Prospects of galaxy cluster studies with ASTRO-H

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& ASTRO-H Science Working Group

Outline

- What is ASTRO-H?
- Why study galaxy clusters with ASTRO-H?
- What will high-resolution X-ray spectroscopy tell us?
- What will broad-band X-ray spectroscopy tell us?
- Further challenges

Reference & Collaborators

arXiv:1412.1176
(one of 17 white papers)

ASTRO-H Space X-ray Observatory
White Paper

Clusters of Galaxies and Related Science

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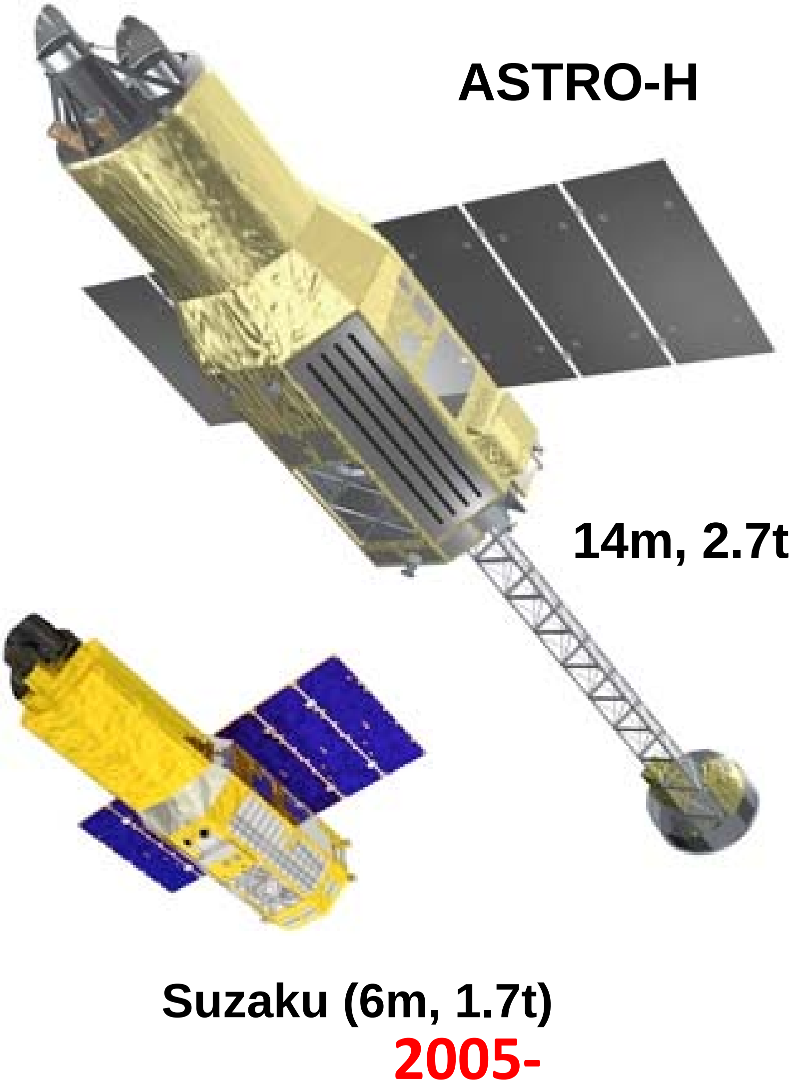
on behalf of the ASTRO-H Science Working Group

What is ASTRO-H?

The 6th X-ray satellite to be launched from Japan in fiscal year 2015

Launch site	Tanegashima Space Center
Launch vehicle	JAXA HII-A rocket
Orbit Altitude	550 km
Orbit Type	Approximate circular orbit
Orbit Inclination	< 31 degrees
Orbit Period	96 minutes
Total Length	14 m
Mass	～2.7 metric ton
Mission life	> 3 years



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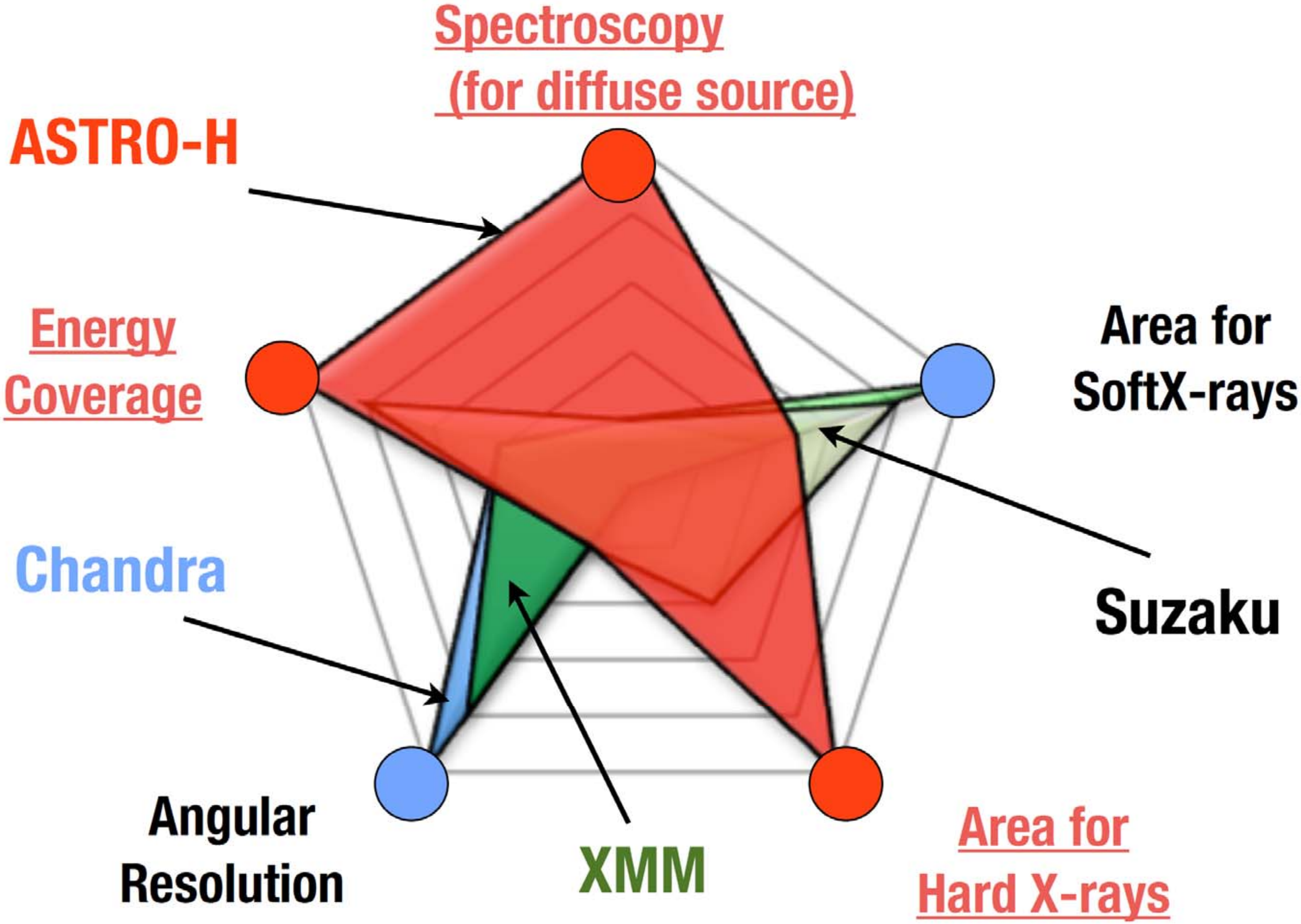
Takahashi et al (2014) SPIE paper

More than 200 scientists
from Japan/US/Europe/Canada

Capabilities (Schematic)



ASTRO-H capabilities

Parameter	Hard X-ray Imager (HXI)	Soft X-ray Spectrometer (SXS)	Soft X-ray Imager (SXI)	Soft γ-ray Detector (SGD)
Detector technology	Si/CdTe cross-strips	micro calorimeter	X-ray CCD	Si/CdTe Compton Camera
Focal length	12 m	5.6 m	5.6 m	–
Effective area	300 cm^2@30 keV	210 cm^2@6 keV 160 cm^2 @ 1 keV	360 cm^2@6 keV	>20 cm^2@100 keV Compton Mode
Energy range	5 –80 keV	0.3 – 12 keV	0.5 – 12 keV	40 – 600 keV
Energy resolution (FWHM)	2 keV (@60 keV)	< 7 eV	150 eV (@6 keV)	4 keV (@40 keV)
Angular resolution	<1.7 arcmin	<1.3 arcmin	<1.3 arcmin	–
Effective Field of View	$\sim 9 \times 9$ $arcmin^2$	$\sim 3 \times 3$ $arcmin^2$	$\sim 35 \times 35$ $arcmin^2$	0.6×0.6 deg^2 (< 150 keV)

Hard X-ray imaging (similar to NuSTAR)

High-resolution spectroscopy (20 -30 times better than CCD)

Wide-field CCD (similar to Suzaku)

What's new?

1. **High resolution (E/ΔE～1000) X-ray spectroscopy**

   First time for extended sources at 0.3-12 keV

   or point-like sources at 4-12 keV

2. **Simultaneous observations with:**

   - Hard X-ray imager: E=5-80 keV, FOV=9'

   (similar to NuSTAR)

   - Soft X-ray CCD: E=5-12 keV, FOV=35'

Trade-off:

- Spatial resolution >1'

- Lower effective area than Suzaku, XMM

Galaxy clusters, particularly at low-z, are amongst the key targets.

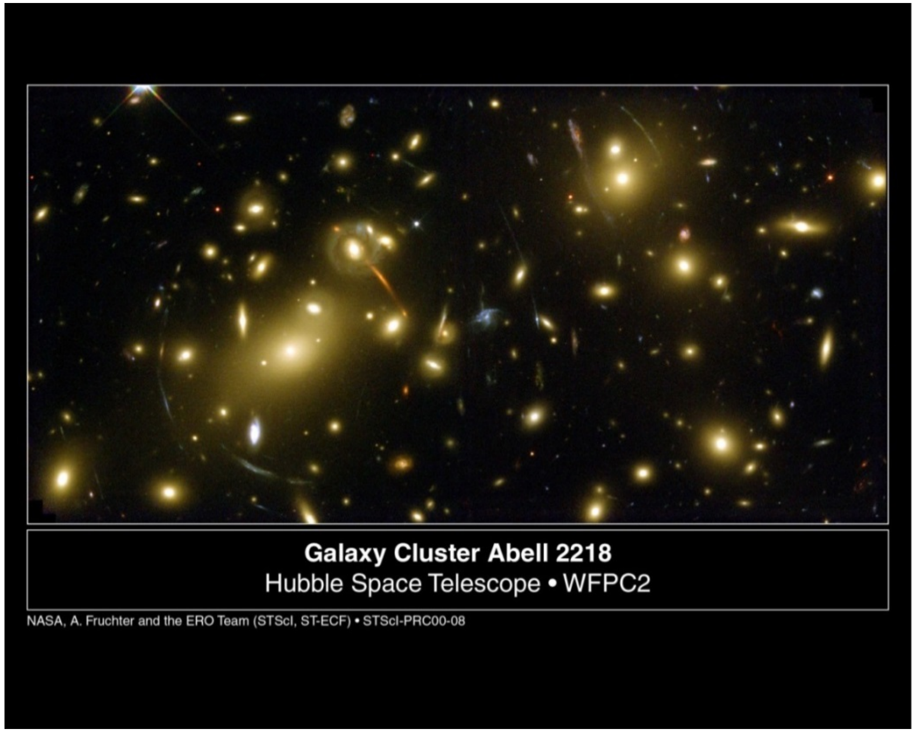
Galaxy Clusters

Largest virialized objects

total mass ～10^{15} $M_{\odot}$

radius ～Mpc=8’(0.1/z)

set by cosmological conditions



Laboratory of structure formation

growth of density perturbations

heating/cooling of plasma

star formation and galaxy evolution

acceleration of relativistic particles

Target of multiwavelength observations

optical/IR, radio, X-rays, etc.

