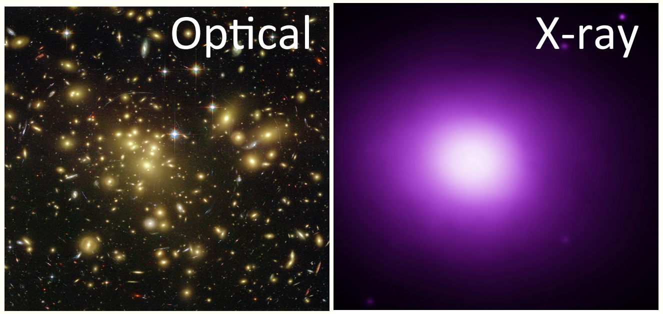
X-ray study of the dark side of the universe

Takaya Ohashi (Tokyo Metropolitan U)

1. X-ray clusters
2. Dark energy
3. Dark matter
4. Dark baryon
5. ASTRO-H

Clusters of galaxies

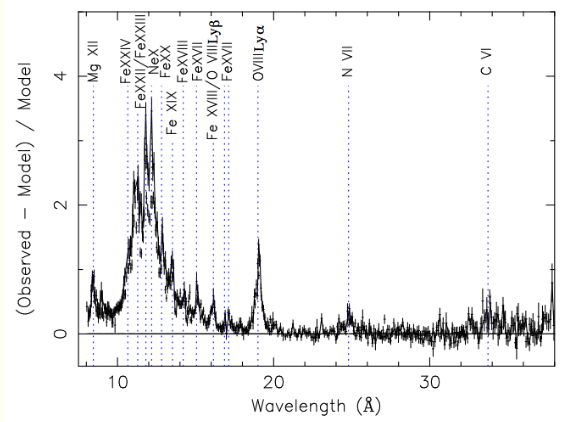
Abell 1689



Credit: Abell 1689, X-ray: NASA/CXC/MIT/ E.-H Peng et al.; Optical: NASA/STScI

- Useful cosmological probe
  - Carrying initial condition in the early universe
  - Structure is relatively simple and common to many systems
- Full of information
  - Gravitational structure (Dark matter distribution)
  - Baryon vs dark matter ratio
  - Power spectrum in large scales
  - Chemical evolution of the universe
  - High energy processes (merger shocks)

X-ray clusters

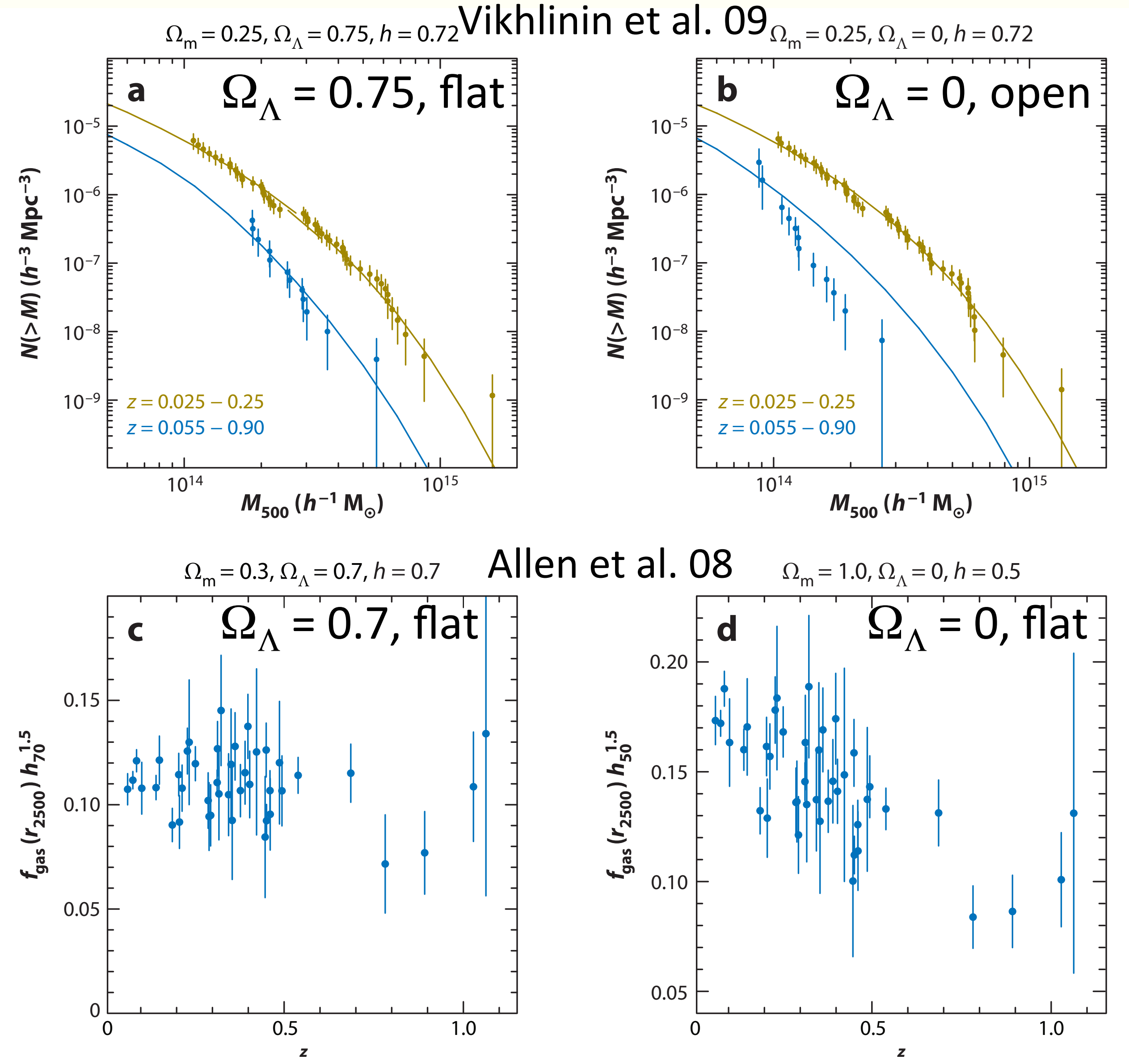


M87 core (Werner+ 06)

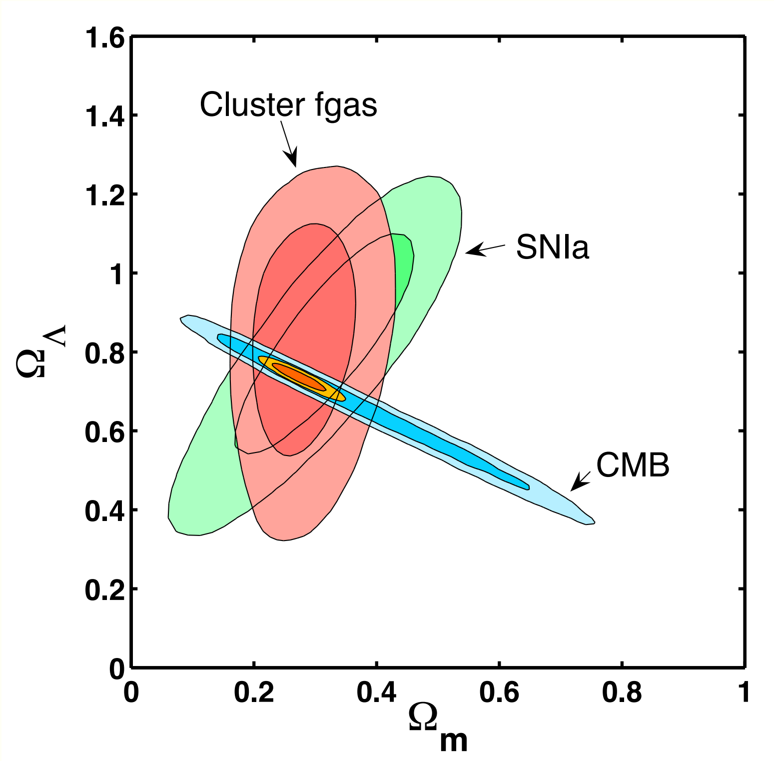
- Brightest objects in the universe
  - Comparable to bright quasars
  - Observable to redshift > 1
- Emission lines from many elements
- Hot gas is optically thin and 3-dimensioanl structure can be recognized
- Spherical symmetry is good approximation
- Temperatures are 2 – 10 keV, and the radiation can be covered with standard X-ray detectors

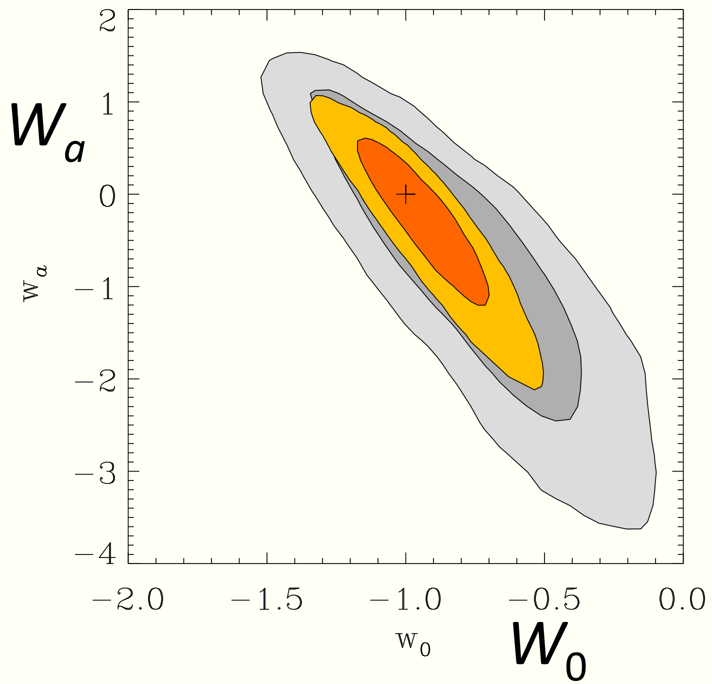
Cluster constraint on dark energy

- S. Allen et al. 2011: a review
- Cluster mass function: distributions of distant and local clusters define growth speed
- Gas mass fraction: First proposed by S. Sasaki (96). Constancy of f_{gas} defines cosmology ($M_{gas} \propto d^{5/2}$, $M_{total} \propto d$)



Cluster constraints





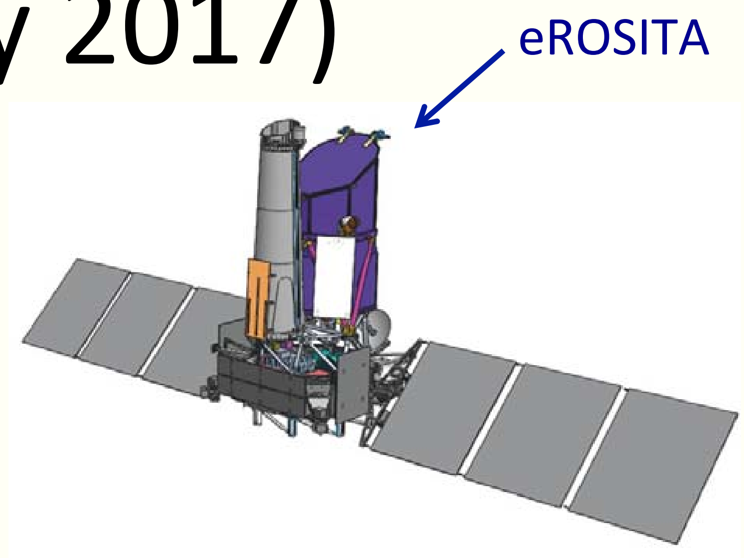
Clusters give $M_{\text{Baryon}}/M_{\text{DM}}$, so Ω_m is constrained using Ω_B from other observations

$$w(a) = w_0 + w_a(1-a)$$

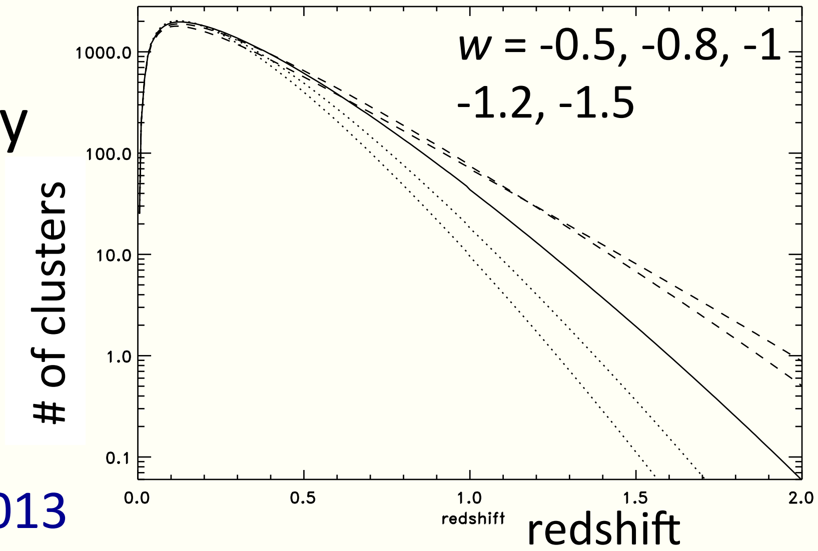
with scale paramter *a*

eROSITA (early 2017)

- All-sky survey of X-ray AGN and clusters, with 30 times higher sensitivity than ROSAT
- 10^5 clusters out to z > 1 (several hundred to z = 1.5), and 3 x 10^6 AGNs will be detected
- Constraining the dark energy is the main purpose
- All sky data will be evenly divided by Germany and Russia



eROSITA on board SRG, to be launched by Russia



Chon, Böhringer 2013

Dark matter

X-rays can study:

- Equilibrium distribution in clusters
- DM motion in colliding clusters
- Search and prospect of warm DM (sterile neutrino)

Distribution of gas and dark matter

- Gas distribution: approximated by b-model
  - Close to isothermal gas sphere

$$n(r) = n_0 \left[1 + \left(\frac{r}{a} \right)^2 \right]^{-\frac{3}{2}\beta}$$

a: core radius
β: beta parameter

- DM distribution: NFW profile
  - Based on numerical simulation, but agrees well with observations

