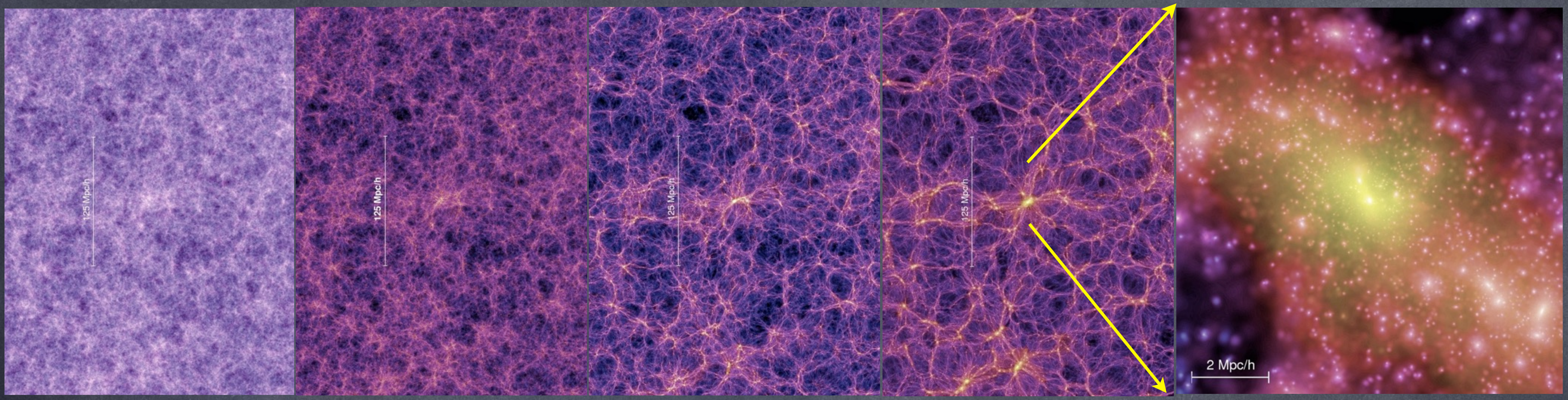
Galaxy clusters

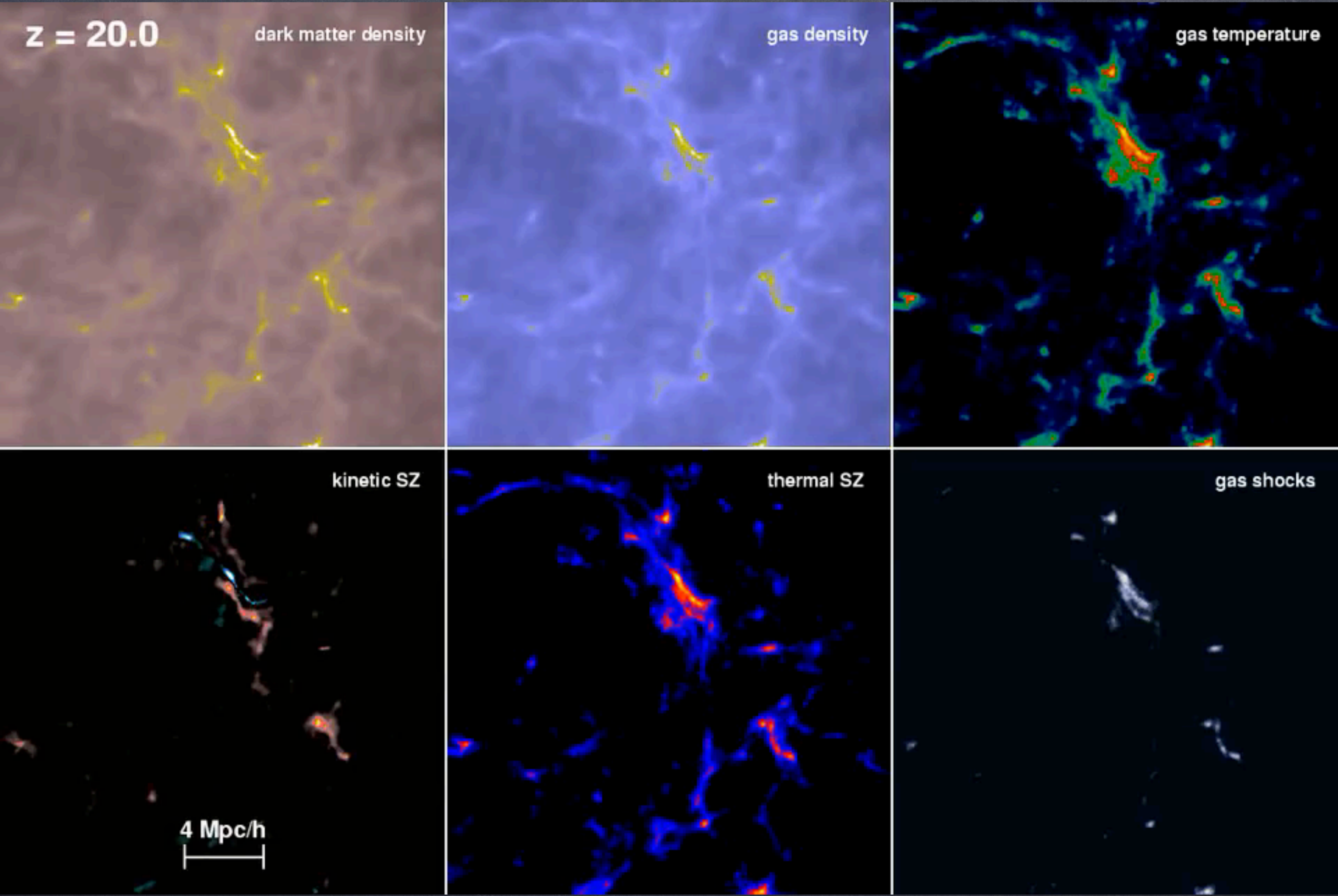
G.W. Pratt
CEA Saclay

Hierarchical structure formation



COSMOLOGICAL SIMULATION BY SPRINGEL ET AL. 2005

- Universe becomes more structured with time
- Clusters: lighthouses of the cosmic web
- **Cosmological tools**: formation & evolution depend on underlying cosmology
- **Representative of the Universe as a whole**: 90% dark matter; 9% hot gas; 1% galaxies
- **Statistical properties** allow us to understand the physics of structure formation


z = 20.0
dark matter density
gas density
gas temperature
kinetic SZ
thermal SZ
gas shocks
4 Mpc/h

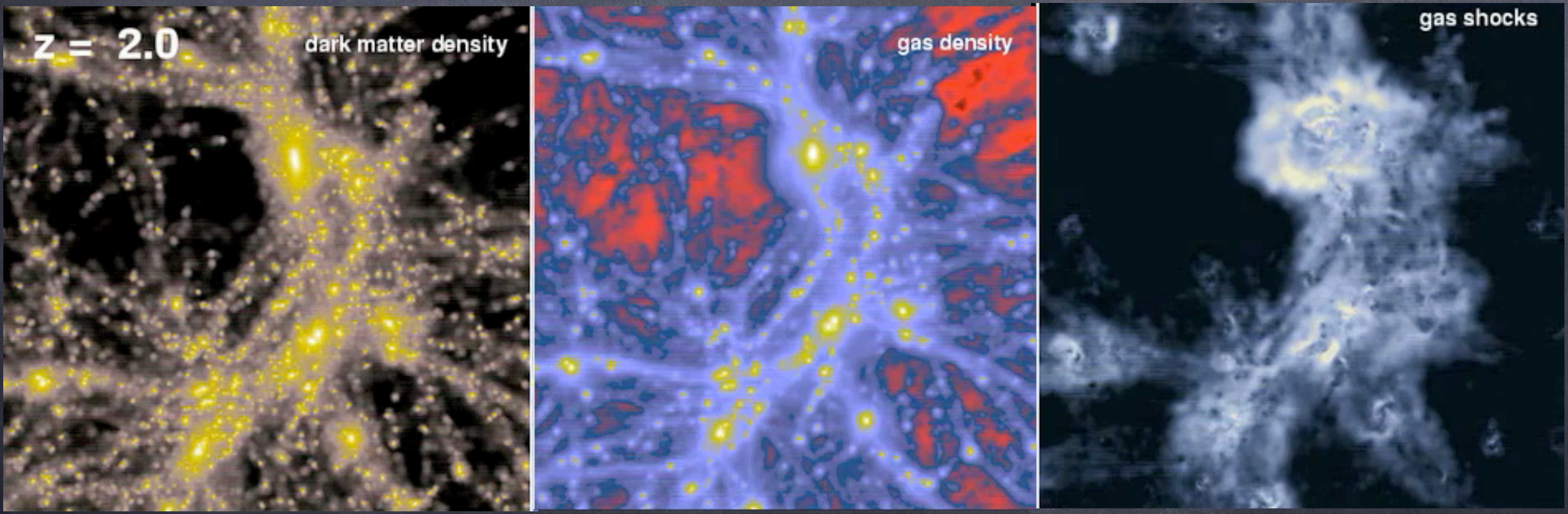
Total mass: 10^{14}-10^{15} $M_\odot$ (~10^{48} g)

Size: ~1-2 Mpc (~10^{24} cm)

Stars < 5%

Gas ~ 10%

Dark matter ~ 85%



V. SPRINGEL

A cluster

- Galaxies
  (Herschel 1785)
- Dark matter
  (Zwicky 1933)
- Gas in ICM
  (X-rays 1960s-1970s; SZ 1970s)

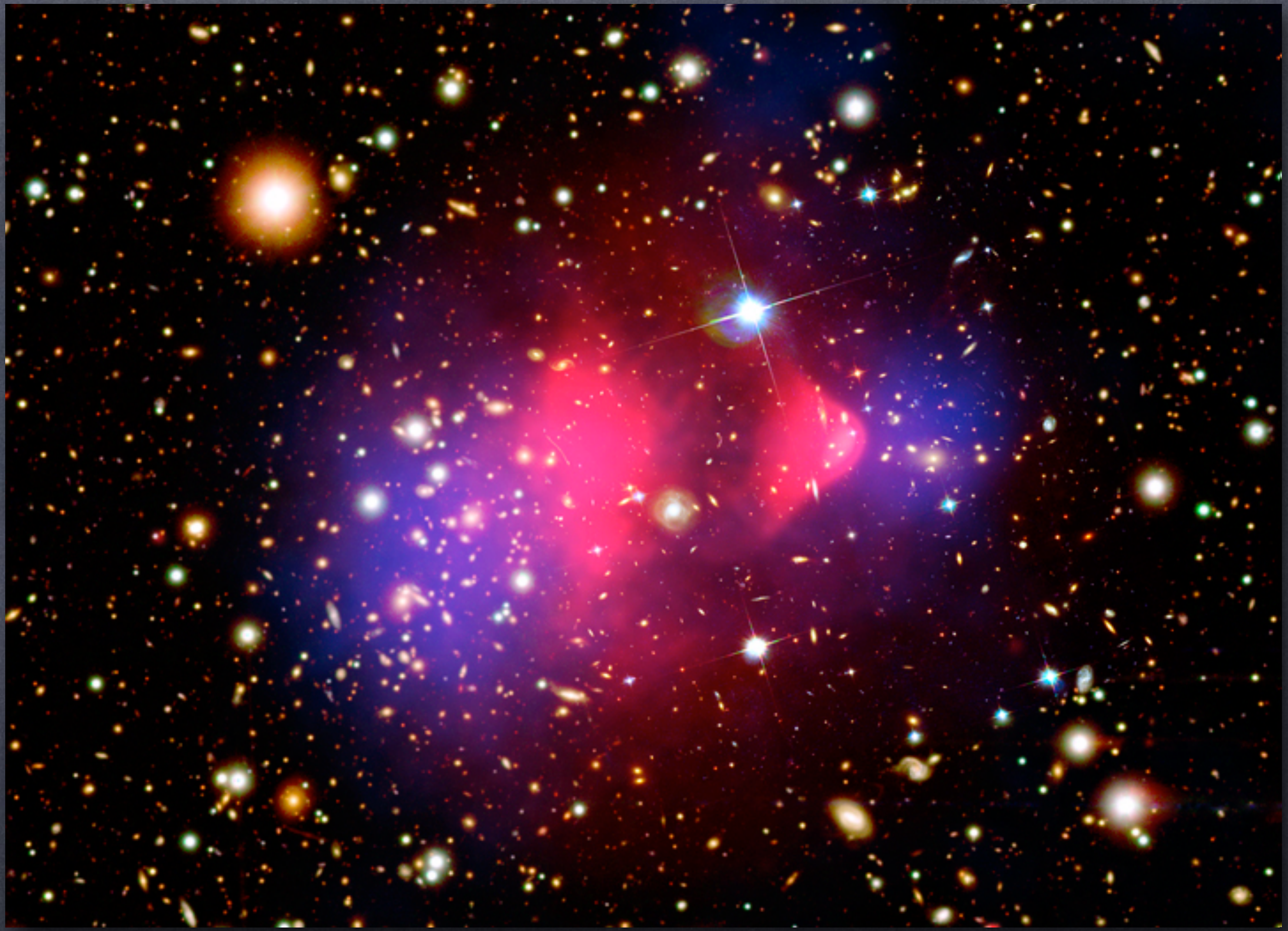
$$\begin{aligned} T &\sim 10^6 - 10^8\,K \\ &\quad (1 - 15\ \mathrm{keV}) \\ n_e &\sim 10^{-4} - 10^{-2}\,\mathrm{cm}^{-3} \\ Z &\sim 0.3\,Z_\odot \end{aligned}$$