※ Units

1pc = 3.09E18 cm

1 $M_{\odot}$ = 1.99E33 g

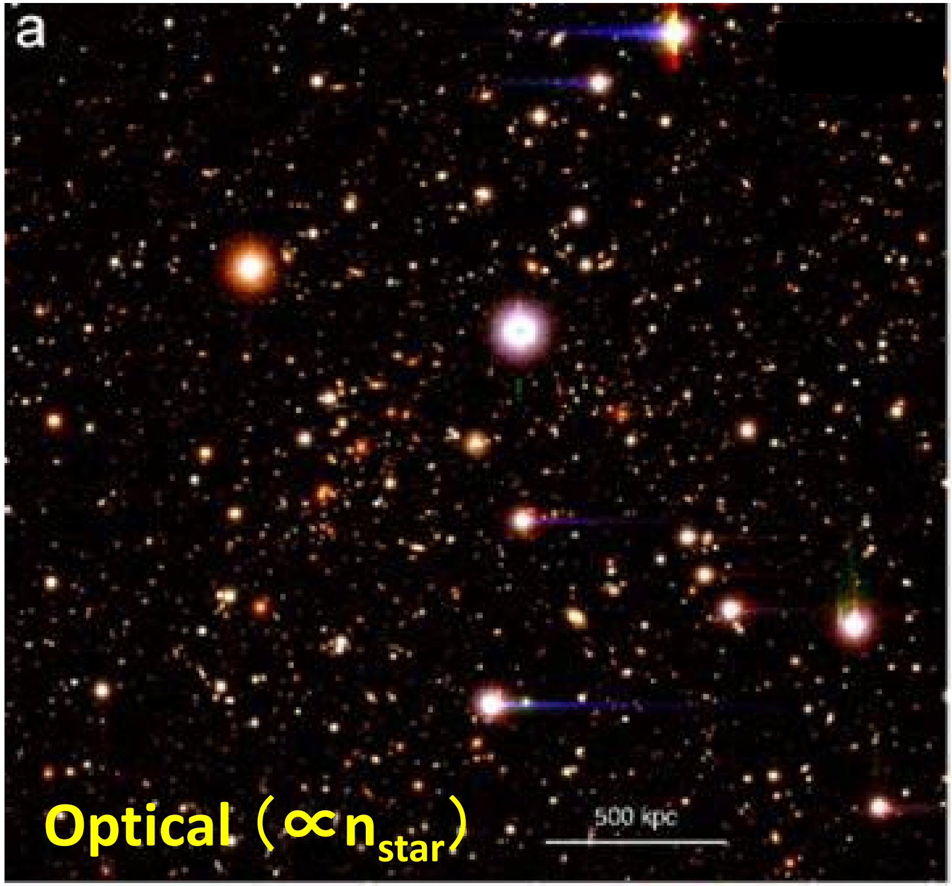
1 yr = 3.16E7 sec

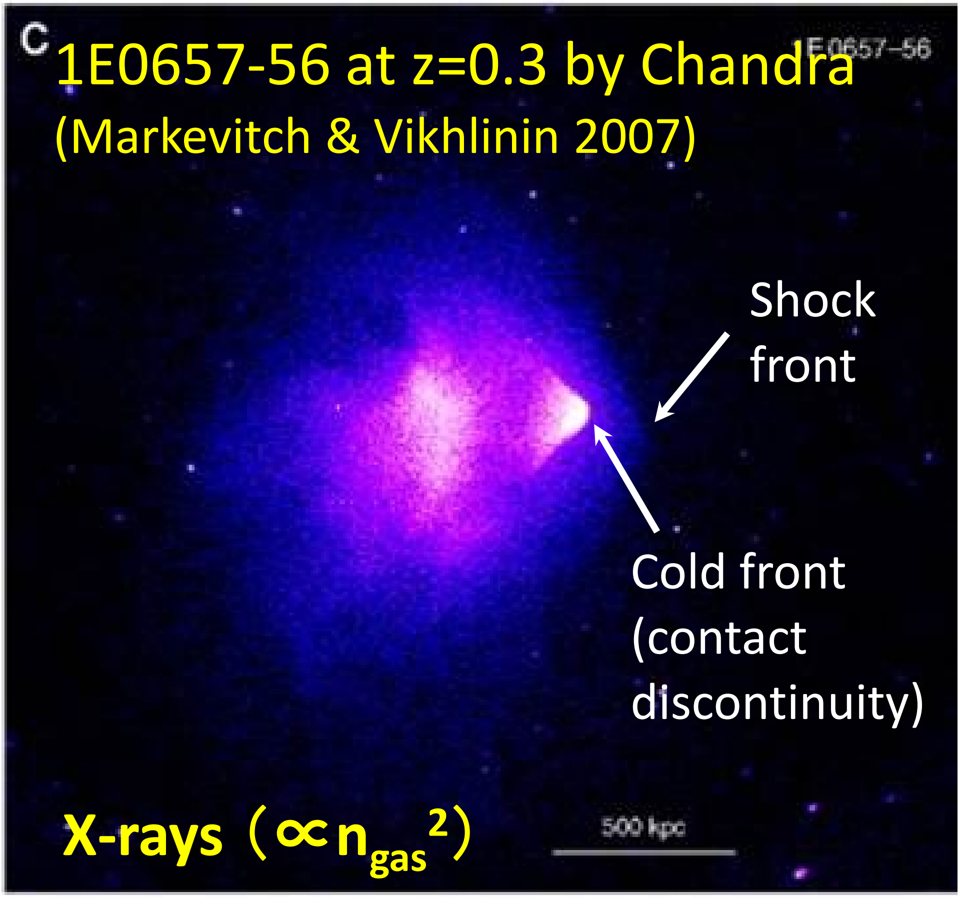
1 keV = 1.16E7 K (kT)

= 1.2 nm (λ)

1 Jy = 1E-23 erg/s/cm2/Hz

Why X-rays for clusters?





~80% of baryon content is X-ray emitting gas

Emissivity $\propto n^2$ → higher contrast against background

However, $E/\Delta E < 50$ by CCD → **ASTRO-H**

Primary goal: measure gas motion

・**Strong circumstantial evidences**

shocks, cold fronts, galaxy motions, simulation results, etc.

・**Key to understanding physics of structure formation**

merger, feedback, viscosity, particle acceleration, etc.

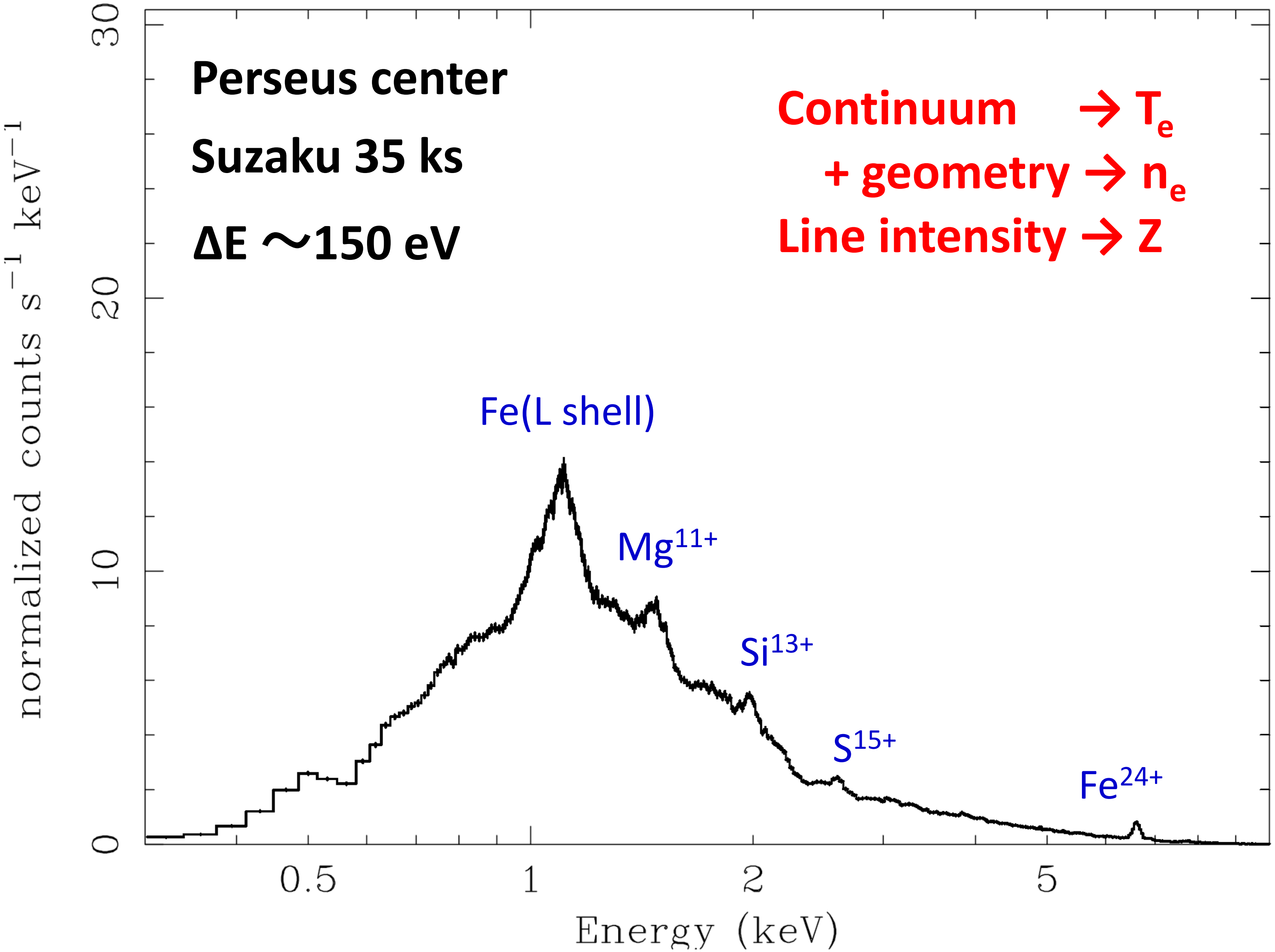
・**Crucial for cosmological studies**

non-thermal pressure support → total mass and its profile

Yet, no accurate measurements so far!

e.g. bulk motion: ΔV=1500±300±300(sys) km/s toward A2256 (Tamura+2011)
turbulence : V>500 km/s from lack of scattering in Perseus (Churazov+2004)
V< 300 km/s for several cluster cores (Sanders & Fabian 2013)

CCD spectrum of a galaxy cluster



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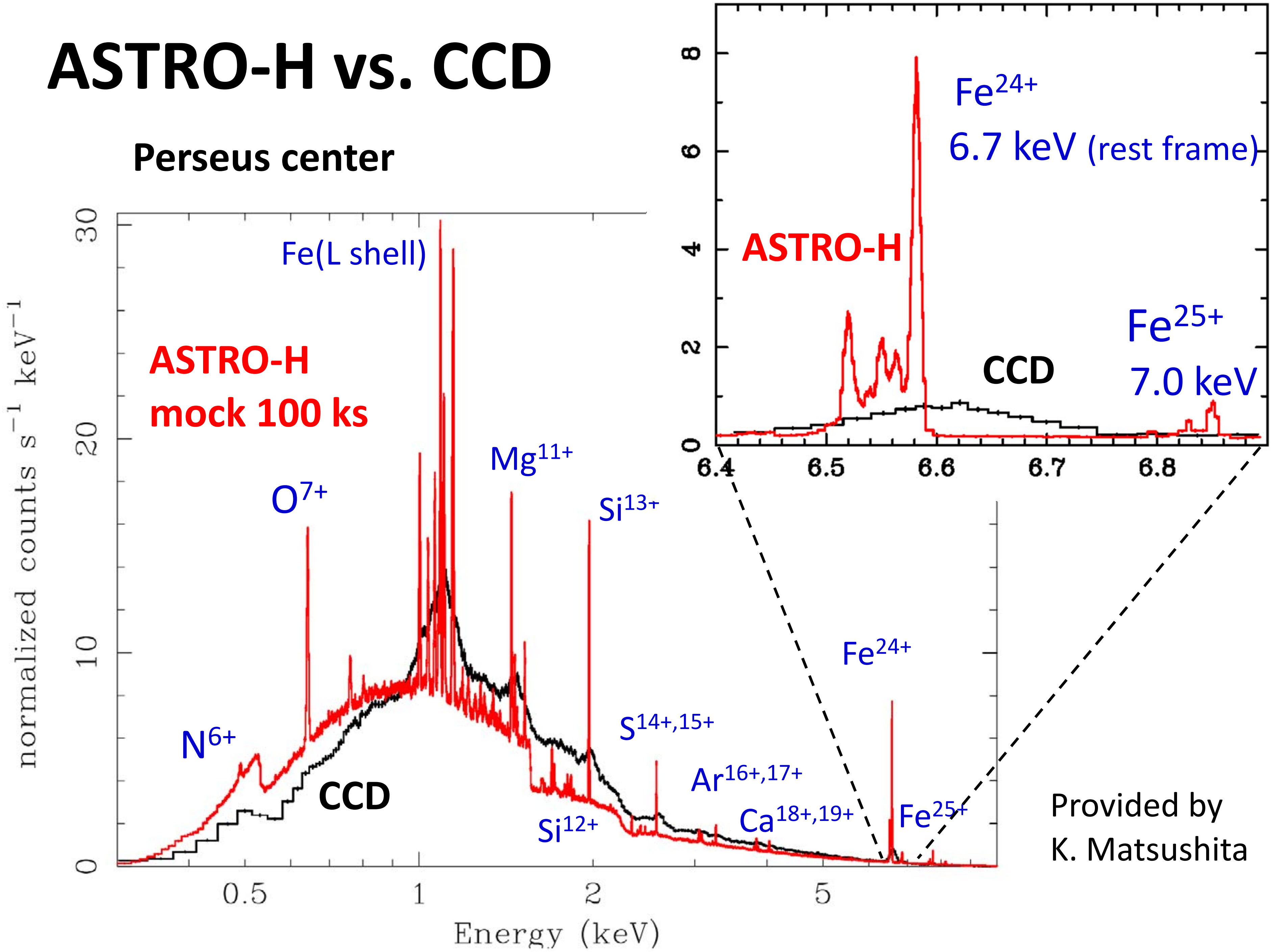
K. Matsushita

ASTRO-H vs. CCD

Perseus center



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Why high spectral resolution?

