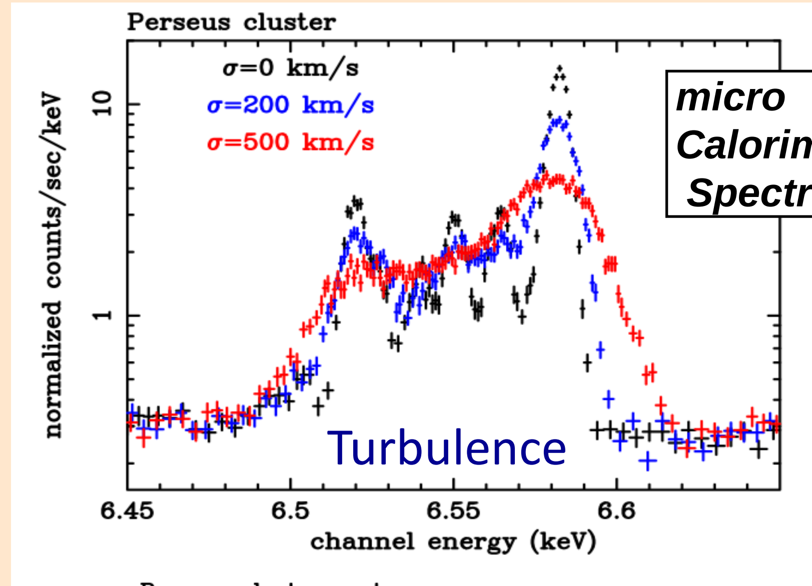
A2256

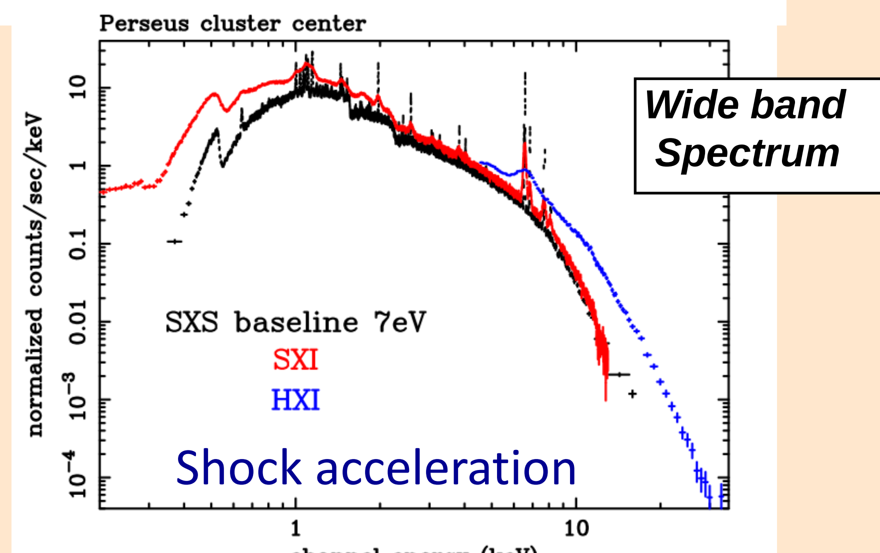
(z = 0.058)





Perseus cluster (r < 2′, 100 ks)





Large-scale structures probed with dark baryon

- The present universe is filled with warm-hot intergalactic medium (WHIM) with $T > 10^6$ K, tracing large-scale structures
- WHIM should be enriched with oxygen due to galaxy outflows in the past
- High-resolution X-ray spectroscopy can detect WHIM, which carries more than half of the baryons
- Very wide field (~ degree) needs to be covered

