The Hot Universe: from Cosmological Filaments to Clusters

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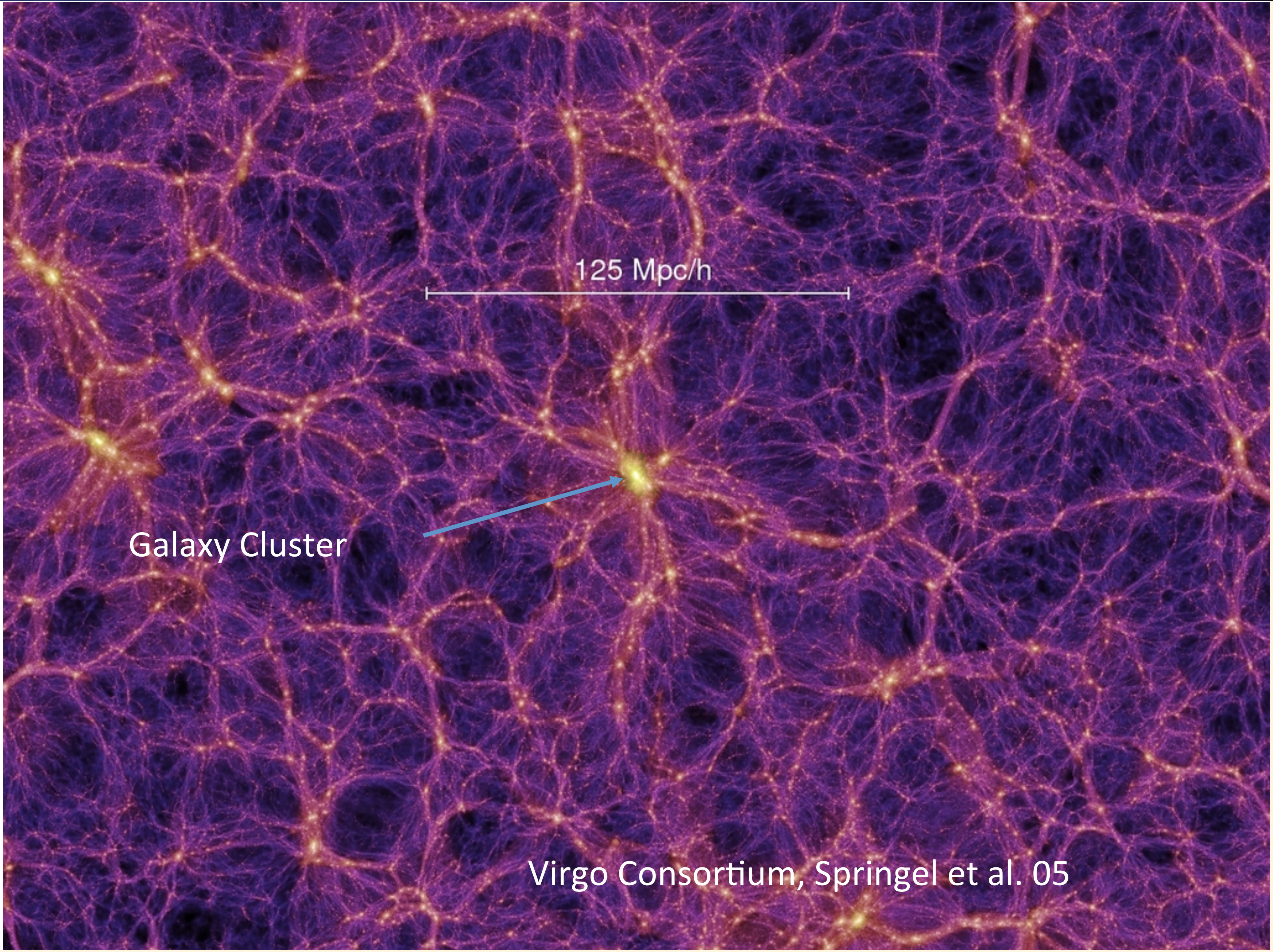
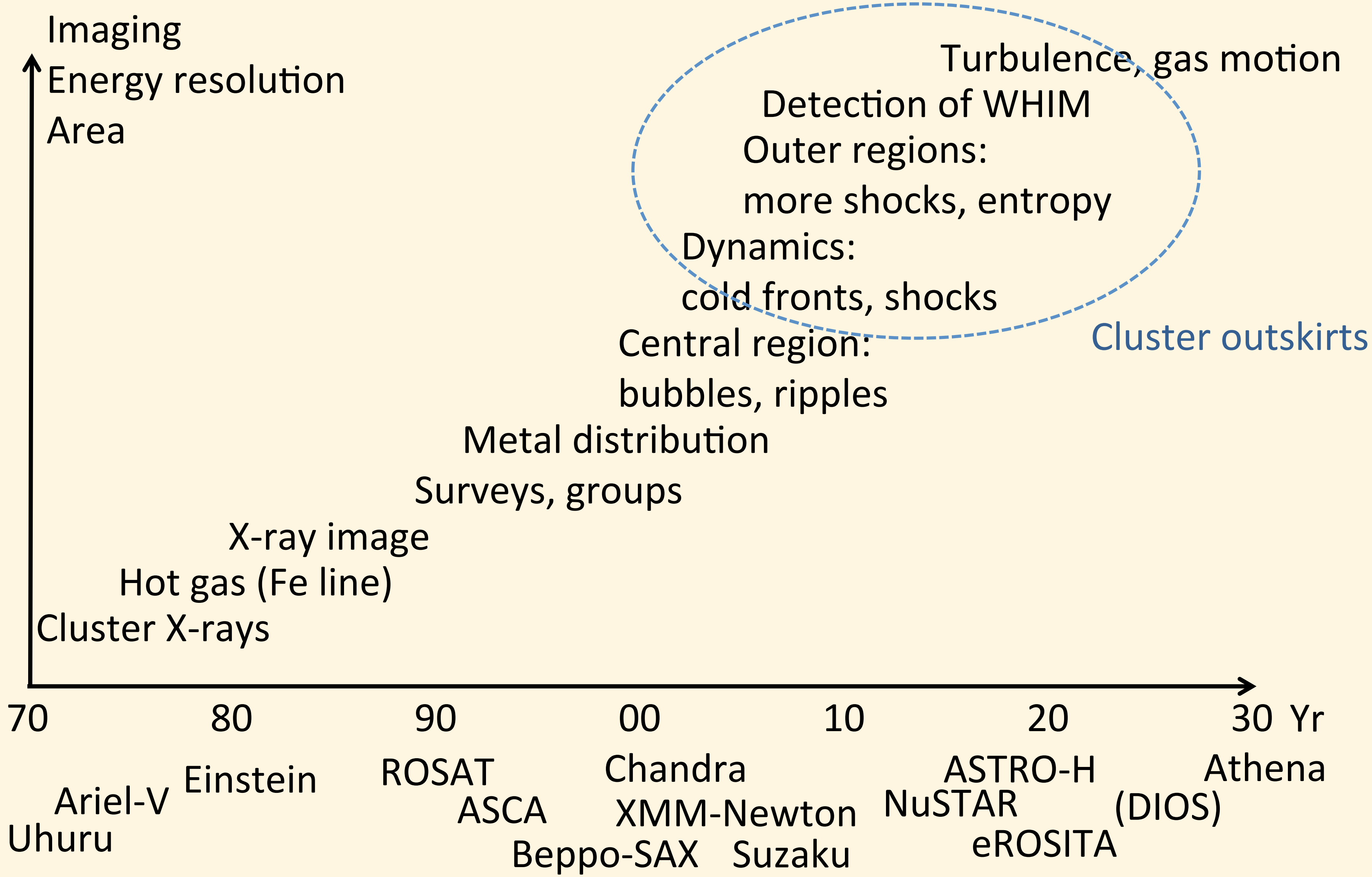
Key question and talk plan

- How does ordinary matter assemble into the large scale structures that we see today?
  - Kaastra: missing baryons and WHIM
  - Pointecouteau: Evolution of groups and clusters
  - Eckert: Astrophysics of groups and clusters
- This talk
  - Structural/thermal evolution – cluster outskirts, shocks
  - Chemical evolution – metal enrichment
  - WHIM – tracer of large scale structure
  - Athena to follow ASTRO-H (and possibly DIOS)