1. Line shift : bulk motion

$$\Delta E = 2.2\mathrm{eV} \left(\frac{V_{\mathrm{bulk}}}{100\mathrm{km/s}}\right)\left(\frac{E_{\mathrm{obs}}}{6.7\mathrm{keV}}\right)$$

2. Line broadening: random motion

Einstein coeff. for He-like Fe @ 6.7keV

FWHMs

natural $W_{\mathrm{nat}} = 0.31\ \mathrm{eV} \left(\frac{A}{4.67 \times 10^{14}\ \mathrm{s}^{-1}}\right),$

+

thermal $W_{\mathrm{therm}} = 4.9\ \mathrm{eV} \left(\frac{kT_{\mathrm{ion}}}{5\ \mathrm{keV}}\right)^{1/2} \left(\frac{m_{\mathrm{ion}}}{56\ m_{\mathrm{p}}}\right)^{-1/2} \left(\frac{E_{\mathrm{obs}}}{6.7\mathrm{keV}}\right),$

+

turbulent $W_{\mathrm{turb}} = 5.3\ \mathrm{eV} \left(\frac{V_{\mathrm{turb}}}{100\ \mathrm{km/s}}\right)\left(\frac{E_{\mathrm{obs}}}{6.7\ \mathrm{keV}}\right),$

+

instrumental

1D (LOS) dispersion

< 7eV spectral resolution is crucial for measuring V～100km/s
& T_{ion} (apart from T_e) can be separated by multiple elements

Impact on ICM properties

Velocity of 100 km/s corresponds to

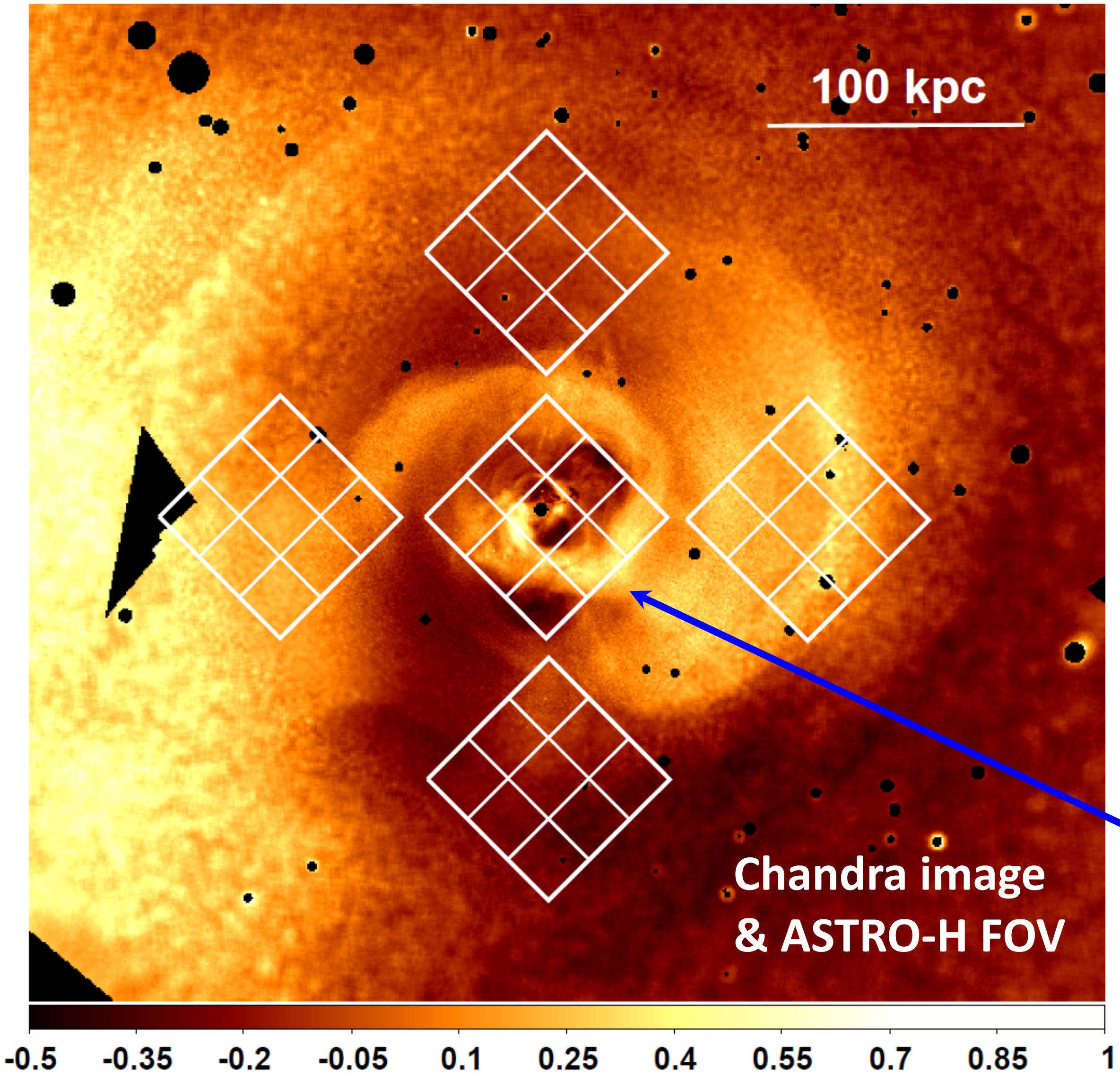
$$\frac{v_{\rm bulk}}{v_{\rm sound}} = 8.7 \times 10^{-2} \left(\frac{v_{\rm bulk}}{100 \ {\rm km \ s^{-1}}} \right) \left(\frac{\mu}{0.6} \right)^{1/2} \left(\frac{kT}{5 \ {\rm keV}} \right)^{-1/2},$$

for bulk motion, and

$$\frac{p_{\rm turb}}{p_{\rm therm}} \simeq 1.3 \times 10^{-2} \left(\frac{v_{\rm turb,1D}}{100 \ {\rm km \ s^{-1}}} \right)^{2} \left(\frac{\mu}{0.6} \right) \left(\frac{kT}{5 \ {\rm keV}} \right)^{-1}.$$

for isotropic turbulence.

Mock observations by ASTRO-H



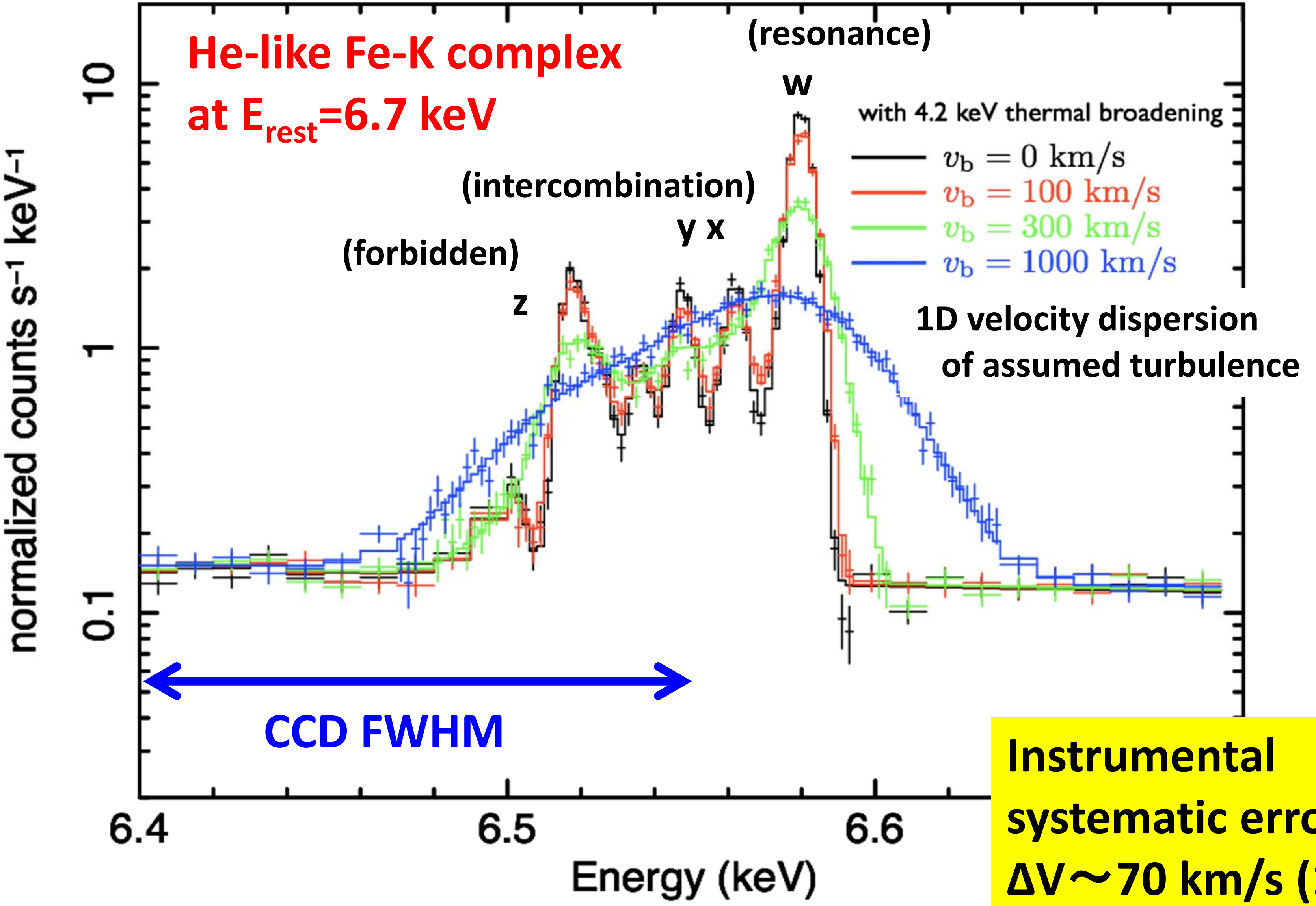
Perseus cluster
@ z=0.018

Brightest X-ray cluster on the sky (Best target for high-res. sepctroscopy)

Weak shocks in the center
Possible site of on-going AGN feedback

3’ × 3’ FOV
1.3’HPD PSF

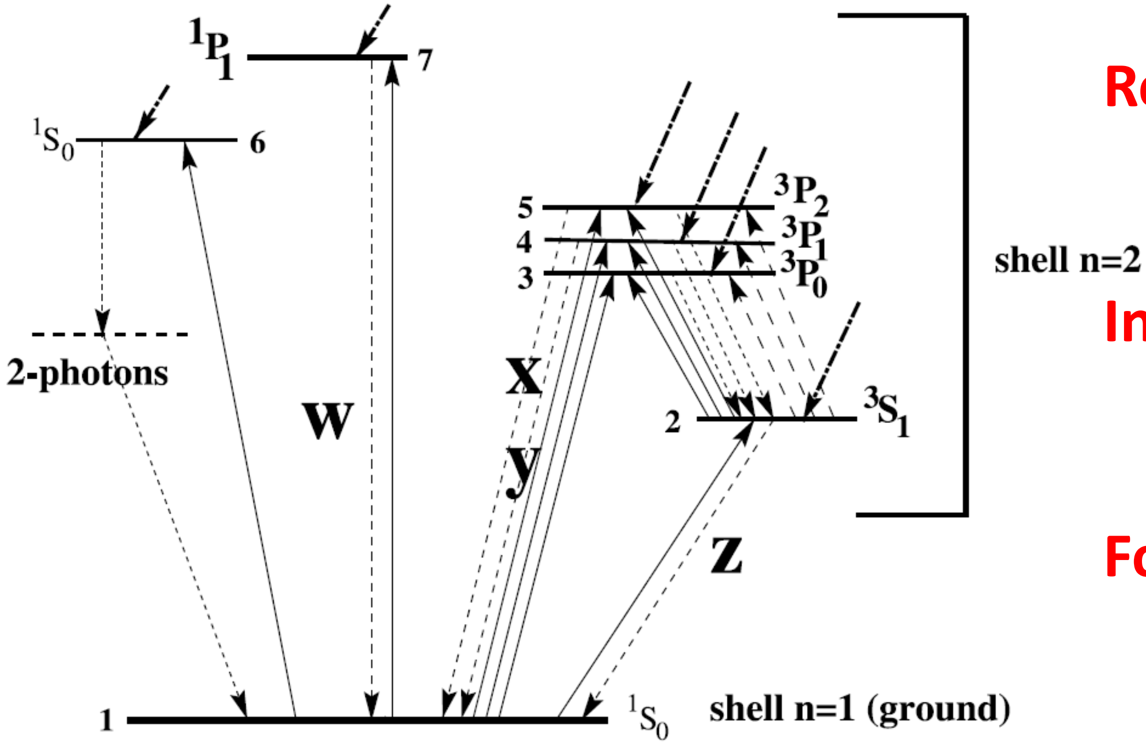
Mock spectra for Perseus center (100ks)