Cosmic structure

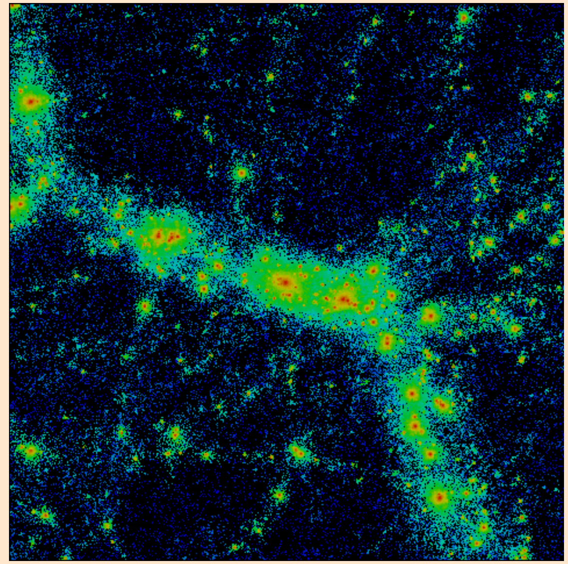
<u>WHIM</u> (10^5-10^7 K) traces the cosmic large-scale structure
= "Missing baryon"

Typical matter density:
$\delta (=n/\langle n_B \rangle) = 10 - 100$

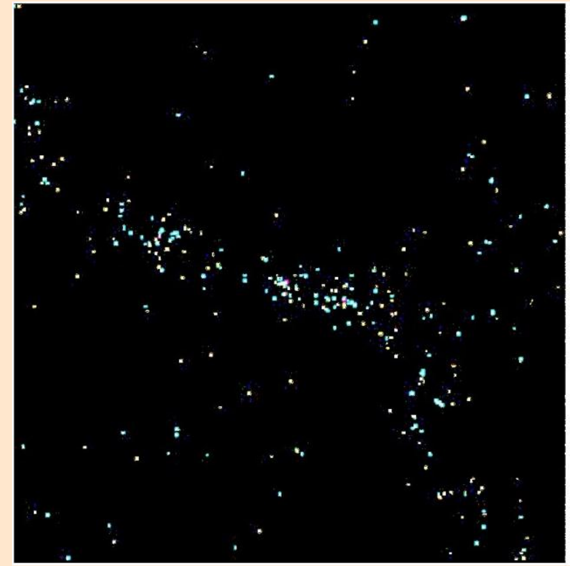
Yoshikawa et al. 2001, ApJ, 558, 520

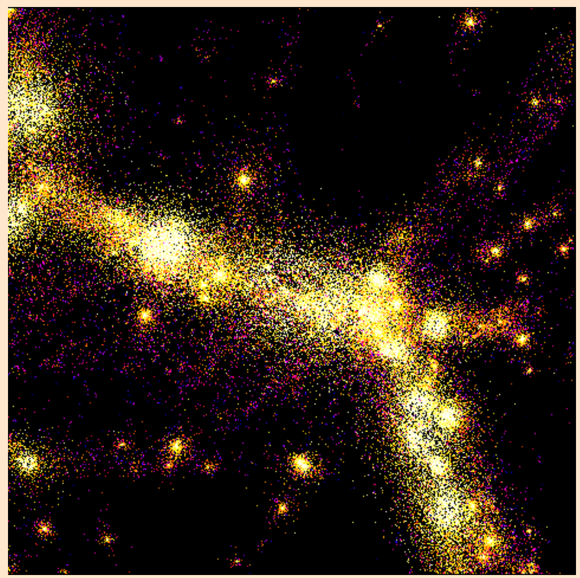
size = 30 h^{-1} Mpc
$\approx$ 5 deg at z=0.1

Dark matter

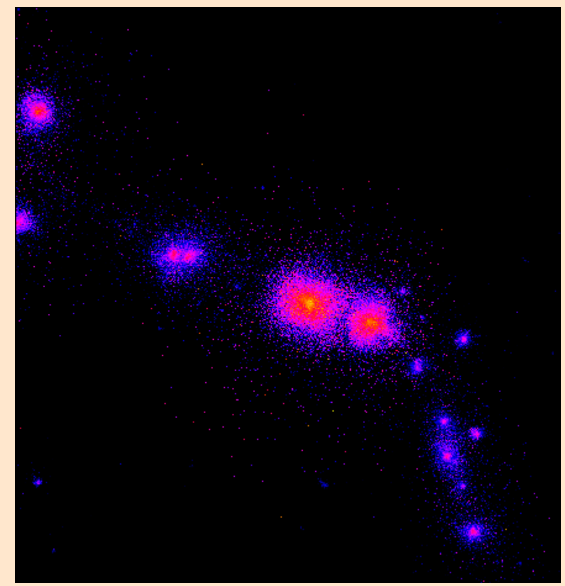


Galaxies (~10^4K)