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1 + r/r_s)^2}$$

... Cusp in the center

Navarro, Frenk & White 97

Mass of clusters

- Hydrostatic equilibrium

$$\frac{dp}{dr} = -\frac{GM\rho}{r^2}$$

M: Gravitational mass

- Hot gas approximated as ideal gas

$$p = nkT = \frac{\rho kT}{\mu m_H}$$

proton mass m_H
mean molecular weight
$\mu = 0.6$

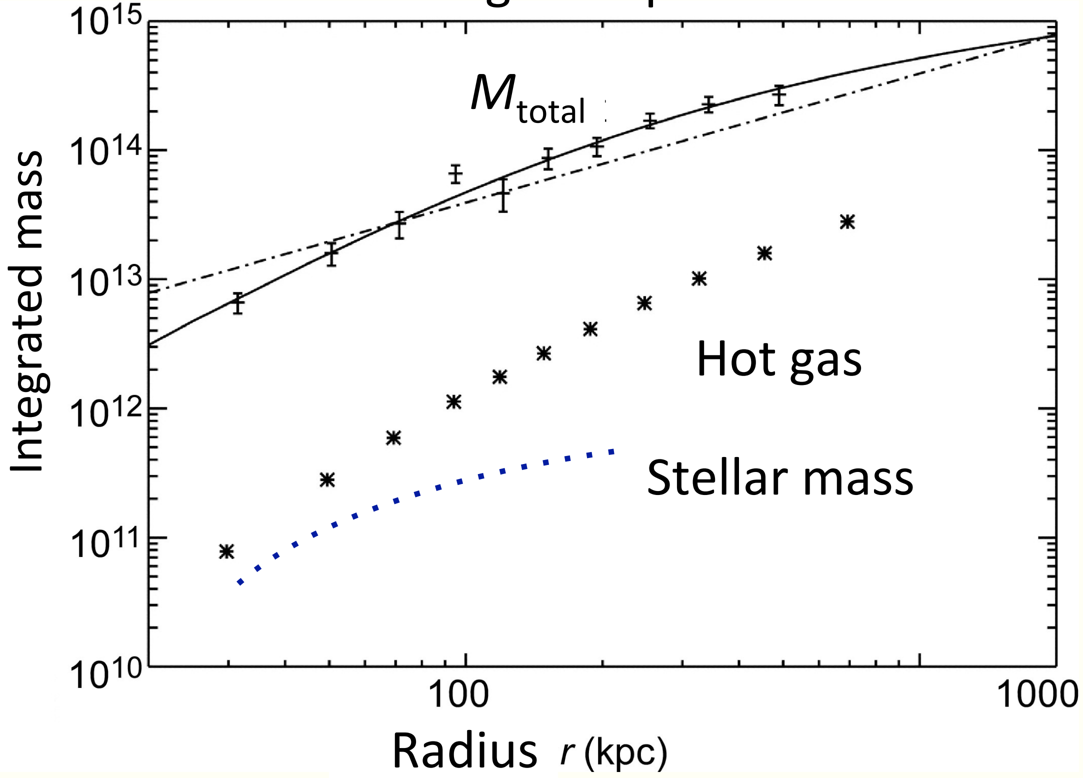
- Gravitational mass

$$M(r) = -\frac{kTr}{\mu m_H G}\left(\frac{d\ln n}{d\ln r} + \frac{d\ln T}{d\ln r}\right)$$

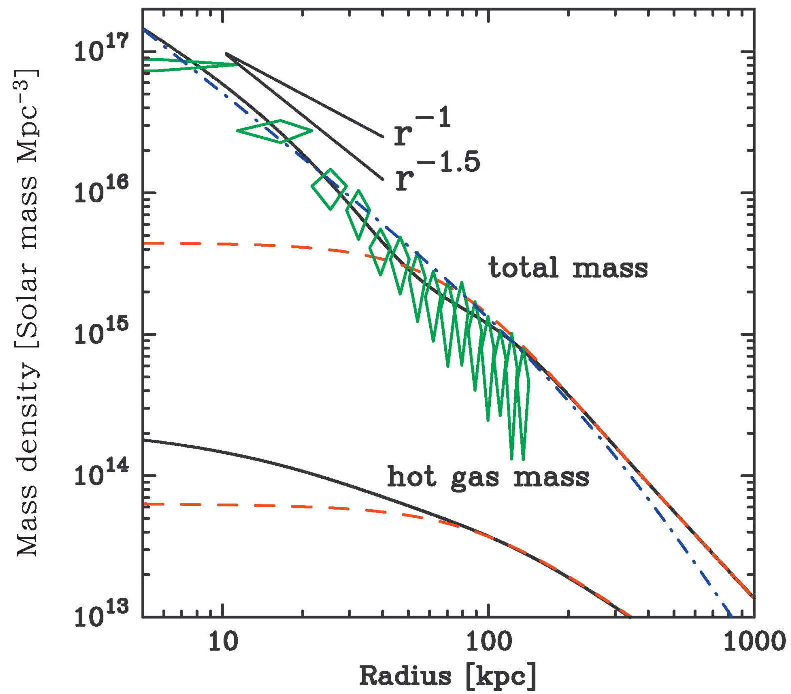
X-ray brightness ⇒ gas mass, Optical brightness ⇒ stellar mass

Mass distribution from X-ray data

Integrated profile



A1060 Differential profile



Gravitational mass is ~ 10 times larger than the hot gas mass

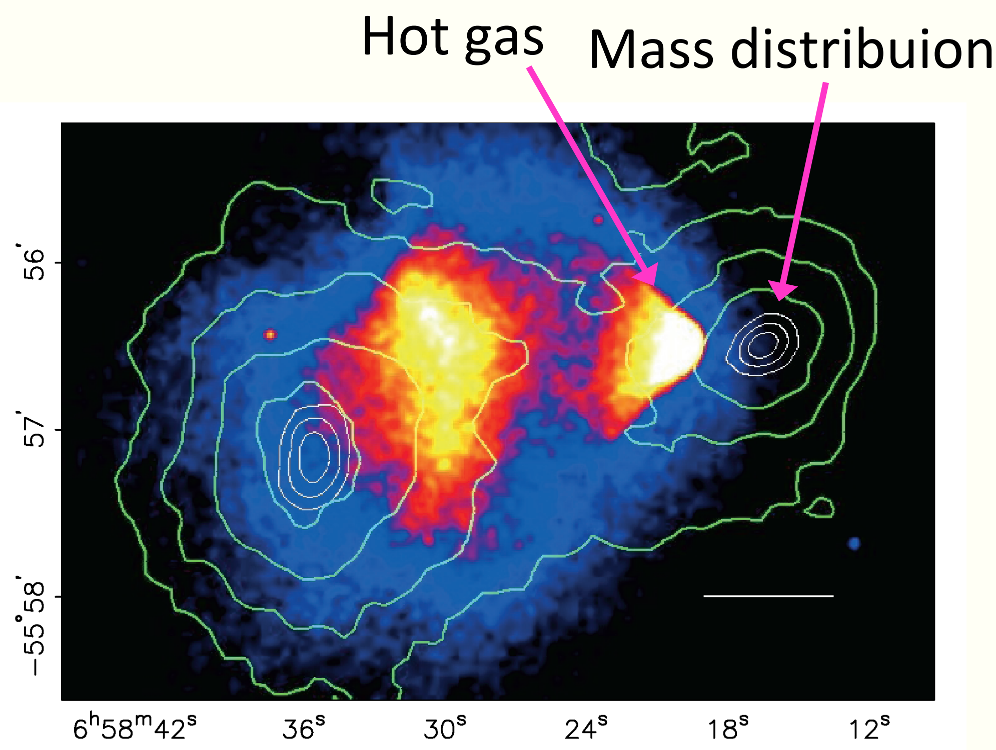
DM distribution is estimated iteratively from the gas profile.

Near the core, gravitational mass shows a cusp-like structure

Hayakawa et al. 2006

Dark matter behavior in a cluster collision

- 1E0657-56 (cluster at z=0.3) :
  Bow shock is clearly seen
- Sub-cluster passes with ~ 3 times the sound velocity
- Weak-lens data shows DM concentrations are offset from the hot gas locations
- DM passes through the collision (no pressure)
  $\sigma/m < 1\ \mathrm{cm}^2/\mathrm{g}$



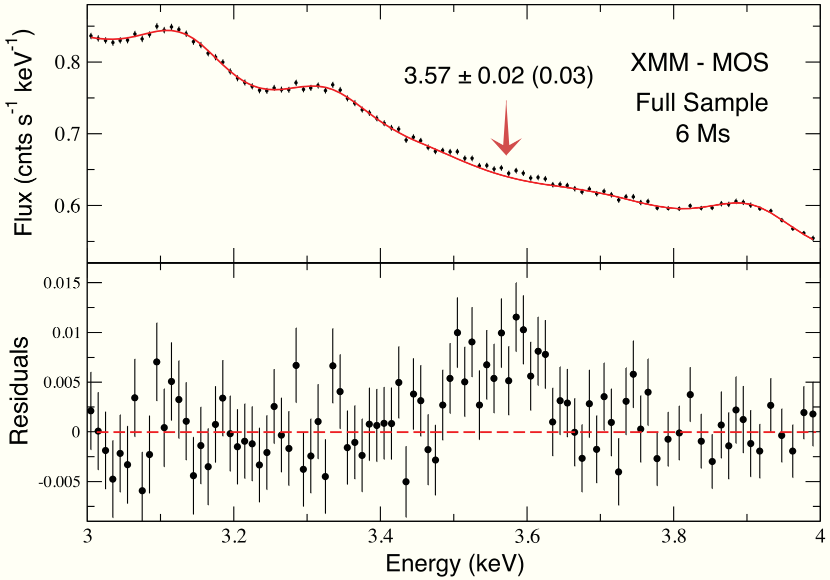
⇨ Evidence of the DM existence

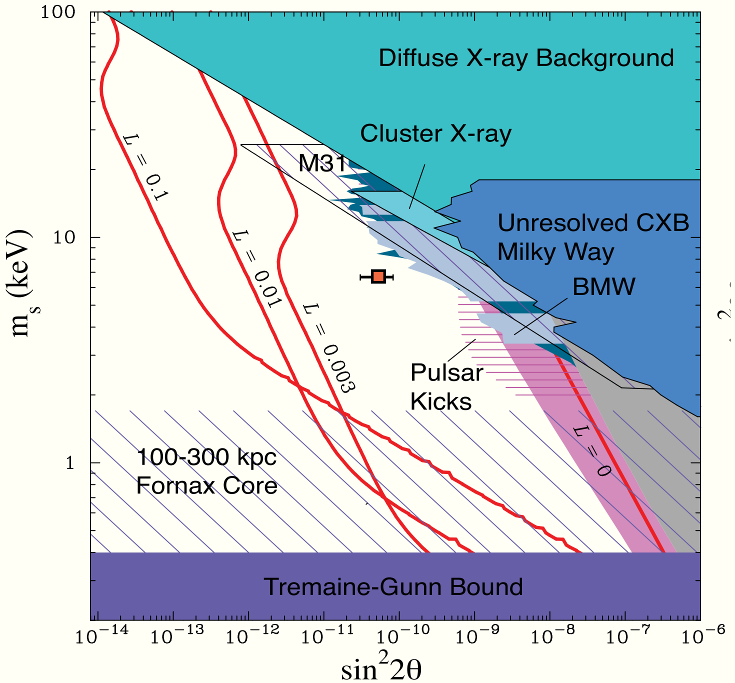
Markevitch et al. 2002, 2004
Clowe et al. 2006

Reports of unidentified emission lines

- Bulbul et al. 2014: Stacked 73 cluster data with XMM-Newton, and 3.5 keV line is found at > 3σ significance
  EW ~ 1 eV: very weak
- Boyarsky et al. 2014: M31 data of XMM-Newton show 3.5 keV line
- Tamura et al. 2015: Suzaku data of Perseus cluster (> 500 ks) show no line at 3.5 keV
- If sterile neutrino is the origin, line width is 35 eV: wider than thermal lines

$$\frac{GM}{r} \approx \frac{1}{2} v^2$$



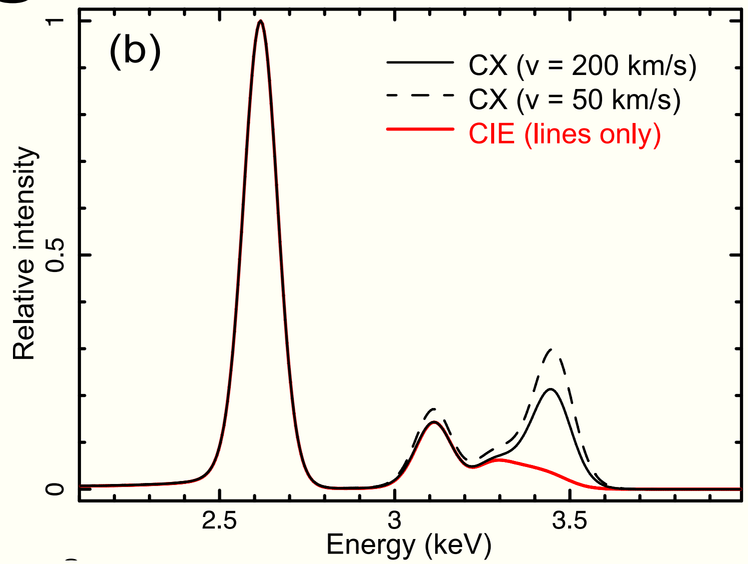


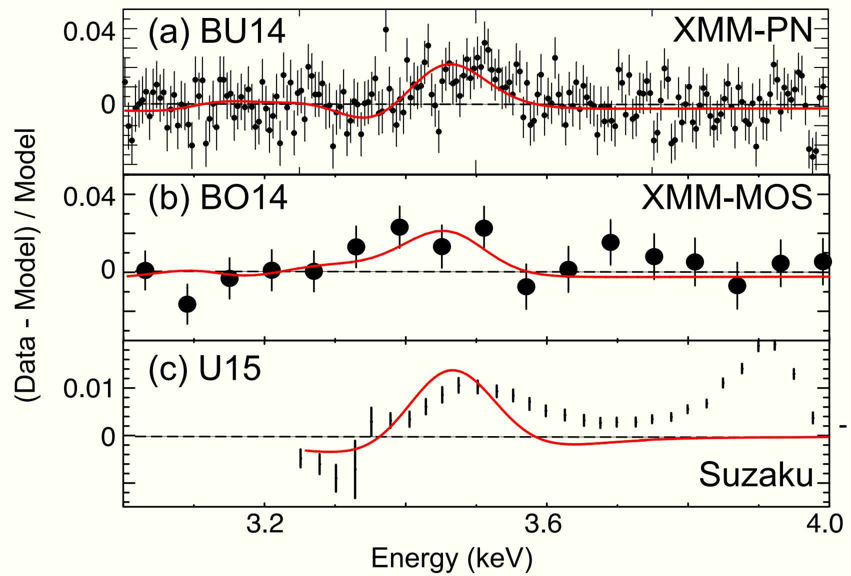
Charge exchange line?