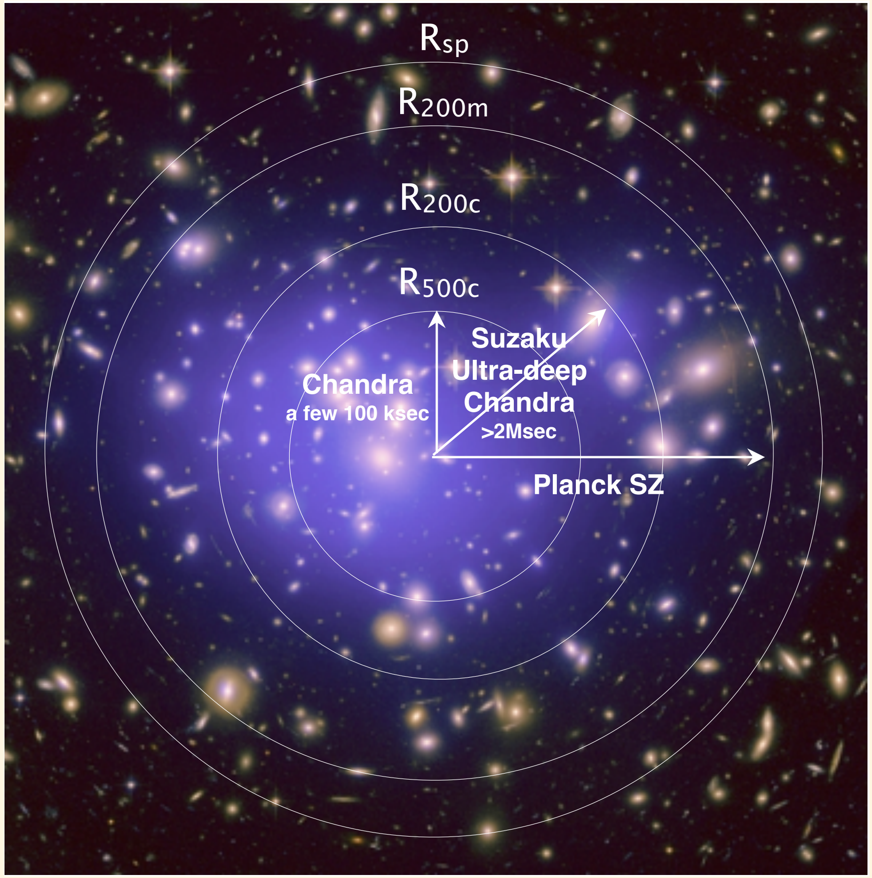
Clusters in large-scale structure



Our understanding of the hot Universe

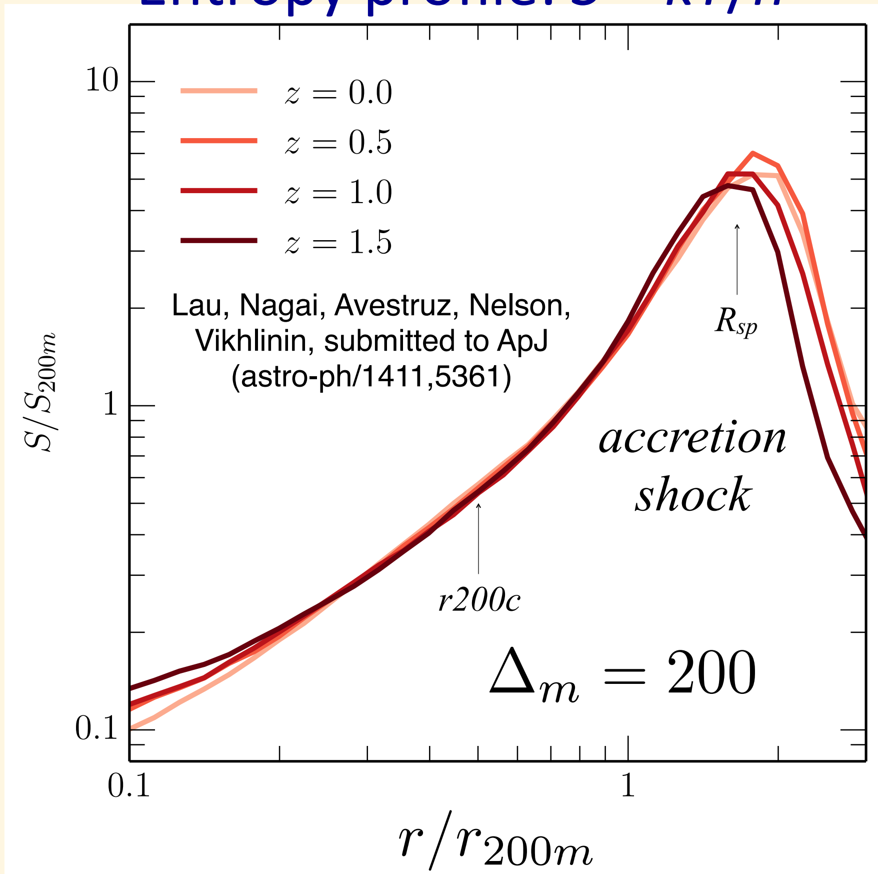


Cluster outskirts are the frontier



D. Nagai: SnowCluster 2015

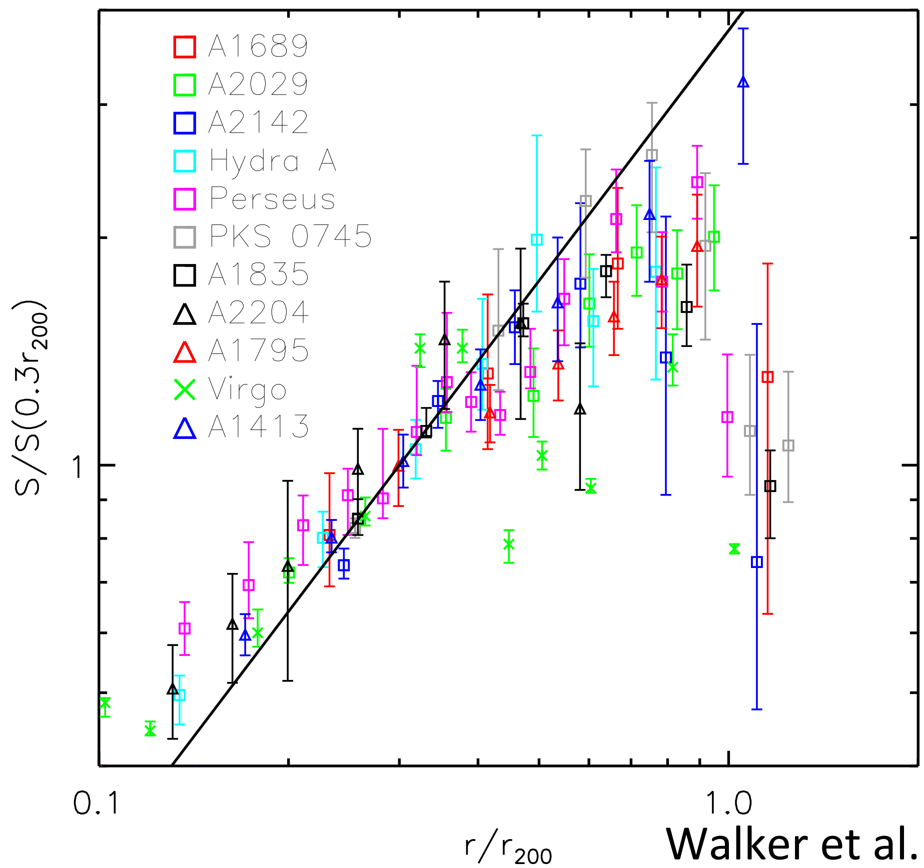
Entropy profile: $S = kT/n^{2/3}$



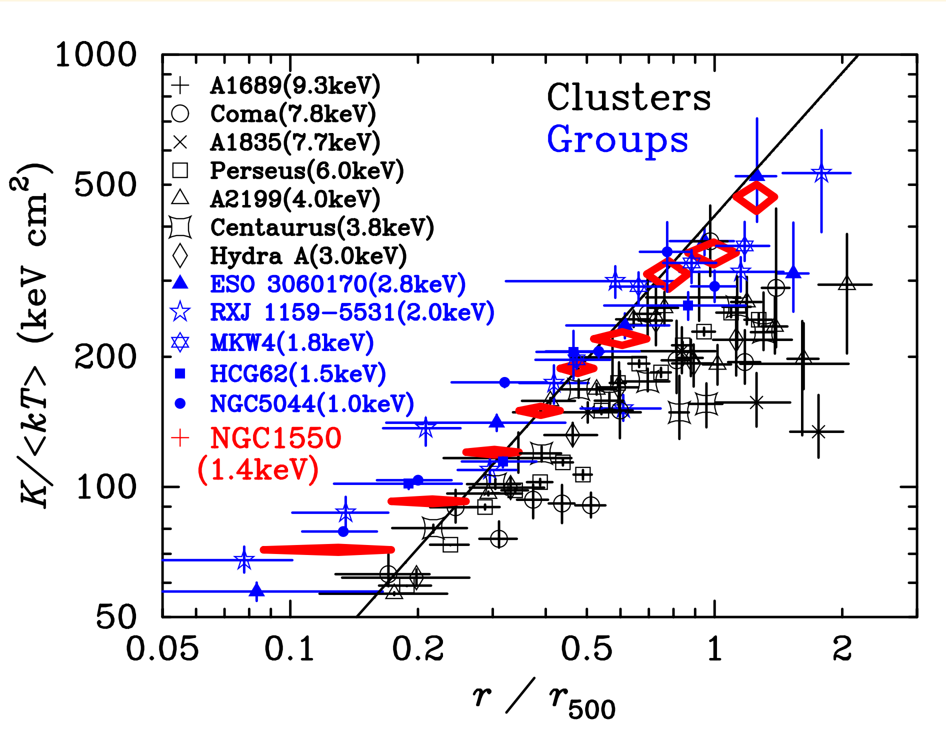
Splashback radius: drop of DM density, corresponds to accretion shock