Mass: 10^{14}-10^{15} $M_\odot$

Stars < 5%

Gas 10%

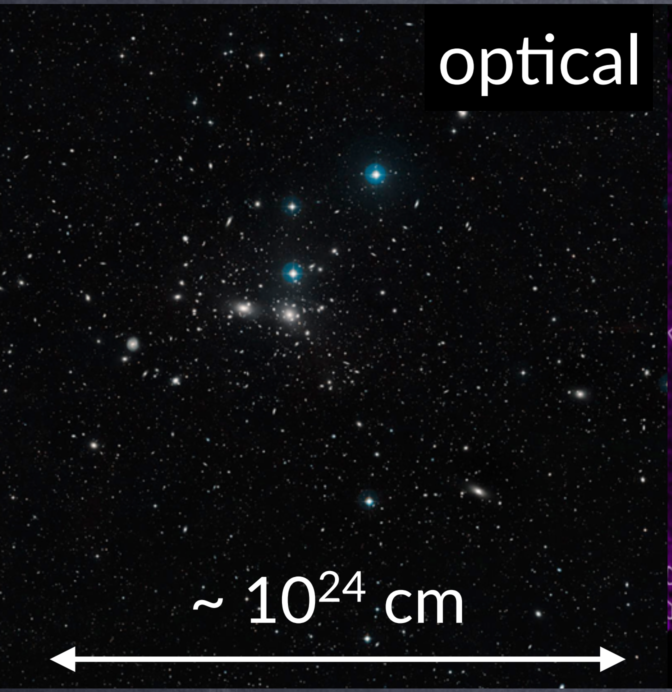
Dark matter 85%



CHANDRA/WFI/MAGELLAN MARKEVITCH, CLOWE ET AL

Observing a cluster

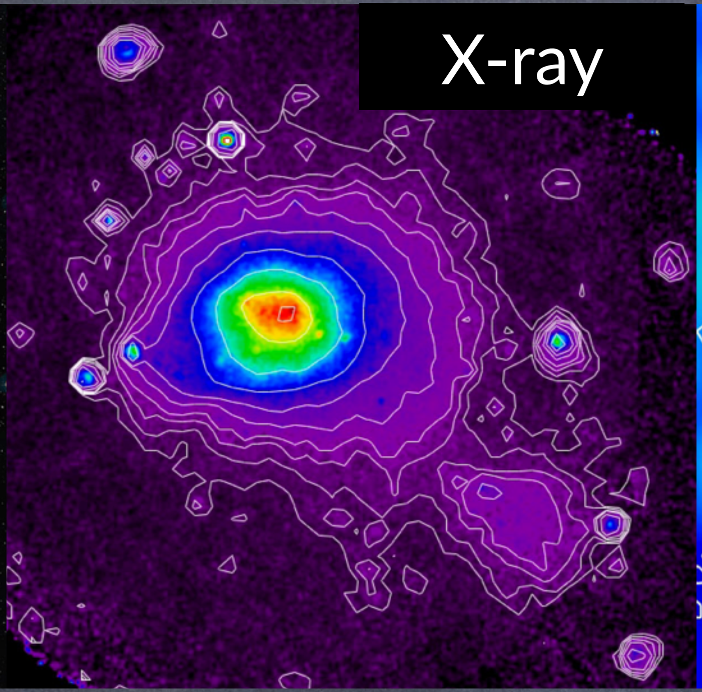
galaxies



lensing

✓ Projected mass

hot gas



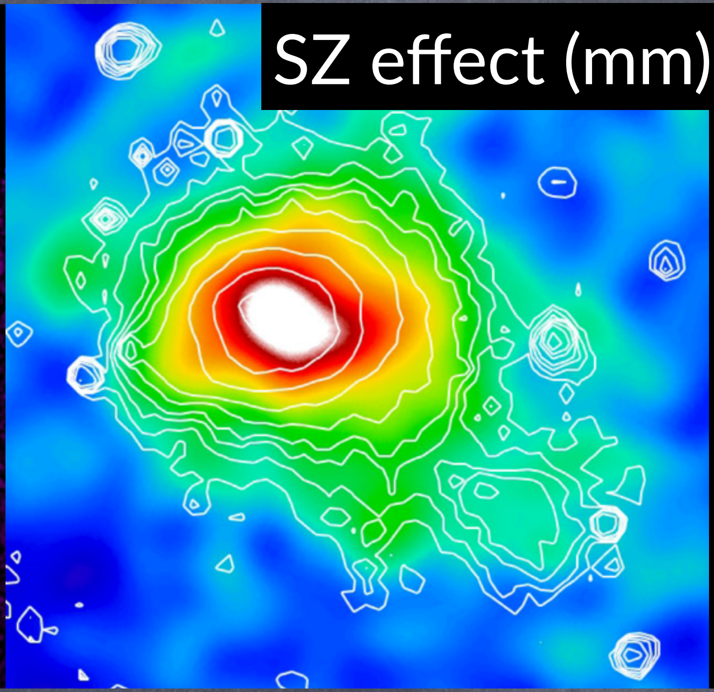
spectro-imagery

✓Temperature

✓Abundances

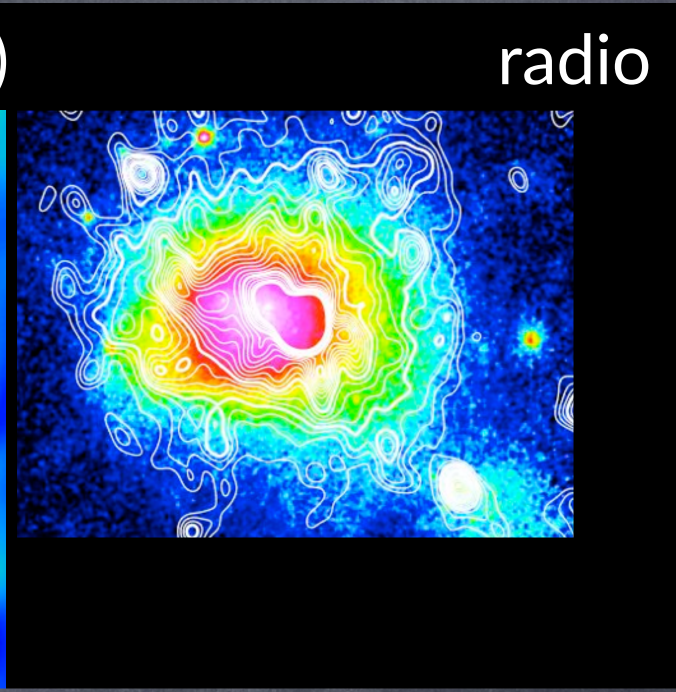
✓Mass

hot gas



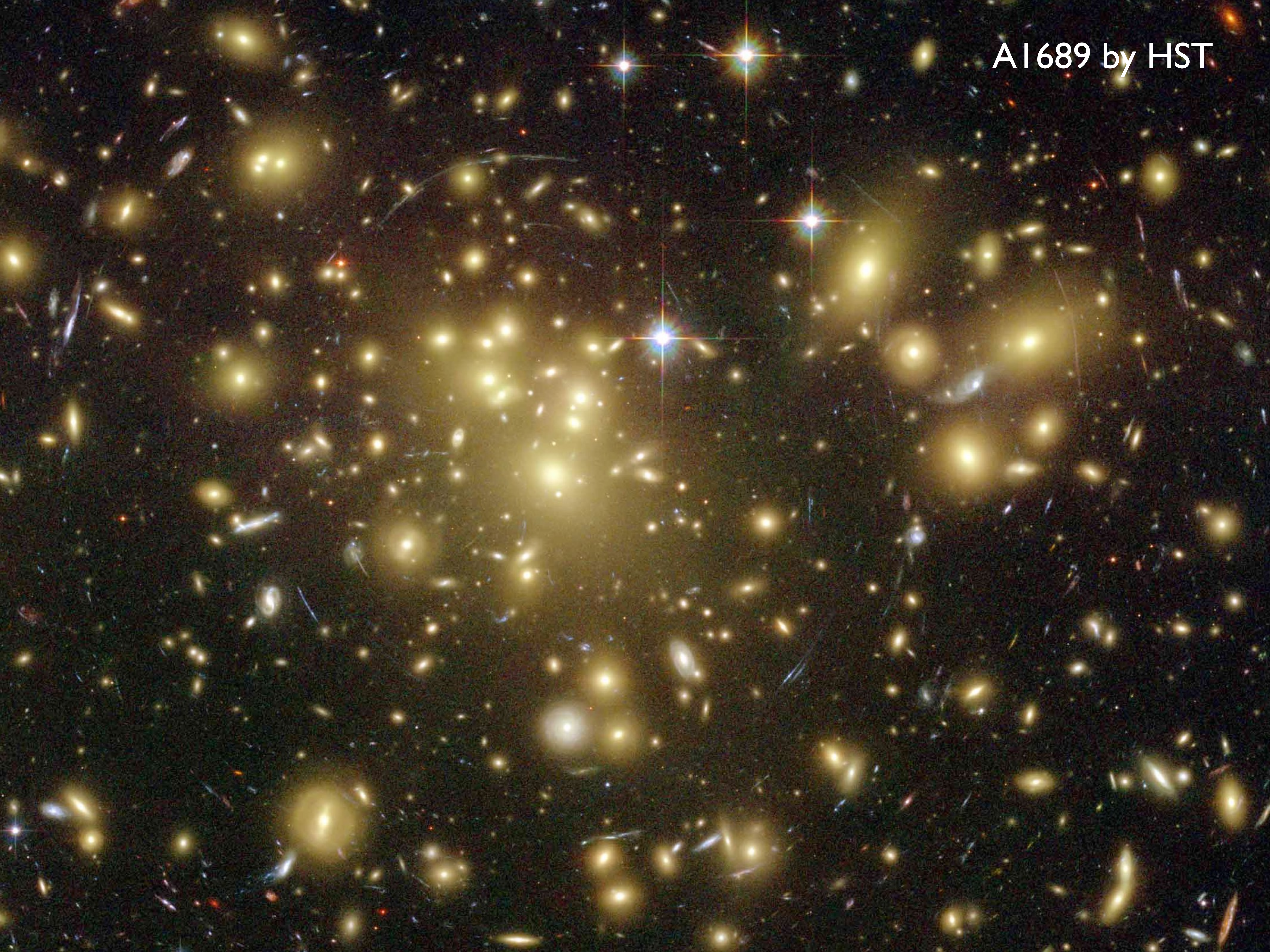
✓distance-independent

accelerated e^-



✓very small mass contribution

✓dynamical indicator

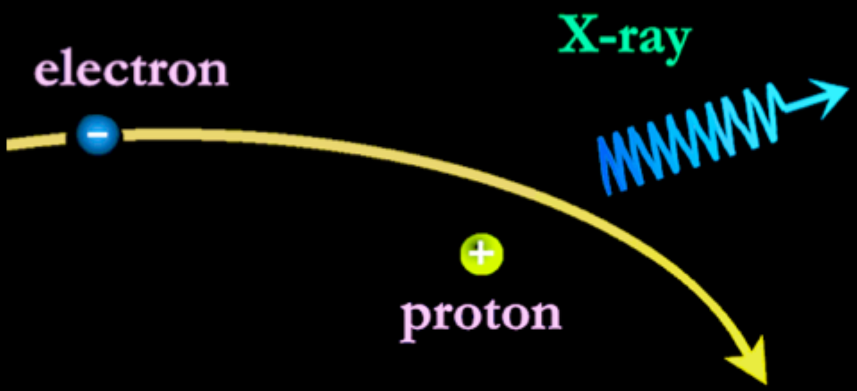


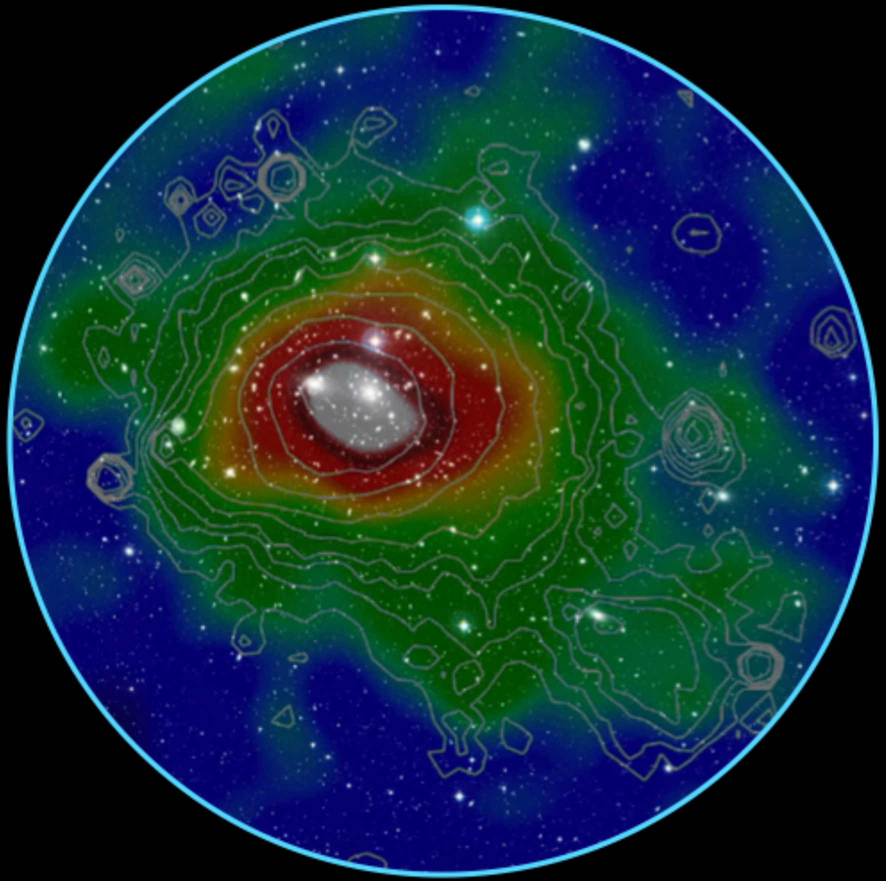
A1689 by HST

A2218 by HST

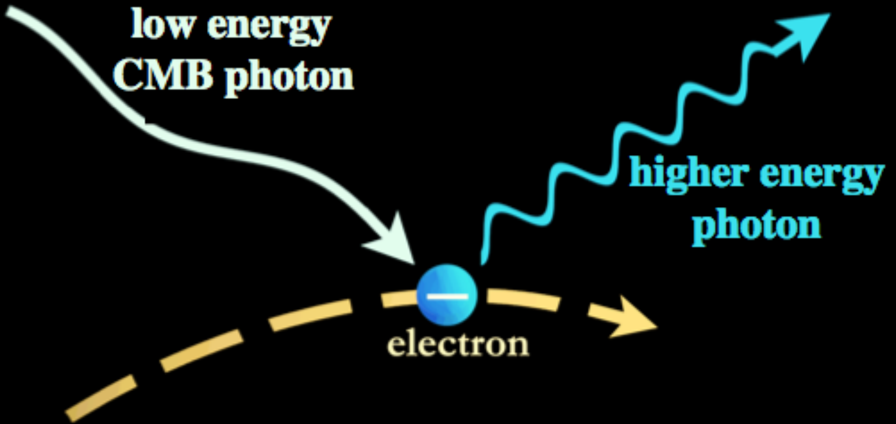
Probing the ICM

Bremsstrahlung





Inverse Compton scattering



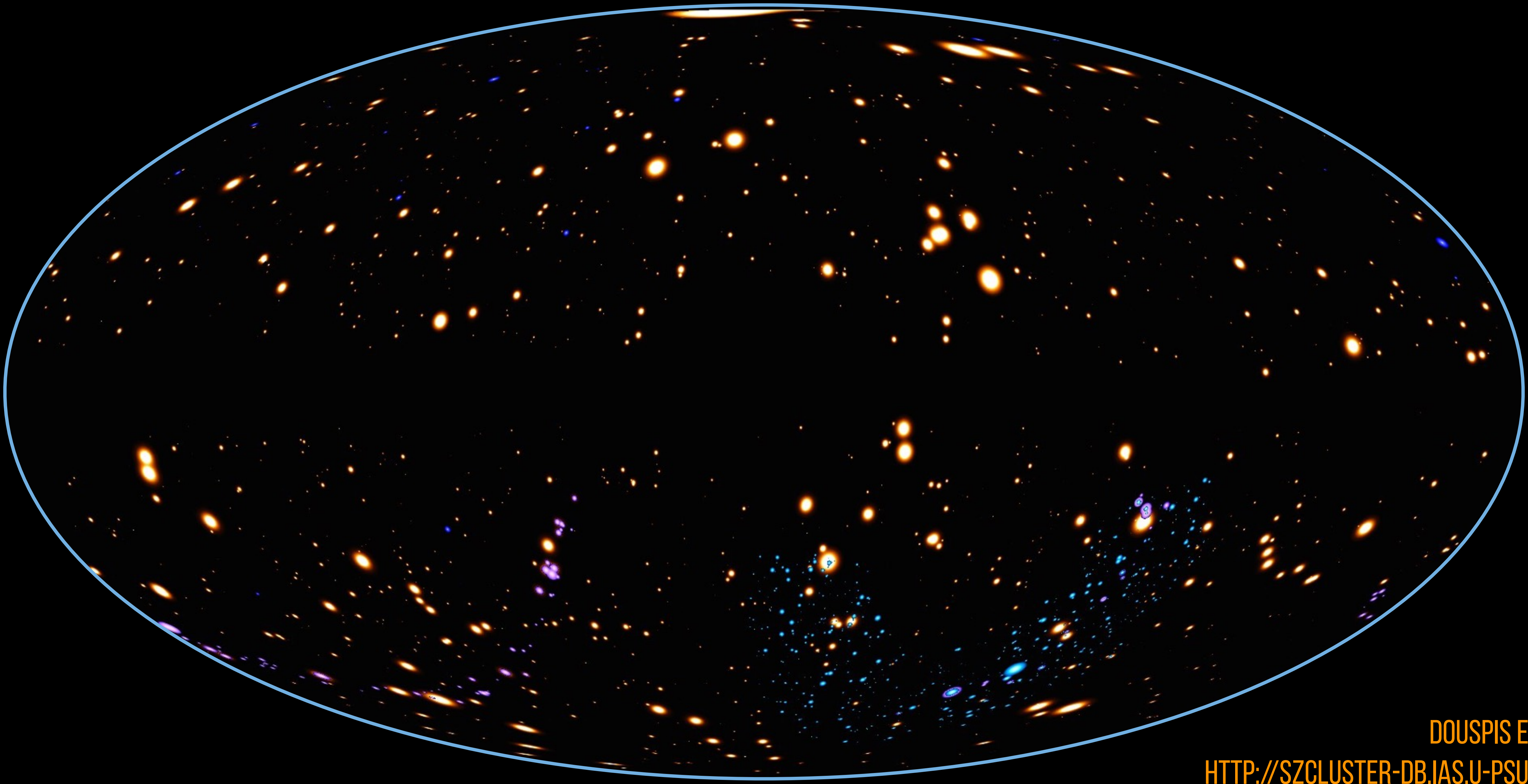
$$E_X \propto \int_V n_e^2 \Lambda(T) dV$$