- Gu et al. 2015, in press, arXiv: 1511.06557
- Interaction of hot and cold gasses produce charge exchange lines:

  $S^{16+} + H \rightarrow S^{15+} + H^{+}$

- Capture probability is maximum at *n* = 9-10, producing 3.5 keV line
- Interaction volume of 3 kpc square times 0.1 kpc depth can explain the line intensity
- Detection of other CX lines with ASTRO-H will confirm this scenario





CX line can fit the data from the Perseus cluster

Search for decay lines from sterile neutrinos

- Intensity of the line:

$$\Gamma \simeq 1.4 \times 10^{-32} \mathrm{s}^{-1} \left(\frac{\sin^2 2\theta}{10^{-10}}\right)\left(\frac{m_{\rm dm}}{\rm keV}\right)^5$$

$$\begin{aligned} \mathcal{N}_\gamma &= \frac{\Sigma_{\rm dm}}{4\pi(1+z)^3} \frac{\Gamma}{m_{\rm dm}} \\ &\simeq 9.3 \times 10^{-5} \mathrm{cm}^{-2}\, \mathrm{sr}^{-1}\, \mathrm{s}^{-1} \frac{1}{(1+z)^3} \left(\frac{\Sigma_{\rm dm}}{10^3 M_\odot \mathrm{pc}^{-2}}\right)\left(\frac{\Gamma}{10^{-32}\ \mathrm{s}^{-1}}\right)\left(\frac{m_{\rm dm}}{\rm keV}\right)^{-1} \end{aligned}$$

- Line energy E

$$E_0 = 0.5\, m_{dm}\, c^2$$

$$E = E_0 / (z+1)$$

- Line width ΔE

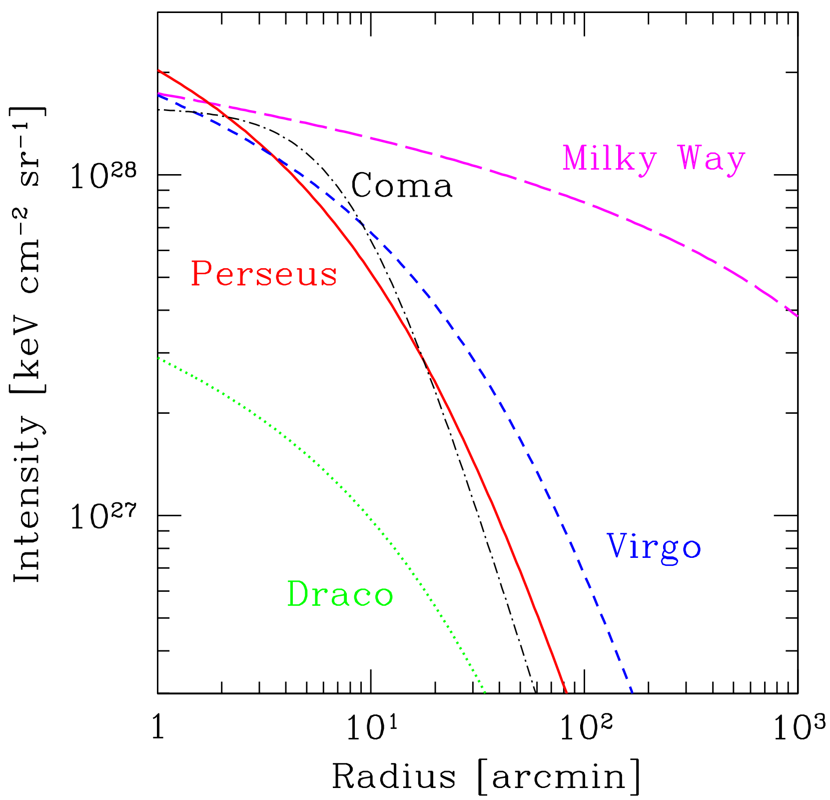
$$\Delta E_0 = 7.9\,\mathrm{eV}\ \frac{\sigma_{dm}}{1000\ \mathrm{km/s}}\ \frac{E_0/(1+z)}{\mathrm{keV}}$$

$\Delta E = \Delta E_0 * \Delta E_{det}$ (convolution)

Σ_{dm}	mass column density
m_{dm}	mass of DM particle
Γ	decay rate
z	redshift
σ_{dm}	velocity dispersion

Possible sources for DM search

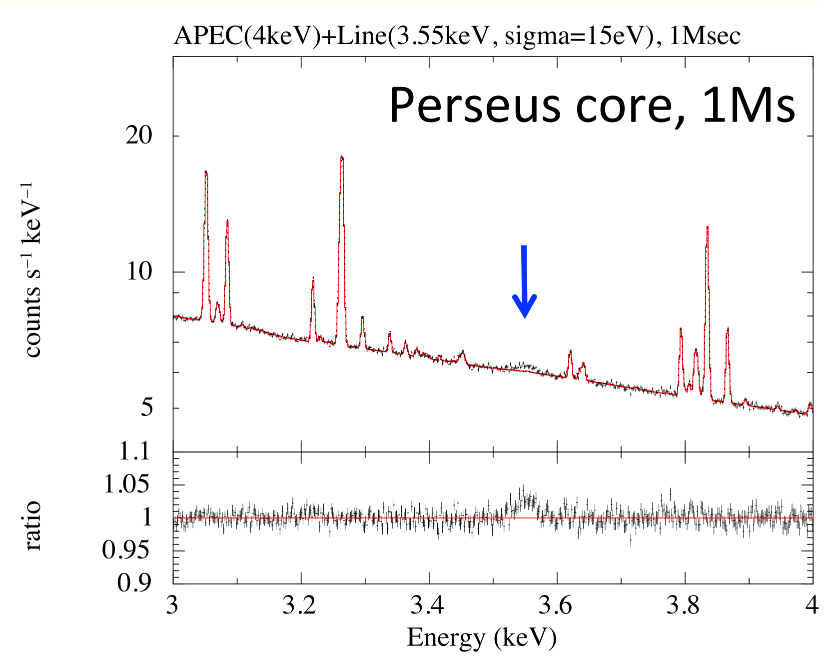
- Tremaine-Gunn limit: E_0 > 0.3 keV for fermionic dark matter (limit on phase-space density)
- Milky Way: signal is strong, but many bright sources and high interstellar absorption limit the sensitivity
- Dwarf galaxies: Low velocity dispersion with low background emission, but the signal is weak
- Clusters of galaxies: Strong decay signal with known mass profile and low absorption column, but the thermal emission is strong

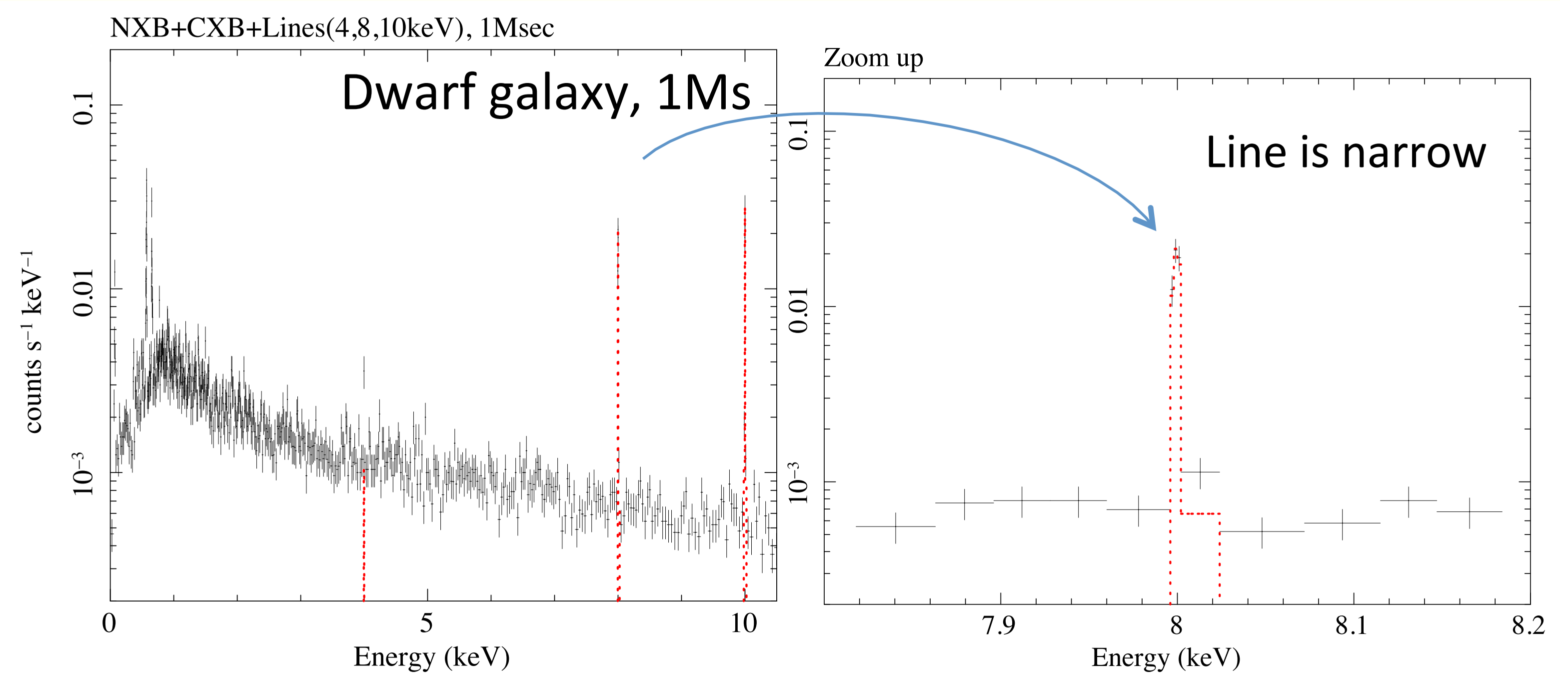


Predicted distribution of dark matter decay line:
X-ray ∝ n^2
DM line ∝ n

Simulated spectra with ASTRO-H

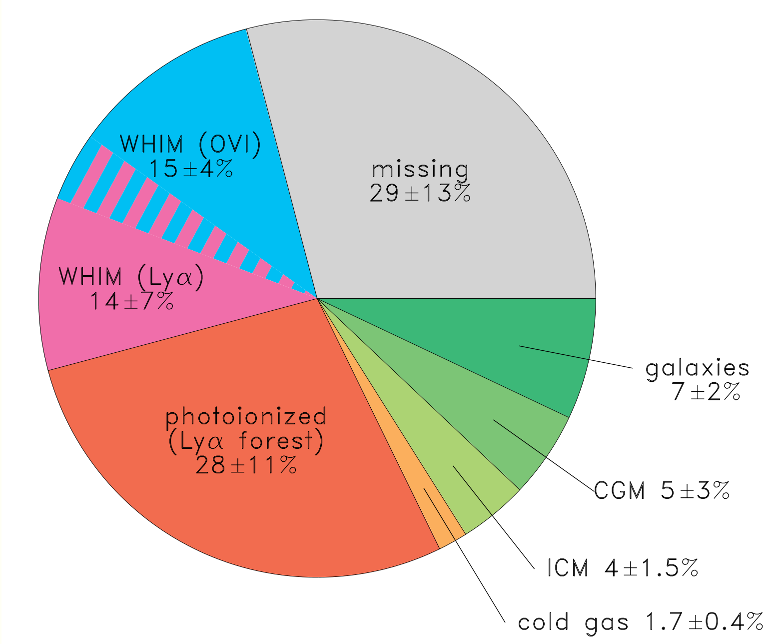
- High spectral resolution (< 7 eV) will allow detection of weak lines
- Because of the small field of view (3 arcmin), long exposure is necessary





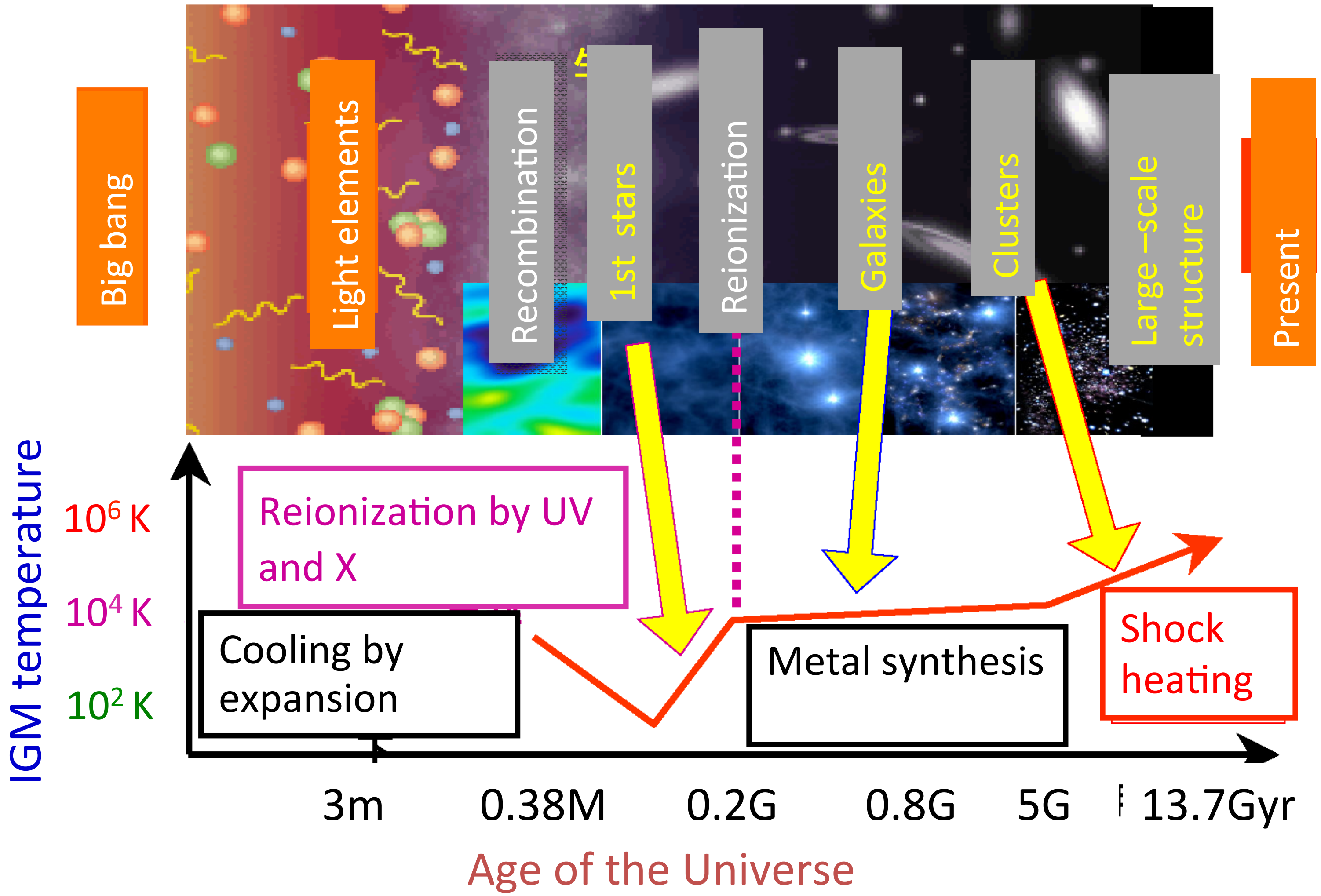
Dark baryon

- Baryons occupy only ~ 5% of the energy density in the local universe
- However, more than half of baryons remain unidentified
- Dark baryons carry important information of the thermal, structural, chemical evolution of the universe
- Baryons are good probe of the dark matter