mean matter density

Observed entropy profiles



Walker et al. 12



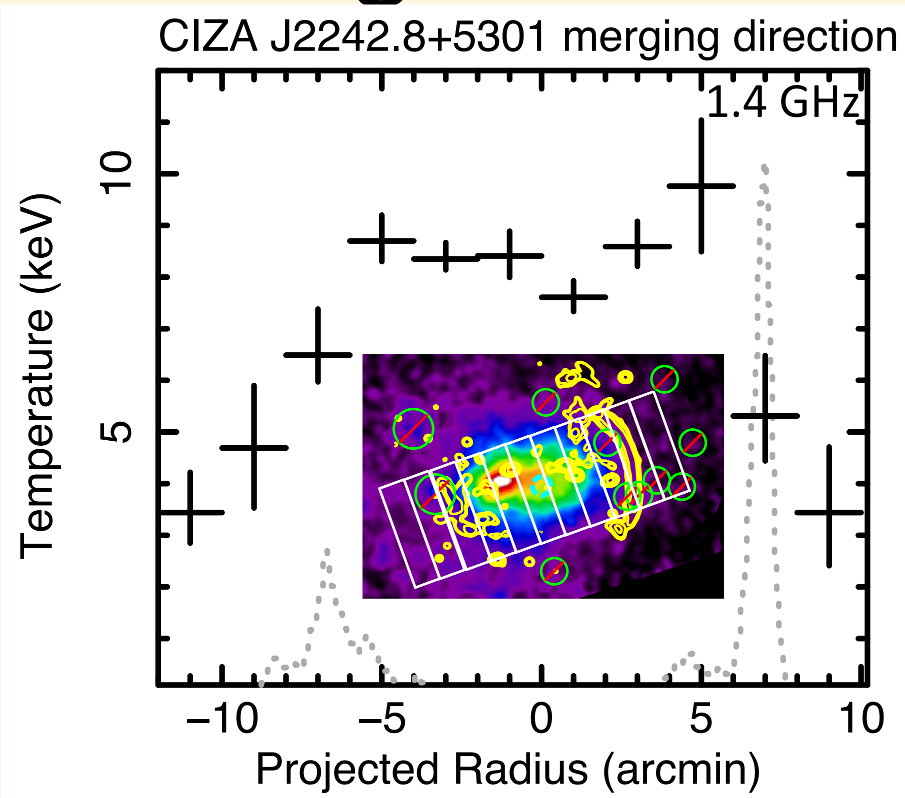
Sasaki et al. 15

Suzaku observations show entropy drops in the cluster outskirts, but not so clear for groups

Ion-electron temperature difference, gas clumpiness, or other reason of non equilibrium

Athena will measure this with >10 times more area

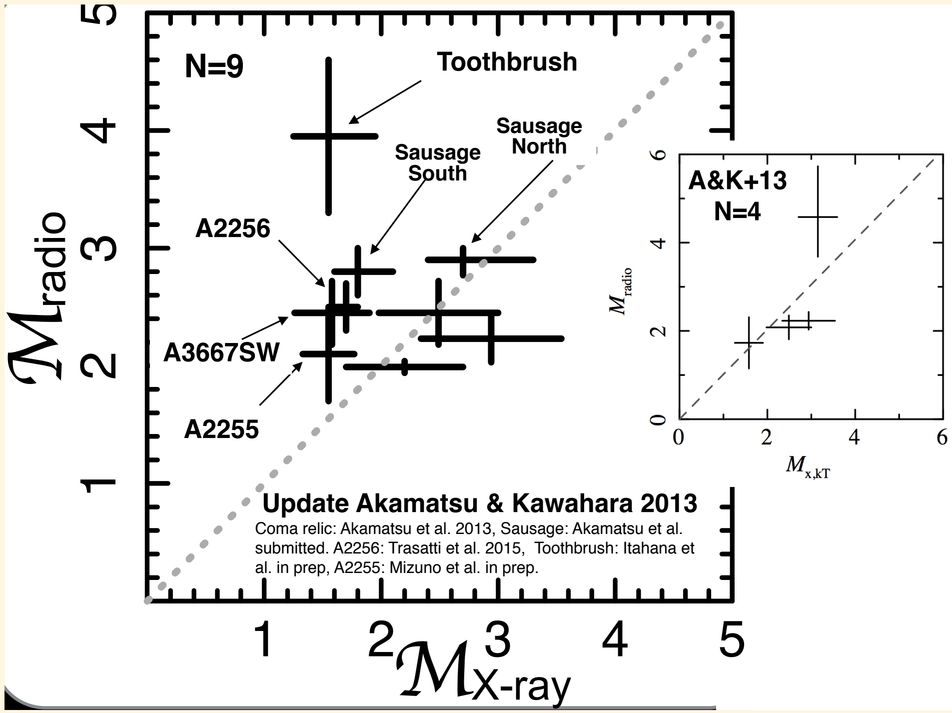
Merger shocks in cluster outskirts



Radio relics are merger shocks with M ~ 3

Good location to see actual processes of gas heating, ion-electron interaction, particle acceleration, and effect of magnetic fields.

High sensitivity like Athena is necessary for detailed studies.



H. Akamatsu "Astroparticle views of galaxy clusters" 2015

arXiv:1507.02285

Spectral resolution: He-like triplet

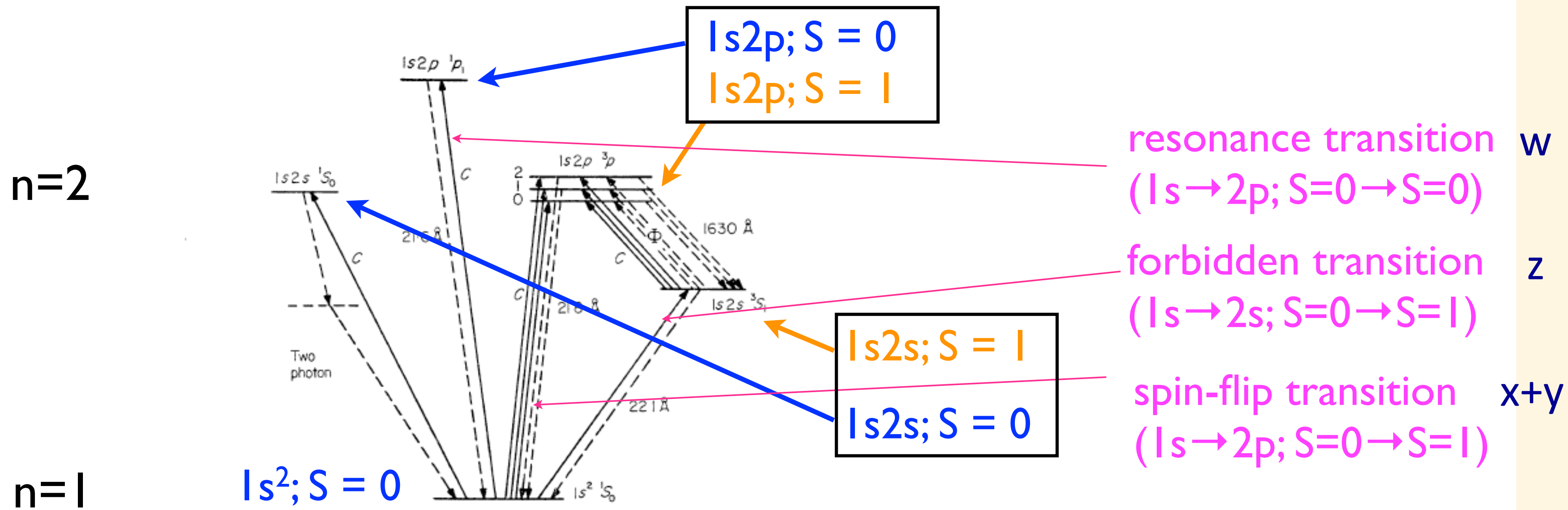
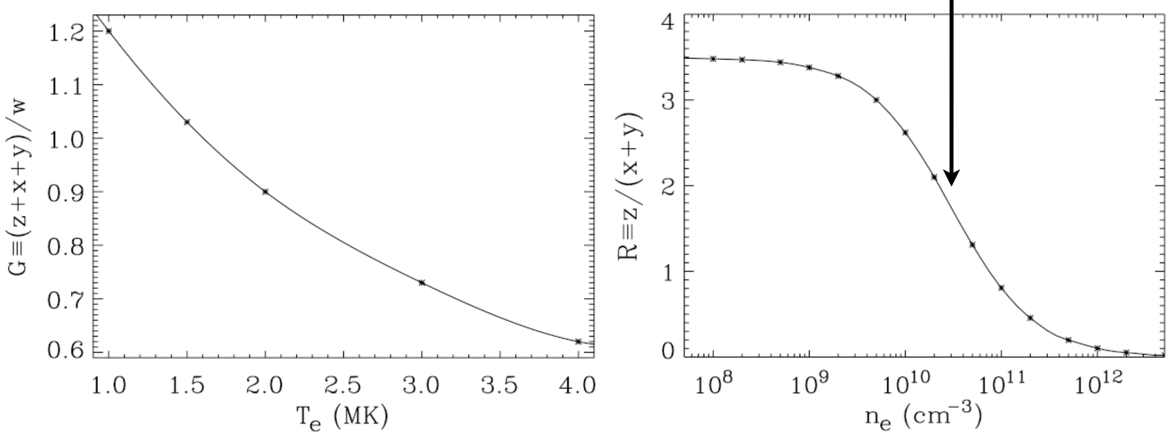


FIG. 1. *The He-like ion, showing those terms and processes involved in the present analysis. The wavelengths indicated apply to the case of oxygen VII.*

He-like Oxygen ‘critical density’