$$Y \propto \int_\Omega (P_{th} = k_B n_e T) d\Omega$$

NB: No z dimming

Blind SZ surveys

ACT	**PLANCK**	**SPT**
780 sqd	41253 sqd	2500 sqd
148 GHz	857, 545, 353, 217, 143, 100 GHz	150 GHz
1,5'	4.5-10'	1.6'
91	**1963**	**747**
Mariage+10, Hasselfield+13	Planck Collaboration+11+13+15	Reichardt+12, Bleem+15

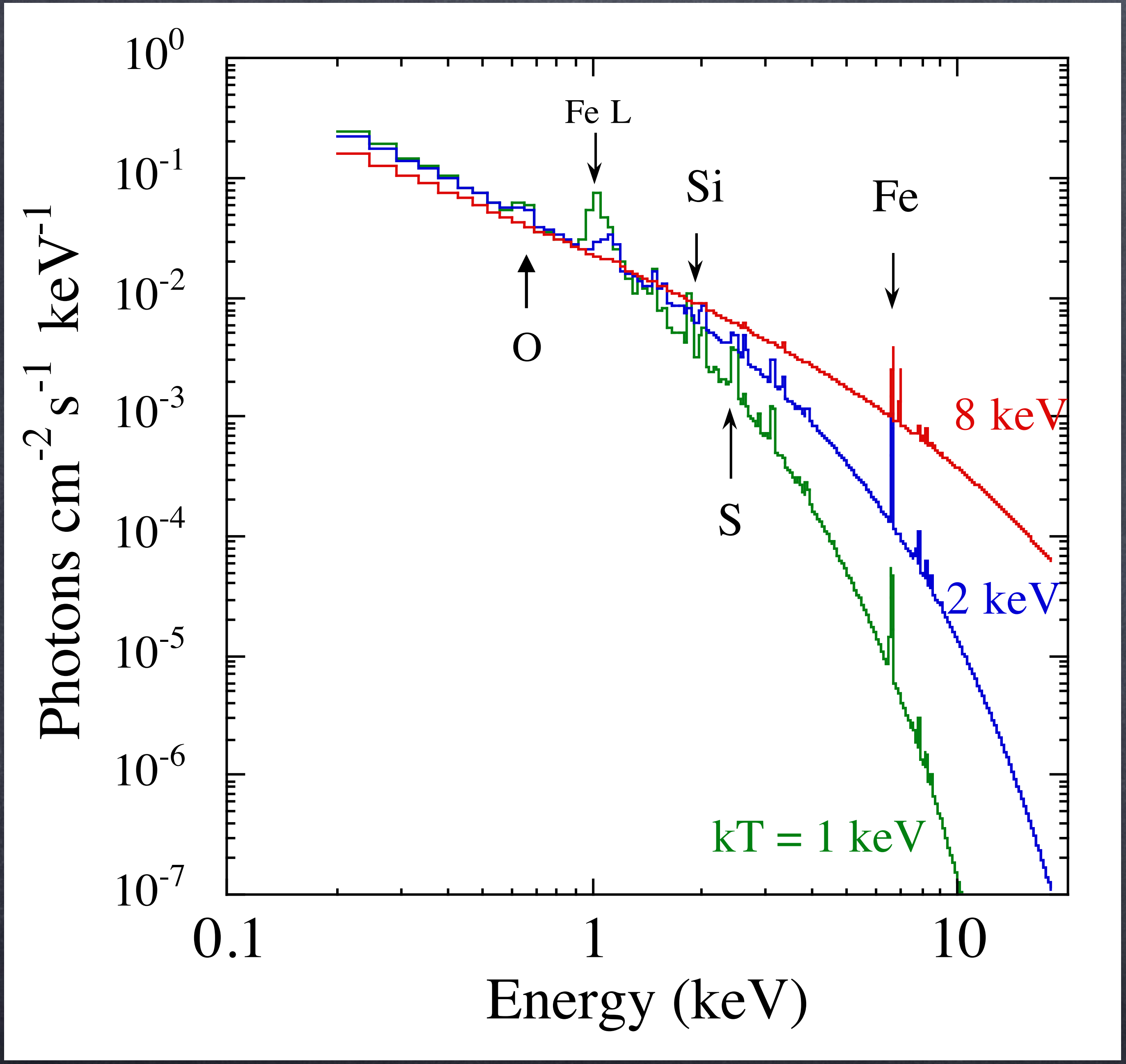


DOUSPIS ET AL

HTTP://SZCLUSTER-DB.IAS.U-PSUD.FR

X-ray information

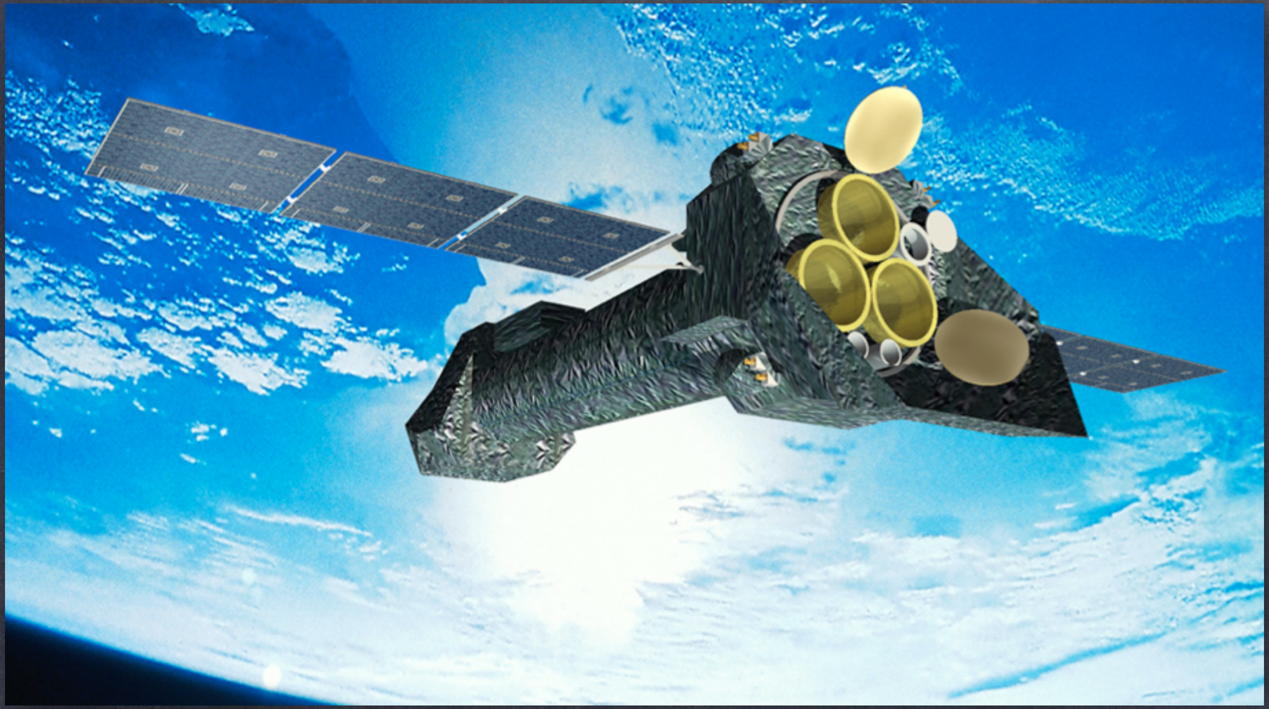
Thermal emission from the ICM

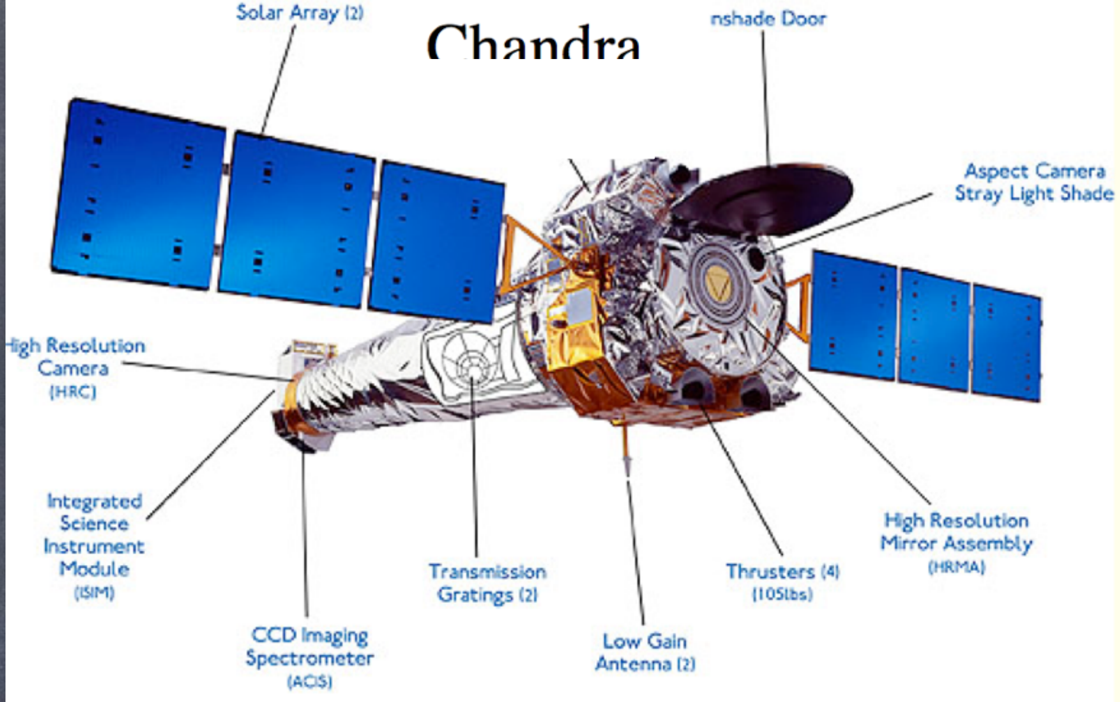


- Fully ionised H+He plasma with highly-ionised heavy elements
- Bremsstrahlung emission (continuum) + lines
- Imagery: gas density distribution
- Spectral shape: kT, Z
  - Need sensitivity > 10 keV

$$\frac{dN(e)}{dE} \sim n_e\, n_i\, V \left[g(E,T)\, T^{-1/2}\, e^{-E/kT} + \mathrm{lines} \right]$$