Instrumental systematic errors ΔV～70 km/s (1σ)

He-like “triplet”

$^{2S+1}L_J$



Porquet 2000

Resonance line (w)

1s2p S=0 L=1 J=1 → $1s^2$

Intercombination lines (x,y)

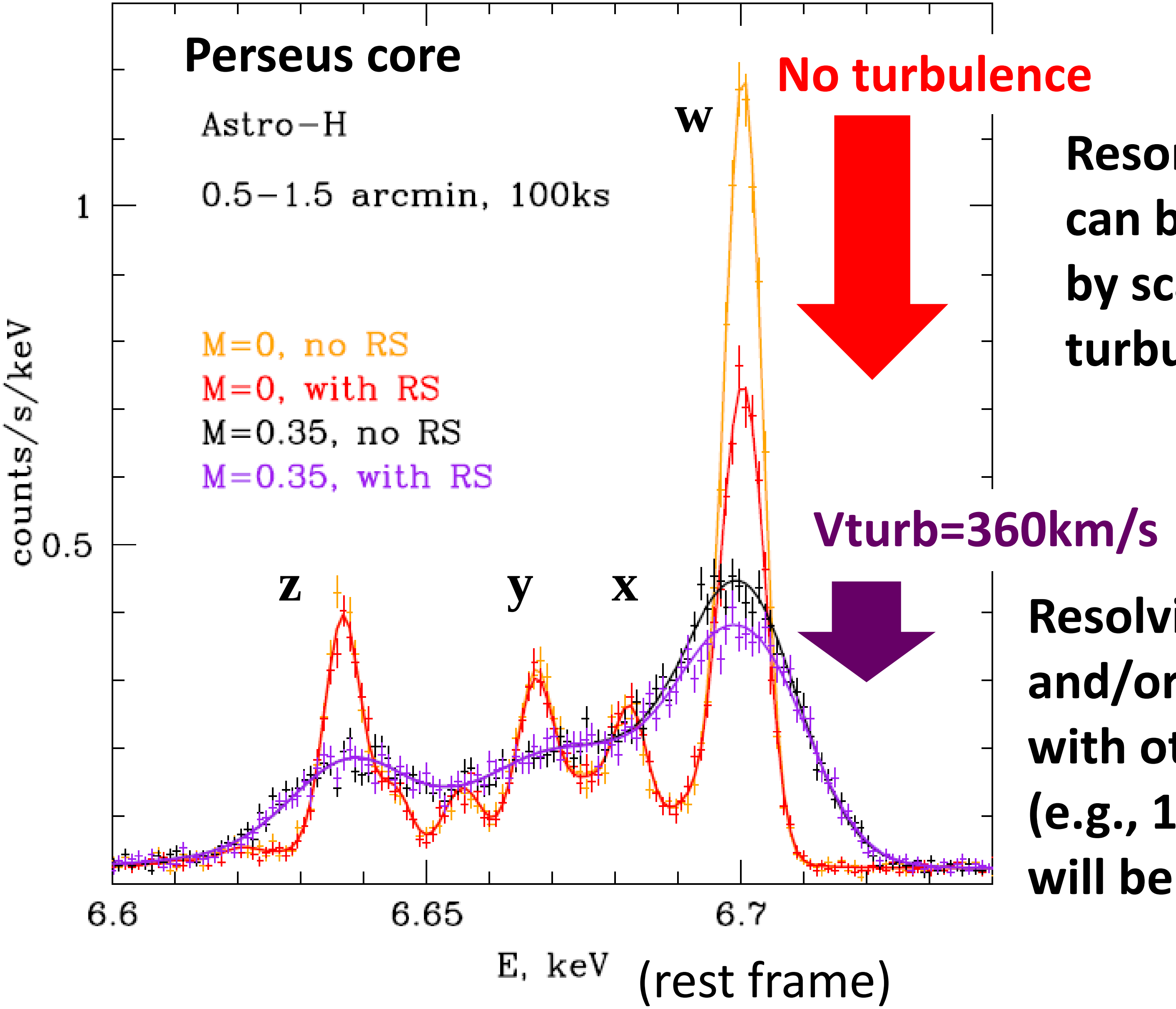
1s2p S=1 L=1 J=2,1 → $1s^2$

Forbidden line (z)

1s2s S=1 L=0 J=1 → $1s^2$

- **ASTRO-H will resolve w, x+y, z lines of He-like Fe-K at 6.7 keV.**
- **The resonance line (w) of 1s2p can be suppressed by scattering.**
- **Relative strength w.r.t. H-like Fe lines will provide a test of collisional ionization equilibrium.**

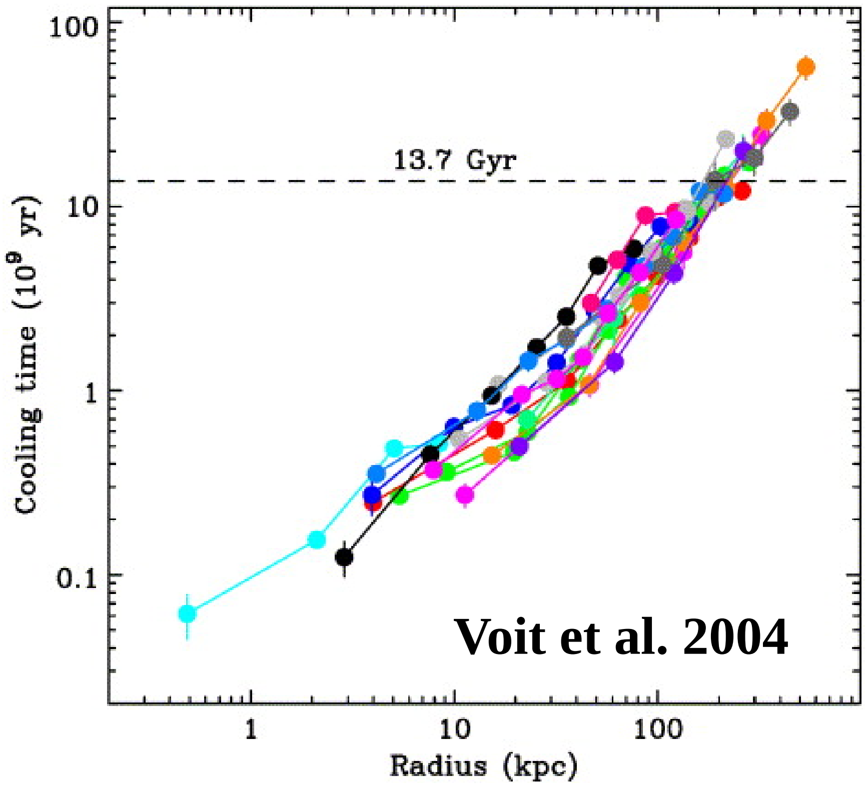
Resonance scattering

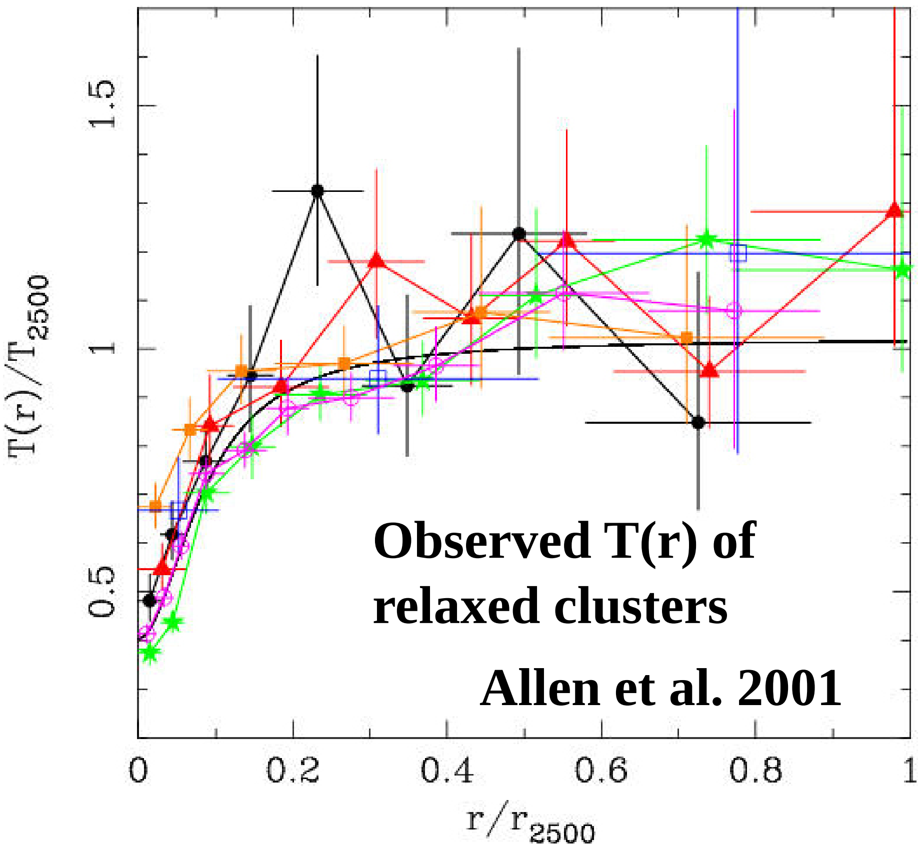


Resonance (w) lines can be suppressed by scattering if turbulence is small.

Resolving line structure and/or combination with other lines (e.g., 1s3p at 7.9 keV) will be crucial.

Gas motion in the core: cooling-flow problem

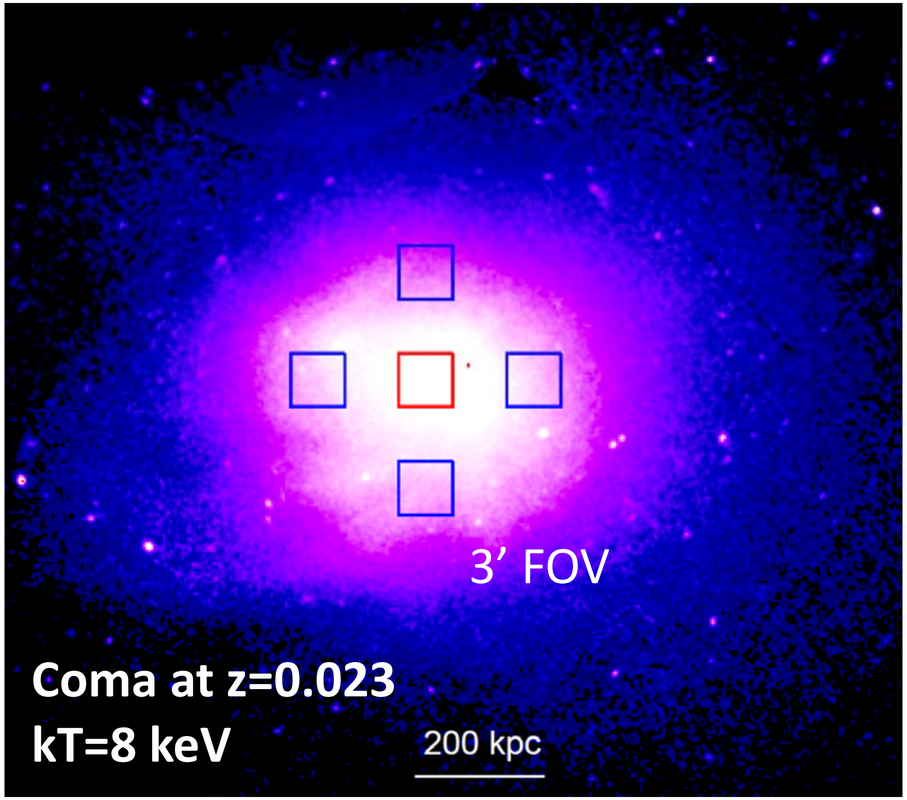




Cluster center :
cooling time < Hubble time
→ overcooling expected

Why is cooling prevented?
(Why no supermassive galaxies?)
Why is T(r) universal?
→ AGN feedback on ICM ?
How is energy dissipated?