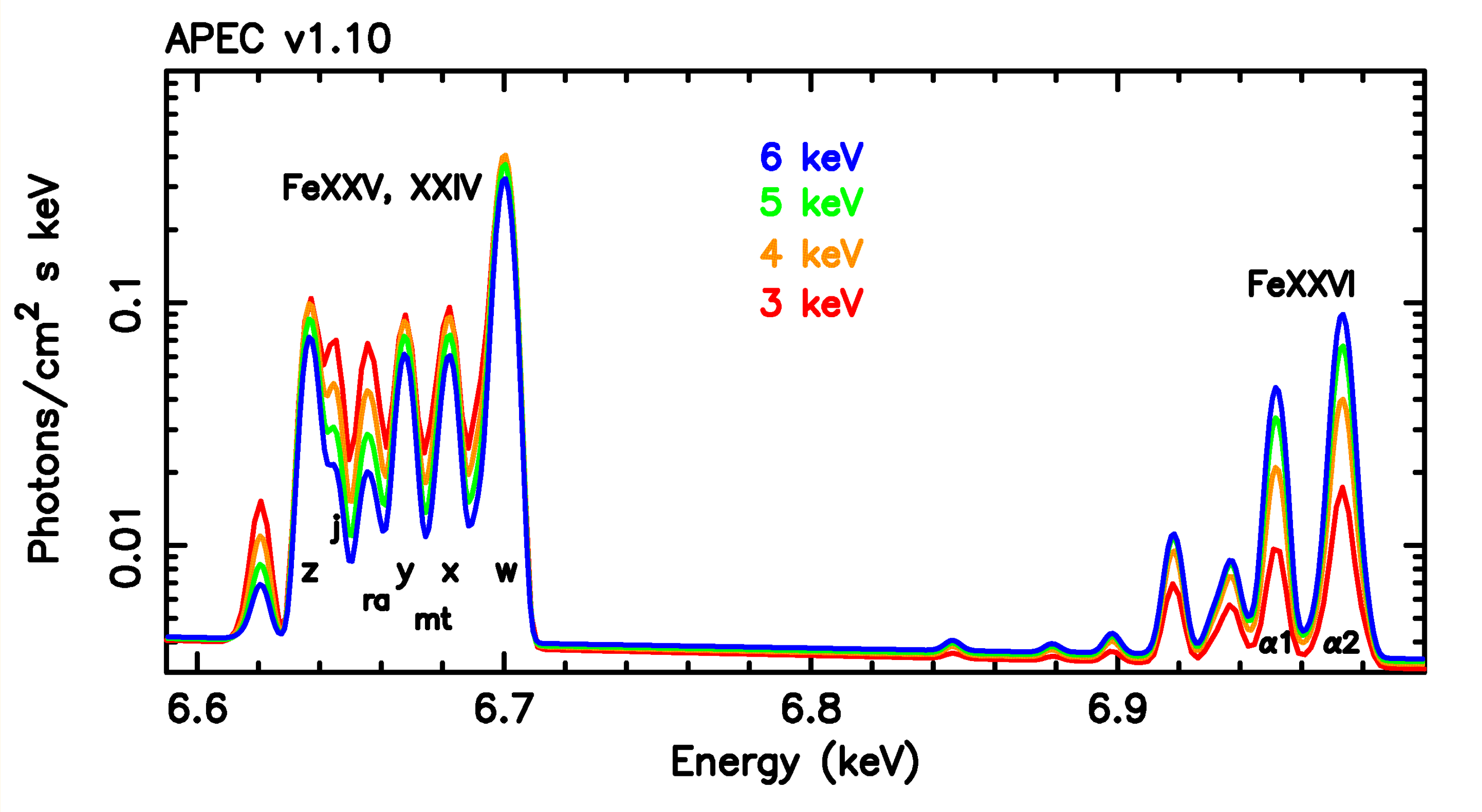


- X-IFU resolves w, x+y, z lines
- Plasma parameters (T_e, n_e) are determined directly
- Non-thermal effect can be studied (satellite lines)

Spectral resolution: Fe line profile

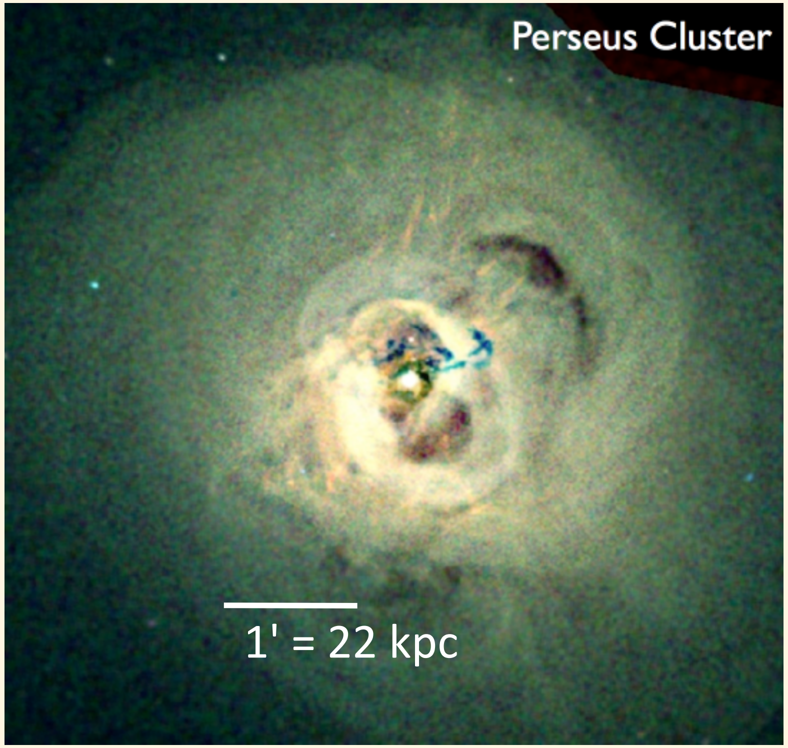
- Profile of FeXXV, XXIV complex is resolved
- Resonance and forbidden lines are separated

→ Electron temperature
Ion temperature
Deviation from Maxwellian

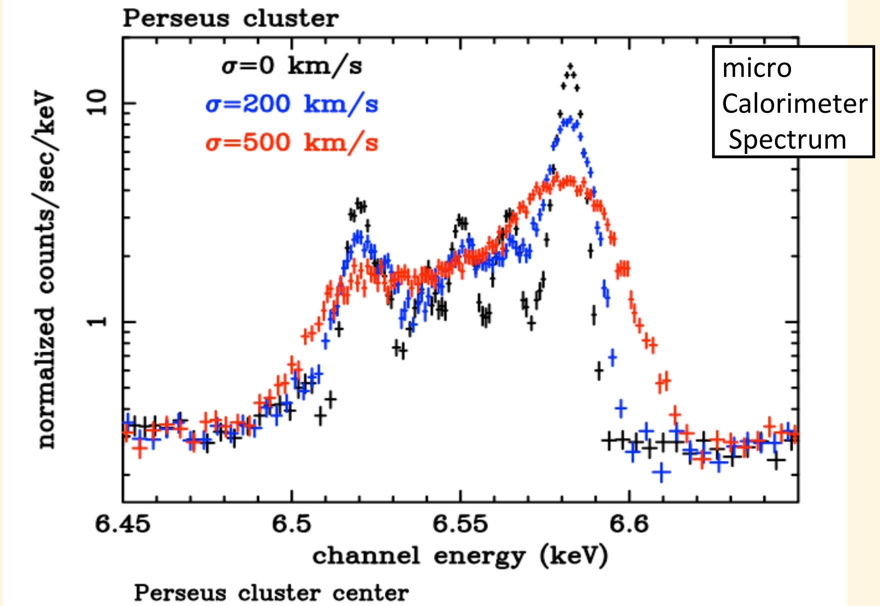


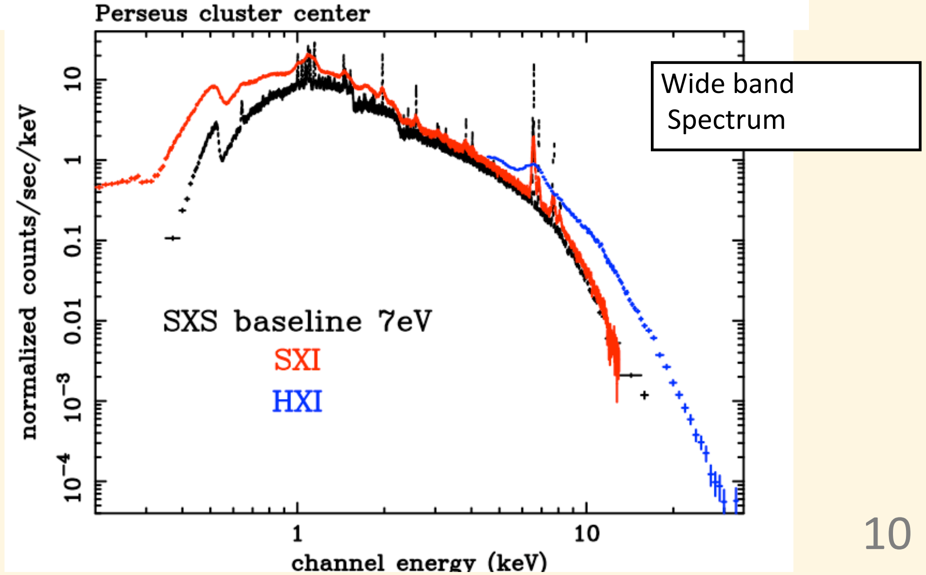
Turbulence in Clusters

Turbulence power spectrum will tell us viscosity, which converts turbulence into heat.
High angular resolution and 10-50 times more area than SXS of Athena allows us to measure it to high wave numbers.