Baryon census from
UV study
Shull et al. 2012

Thermal history of the universe



WHIM (warm-hot intergalactic medium) will tell us the evolution of the hot-phase material in the universe

Cosmic structure

WHIM (10^5-10^7 K) traces the cosmic large-scale structure

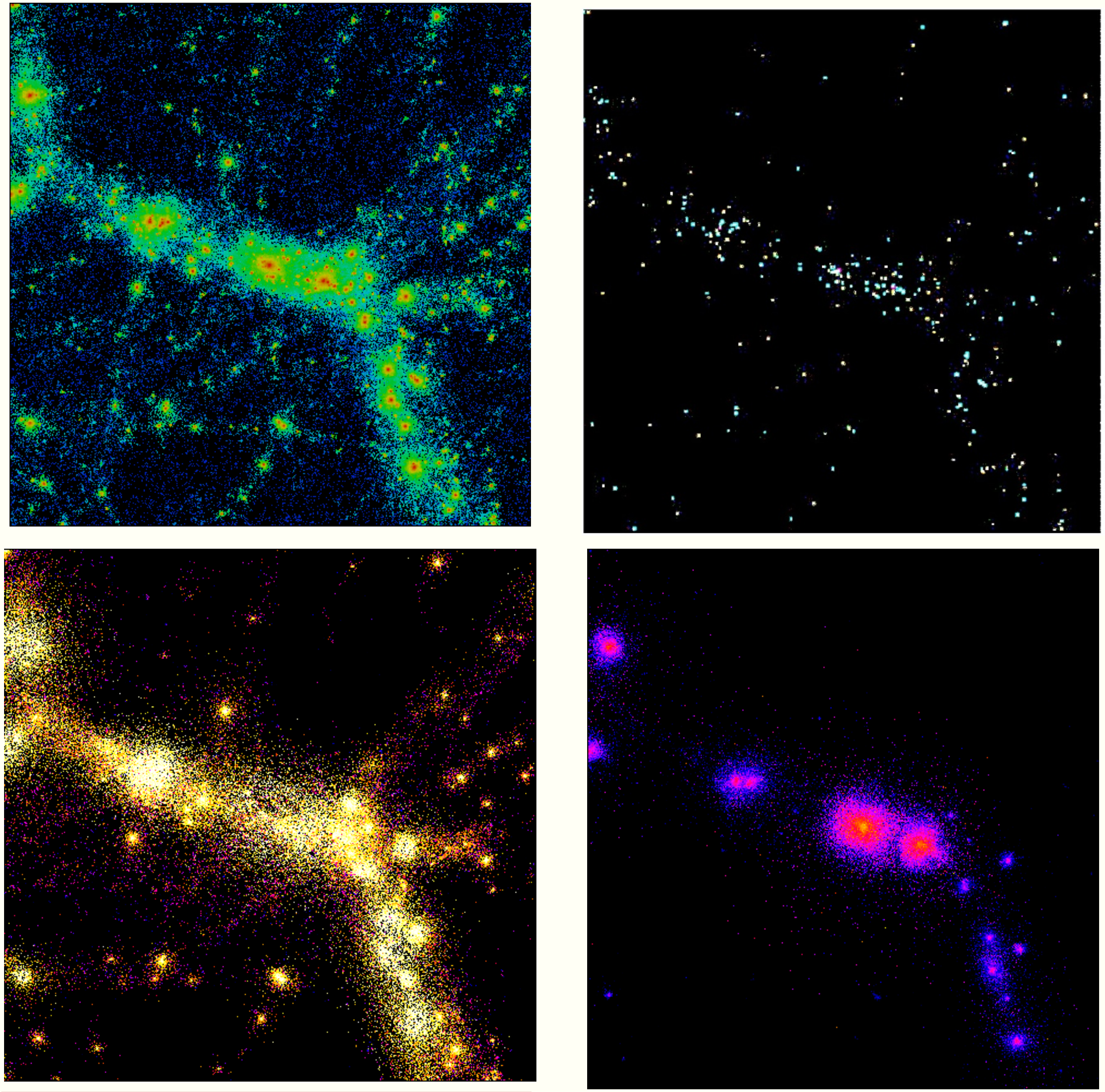
= “Missing baryon”

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

Yoshikawa et al. 2001, ApJ, 558, 520

size = 30 h^{-1} Mpc
≈ 5 deg at z=0.1

Dark matter | Galaxies (~10^4K)

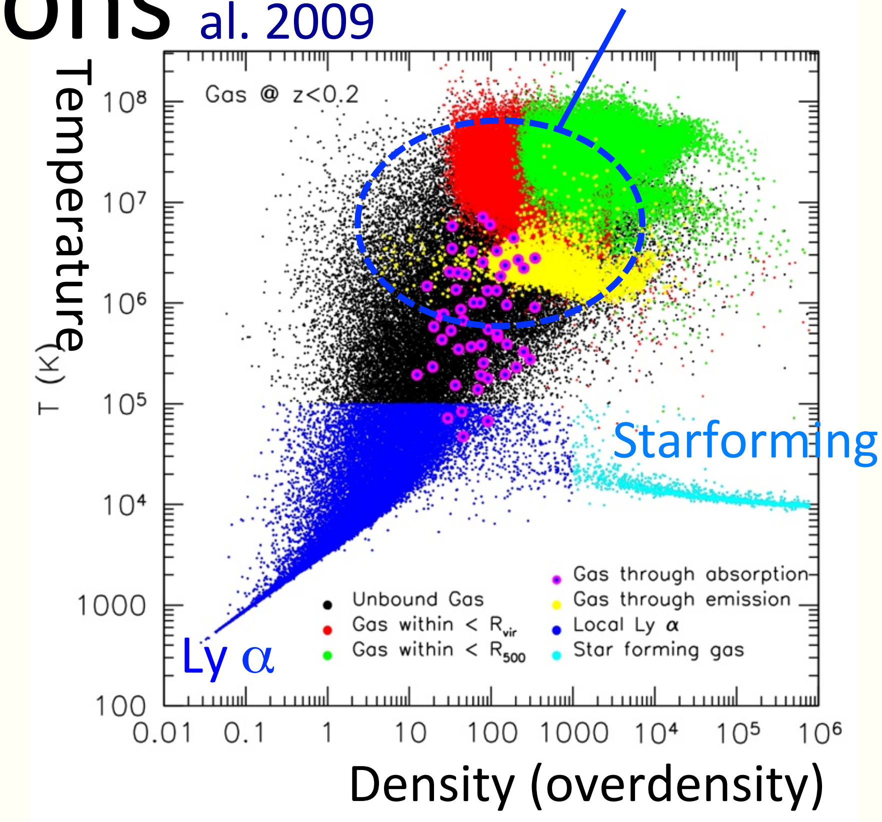


IGM (10^5-10^7K) | Cluster gas (10^7K)

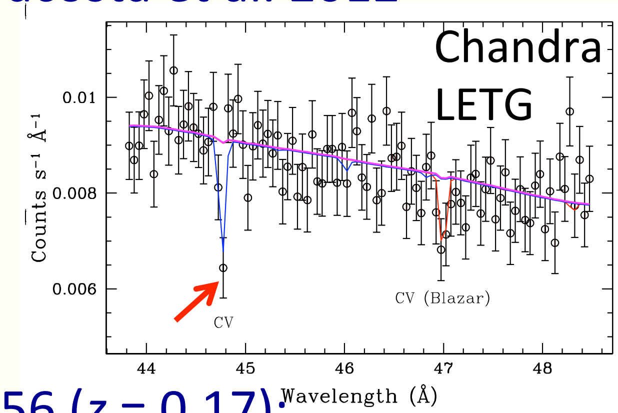
Search for Dark Baryons

- Numerical simulations indicate much of local baryons are in the form of Warm-Hot Intergalactic Medium (WHIM: ~ 10^6 K)
- Absorption lines can detect low-density gas – but, geometry and thermal structures are difficult to estimate
- Emission lines like H-like and He-like triplets are simple, and spatial structure can be measured
- High-resolution spectra can separate from Galactic emission with redshifts

Branchini et al. 2009

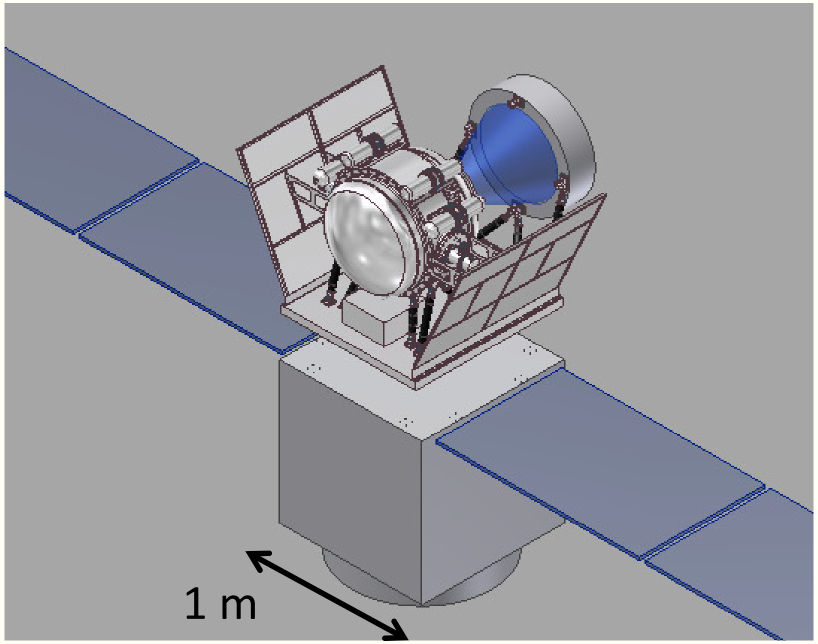


Zappacosta et al. 2012

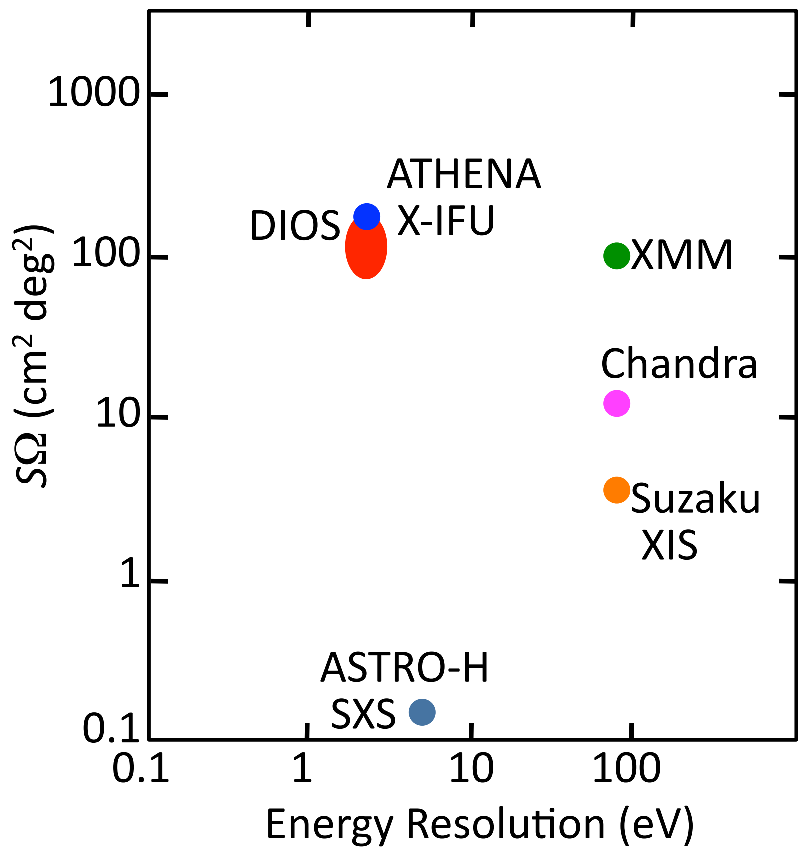


Blazar H2356 (z = 0.17):
C V line at z = 0.112 (4.2σ)

DIOS and its grasp ($S\Omega$)



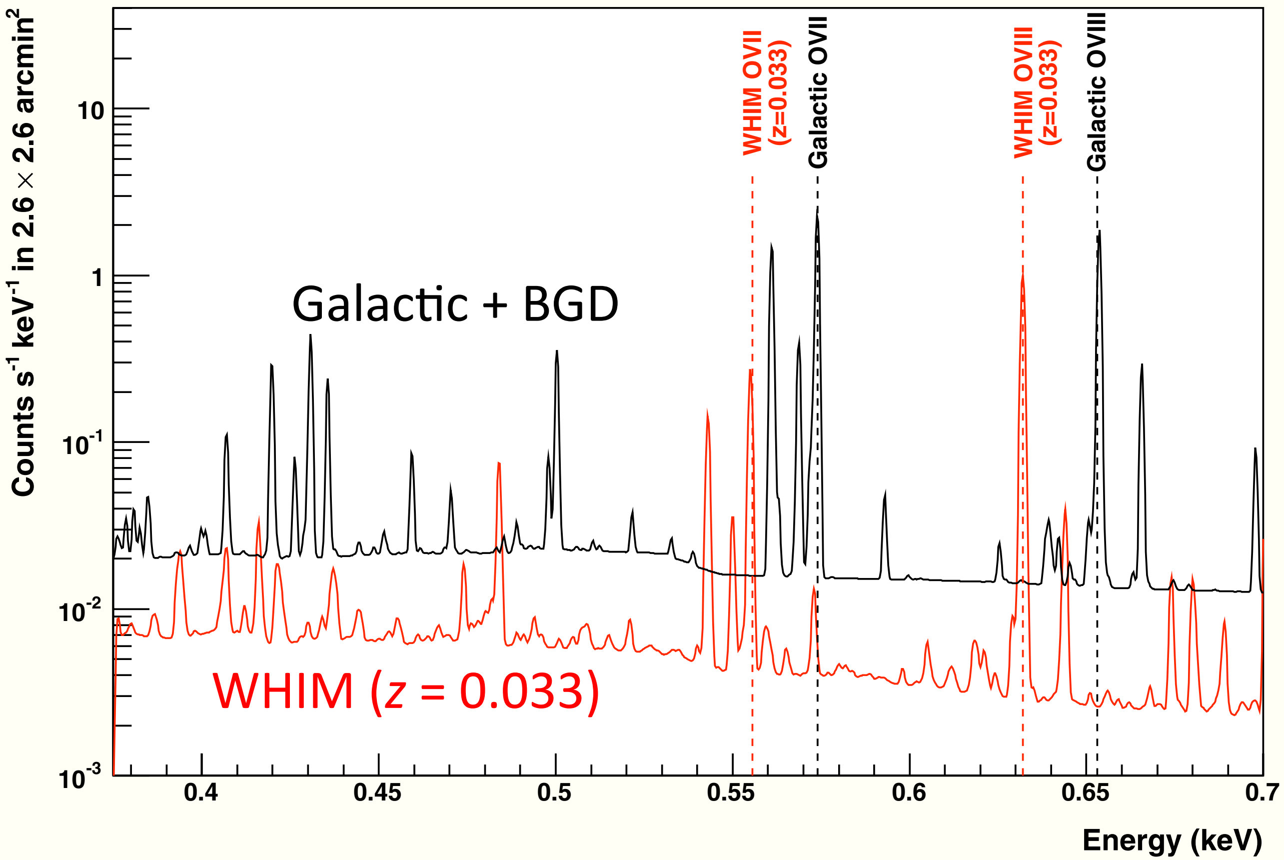
Orbit: 550 km altitude,
Inclination 30°, period 95 min