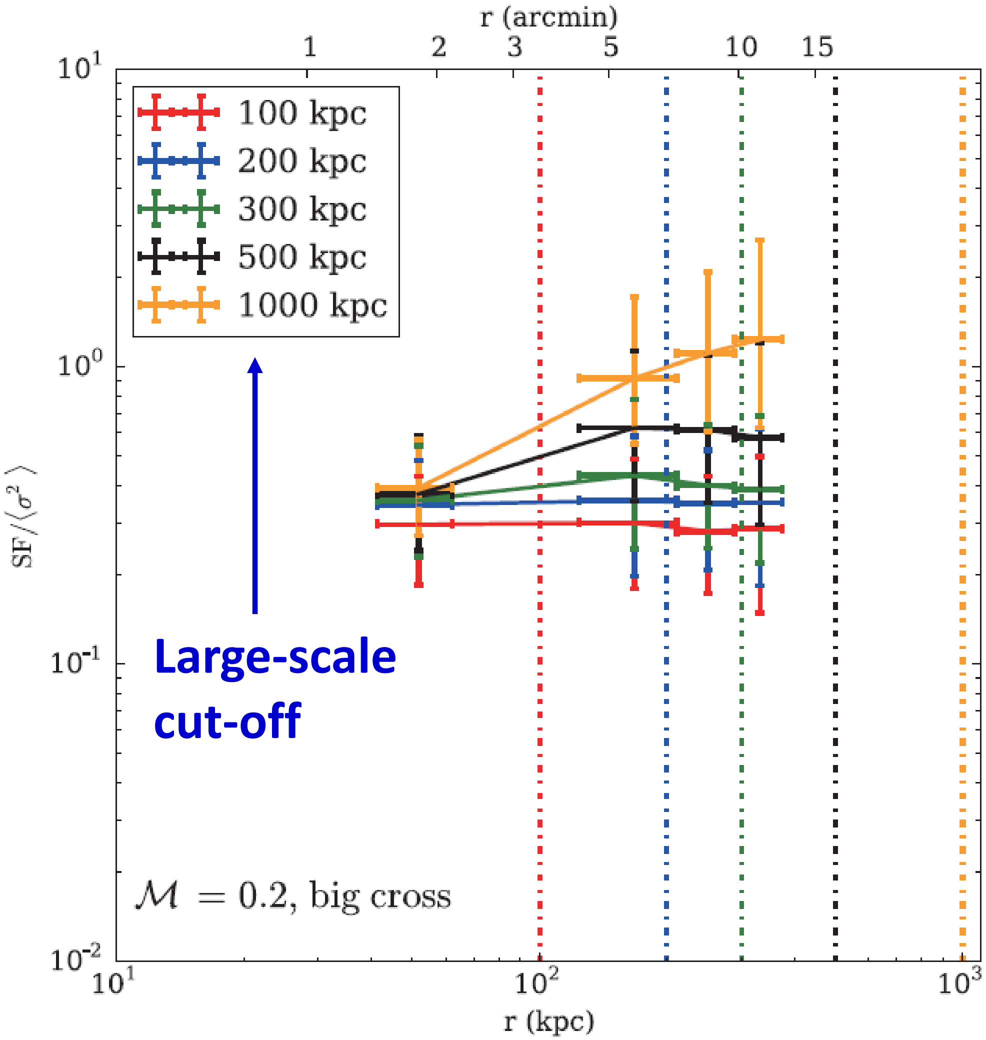
Power spectrum of turbulence



Simulations assuming **Kolmogorov spectrum with a cut-off**

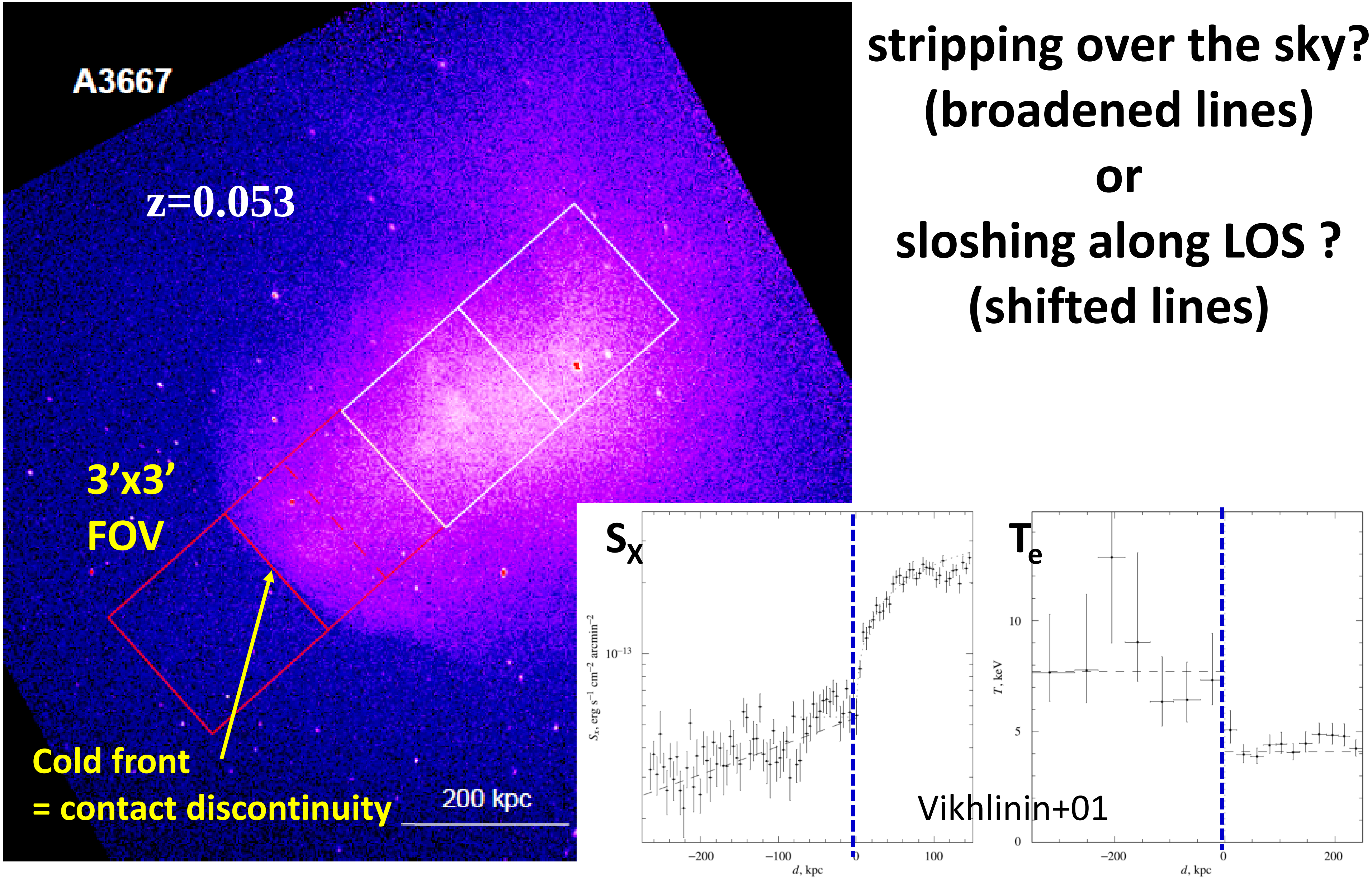
→ **$SF(r)=<[v(x+r)-v(x)]^2>$**

(ZuHone & Markevitch 2014)



Can probe **the largest scale** that drives turbulence. Insensitive to the power at small scales (<100kpc).

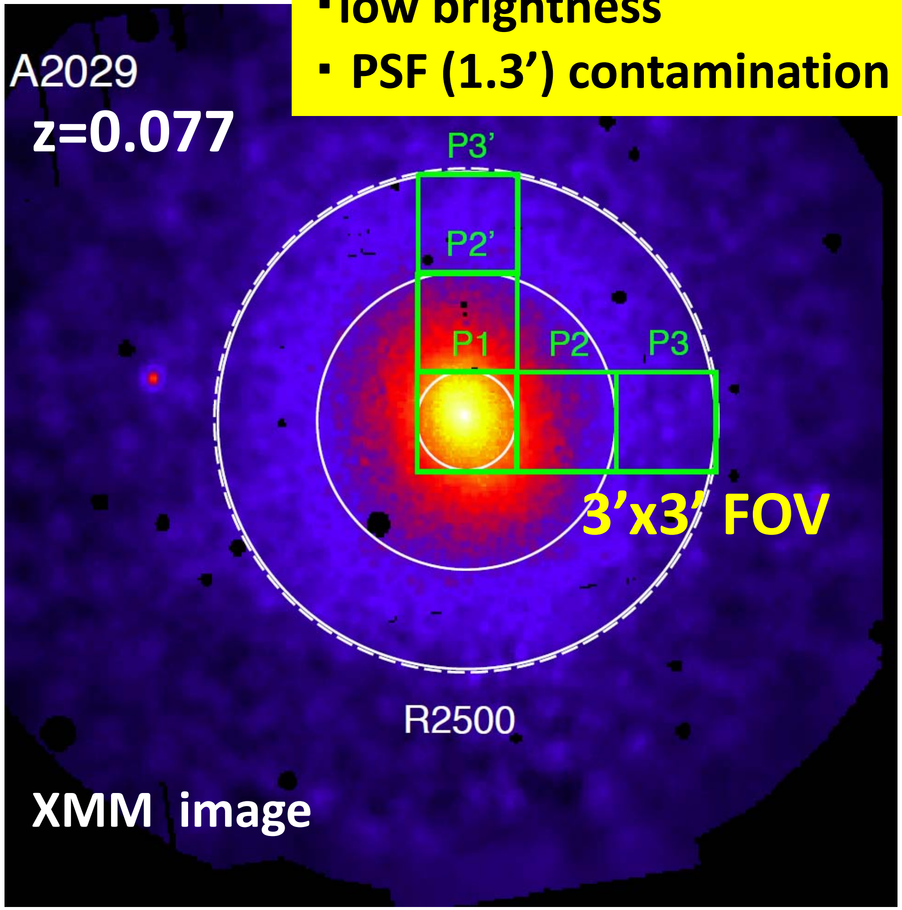
Origin of cold fronts

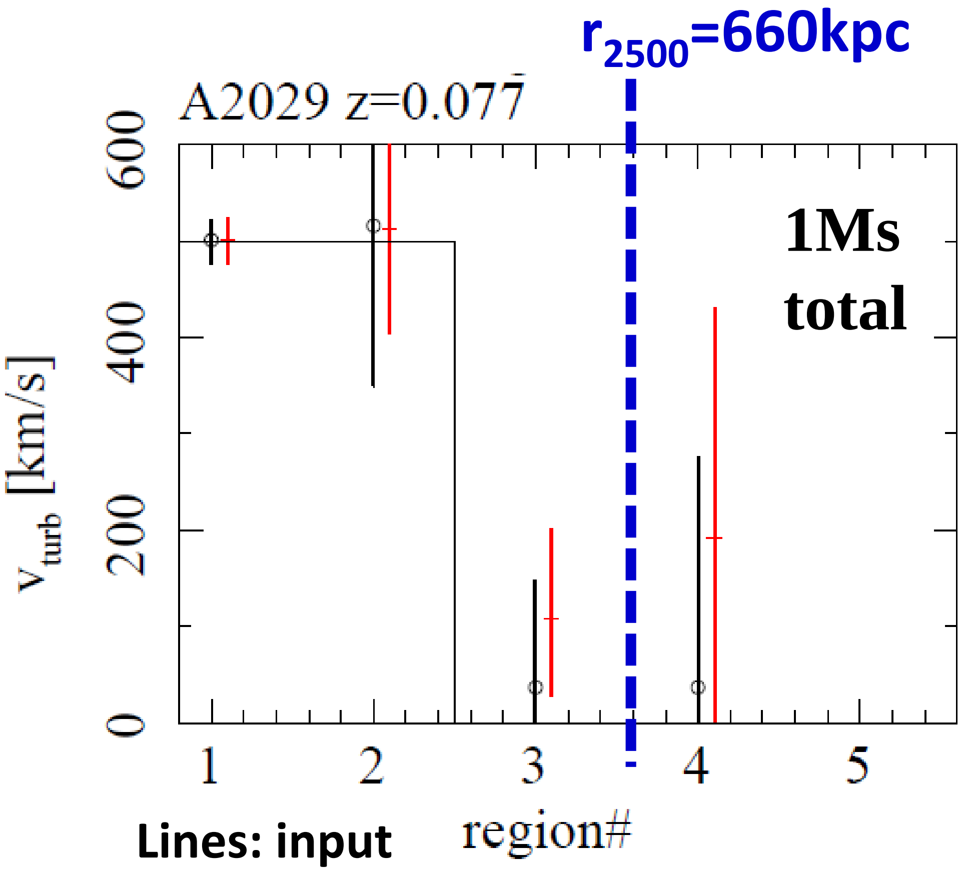


stripping over the sky?
(broadened lines)
or
sloshing along LOS ?
(shifted lines)

How relaxed can galaxy clusters be? How much is turbulent pressure?

Challenges:
- low brightness
- PSF (1.3') contamination





Lines: input
○ PSF corrected
+ PSF uncorrected

ΔV ~100km/s will be achieved out to ~r_{2500} ~1/4 r_{200} at z<0.1

High resolution X-ray spectra will tell us

- **Gas velocities**：
  Bulk motion （line shift）
  Random motion including turbulence（line width）

New !