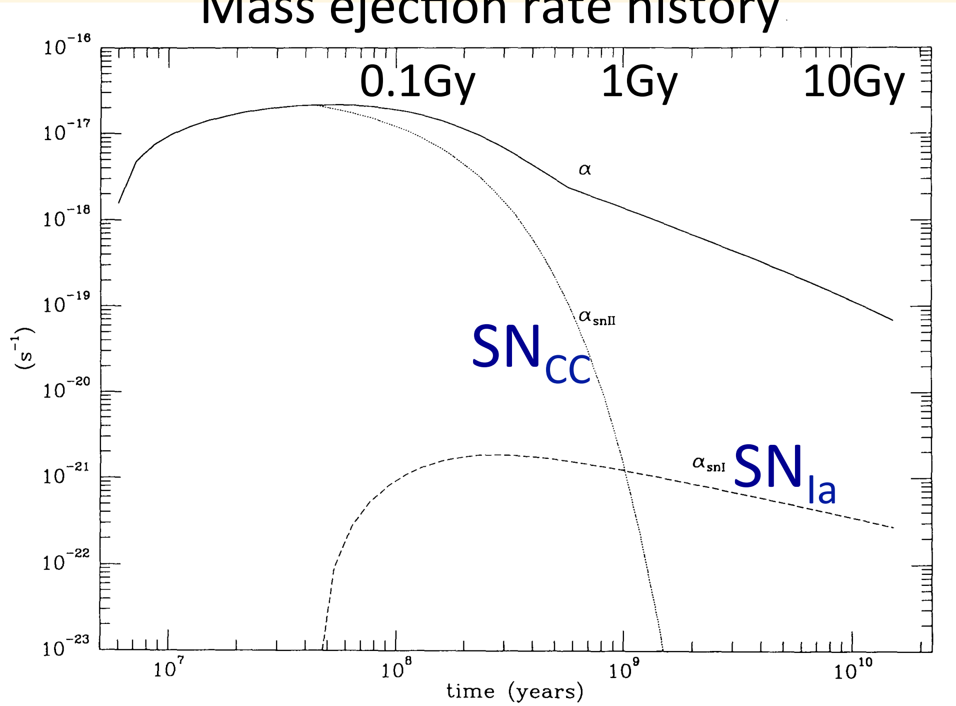
Perseus cluster (r<2', 100ks)
Turbulence and temperature structure





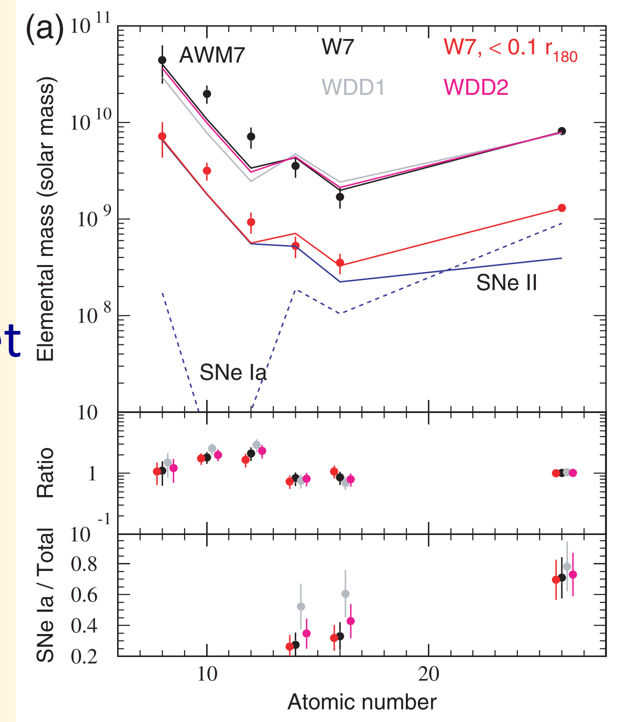
Chemical evolution

Mass ejection rate history



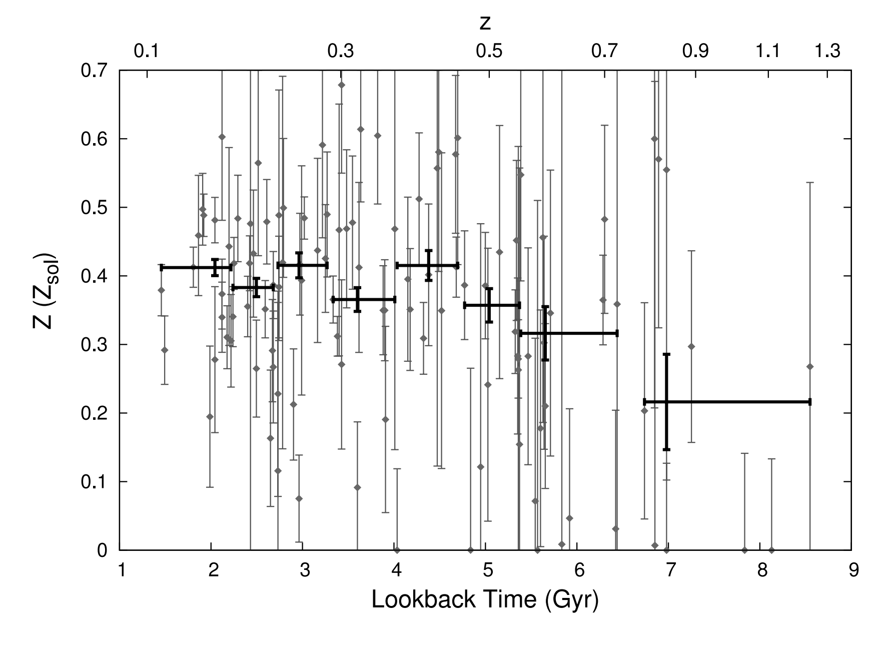
David et al. 90

Sato et al. 07



Abundance pattern should evolve in time

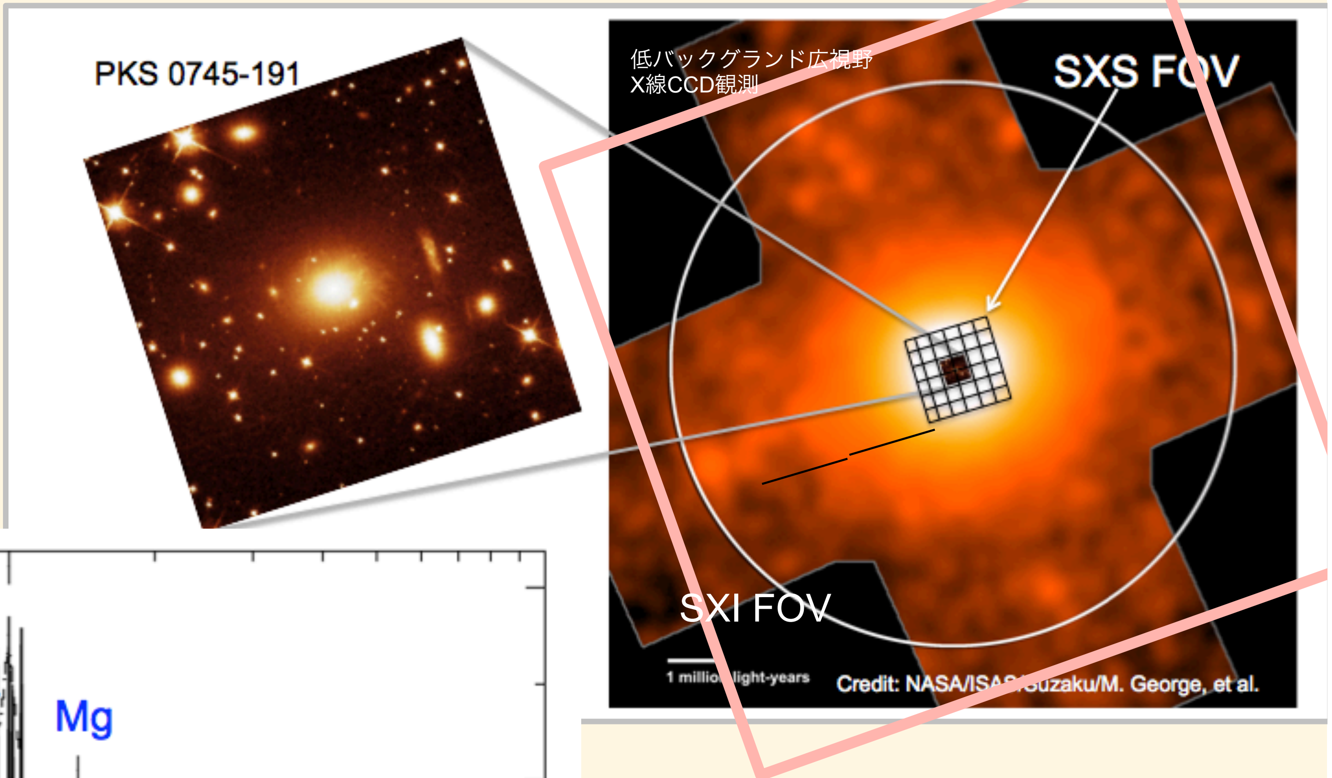
Clear evidence of metal enrichment history will be provided by high sensitivity observations