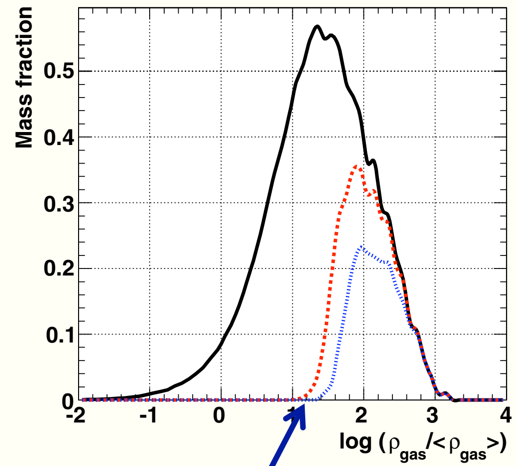
4-reflection telescope and TES calorimeter array
ΔE < 5 eV, Energy range < 2 keV, F.O.V. = 50×50 arcmin^2
Mechanical coolers are same as ASTRO-H

DIOS: Expected spectrum

Takei et al. 2011



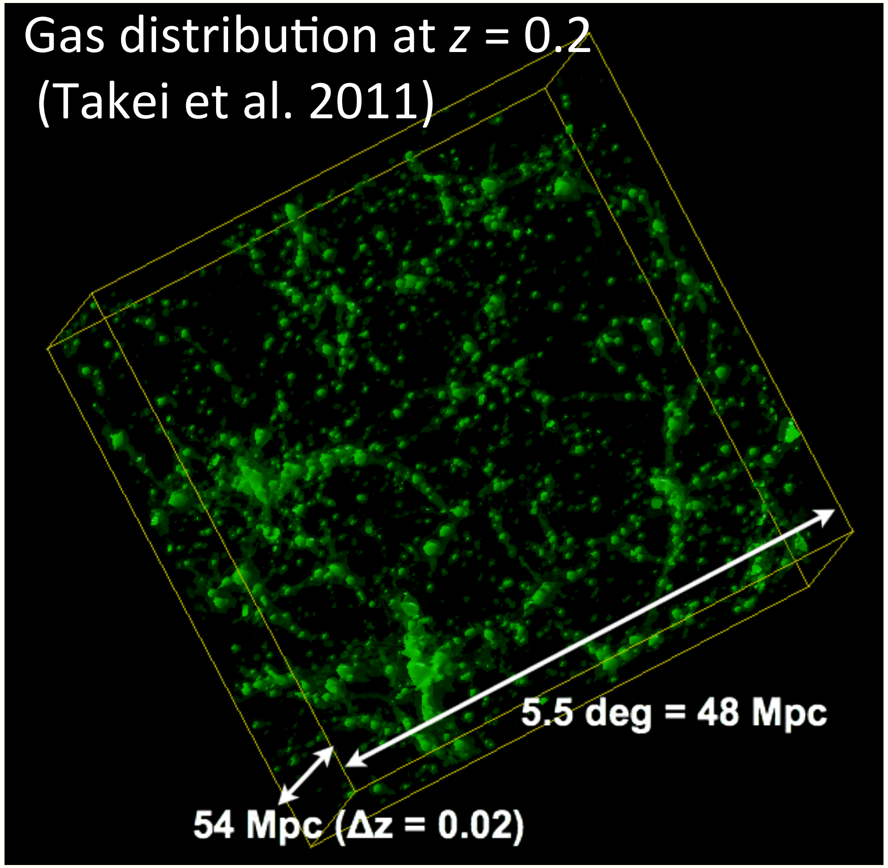
Detectable fraction

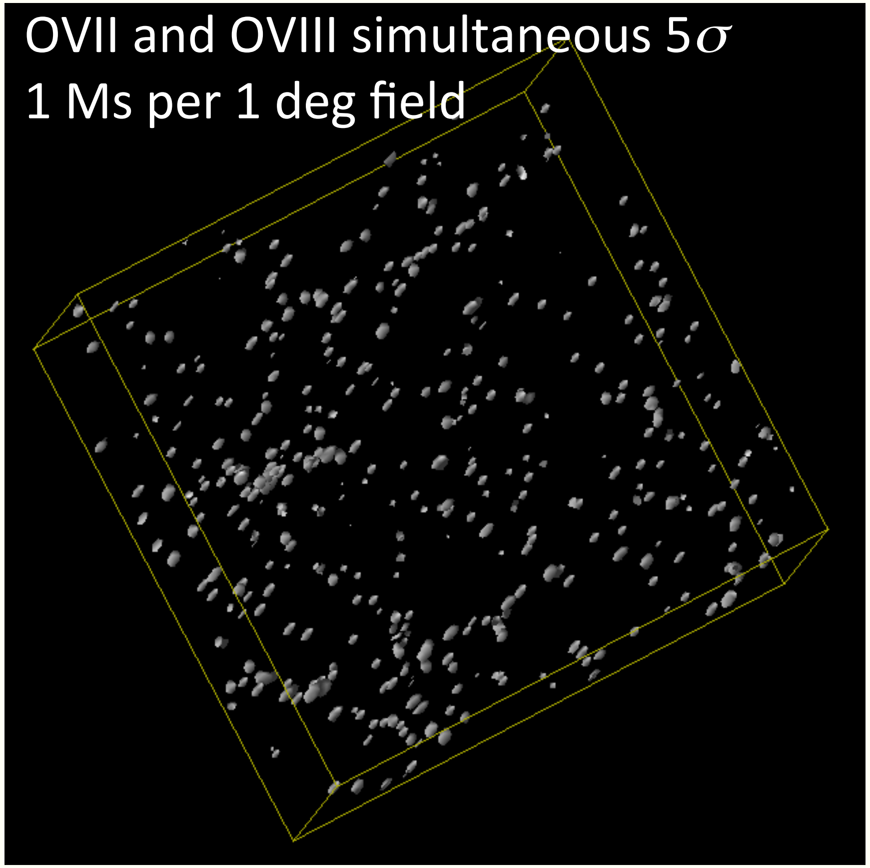


5 Ms (!) with DIOS

- Line-free energy ranges of MW emission give us windows in redshift space for WHIM detection
- 5 deg × 5 deg survey (1 Ms × 30) plus one deep (5 Ms) pointing can be a plan

Expected 3D map at z = 0.2



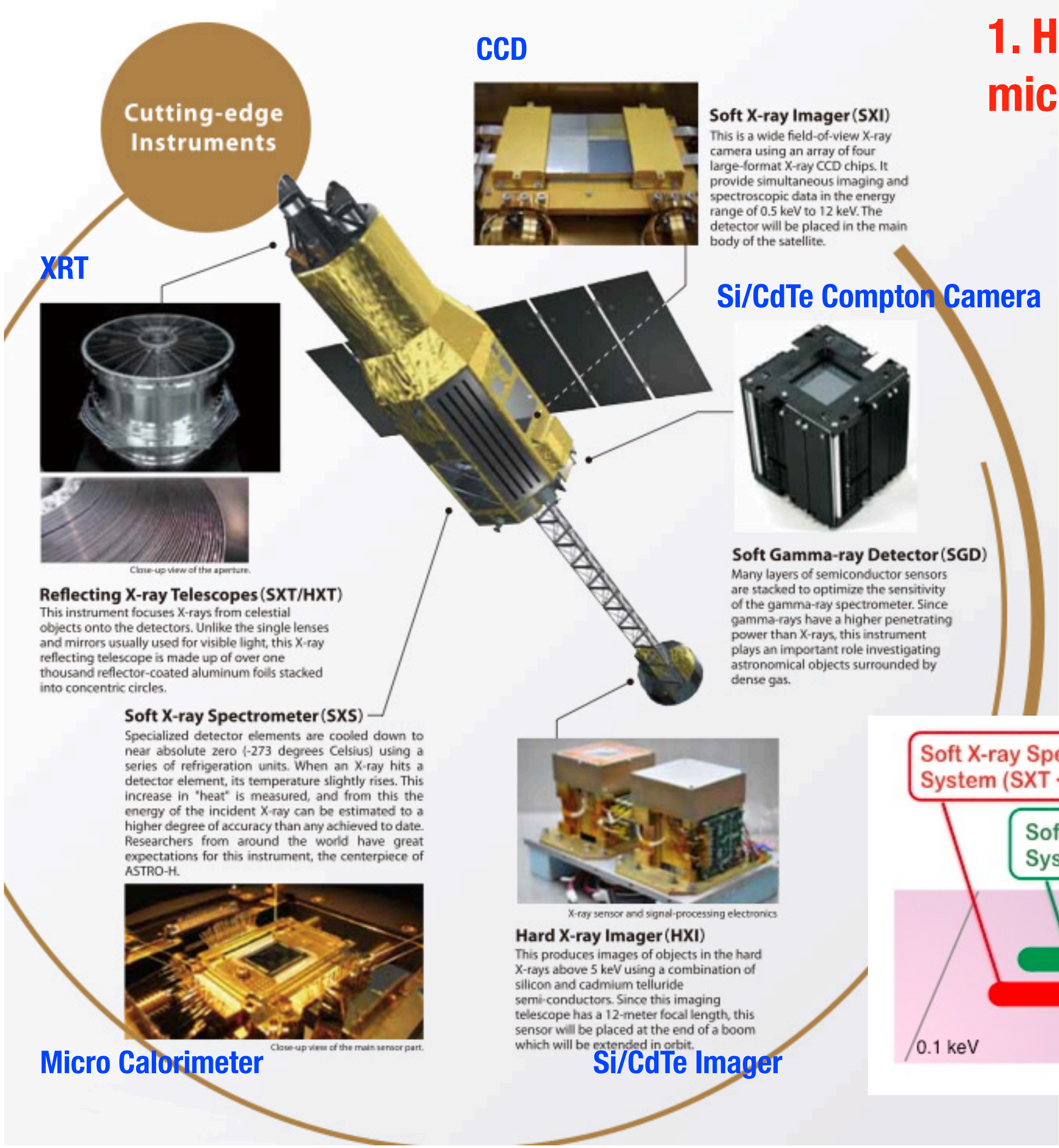


0.5 – 1 Msec pointing per position. About 30 points mapped.
DIOS can pick up filaments and faint galaxy groups.
Overdensity $\rho/<\rho>$ ~ 30 is explored, revealing about 30% of baryons.

ASTRO-H

- Launch date is February 12, 2016
- http://astro-h.isas.jaxa.jp/en/
- Science white papers:
  arXiv:1412.2351 (introduction)

Mission overview

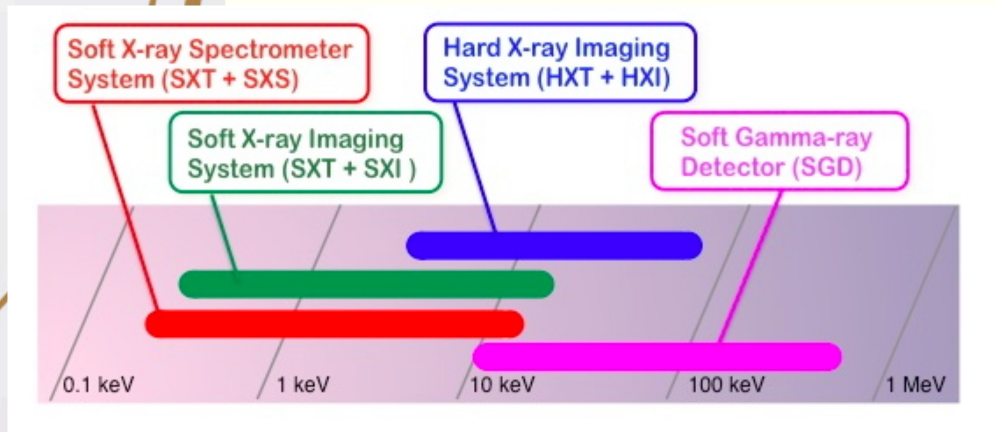


1. High Resolution Spectroscopy by a micro-calorimeter array

ASTRO-H is the first mission to carry out high resolution spectroscopy of extended objects at Fe-K