Operating X-ray observatories





XMM

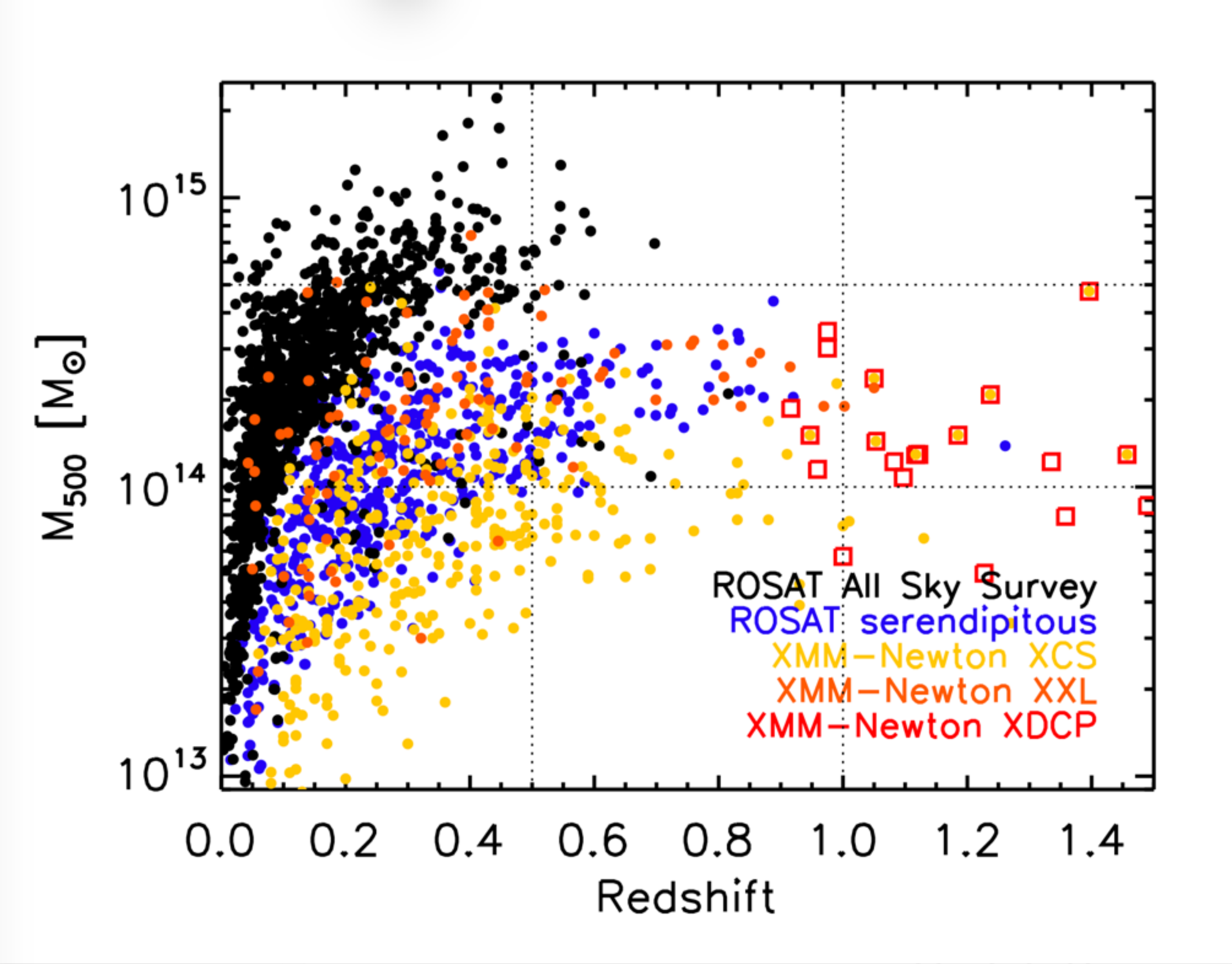
- 3 telescopes
- FoV 30′
- FWHM ~ 10″

Chandra

- 1 telescope
- FoV 17′ X 17′
- FWHM <0.5″

Spatially-resolved spectroscopy ΔE/E ~150 eV
+ high-resolution dispersive spectroscopy

Detection of new clusters in X-rays



COMPILATION BY M. ARNAUD, AFTER PIFFARETTI ET AL 2011, MERTHENS ET AL 2012, FASSBENDER ET AL 2012, PIERRE ET AL 2016

- Clusters are the only extragalactic extended X-ray sources but need large sky coverage to maximise number of detections

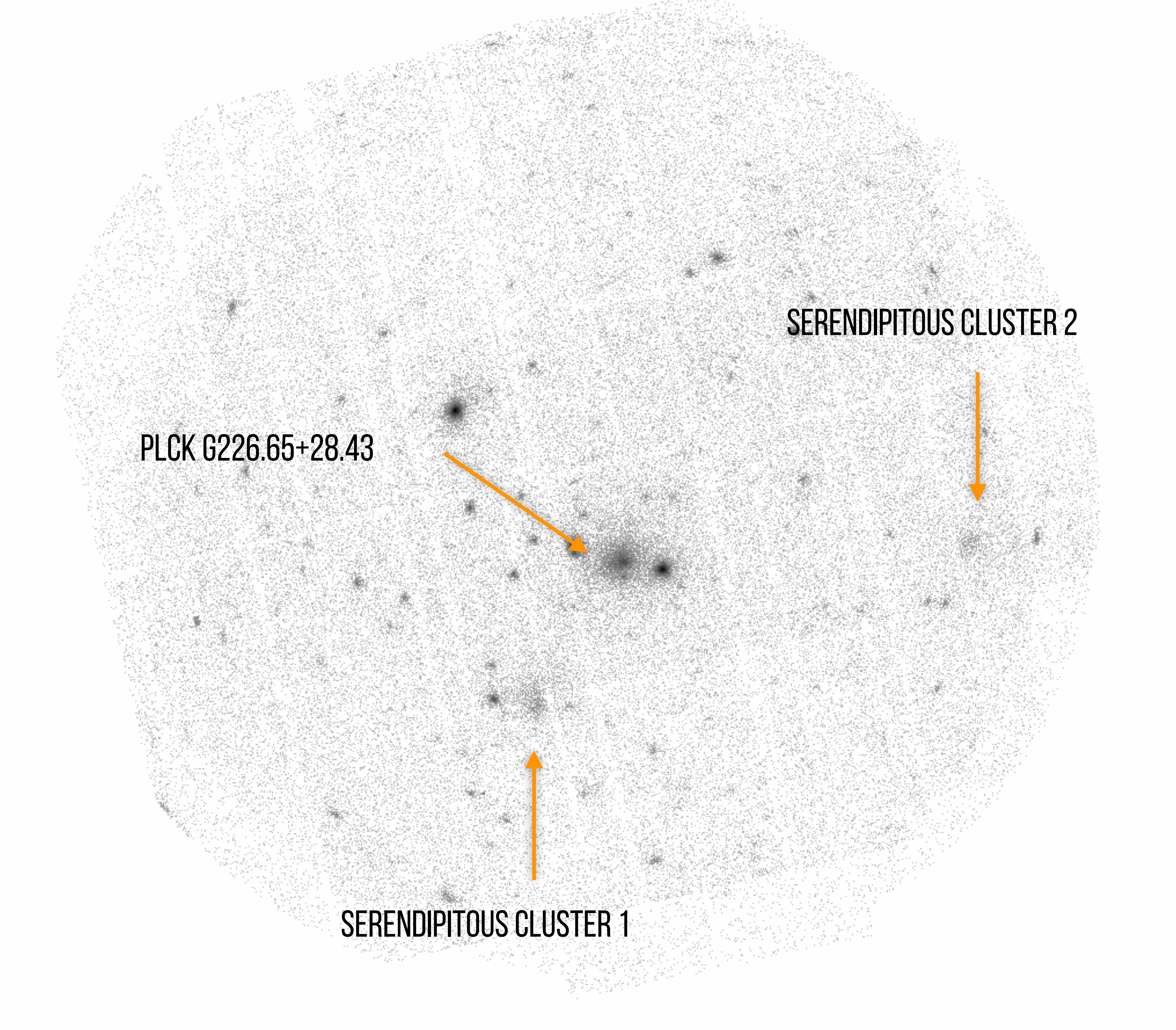
- About 2000 clusters found in ROSAT All-Sky Survey (1990), ROSAT serendipitous surveys

- Several hundred more found in XMM surveys

- X-ray emission subject to redshift dimming

$$S_X \propto (1+z)^{-4}$$

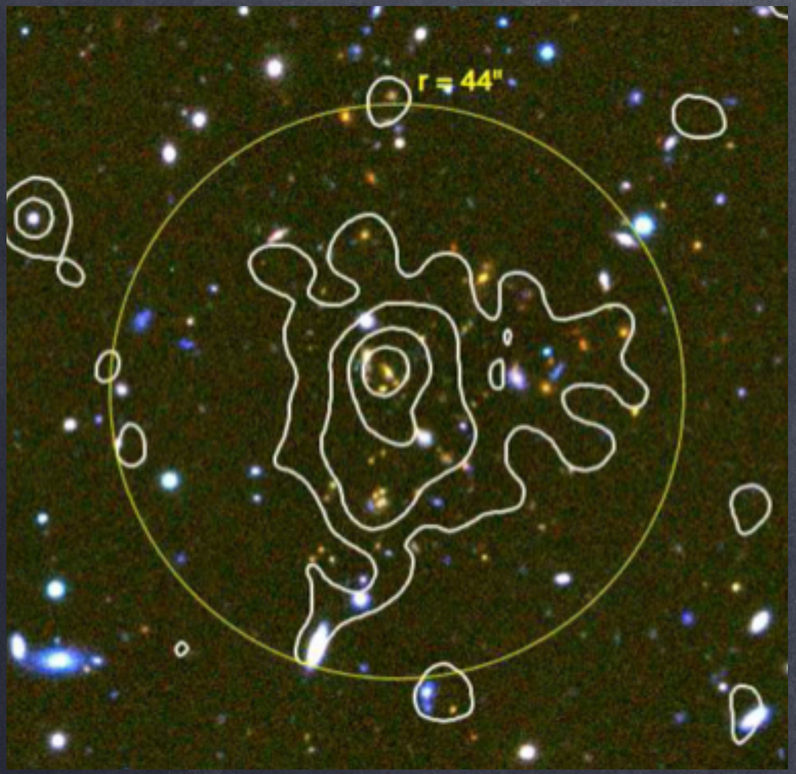
Serendipitous detection of new clusters

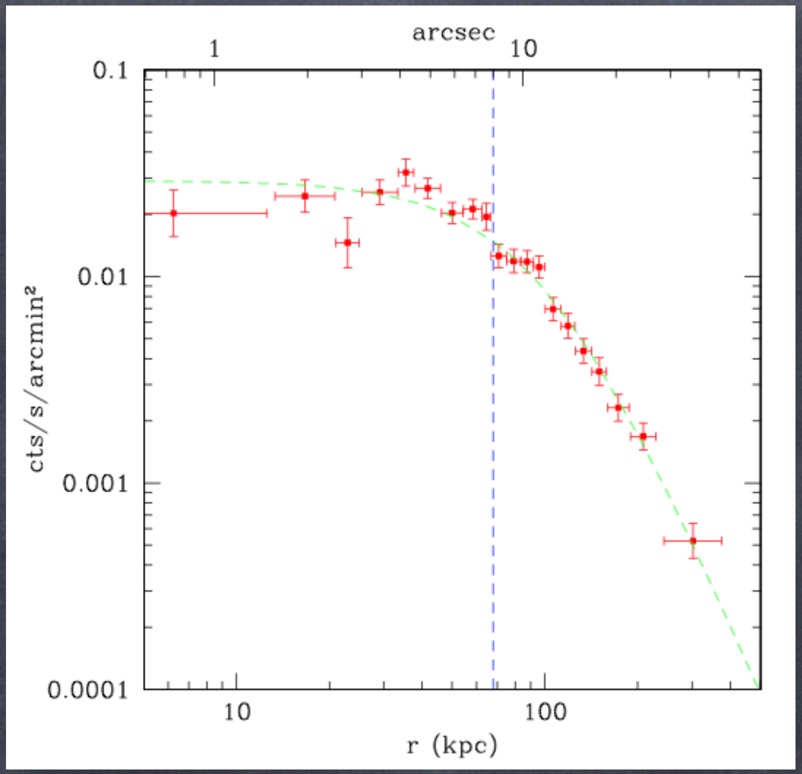


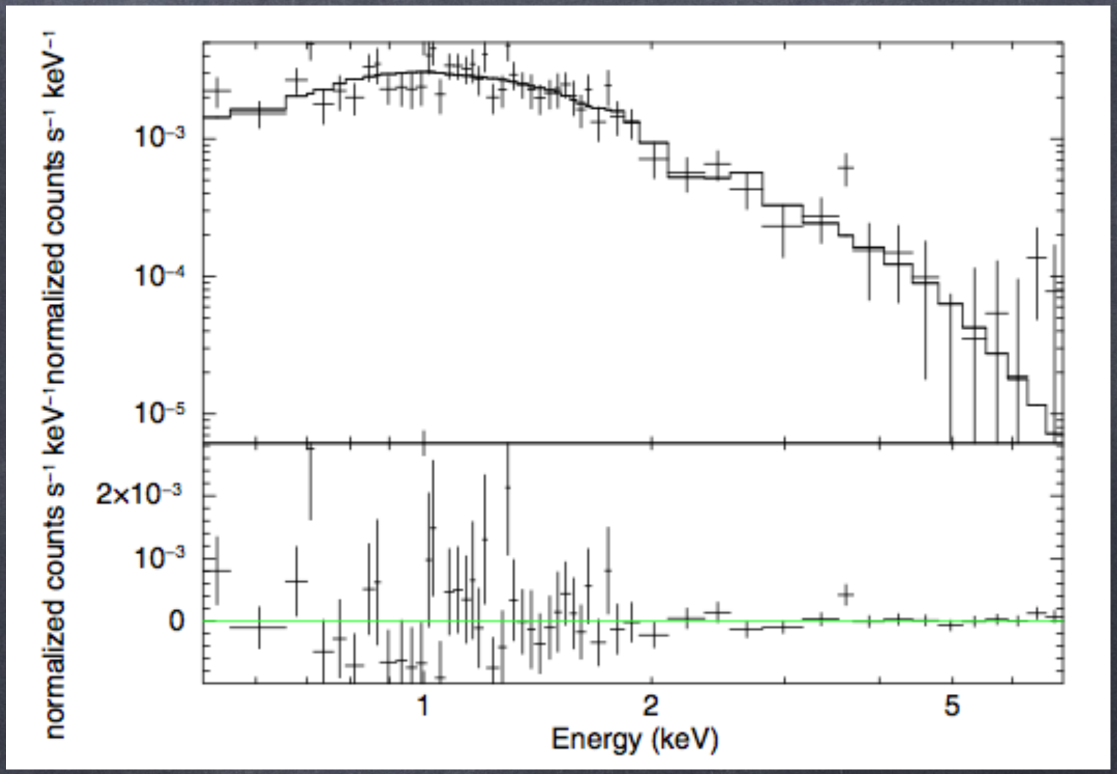
FIELD CENTRED ON PLCK G226.65+28.43, PI M. ARNAUD