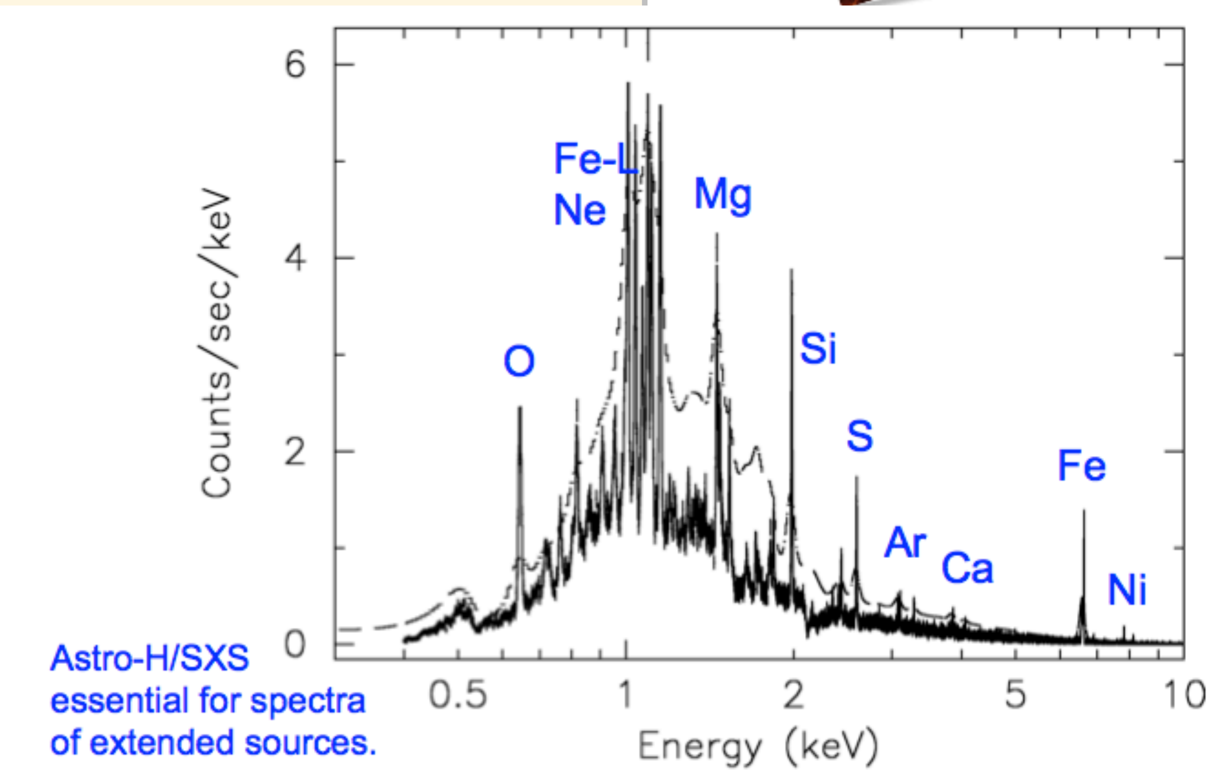


Maughan et al. 08

Elemental distribution in clusters

Cluster gas is very metal-rich, and high sensitivity of Athena will show detailed (patchy?) metal distribution in clusters

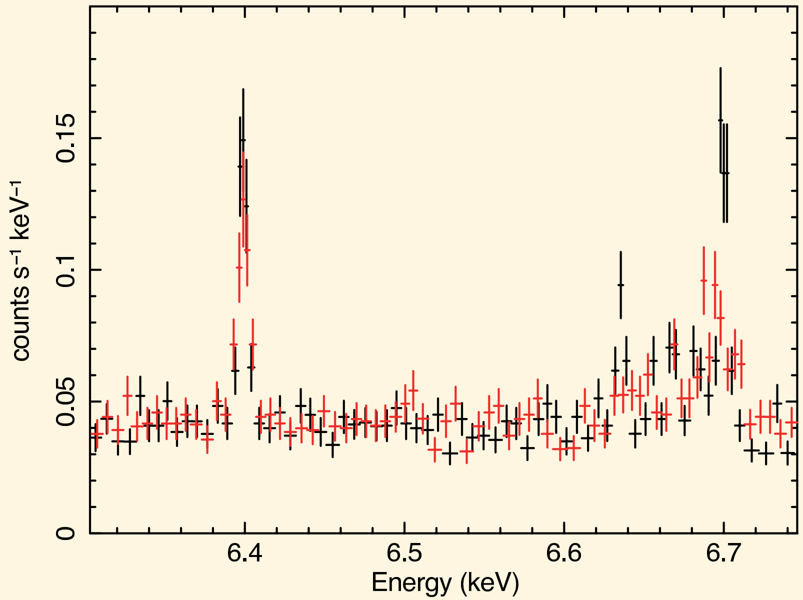




Centaurus cluster simulation for ASTRO-H: very high metal abundance in the center

Enrichment by galactic winds

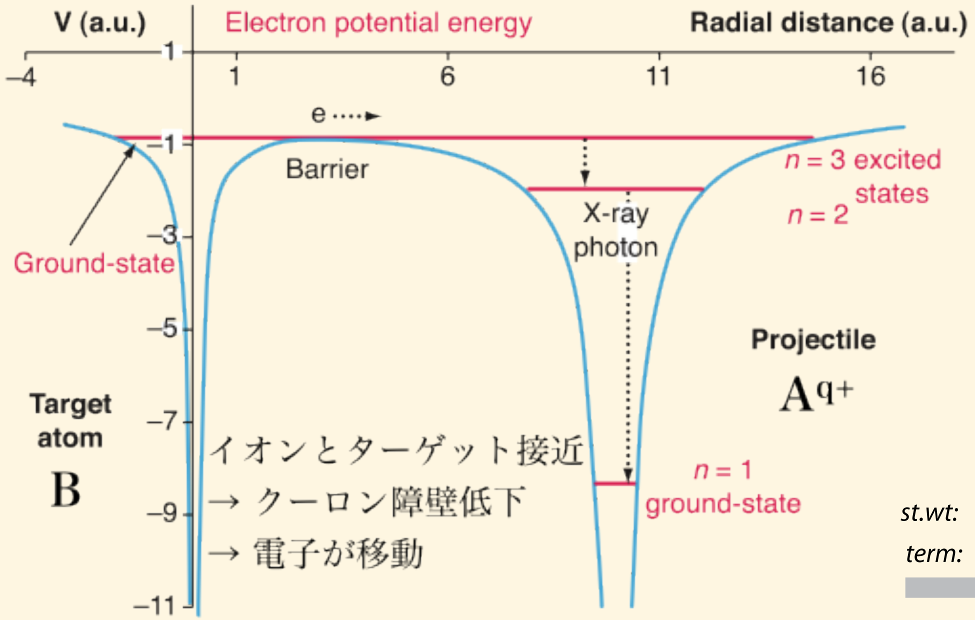
- Starburst galaxies: enrichment and heating of intergalactic space (and clusters) with galactic winds
- All galaxies experience such a period → feedback in the universe
- Athena will measure gas velocity, metal abundance and heating effect with high precision



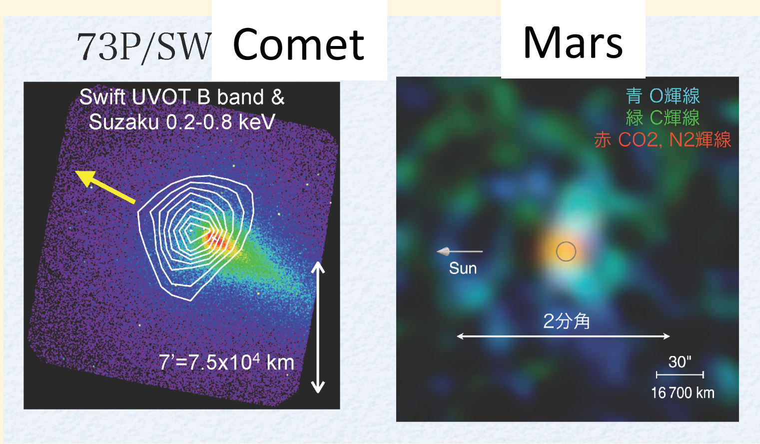
ASTRO-H: M82 200 ks simulation for wind velocities 0 (black) and 500 (red) km/s

M82 (Xray: blue, IR: red, Opt: white)

Spectral resolution: Charge exchange



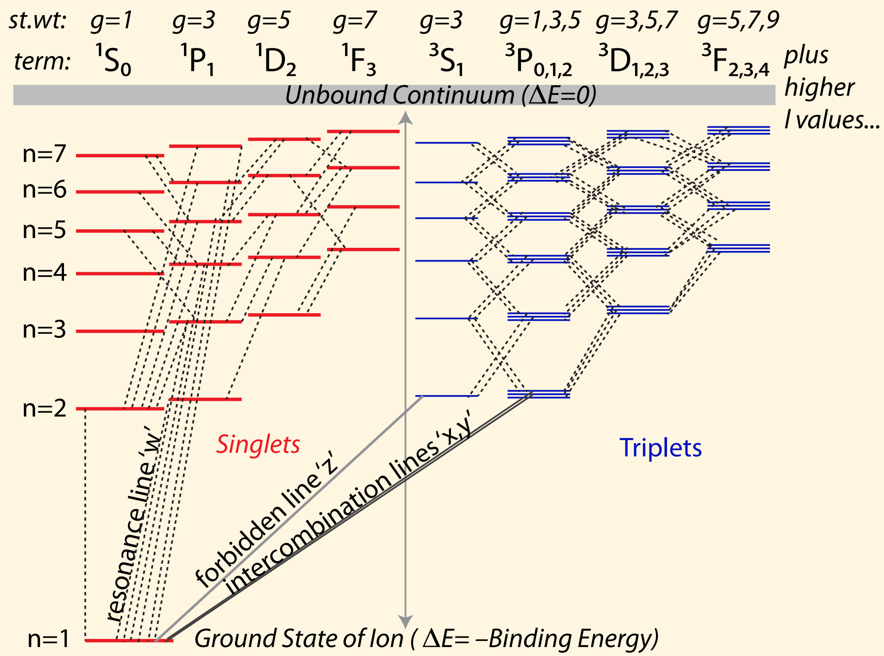
$O^{+7} + H \rightarrow O^{+6*} + p$



Collision of ion and neutral atom

- Large cross section (10^{-16} cm^2)
- Stellar wind and planetary gas
- Hot wind and neutral gas