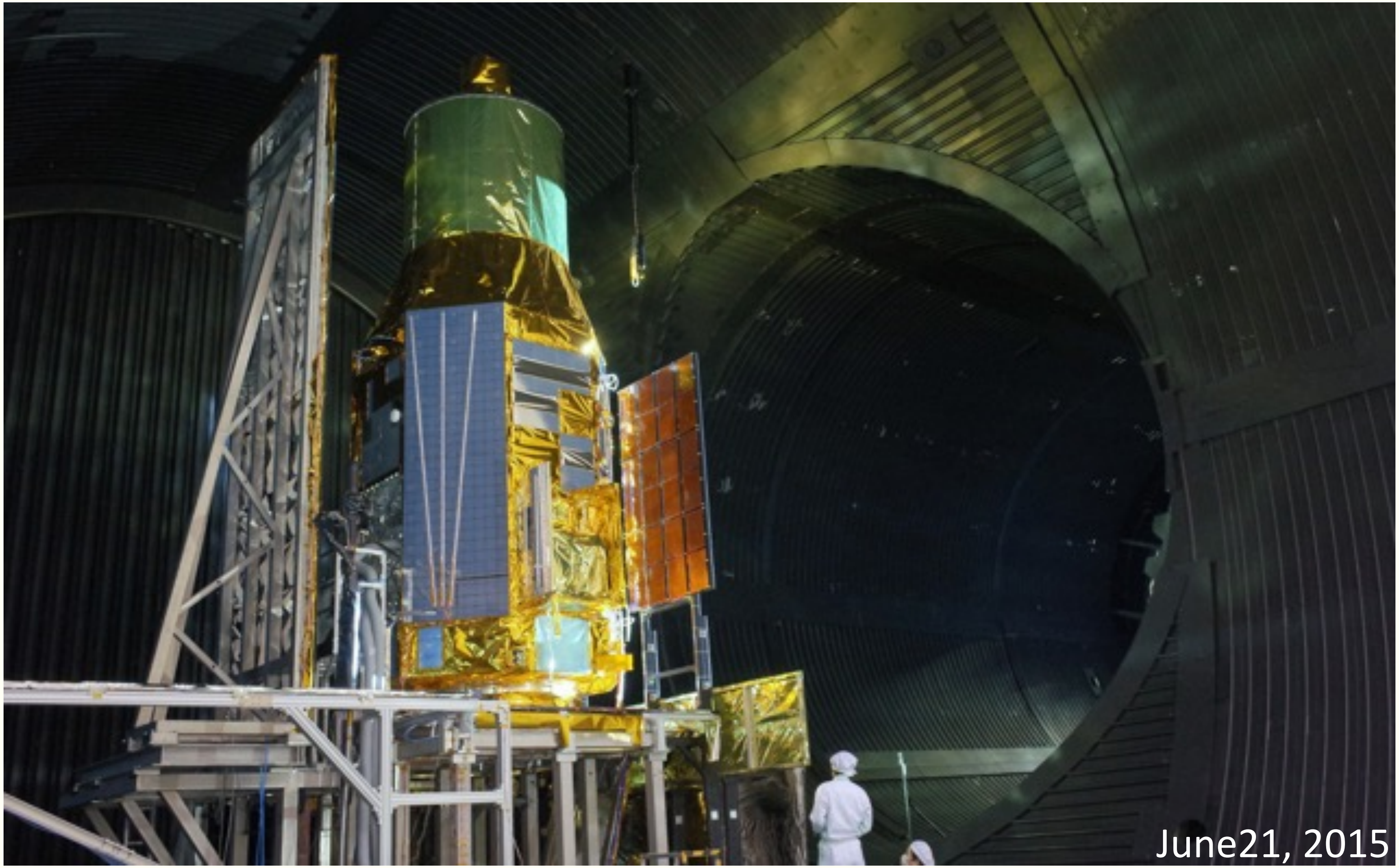
2. Wide Band /High Sensitivity Observation

0.3 keV - 600 keV : Four Instruments including Hard X-ray Focusing optics



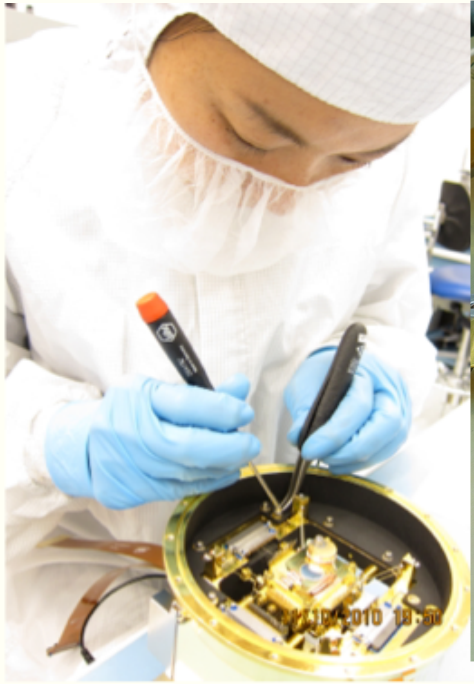
ASTRO-H Team

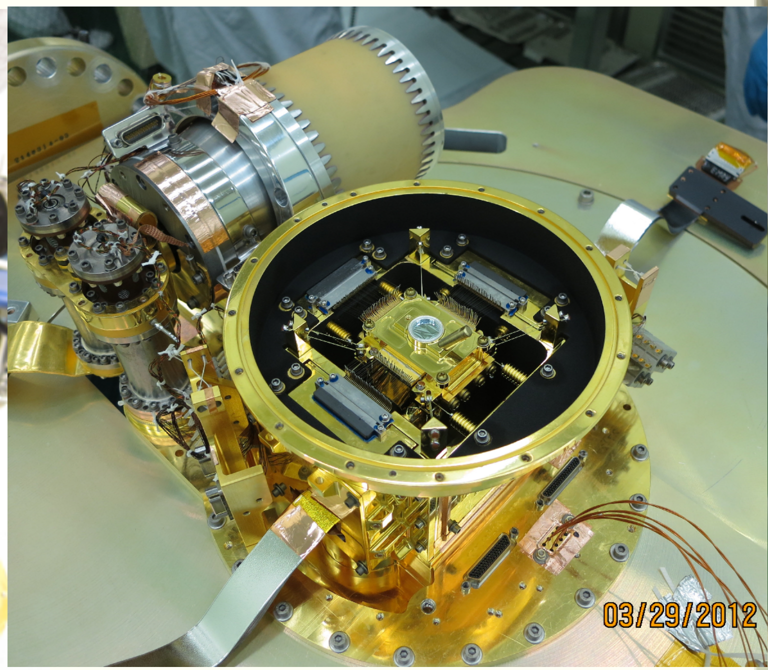
ASTRO-H in thermal vacuum chamber



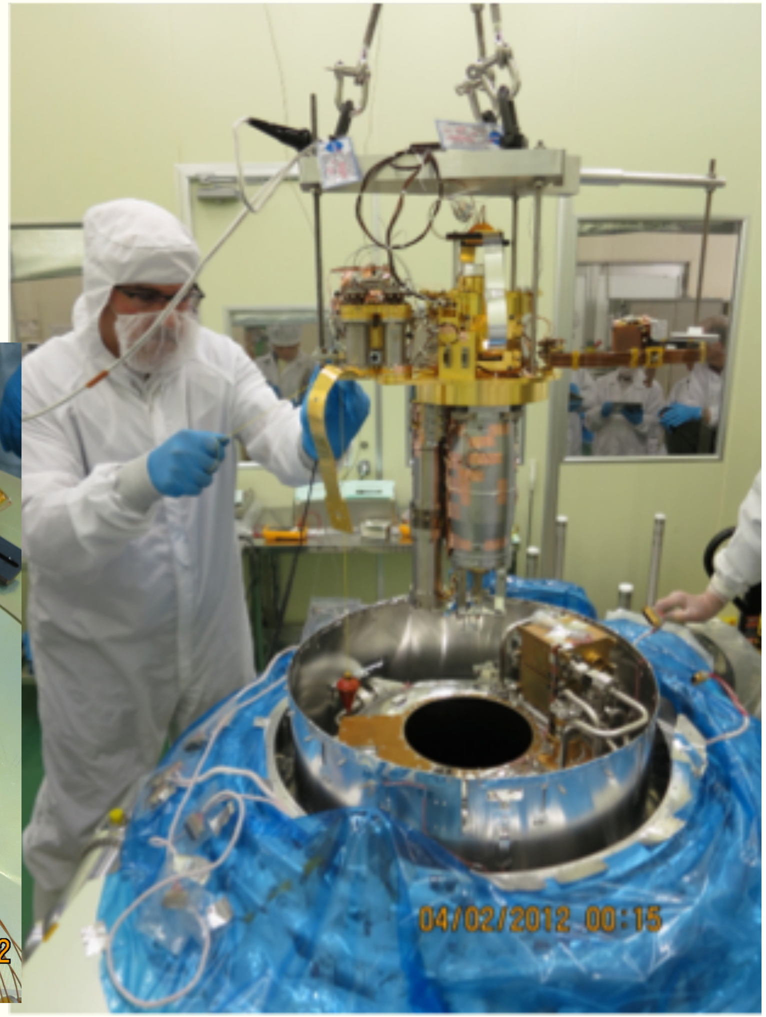
Microcalorimeters and dewar

- X-ray micro-calorimeter spectrometer with energy resolution better than 7 eV (FWHM)
- 6 × 6 array with 3’ × 3’ field of view
- Operated at 50 mK
  - Nominal expected liquid He lifetime 3.3 years





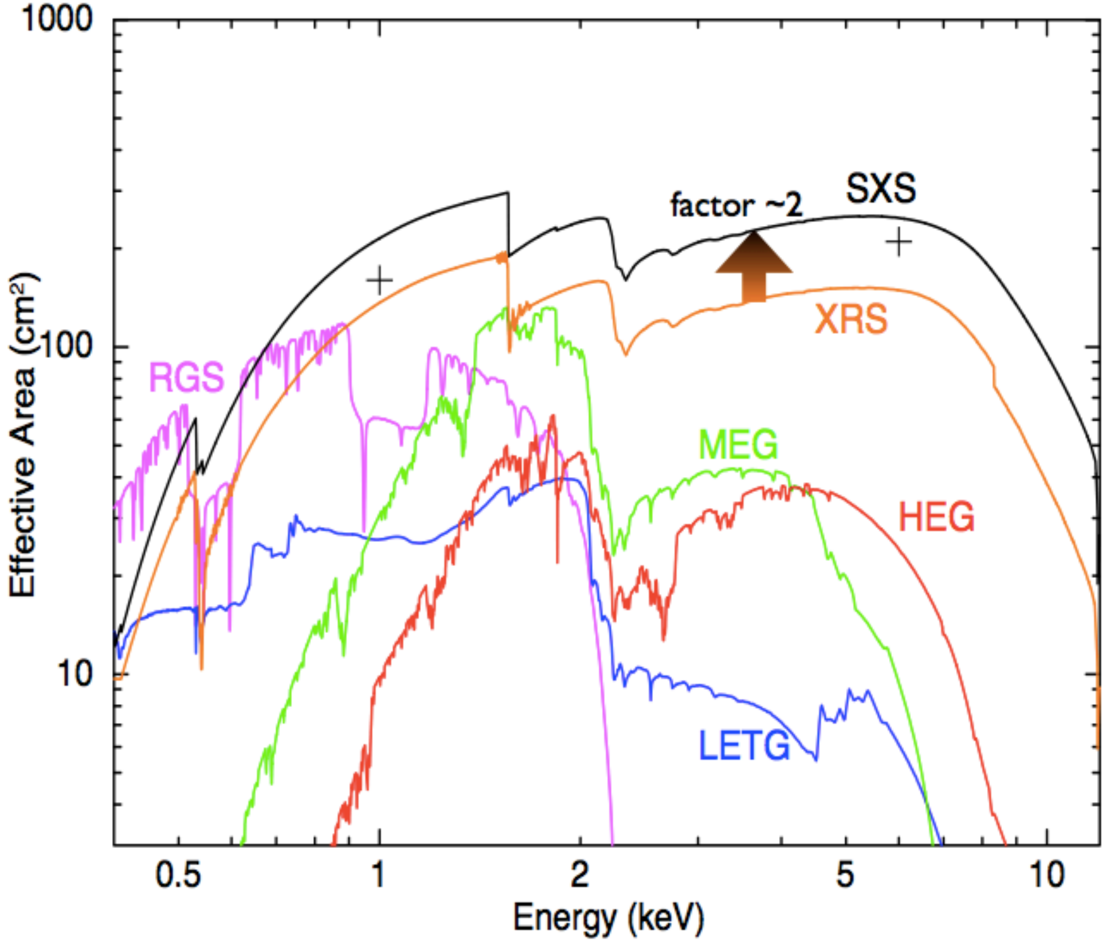
SXS detector assembly



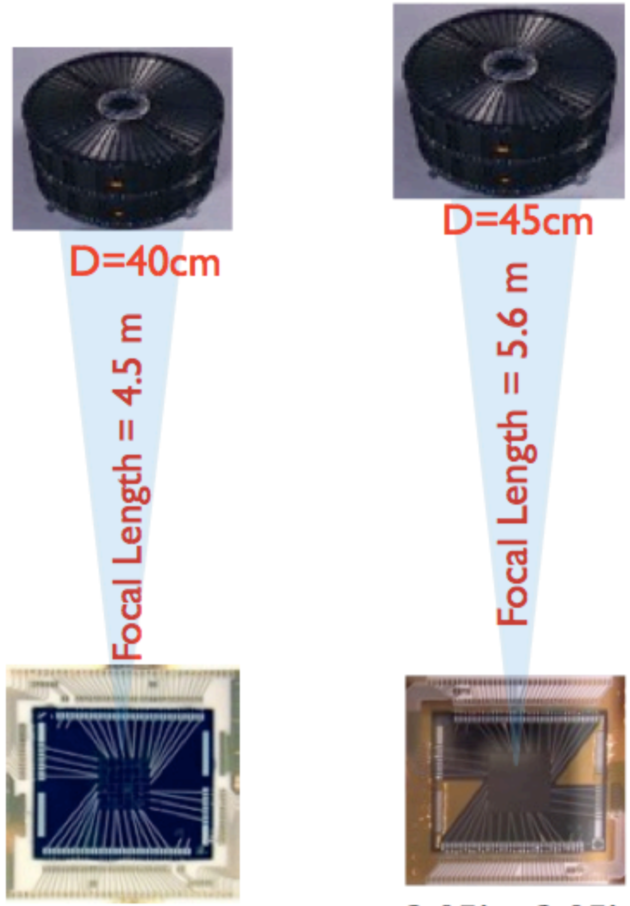
Sumitomo Heavy Industries, Ltd.