- **Ion temperature** （widths of various metal lines）

- **Electron temperature & density** (continuum or lines)

Better quality

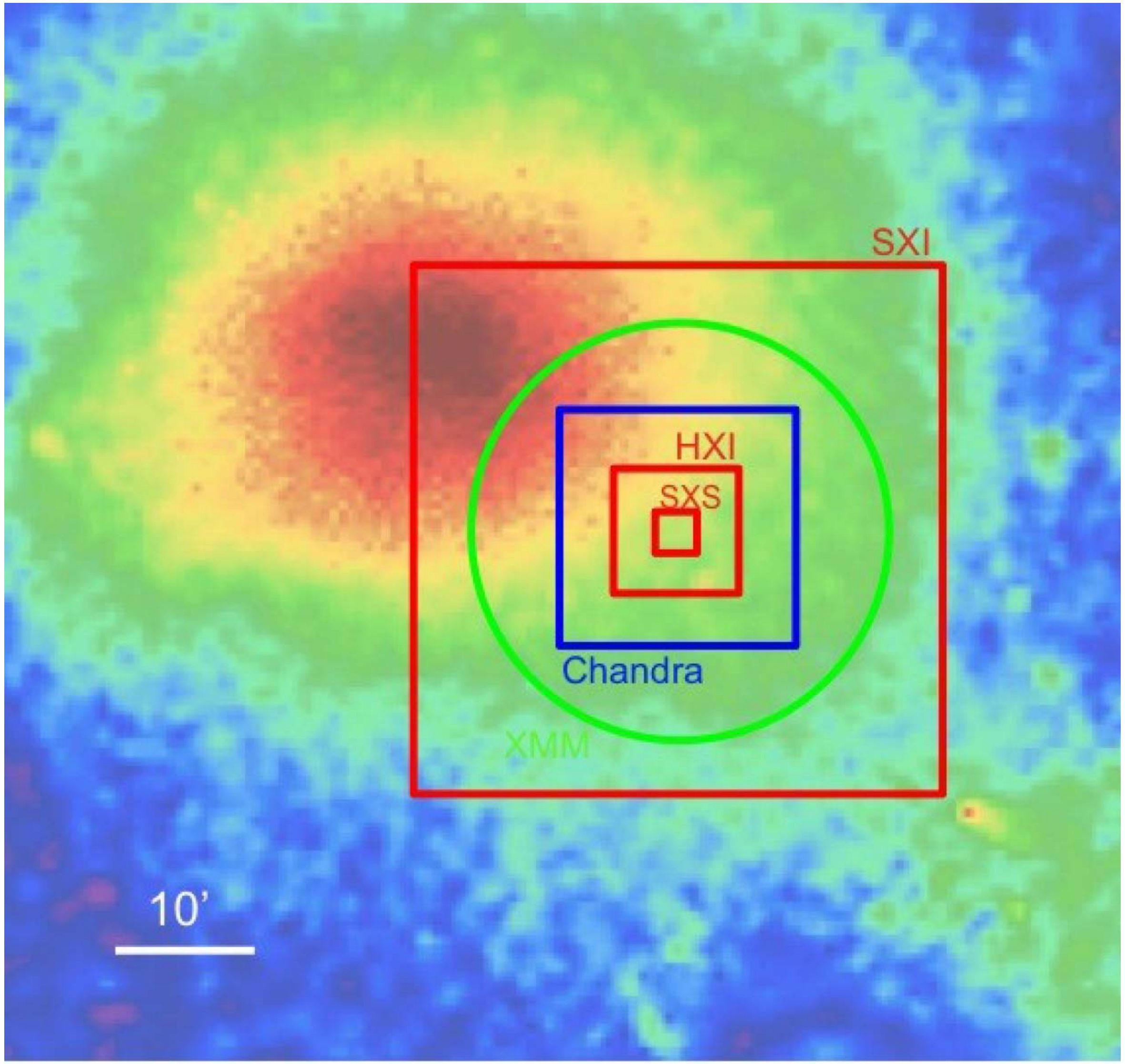
- **Departure from ionization equilibrium** (line ratios)

- **Metal abundances**（O, Ne, Mg, Si, S, Ar, Ca, Cr, Mn,Fe, Ni,,,）

etc.

※ ASTRO-H is suitable for bright nearby clusters.
Fainter or more distant regions will be studied by future missions.

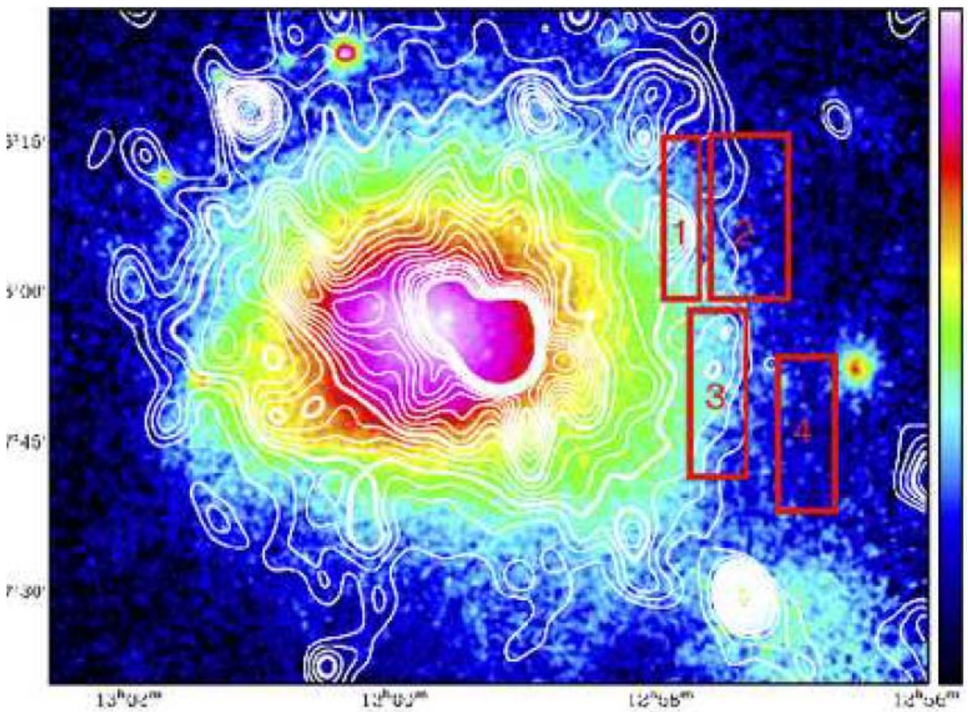
Broad-band & Wide-field



ASTRO-H
1) High resolution spec (SXS): 3'x3' FOV
2) Hard X-rays (HXI): 9'x9' FOV
3) Soft X-ray CCD (SXI): 35'x35' FOV

Early observations will be driven by 1) but simultaneously yield deep data by 2) and 3)

Cosmic ray electrons in galaxy clusters



Radio (contours) & X-ray (color)
in Coma cluster
(Brown & Rudnik 2011)

Relativistic ($\gamma \sim 10^4$) electrons

- Unknown origin/mechanism
  in-situ or secondary ?
- Only observed in radio
  via synchrotron
- Must emit hard X-rays
  via inverse-Compton

$$F_{sync} \propto n_e B^2$$
$$F_{IC} \propto n_e U_{CMB}$$

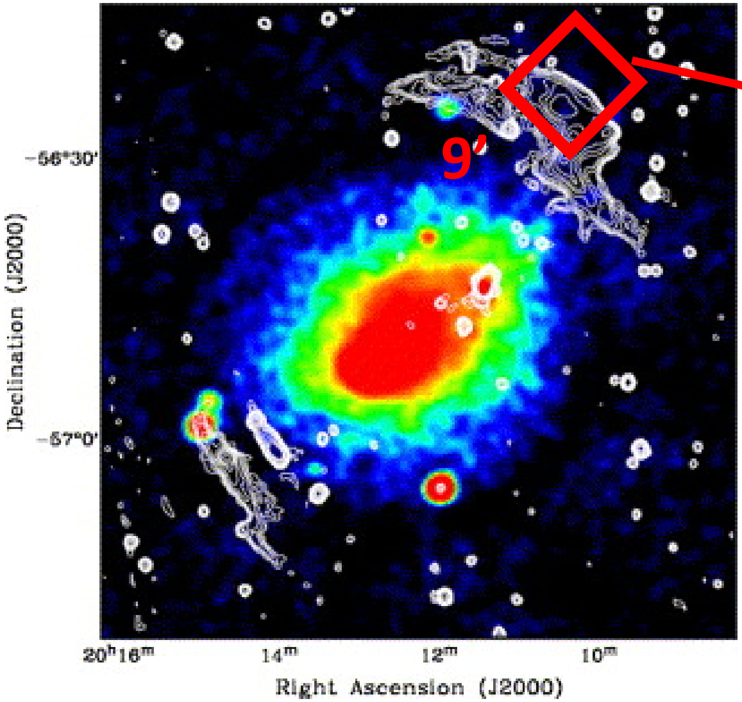
→ **Large-scale B**

So far, only upper limits on F_{IC}

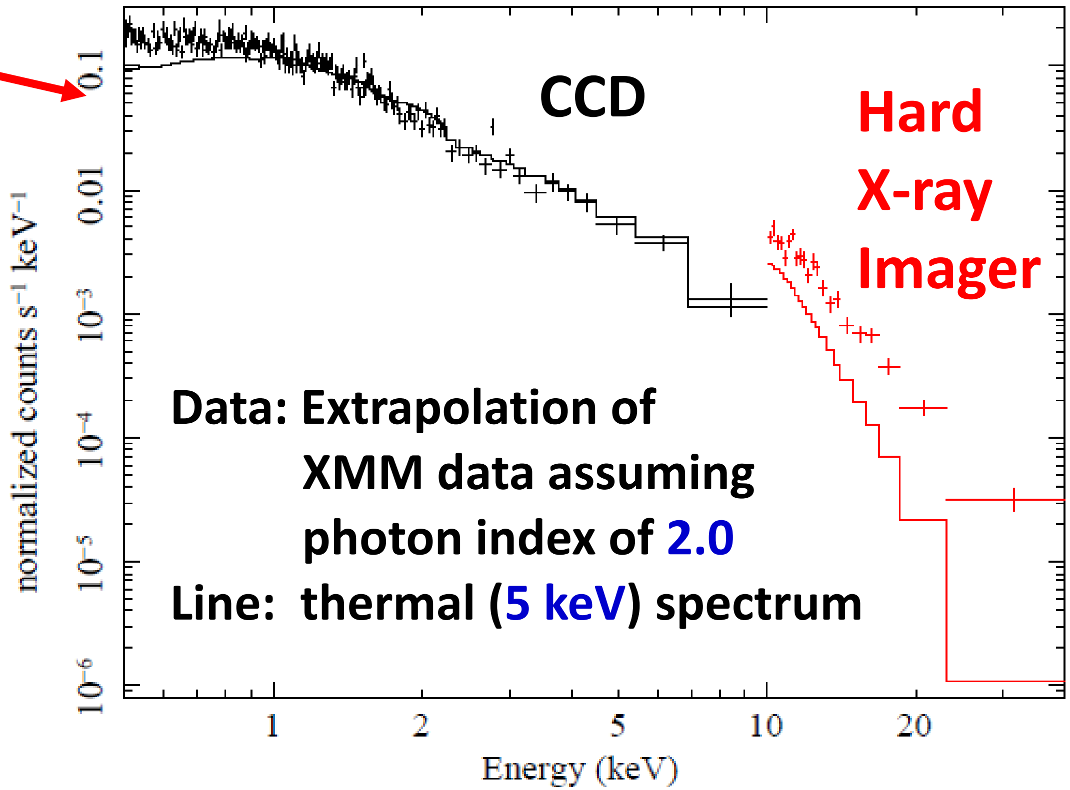
or $B > 0.1 \sim 1\mu G$

Broad-band: Non-thermal emissoin

A3667 NW relic (3.7Jy@1.4GHz, Johnston-Hollitt et al. 2008)