IGM (10^5-10^7K)

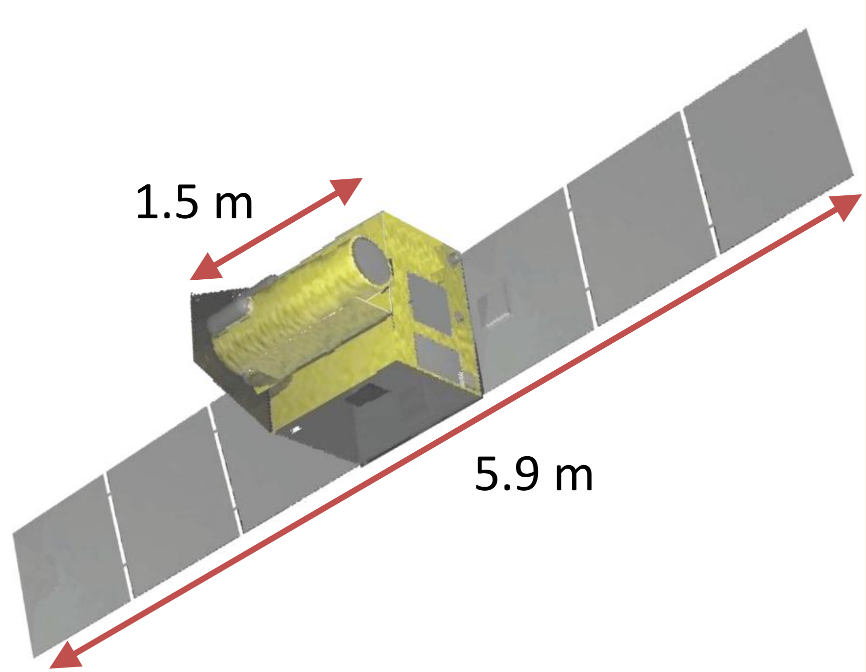


Cluster gas (10^7K)

DIOS: diffuse intergalactic oxygen surveyor

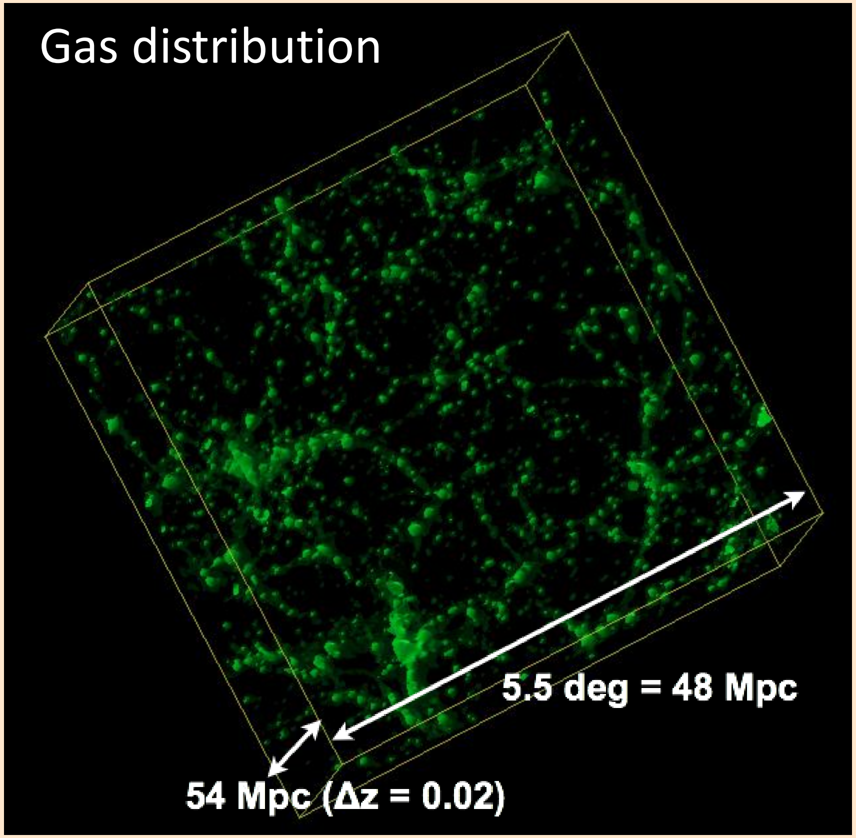
JAXA's small scientific satellite series