X-ray information from distant clusters

Chandra observation of XDCP J0044.0-2033 at z=1.579



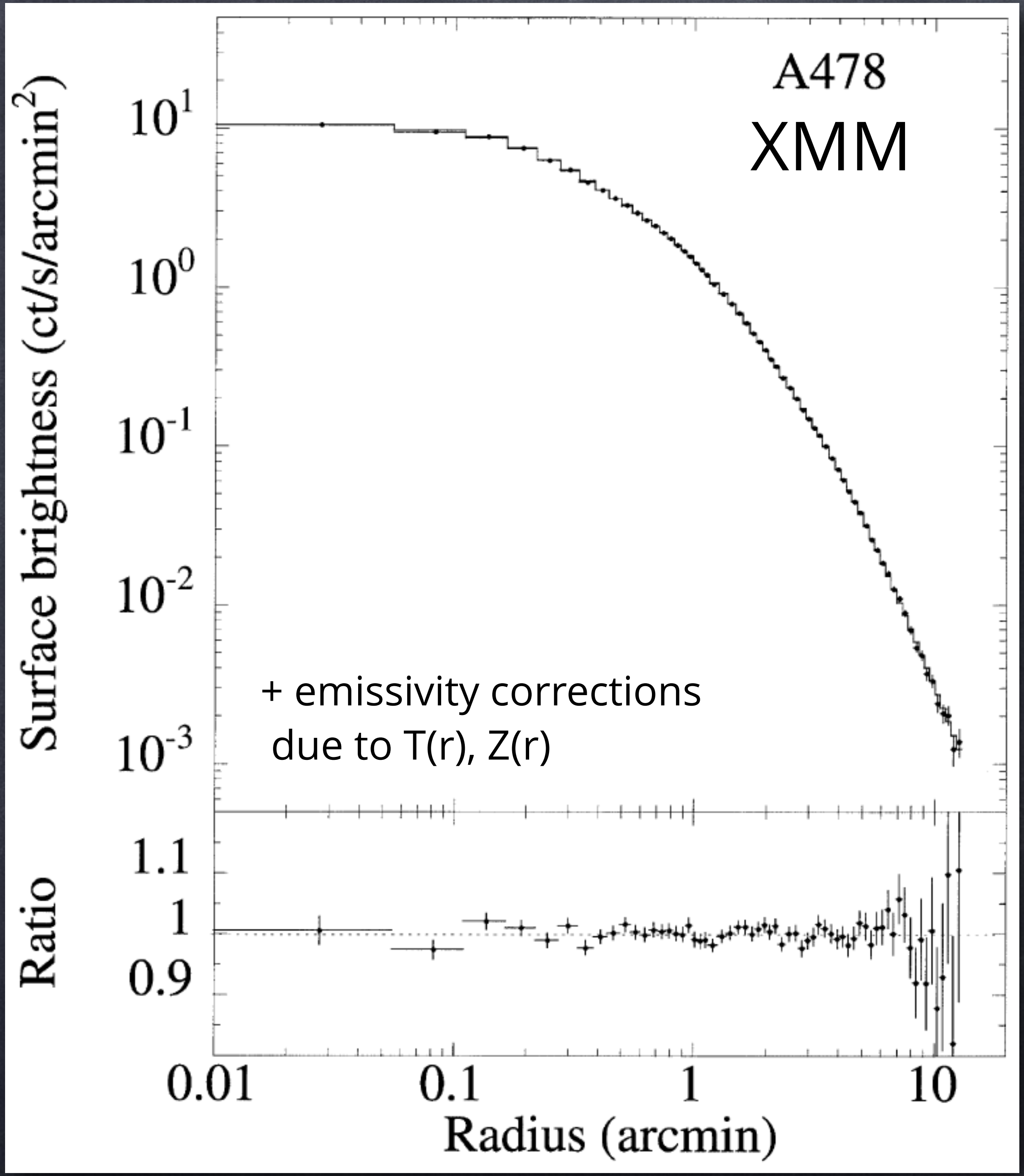




TOZZI ET AL 2015

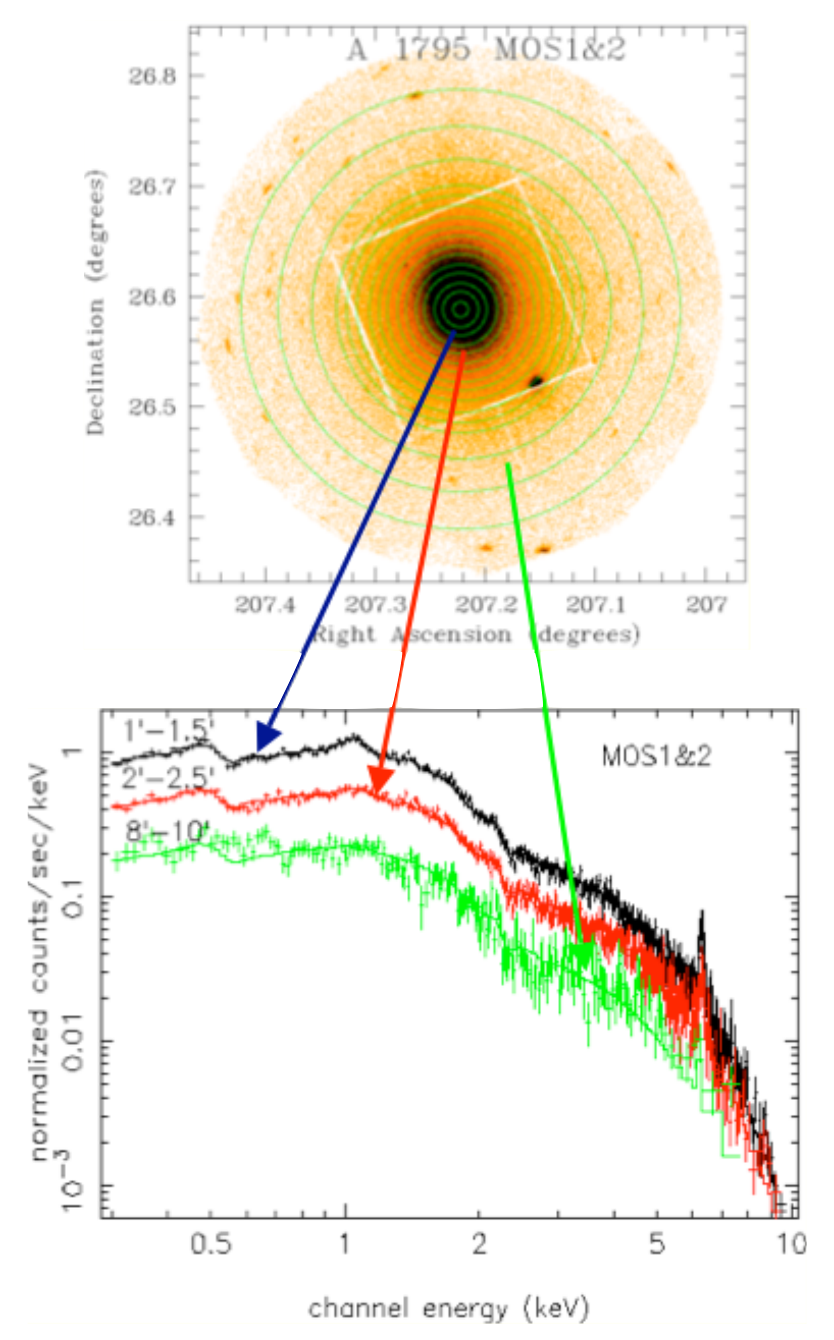
- Morphology: first indication of dynamical state
- Surface brightness: gas density, L_X
- Global temperature: mass

X-ray observational tools for low-z objects



+ emissivity corrections due to T(r), Z(r)

POINTECOUTEAU ET AL 2004 (ABELL 478)



ARNAUD ET AL 2001 (ABELL 1795)

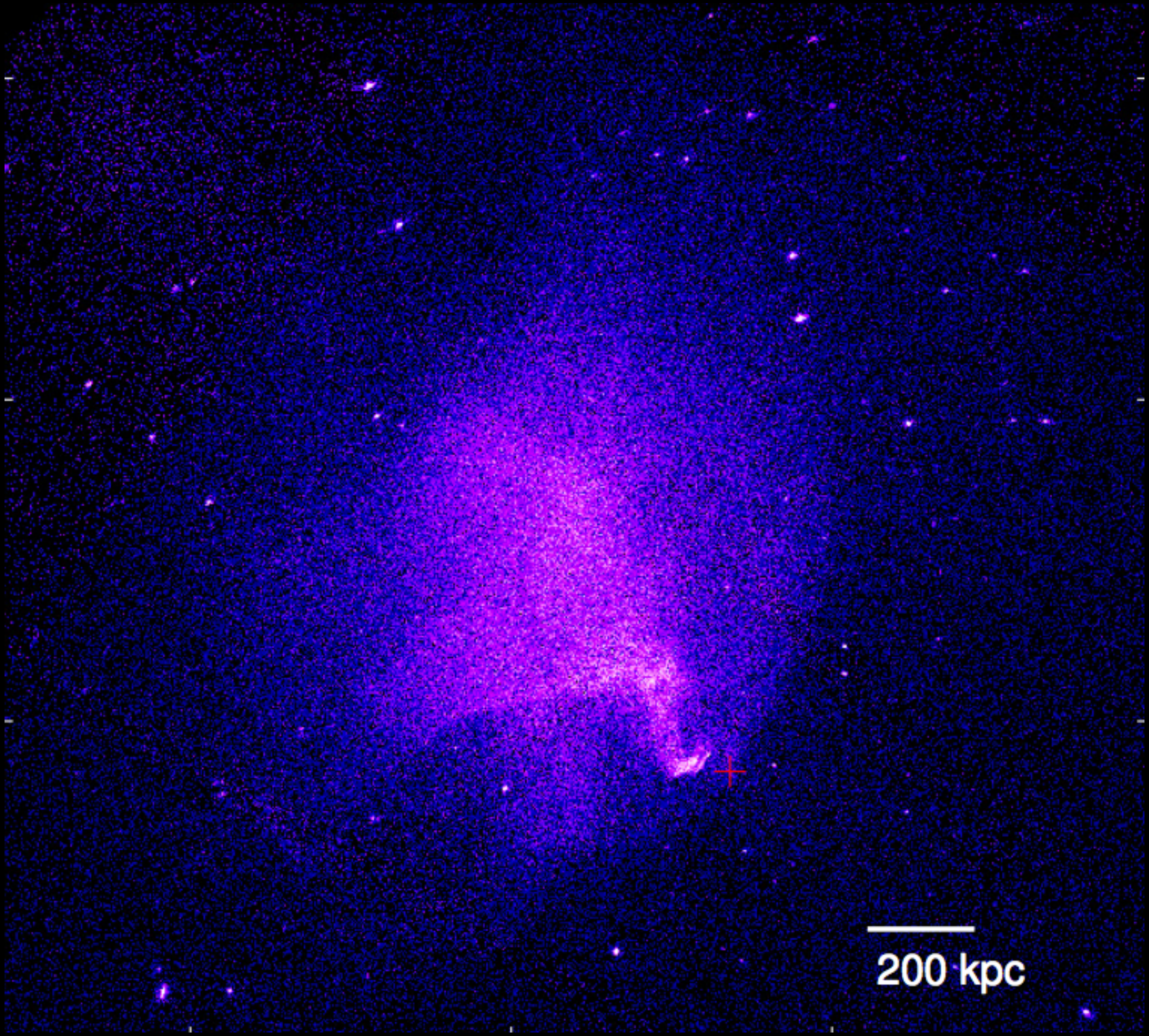
X-ray mass measurement

- Assume spherical symmetry
- Hydrostatic equation: $\frac{1}{\rho}\frac{dP}{dr} = -\frac{GM(r)}{r^2}$
- Ideal gas: $P = nkT = \frac{\rho}{\mu m_p} kT$

$$M(r) = -\frac{kT}{\mu m_p}\frac{r}{G}\left[\frac{d\ln\rho}{d\ln r} + \frac{d\ln T}{d\ln r}\right]$$