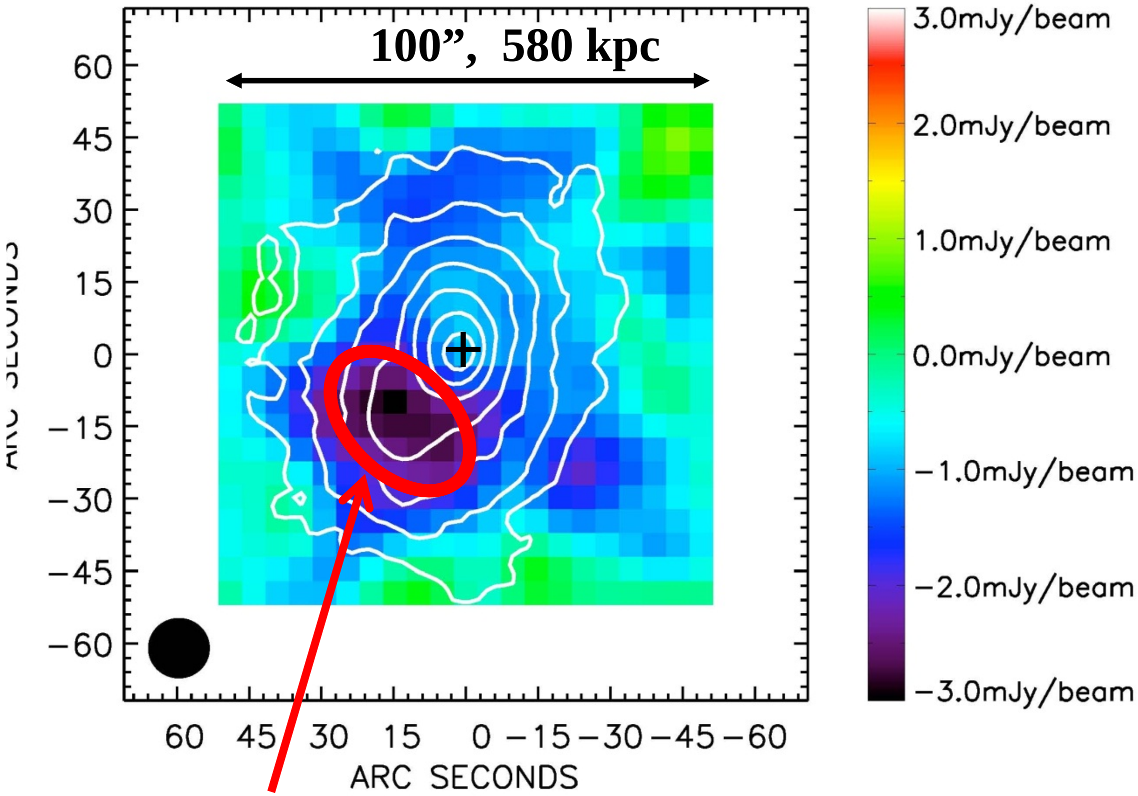


color: X-ray, contours: radio
(Feretti et al. 2004)



- PSF (1.7'HPD) is larger than NuSTAR (1'), but a pre-collimator blocks contamination from outside FOV → off-center relics
- 6 times deeper than Suzaku → if no-detection, B>4 μG (current best estimate: depends on backgrounds in orbit)

Broad-band: very hot (kT>>10keV) gas



150GHz SZ image of RXJ1347-1145

- **SZE & Chandra X-ray** (TK+04)

  $I_{SZ} \propto \int n_e T_e \, dl$ & $I_X \propto \int n_e^2 \Lambda(T) \, dl$

  → $kT_{excess} = 28.5 \pm 7.3$ keV

- **Suzaku 0.4-60 keV & Chandra** (Ota+08)

  → $kT_{excess} = 25.3^{+6.1}_{-4.5}$ keV

Likely in the transient state right after (<Gyr) shock heating.

Also inferred in
A3667 (Nakazawa+09)
A2163 (Ota+14)
Bullet cluster (Wik+14)
etc.

Broad-band spectra are crucial for separating this gas from cooler or non-thermal components.

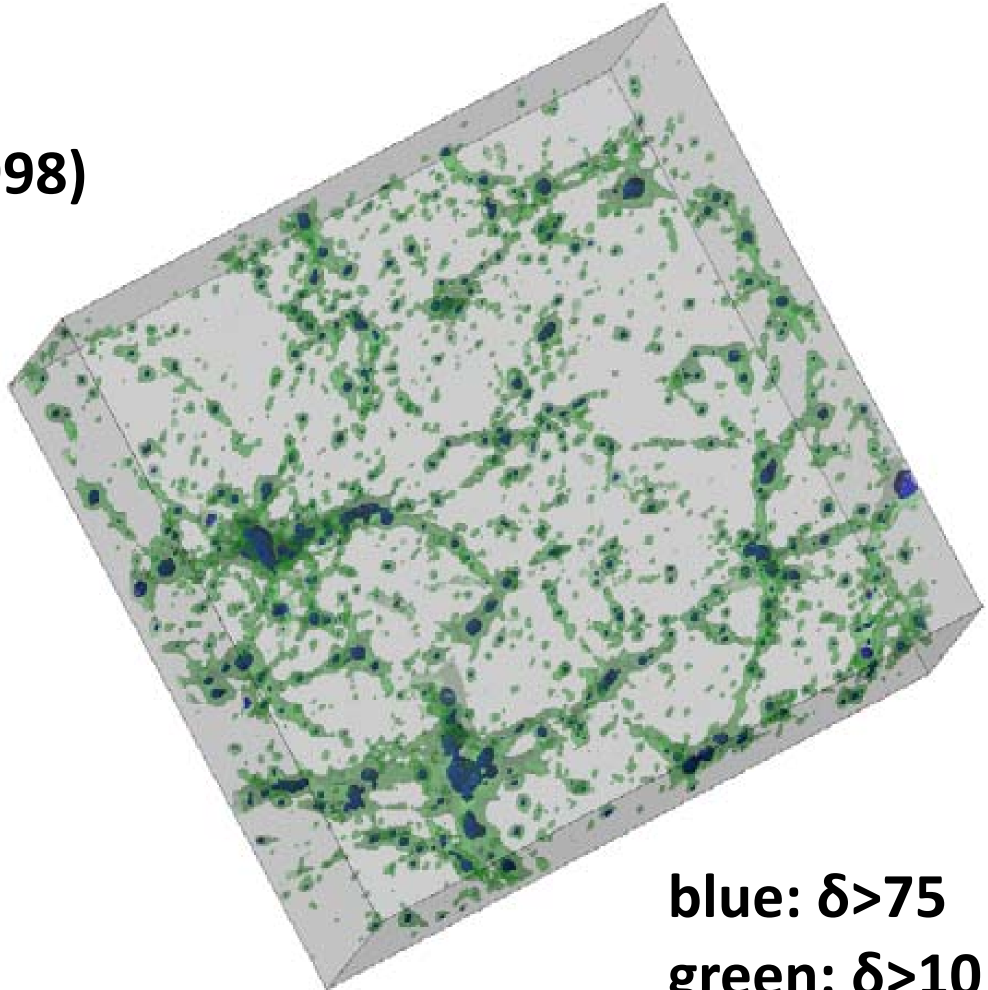
Further challenges:
Search for missing components of the Universe

Warm Hot Intergalactic Medium

・Observed baryon density < Ω_B
(Fukugita, Hogan & Peebles 1998)
→ Missing Baryon

・Theoretical prediction:
→ Bulk of baryon is WHIM
with $kT = 10^5 \sim 10^7$K
$\delta = 10 \sim 100$
(e.g., Cen & Ostriker 1999)

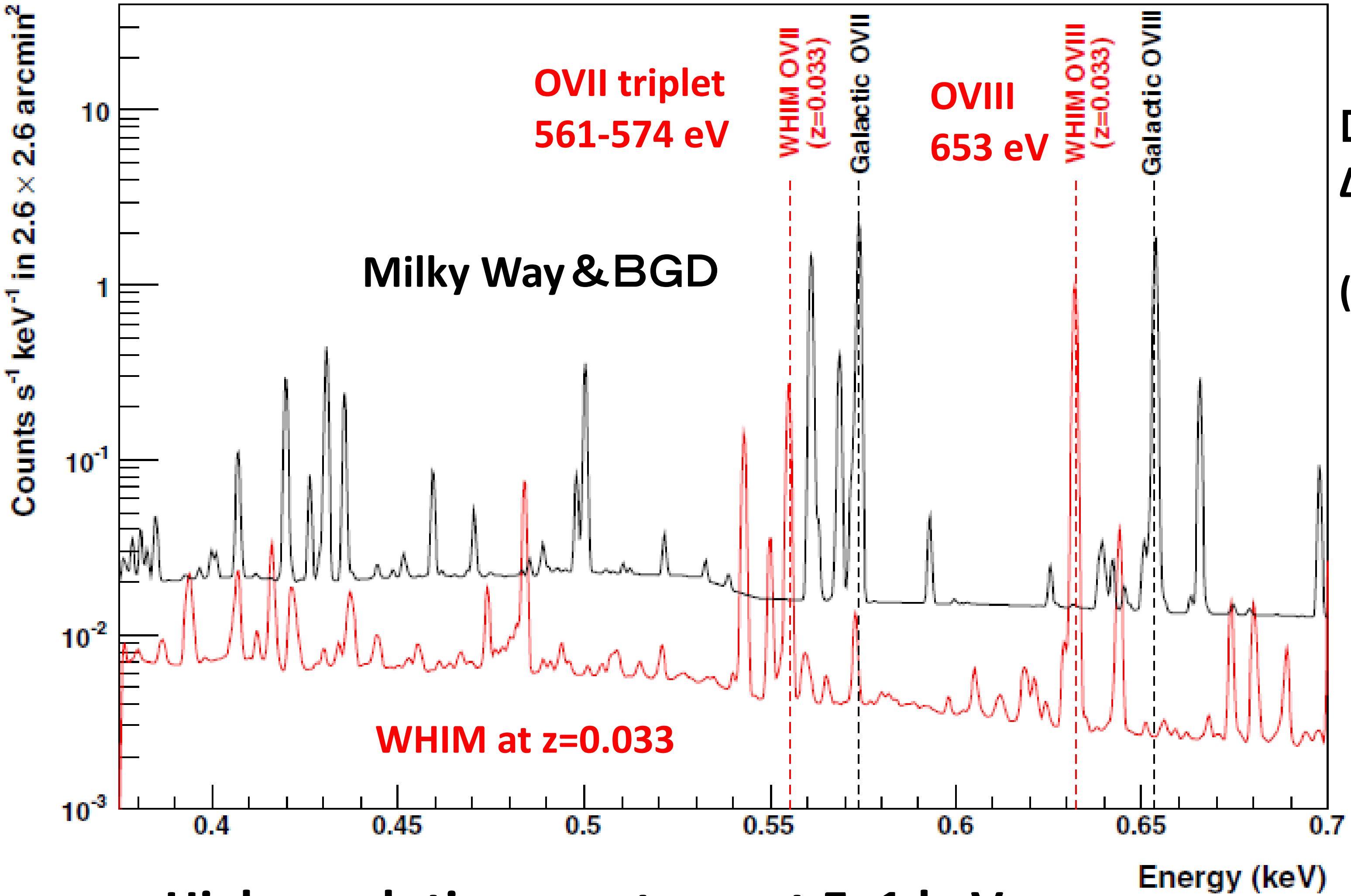
⇒ Can be probed in soft X-rays
via OVII, OVIII, NeIX,,,
(probes higher T than UV,
less sensitive to photoionization)

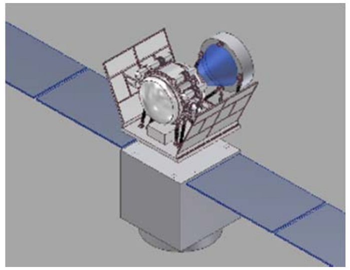


blue: $\delta > 75$
green: $\delta > 10$

Simulated distribution of WHIM
70Mpc=5.5 deg at z=0.2
(Takei et al. 2011)

Mock WHIM spectrum (DIOS)





DIOS 5Ms
ΔE=2eV
FOV=1 deg
(Takei et al. 2011)

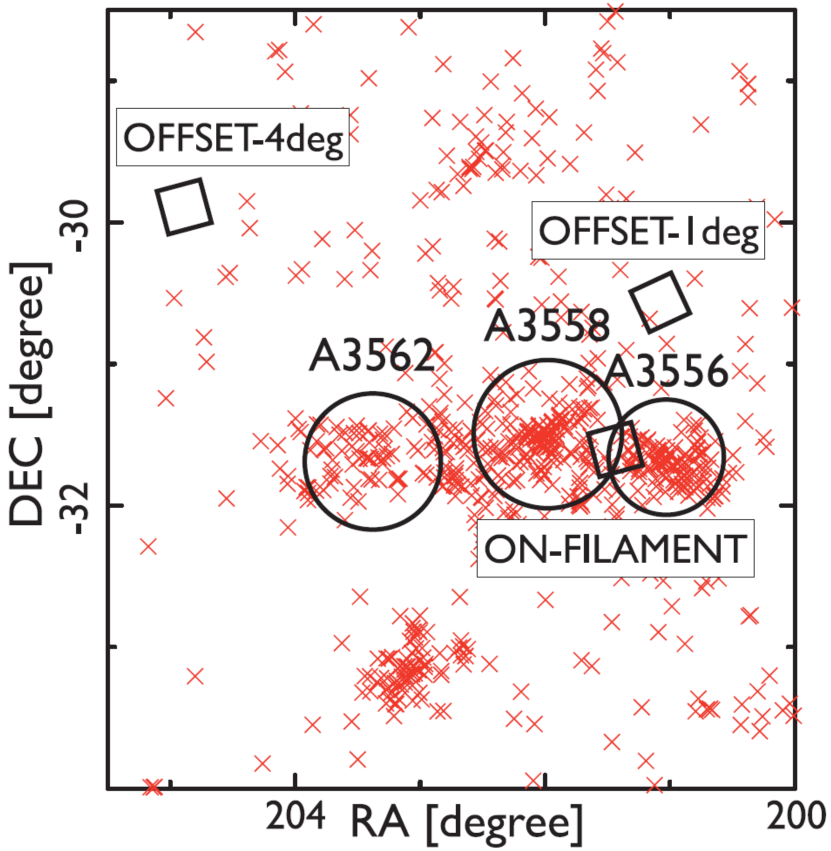
After ASTRO-H!