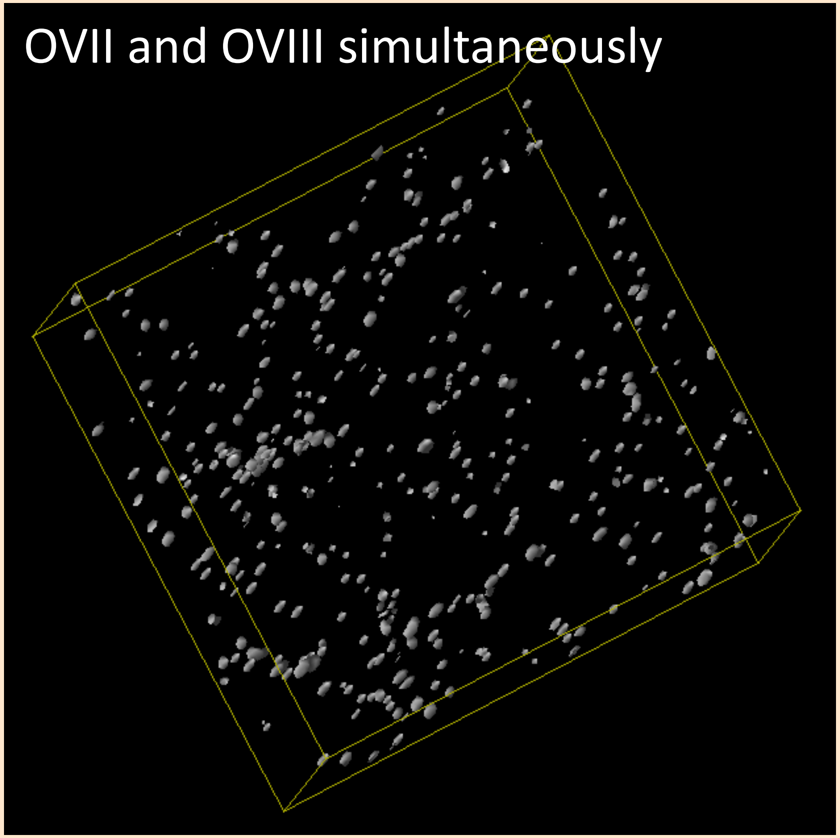
Mass	total	~ 400 kg
	payload	~ 200 kg
Size	launch	1.2 × 1.45 × 1.4 m
	in orbit	5.9 × 1.45 × 1.4 m
Attitude	control	3-axix
	accuracy	≦30 arcsec
Power	total	500 W
	payload	300 W



Orbit: 550 km altitude,
Inclination 30°, period 95 min
Launch: 2016-2017 hoped

Expected 3D map at z = 0.2





DIOS can pick up dense parts of the filaments nicely

Nearly half of the mass with $\rho/\langle\rho\rangle \sim 30$ will be detected

Summary

- High-resolution X-ray spectroscopy is a powerful method to study cosmic evolution in all scales of hierarchy
- New technology such as microcalorimeters (with $\Delta E < 5$ eV) are under development and will be applied to space observations soon
- The process working in the actively evolving universe and hierarchical structure formation will be revealed by Japan-led X-ray missions