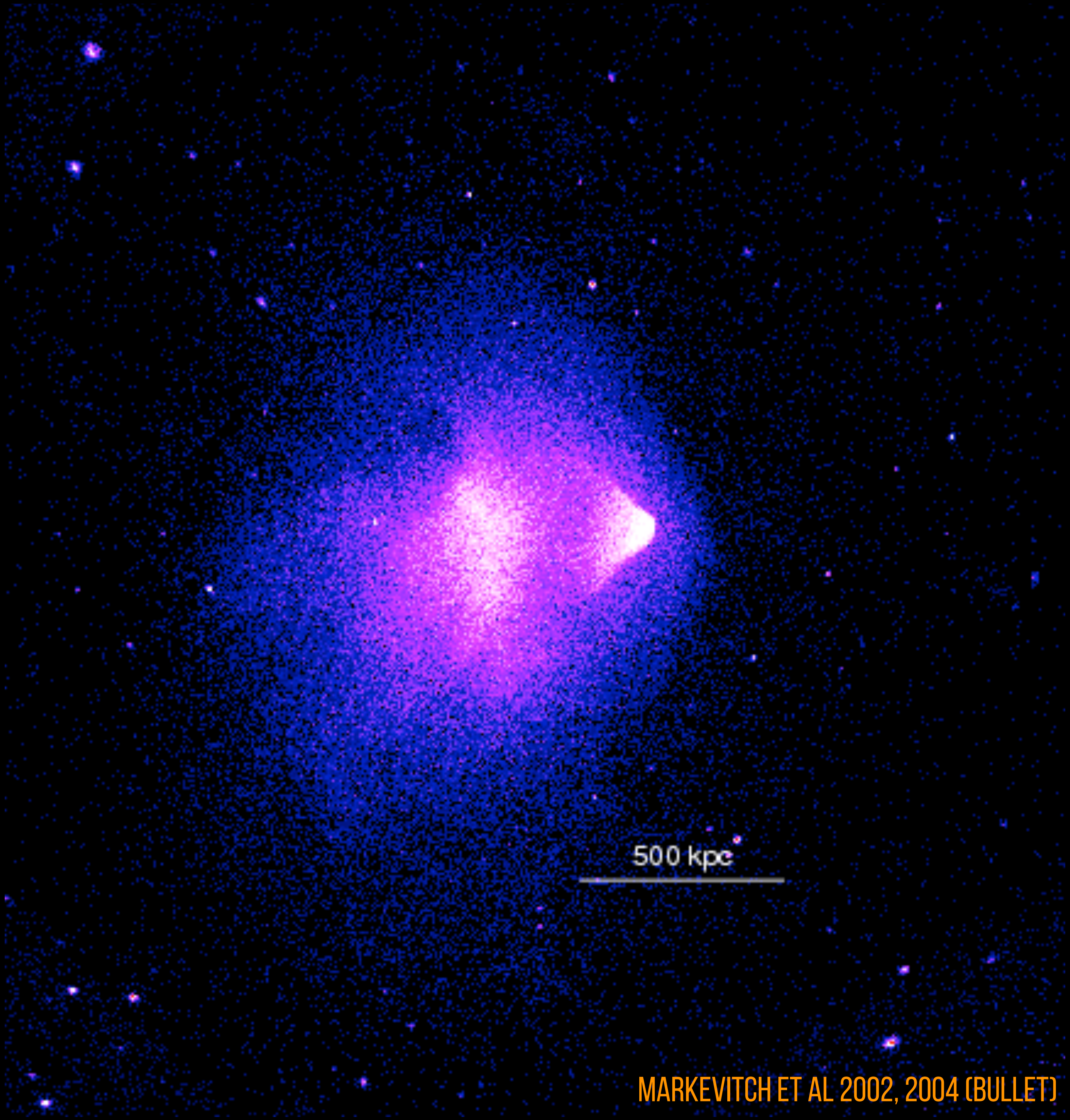
Clusters in formation

Clusters in formation



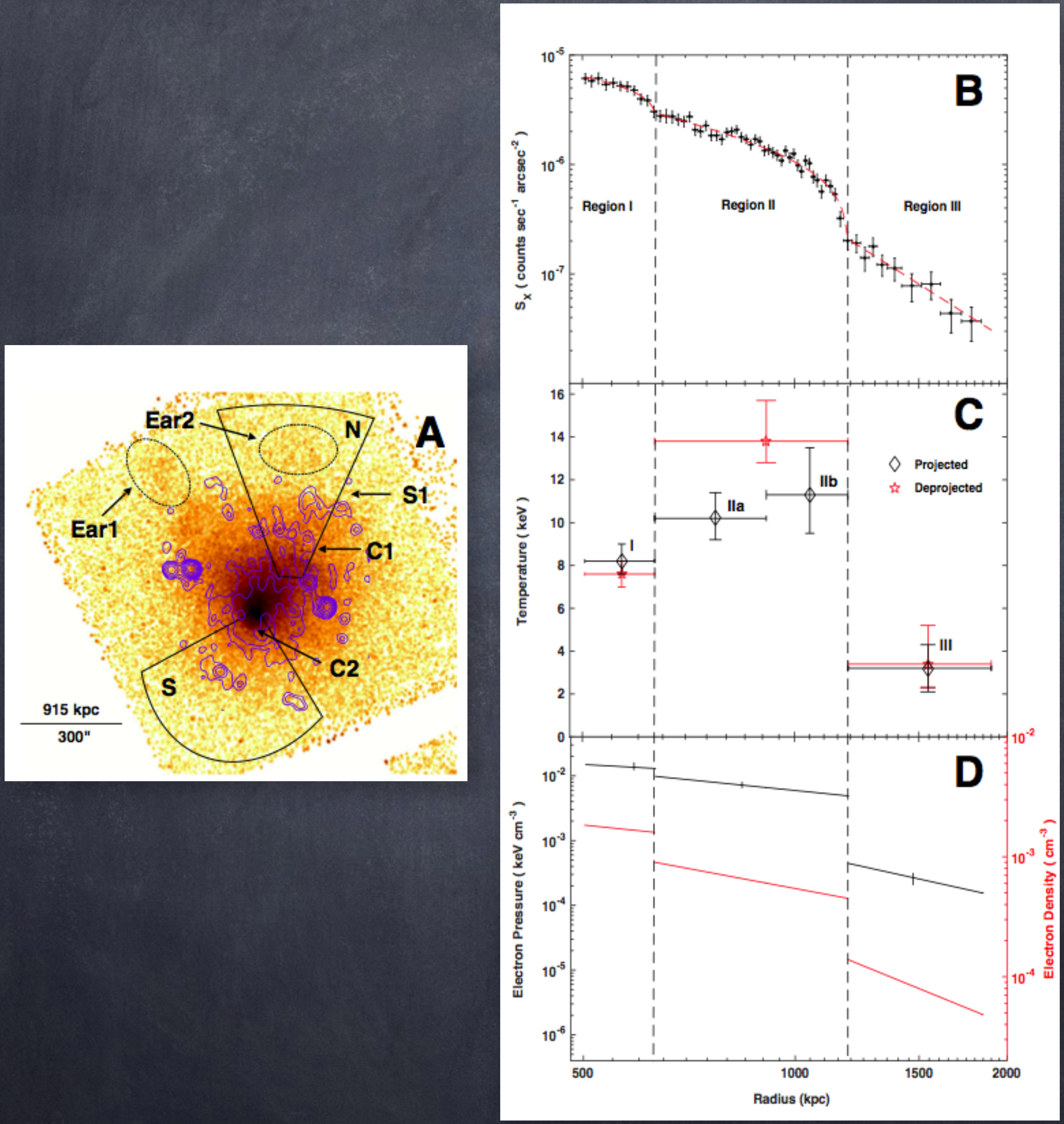
WANG ET AL 2016 (A520)

Clusters in formation



MARKEVITCH ET AL 2002, 2004 (BULLET)

Shocks



DASADIA ET AL 2016

- Rankine-Hugonoit jump conditions for 1D shock

LANDAU & LIFSHITZ 1959

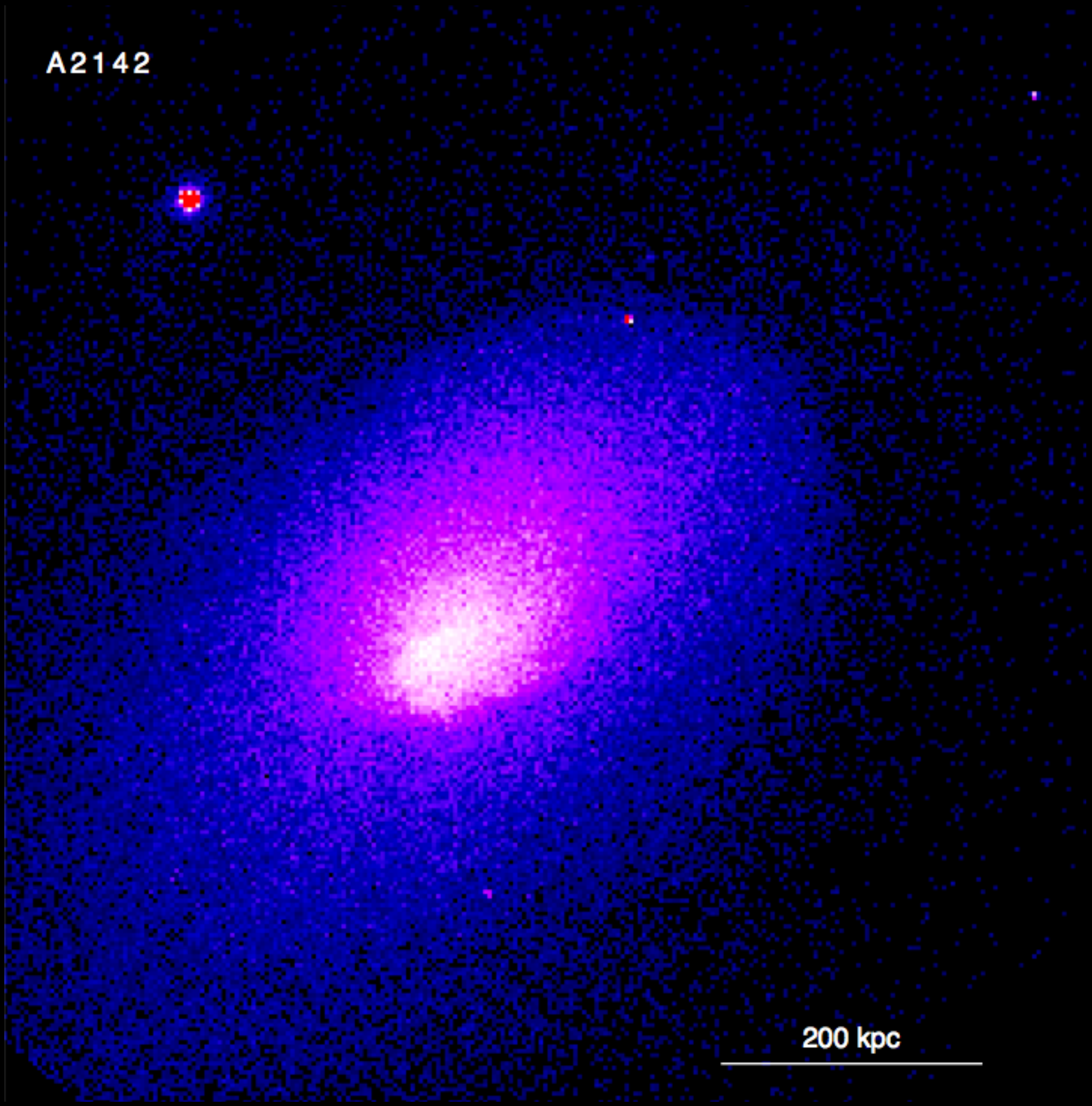
$$\frac{1}{C} = \left[4\left(\frac{T_2}{T_1}-1\right)^2 + \frac{T_2}{T_1}\right]^{1/2} - 2\left(\frac{T_2}{T_1}-1\right)$$