High resolution spectrum at E<1 keV

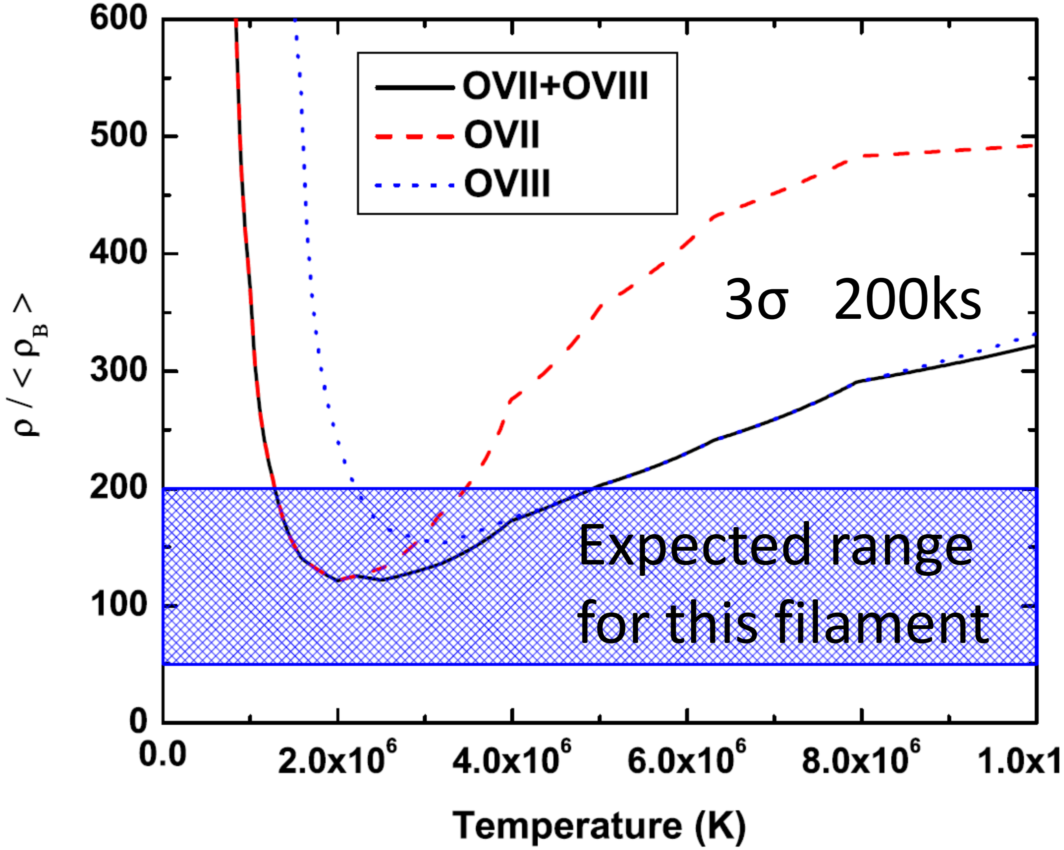
→ separate redshifted OVII , OVIII lines from Milky Way

ASTRO-H will serve as a pathfinder

Expected limits by ASTRO-H



Shapley supercluster at z=0.048 (Mitsuishi+2012)



ASTRO-H can resolve OVII/OVIII emission lines for the first time; Limits on δ scale as $(Z/0.3solar)^{-1/2}(L/3Mpc)^{-1/2}$

Dark Matter

- No detection in laboratory experiments or in γ-rays, so far.

- Robust (nearly model-independent) bounds:
  a) If **fermion**,
  phase space density for dSph → $m_{DM} > 0.4$ keV
  (Tremine & Gunn 79; Boyarsky+09)
  b) If **initial velocity ～ thermal**,
  free-streaming < galaxy scale → $m_{DM} >$ O(keV), WDM

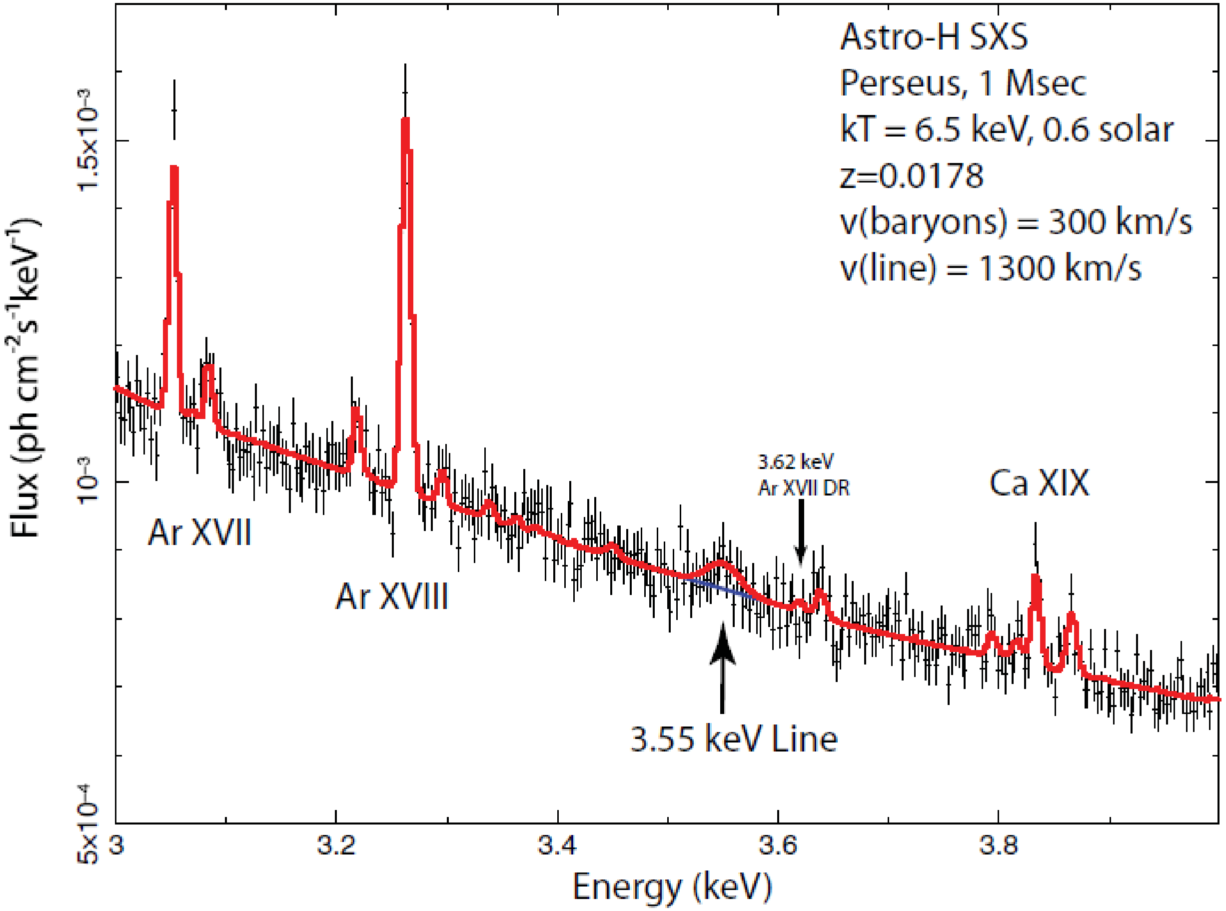
⇒ The lightest plausible candidates can be searched in X-rays,
if they decay into photons within ～10^{20} yrs

$$F_X \sim 3\times10^{-14}\mathrm{erg/s/cm^2}\left(\frac{\Gamma}{(10^{20}\mathrm{yr})^{-1}}\right)\left(\frac{E_\gamma}{mc^2/2}\right)\left(\frac{M_{\mathrm{DM}}^{\mathrm{FOV}}}{10^{10}M_\odot}\right)\left(\frac{D_L}{\mathrm{Mpc}}\right)^{-2}$$

Decay rate = 1/lifetime

DM Surface density

How can we verify/reject a DM line?



Expected ASTRO-H spectrum of a suggested unidentified line at 3.55 keV (Bulbul et al. 2014; see also Tamura et al. 2015)

Line width: v-dispersion vs. Plasma lines: thermal $\propto (m_{ion})^{-1/2}$ & turbulence

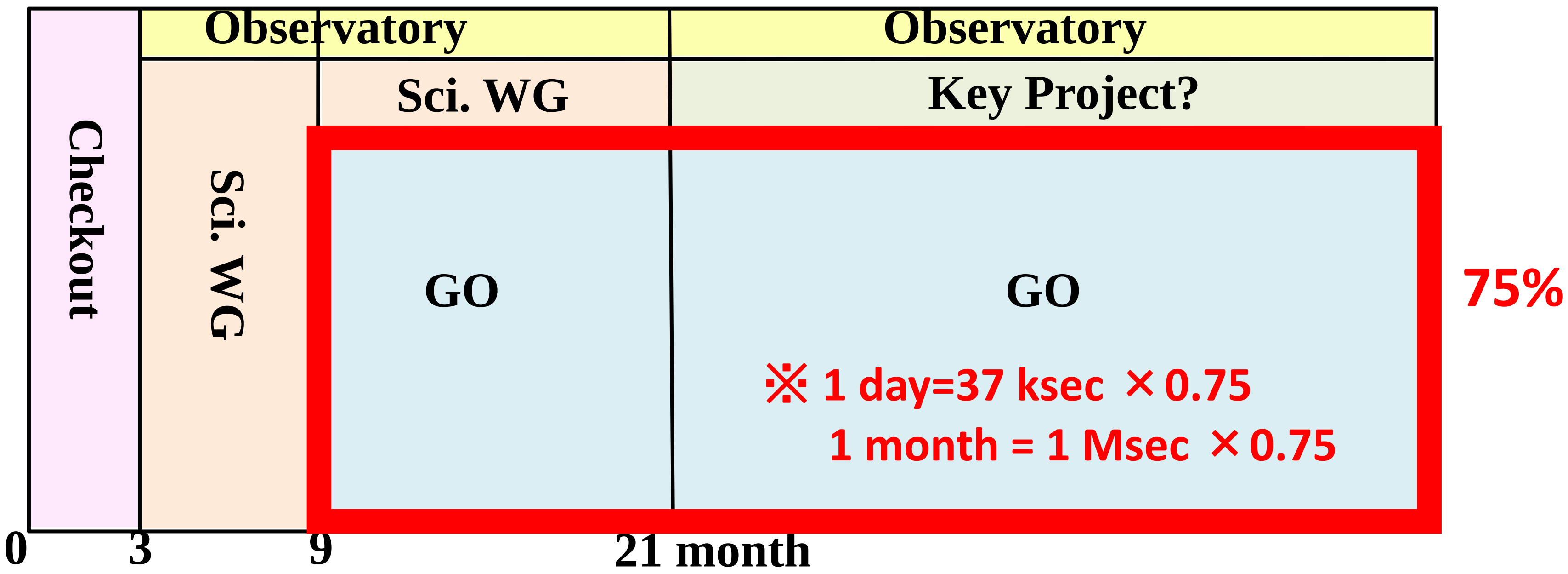
Line centroid: redshift vs. instrumental effects i.e., $\Delta z<0.01$ → $\Delta E<10eV\ (E/keV)$

Can be distinguished for the first time by ASTRO-H.

ASTRO-H Operation Schedule

Phase 0 : 3 Months : Satellite/Instruments Check out (including Calibration))
Phase 1 : 6 Months : SWG 90 % (PV Phase) Observatory 10 %
Phase 2 : 12 Months : SWG Carry Over 15 %, GO 75 %, Observatory 10 %
Phase 3 : Rest of the mission : KeyProject 15 % (TBD) , GO 75 %, Observatory 10 %

Observatory 10 % = Calibration + TOO + Director's Time



Data policy among J/Europe/US in the GO time, would be similar to the Suzaku case. But we are planning to introduce key-project type and/or early-data-released type observations from early phase of the mission.

Summary

1. ASTRO-H (launch fiscal year 2015) calorimeter ($\Delta E<7$ eV) will resolve the metal lines of intracluster gas for the first time.

2. Expected accuracy for bright cluster cores: $\Delta V \sim 100$ km/s (90%).
   i.e., bulk velocity ～10% of the sound speed
   turbulent pressure ～1% of thermal pressure
   Velocity profile can be measured out to $\sim r_{2500}$ at $z<0.1$.
   (limited by photon counts and PSF)

3. Improved measurements of gas temperature, ionization balance, metal abundances, etc. & Search for missing baryon and DM

4. Simultaneous observations by Hard X-ray Imager (E>10keV, FOV=9') and CCD (E<10keV, FOV=35') will enable broadband & wide-field spectroscopy.