SXS dewar

High resolution spectroscopy



Suzaku XRS | ASTRO-H SXS



2.92’ x 2.92’ | 3.05’ x 3.05’

624 μm pixel
6x6 array
31 pixel readout

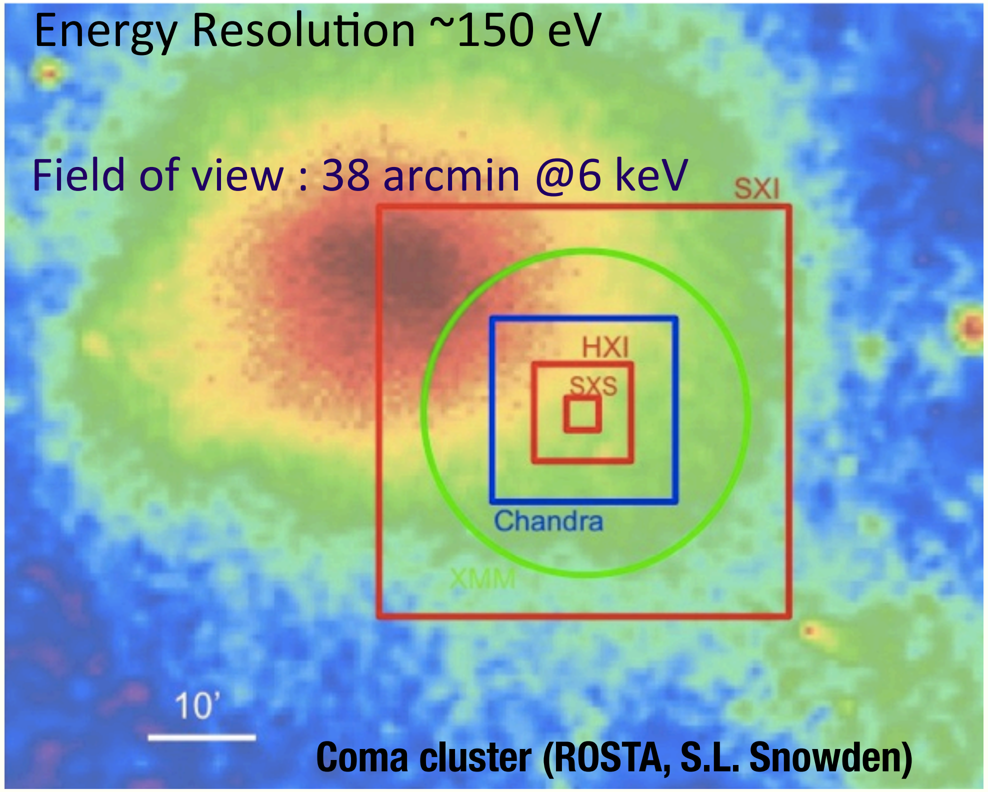
814 μm pixel
6x6 array
34 pixel readout

Soft X-ray imager

Large FOV X-ray CCD (F.L. 5.6 m)

Energy Resolution ~150 eV

Field of view : 38 arcmin @6 keV



Recent Progress

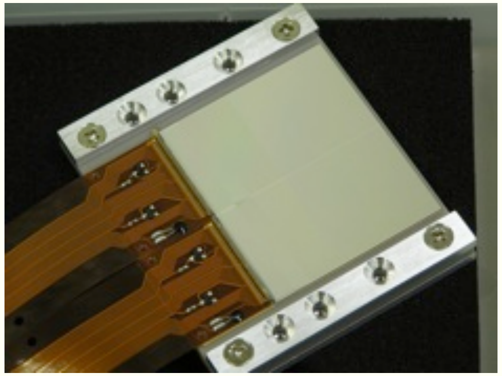
EM Model/

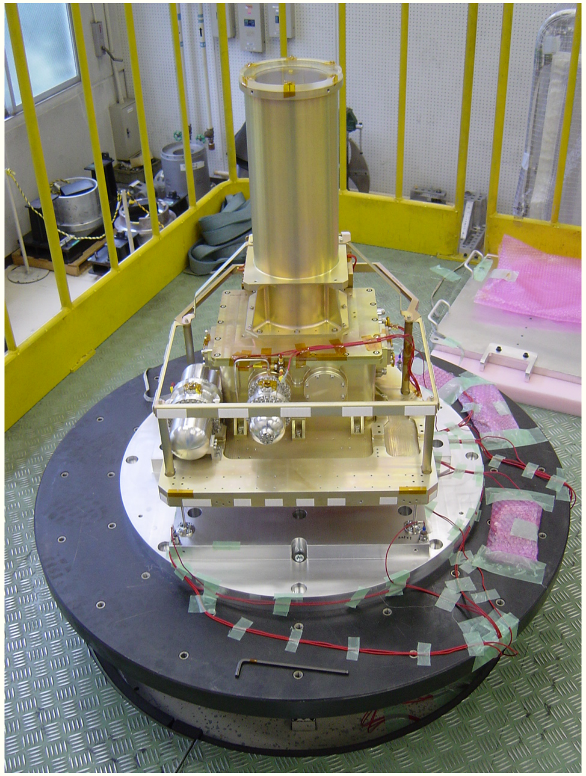
Thermal Balance Test

(2011/June)

4CCD chips/62x62mm^2

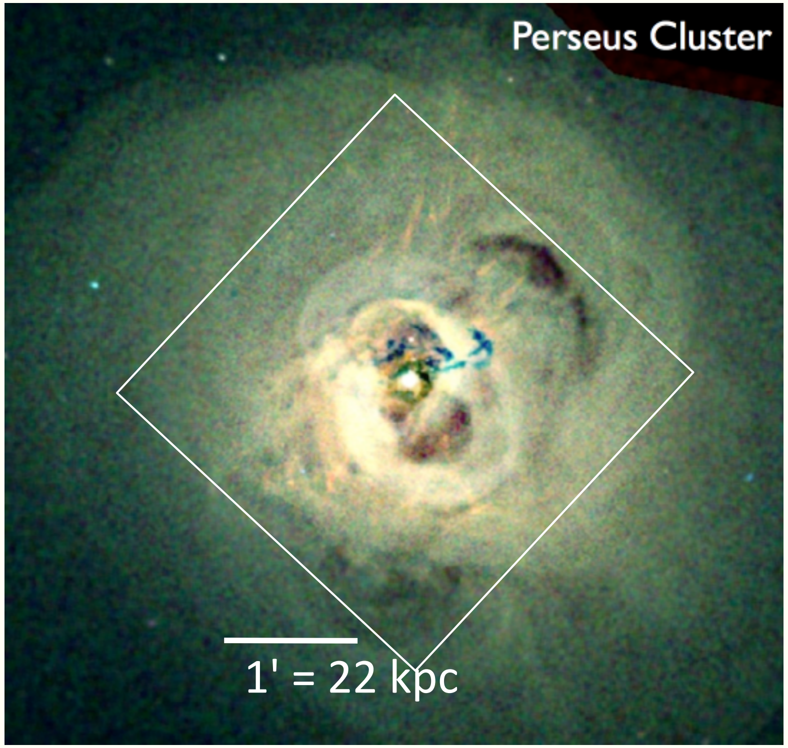
Depletion Layer ~200 micron



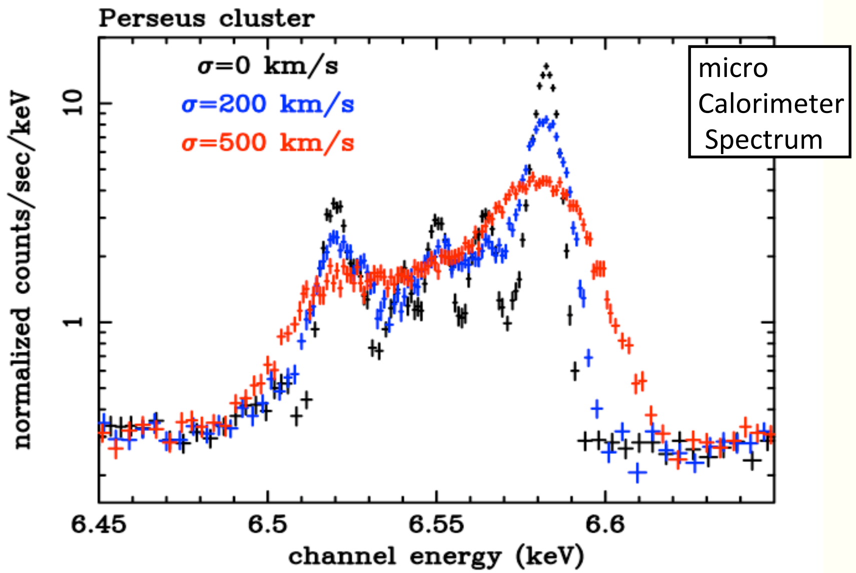


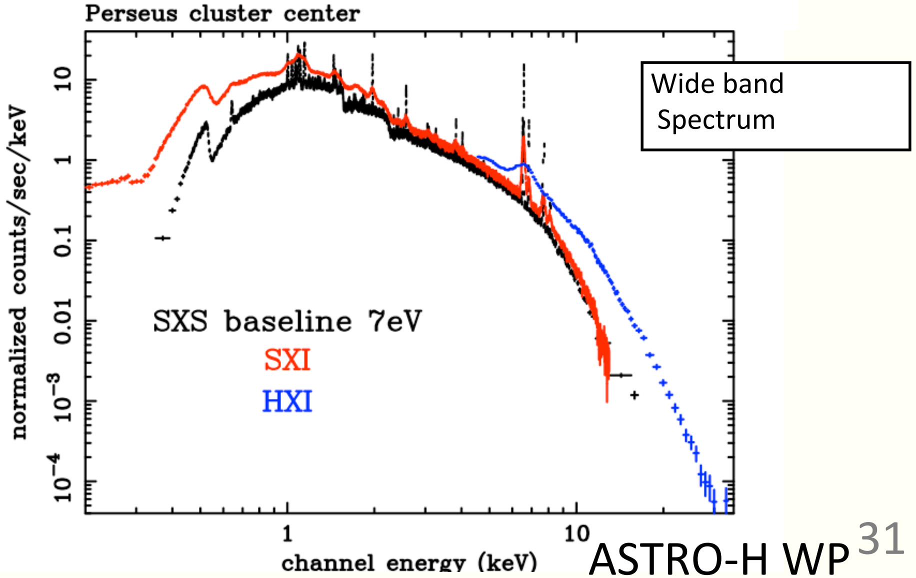
Turbulence in Perseus Cluster

The Perseus Cluster:
Brightest extragalactic extended X-ray source with very strong Fe-K line
X-ray image suggests turbulence or gas motion



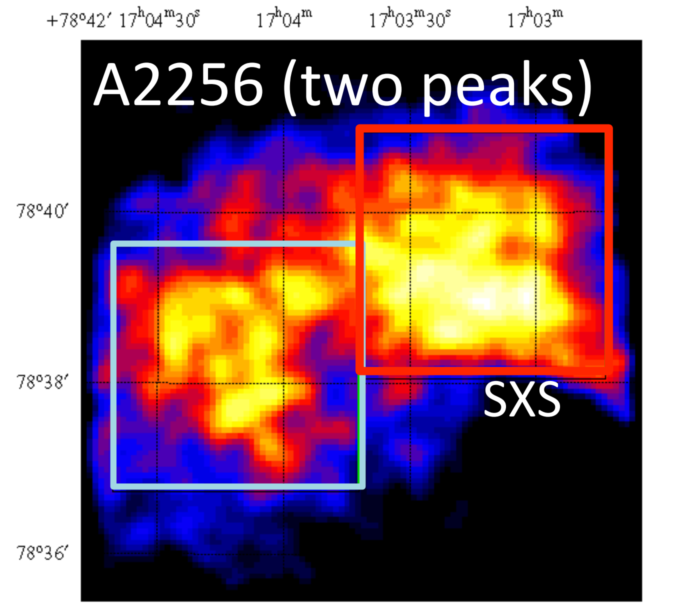
Perseus cluster (r<2', 100ks)
Turbulence and temperature structure

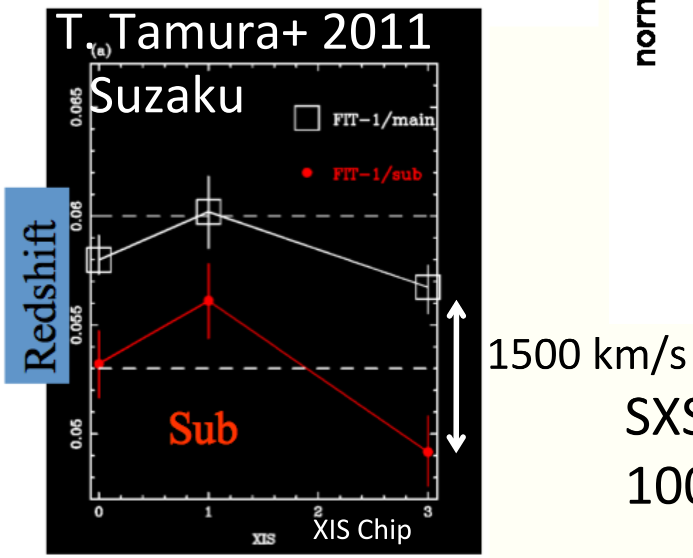


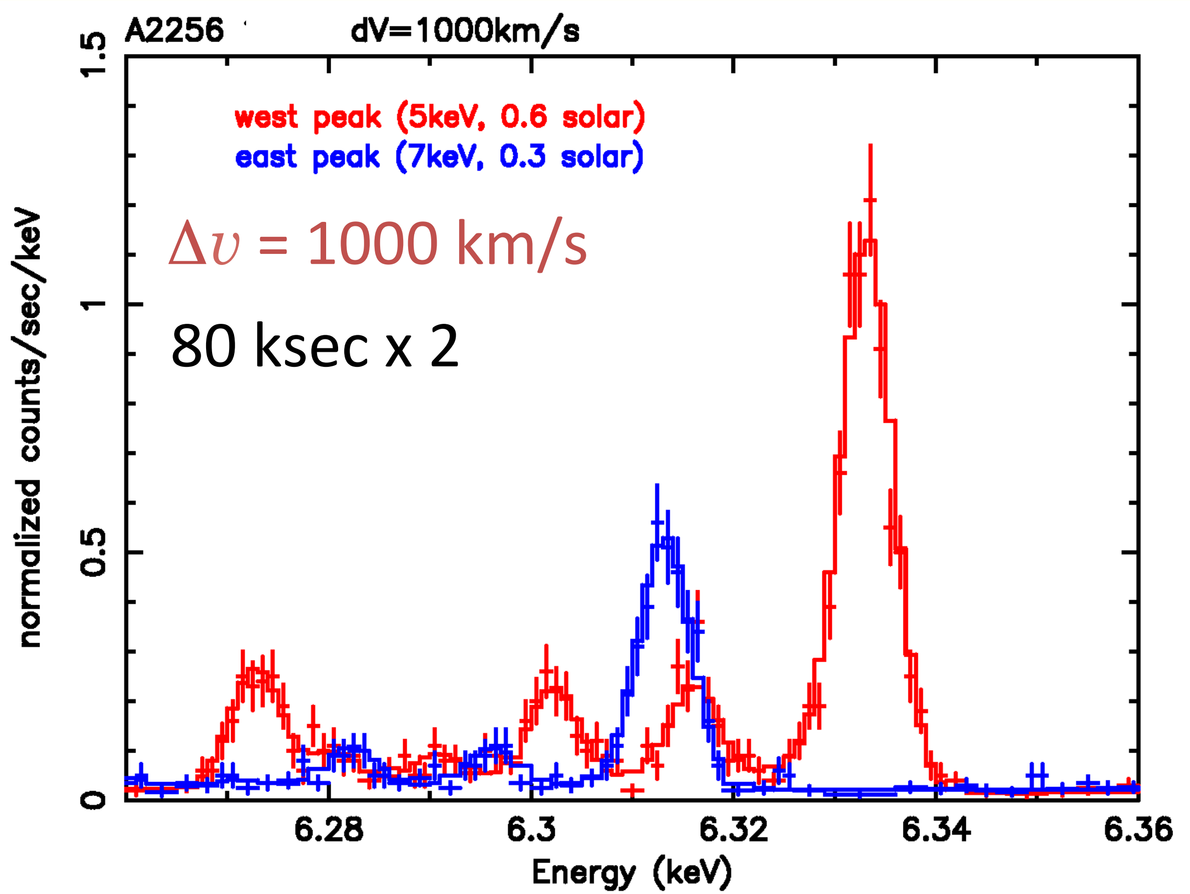


Cluster dynamics: Gas bulk motion

- With SXS, the velocity of matter can be derived from the energy shift and width of emission lines