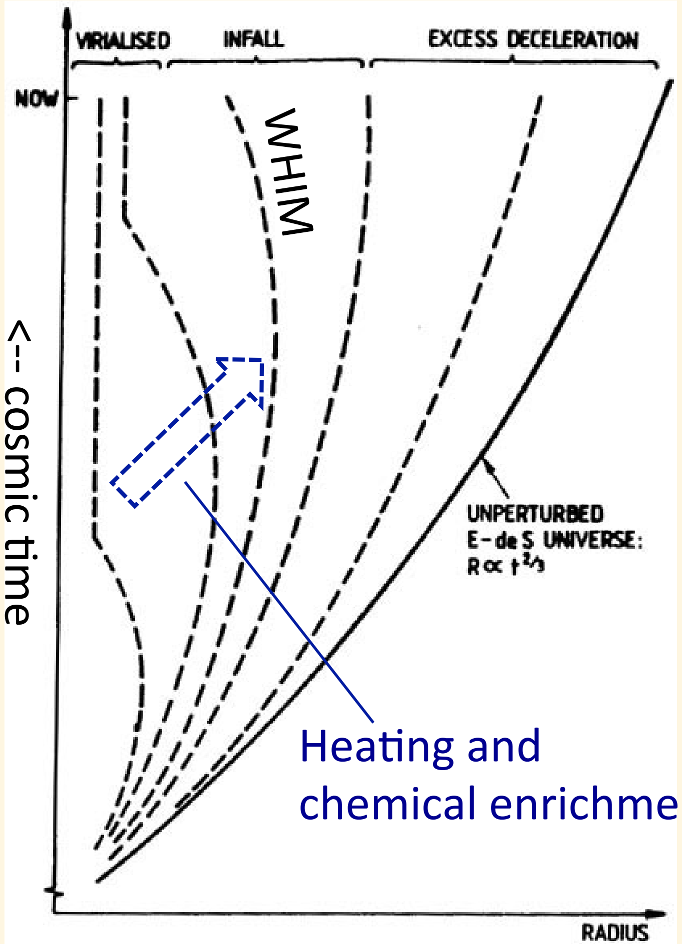
-- highly ionized lines and forbidden lines are strong



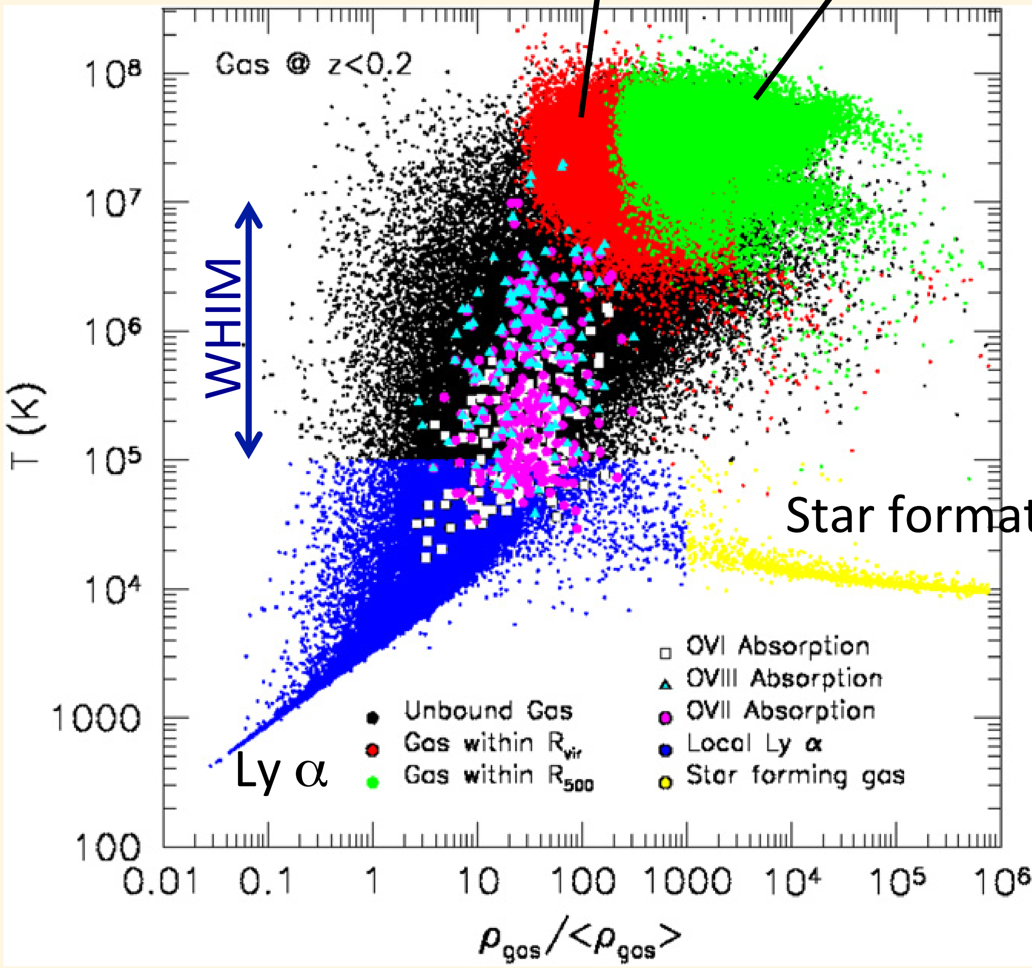
WHIM: warm-hot intergalactic medium

WHIM carries unique information on structural, thermal and chemical evolution of the Universe.

Low surface brightness, so high sensitivity is essential.



Review by M. Rees 92



Branchini et al. 09

Cosmic structure

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

= "Missing baryon"

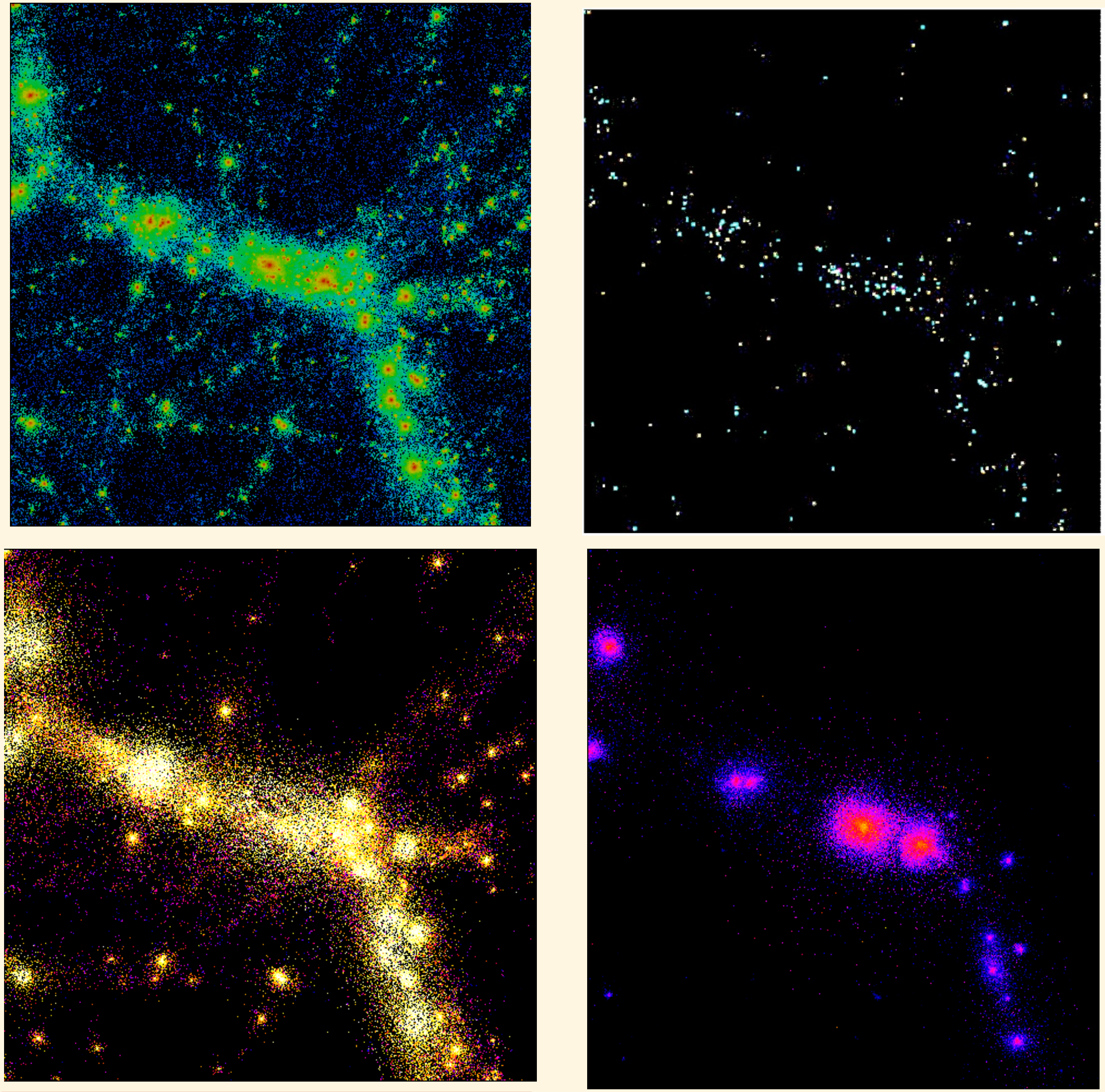
Typical matter density:

$\delta\,(=n/\langle n_B\rangle)$ = 10 - 100

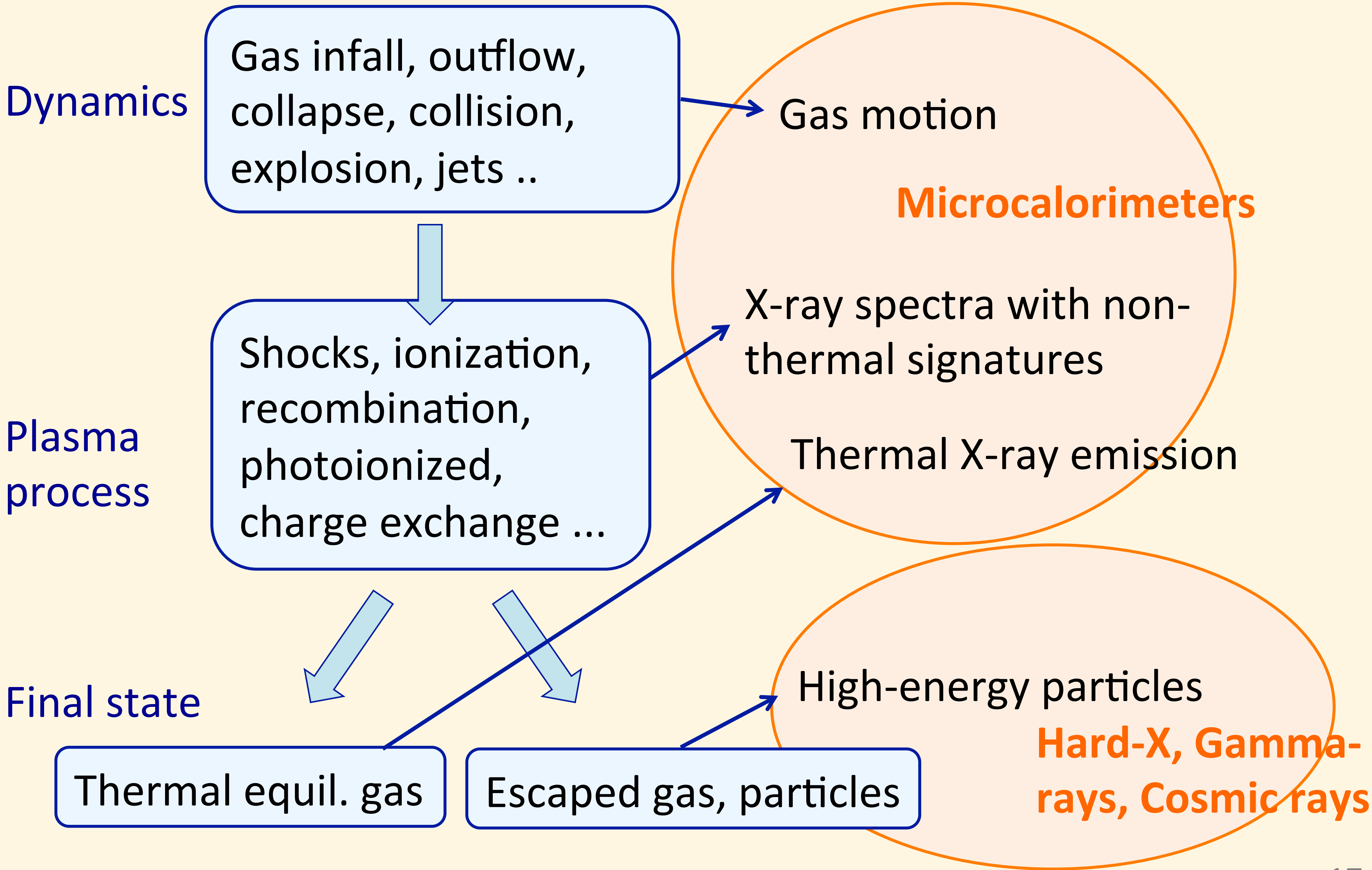
Yoshikawa et al. 2001, ApJ, 558, 520

size = 30 h^{-1} Mpc

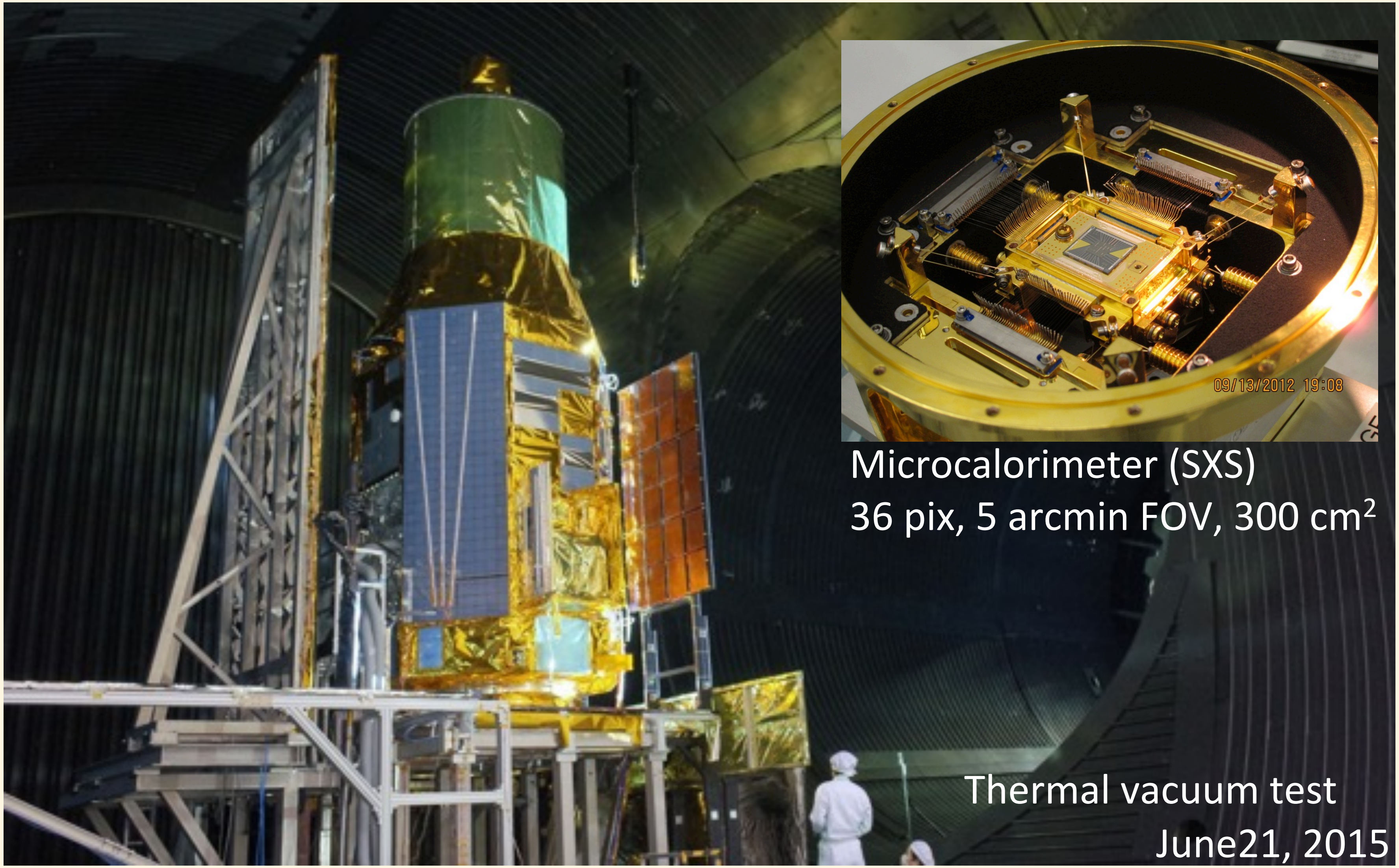
≈ 5 deg at z=0.1



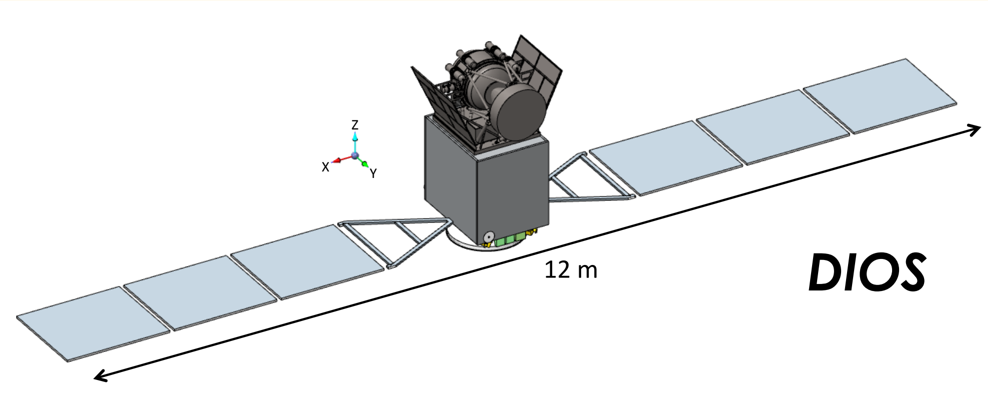
Plasma processes and spectroscopy



ASTRO-H will fly in early 2016



DIOS: dark baryon surveyor



Satellite mass: 800 – 900 kg
FOV: 30 – 50 arcminmin
Area: 200 – 1000 cm^2
Angular resolution: 3 – 5 arcmin
WHIM emission + GRB afterglow
Spectroscopy of bright or extended objects

Technology demonstration for Athena

ASTRO-H (2016)	DIOS (2022-23)	Athena (2028-)
Si calorimeter 36 pix, 7 eV He + ST/JT + 3ADR	TES calorimeter 256 pix, 2-5 eV time domain mpx Cryogen free ST/JT + 3ADR	TES calorimeter 3800 pix, 2-3 eV freq domain mpx Cryogen free ST/JT + Sorption+ADR or Dilution

Summary

- Athena will open many new features about how the "Hot Universe" has been formed over the cosmic time scale.
- Athena brings substantial improvement in all sensitivity axis (effective area, angular resolution, and energy resolution).
- What I have introduced here are only small examples, and much more will be presented later.
- Finally, let us hope the successful launch of ASTRO-H, which will show us the power of microcalorimeters.