- Mach number

$$\mathcal{M}^2 = \frac{3C}{4-C}$$

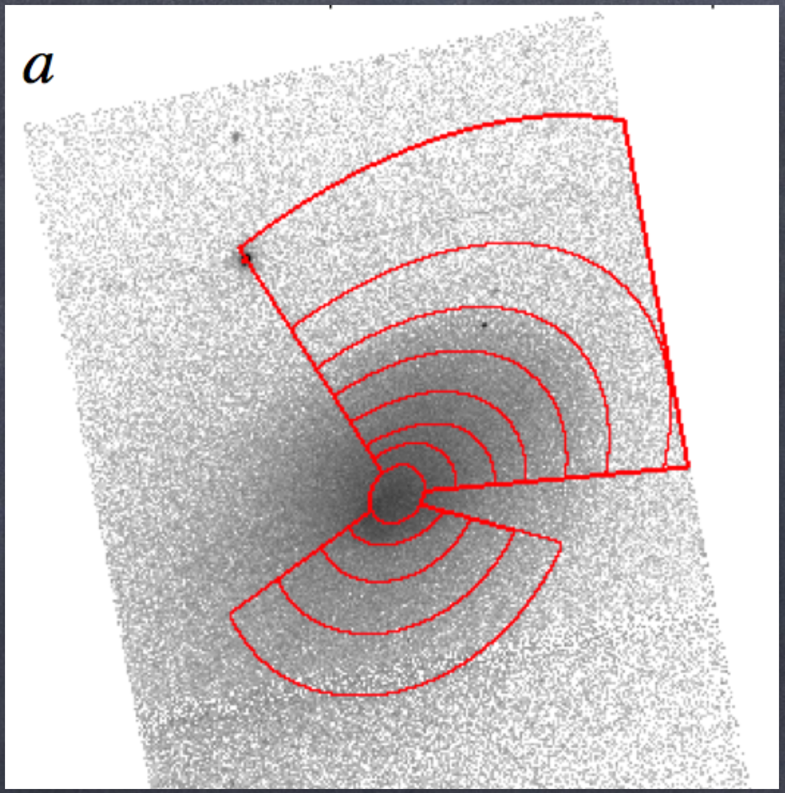
- Typical shock Mach numbers ~1-4

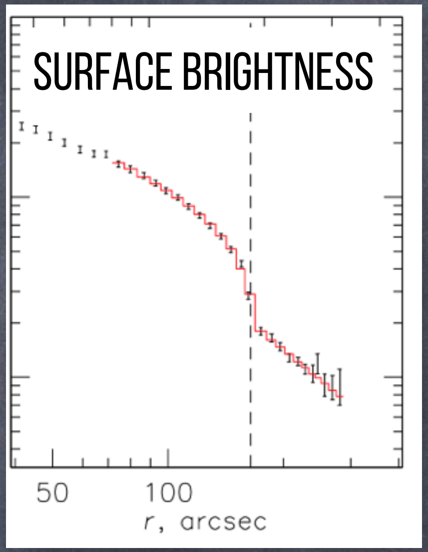
Cold fronts

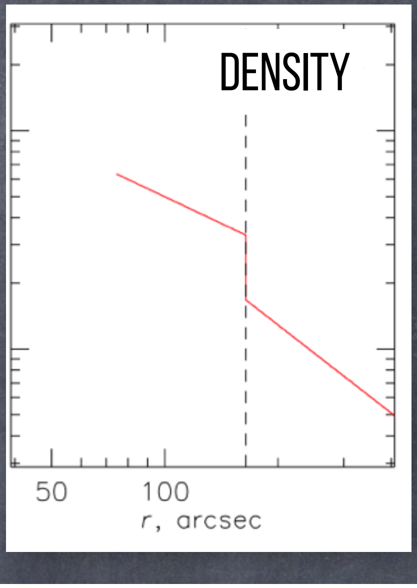


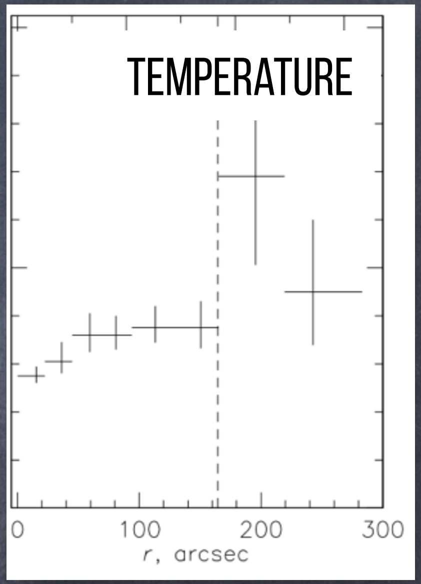
MARKEVITCH & VIKHLININ 2007

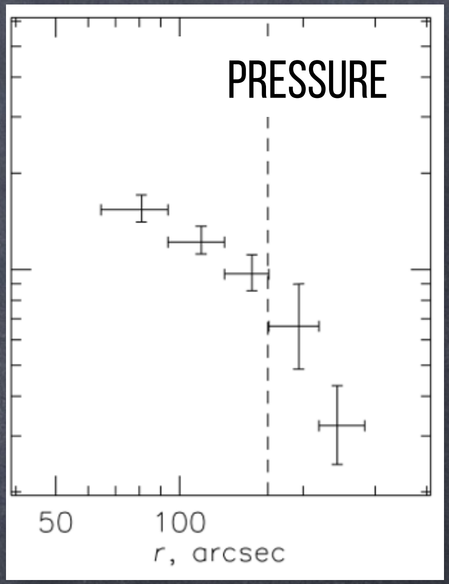
Cold fronts







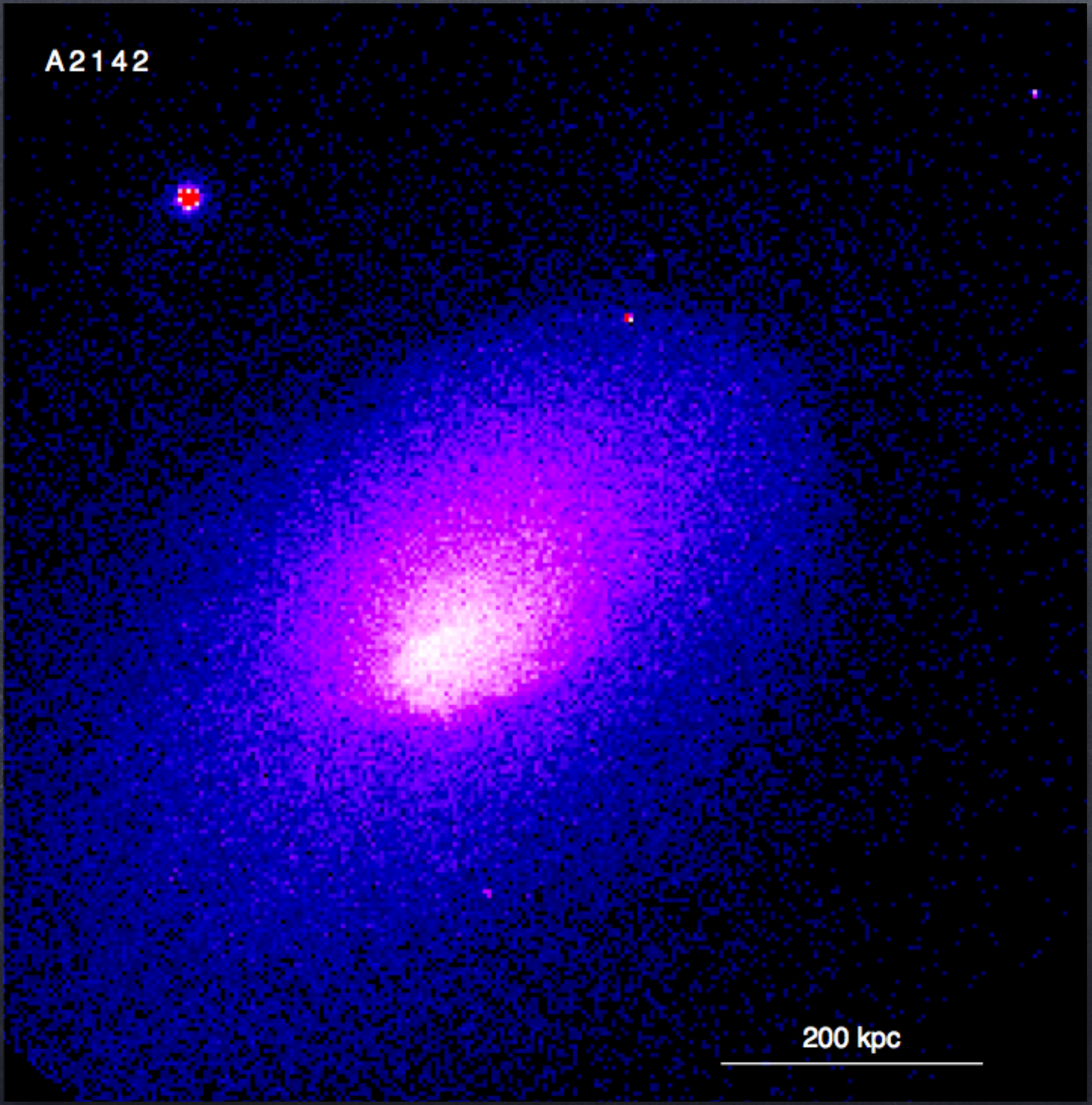




MARKEVITCH & VIKHLININ 2007

- Abrupt kT, n_e jumps but no pressure jump ⇒ not a shock
- Dense subcluster cores moving at near sonic velocity
- Gas sloshing in dark matter potential

Cold fronts



MARKEVITCH & VIKHLININ 2007

Cores

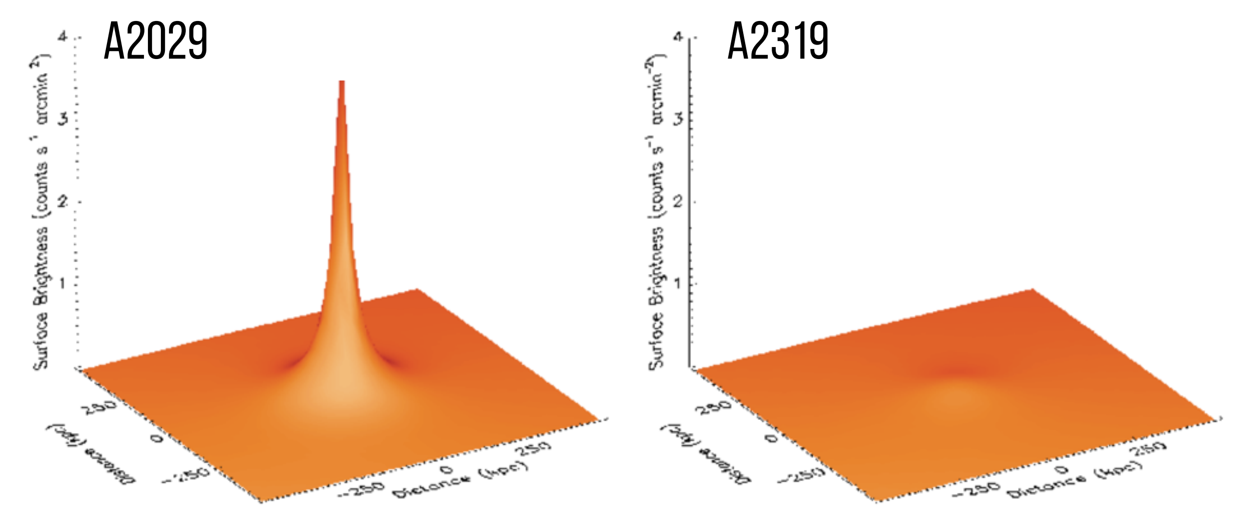
Cooling cores (before 1999)

- In a cluster in equilibrium, the cooling time of the central gas is very short
  - $n_{e,0} \sim 10^{-3}\ \mathrm{cm}^{-3}$
  - $t_{\mathrm{cool}} \sim 8.5 \times 10^{10}\ \mathrm{yr}\ (n_e/10^{-3}\ \mathrm{cm}^{-3})^{-1}\ (kT/8.6\ \mathrm{keV})^{1/2} < t_{\mathrm{H}}$

- The gas cools:
  - $P = n_e\, kT$
  - Density increases, the gas flows towards centre
  - The gas continues to cool, star formation begins

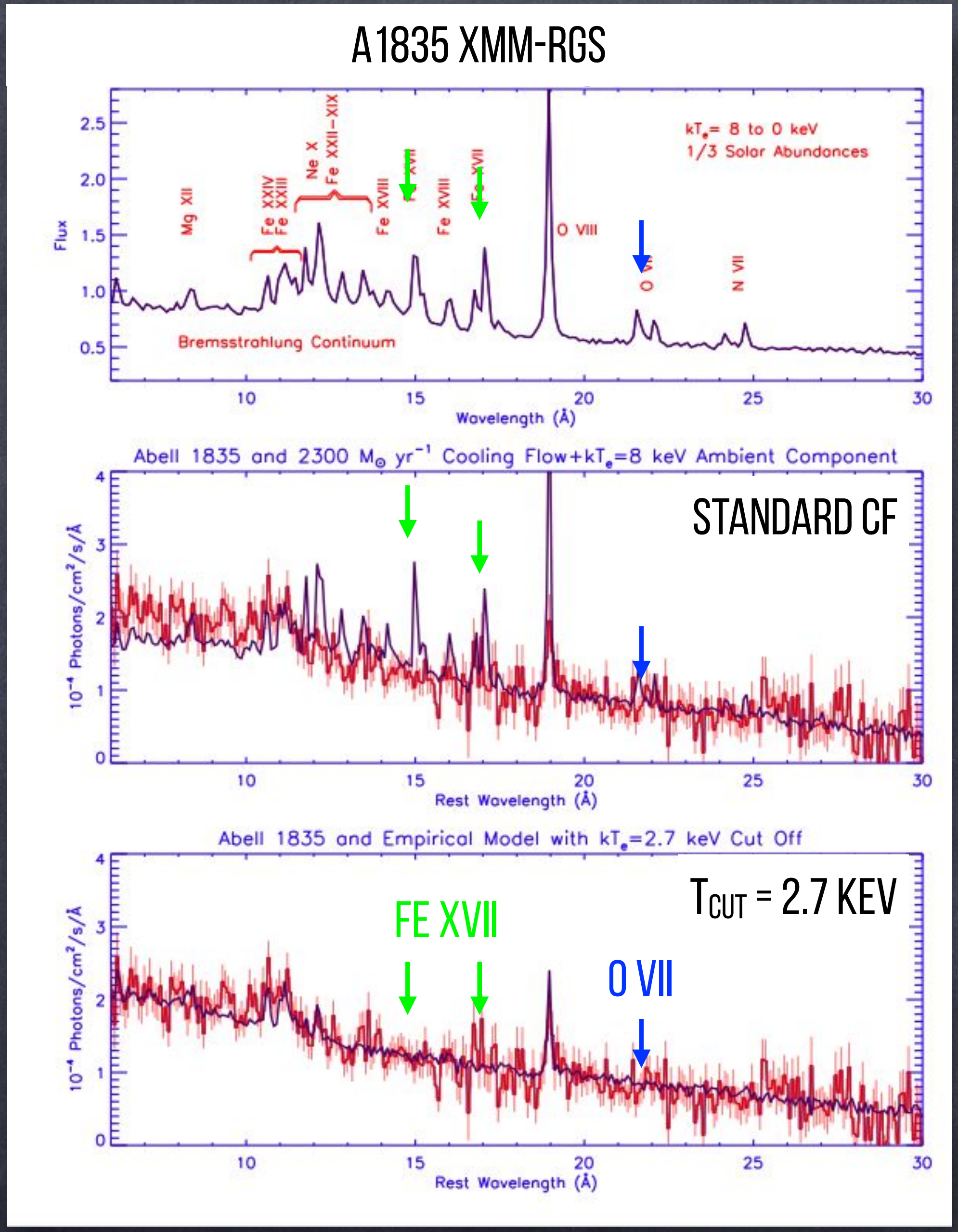
- But
  - $\dot{M}_X \sim 10 - 1000\, M_\odot\ \mathrm{yr}^{-1}$
  - $\dot{M}_* \sim 1\%\, \dot{M}_X$