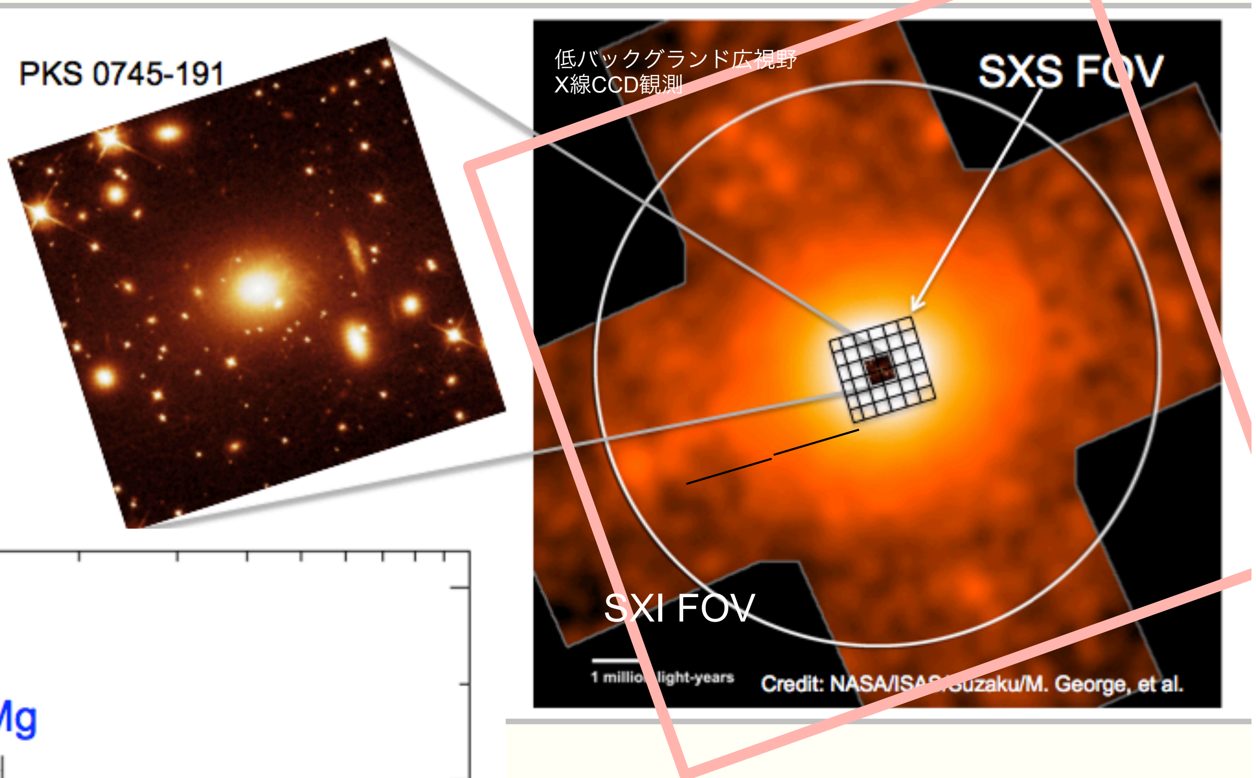


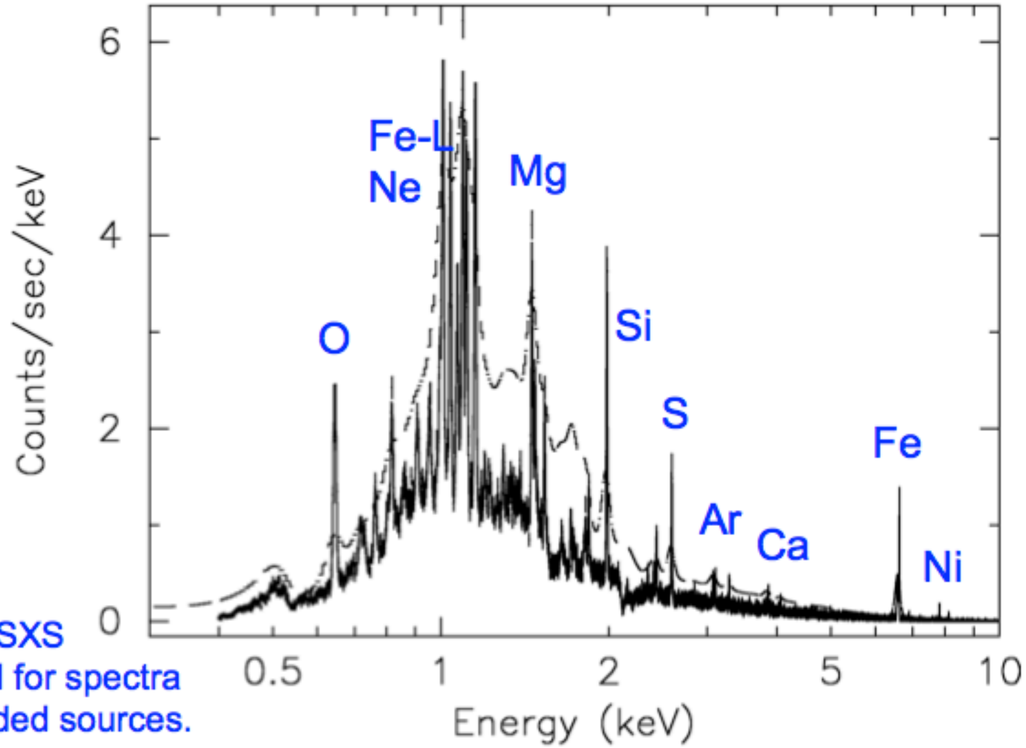


SXS spectra of a merging cluster A2256 assuming 1000 km/s difference in the line-of-sight velocity

Clusters of galaxies

Dynamics
（Turbulence, collisions)
Non-thermal emission
Temperature map
Heavy metal distribution

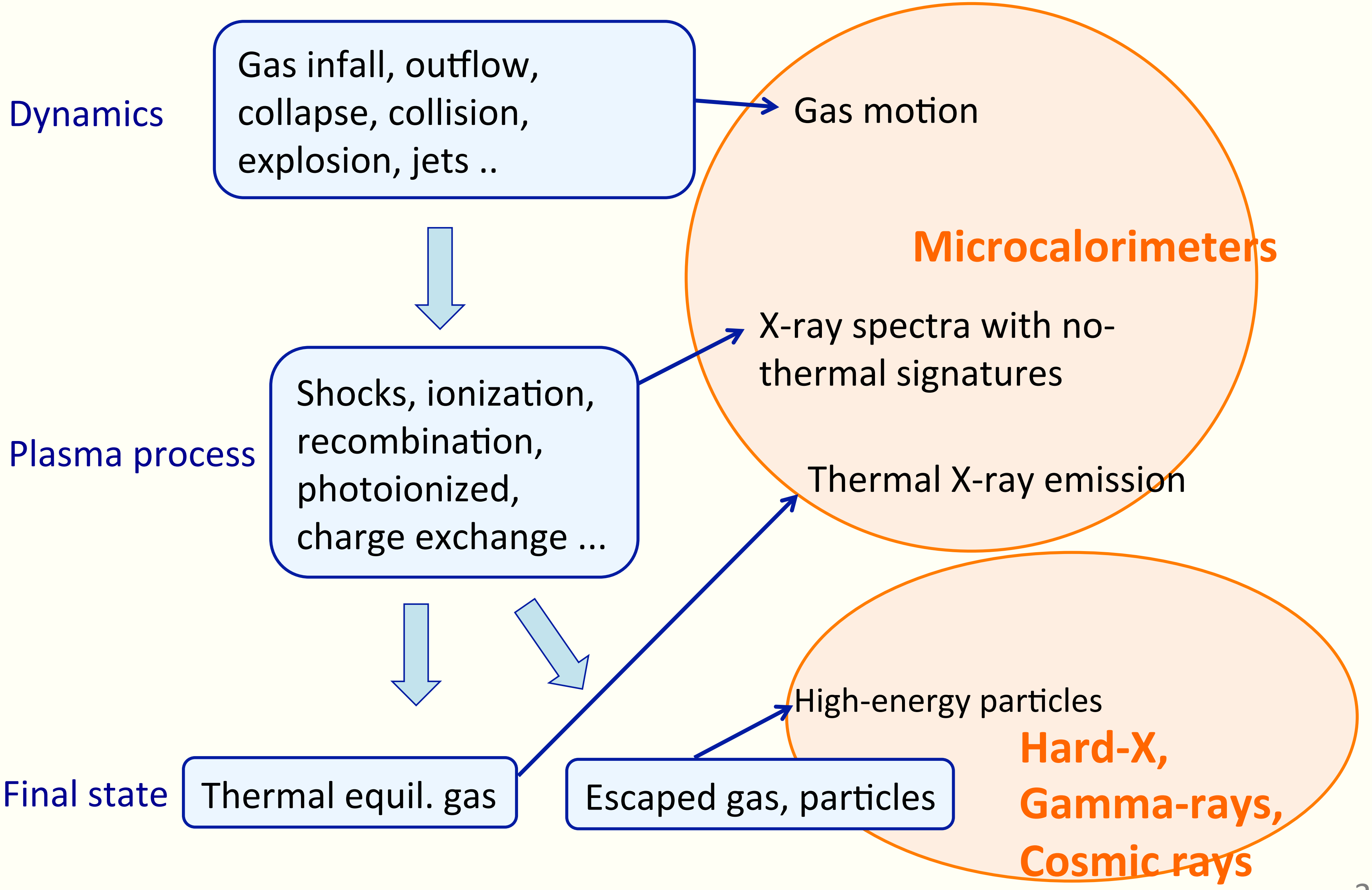




Astro-H/SXS
essential for spectra
of extended sources.

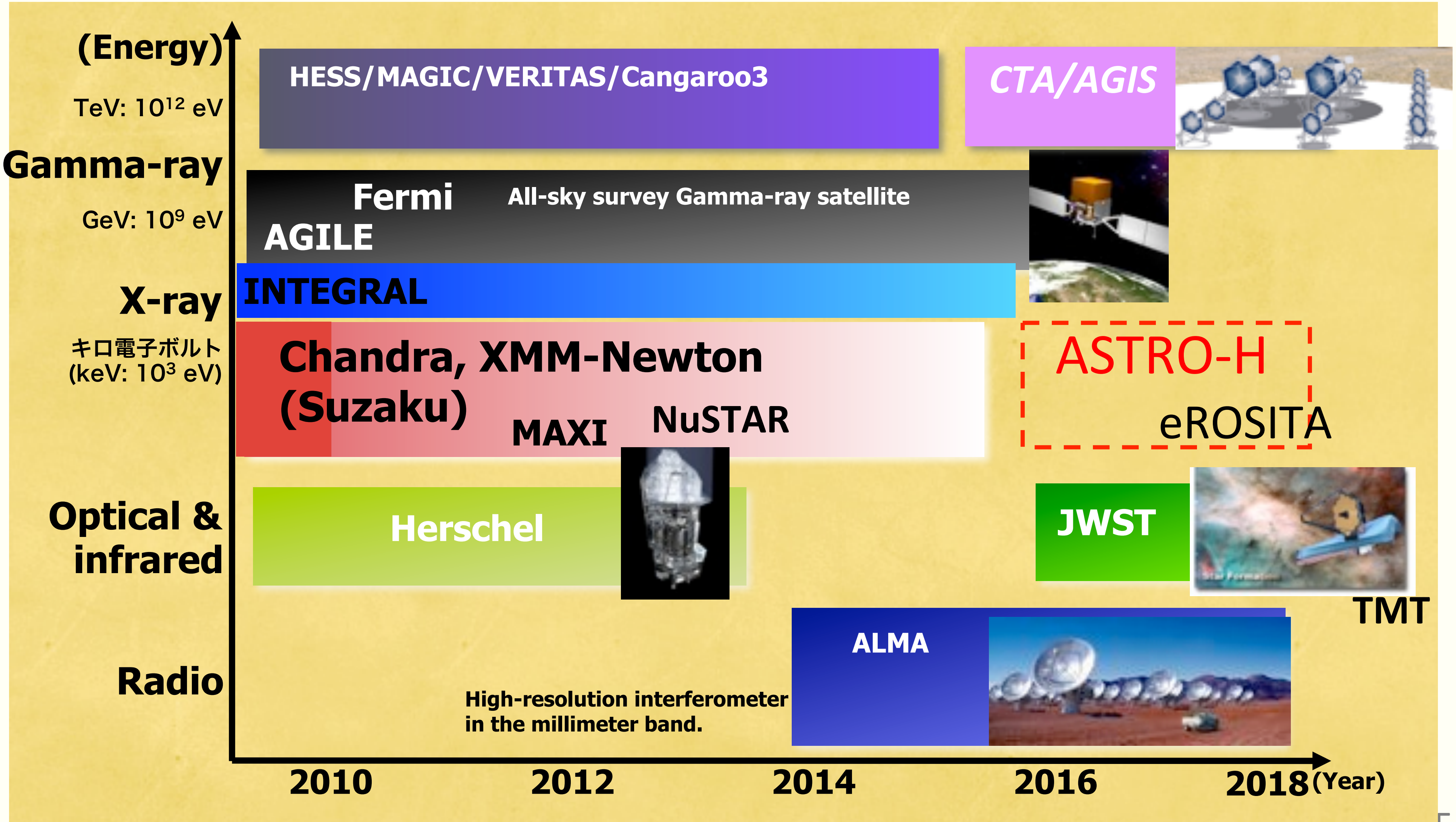
Centaurus cluster simulation: very high metal abundance in the center

Plasma evolution and spectroscopy



ASTRO-H - Synergy with other BIG missions

ASTRO-H will be the only "General Observatory in X-ray" in the mid 2010's. There is a world-wide devoid of future X-ray missions around 2016.An X-ray mission is indispensable to maximize the scientific yields expected by large radio, infrared, and optical missions.



Summary

- X-ray emission from clusters is a powerful probe in constraining the cosmology independently from other methods.
- All sky survey with eROSITA will bring us detailed view of the cluster evolution.
- Microcalorimeters (on ASTRO-H and DIOS) are new powerful instrument in measuring gas dynamics and (non) thermal features.
- ASTRO-H, with launch scheduled on February 12, is a major international observatory and an important jumping board for future X-ray astronomy.
- ASTRO-H Science White Papers (16 papers) were released in December 2014
  - arXiv:1412.2351 ASTRO-H White Paper – Introduction
  - ASTRO-H homepage: astro-h.isas.jaxa.jp

END