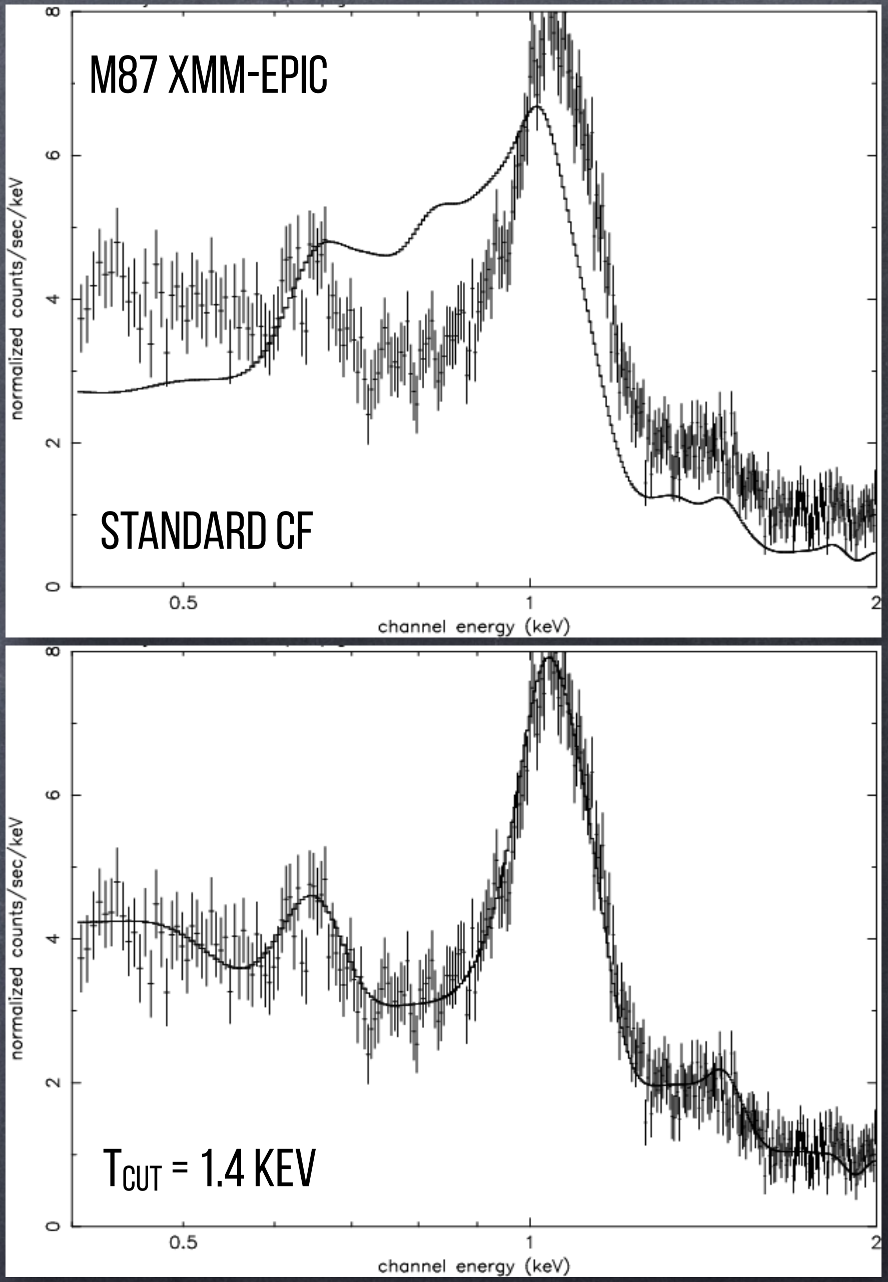
- Problem for the model?



MILLION & ALLEN 2009

Key new observations - I



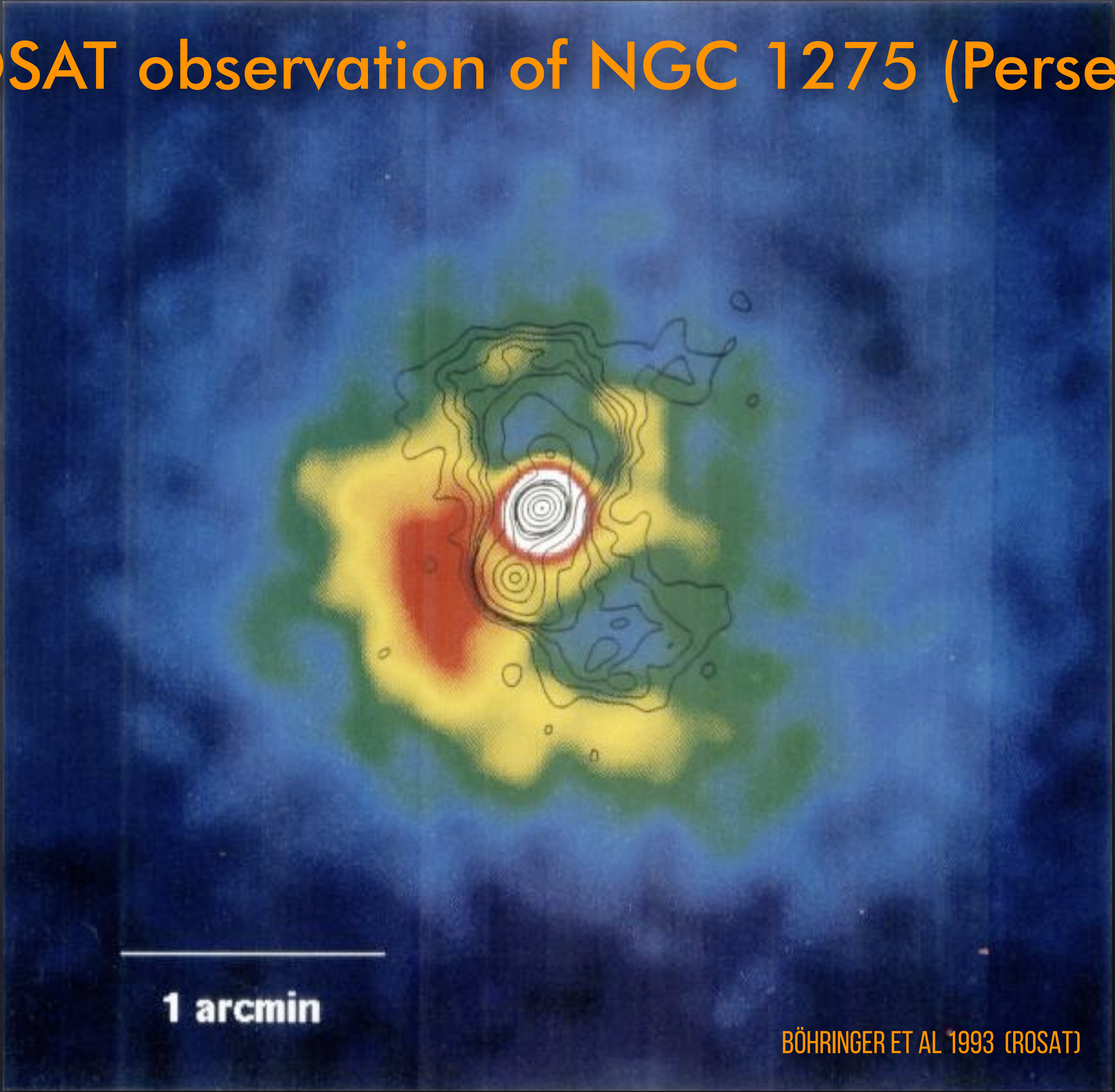


XMM-RGS observation of Abell 1835; XMM-EPIC observation of M87

- Gas does not cool as much as previously thought
- In general, $T_{min} \sim T_{vir}/3$

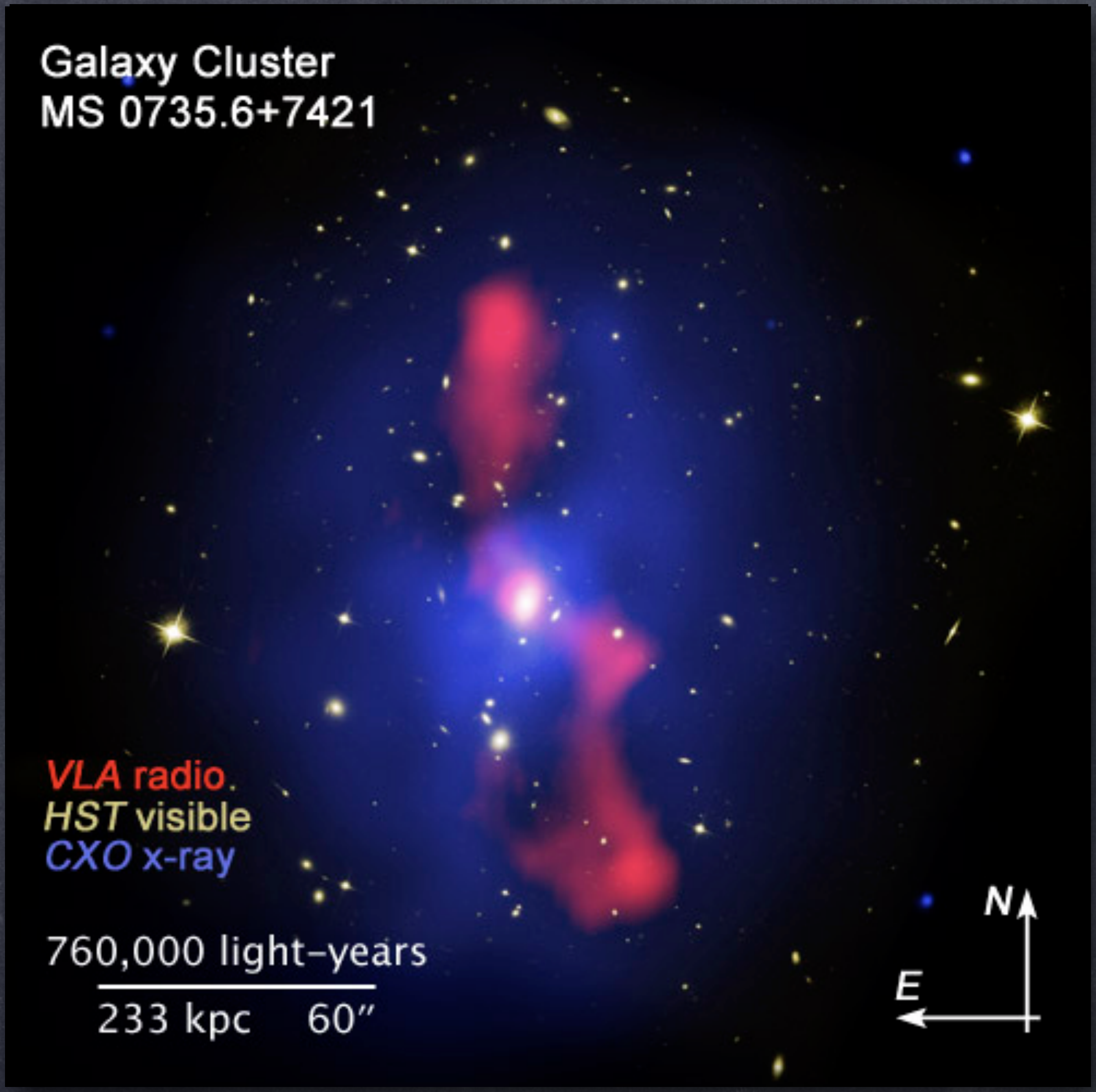
PETERSEN ET AL. 2001, 2003
BÖHRINGER ET AL 2001

ROSAT observation of NGC 1275 (Perseus)

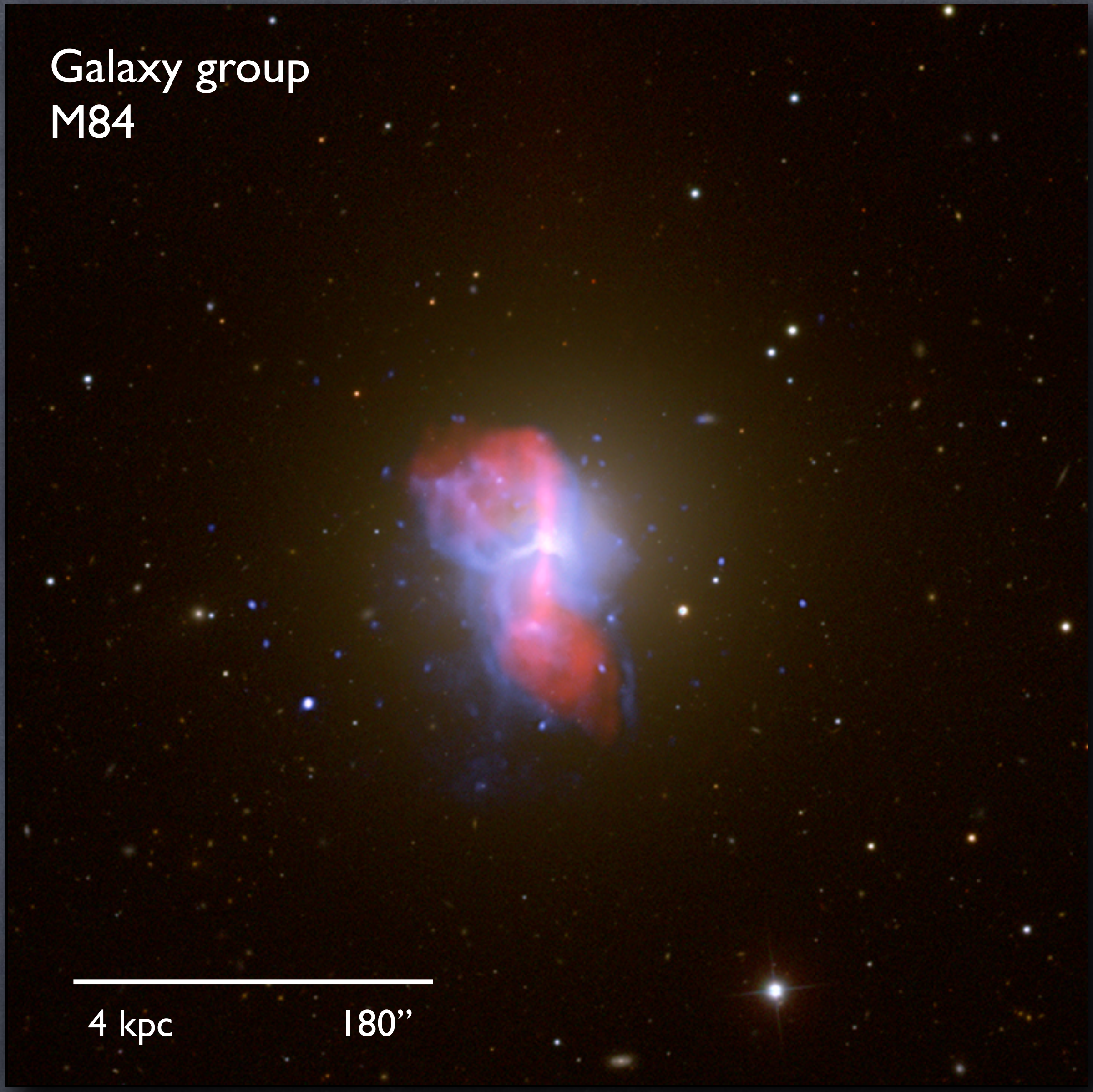


BÖHRINGER ET AL 1993 (ROSAT)

Key new observations - II



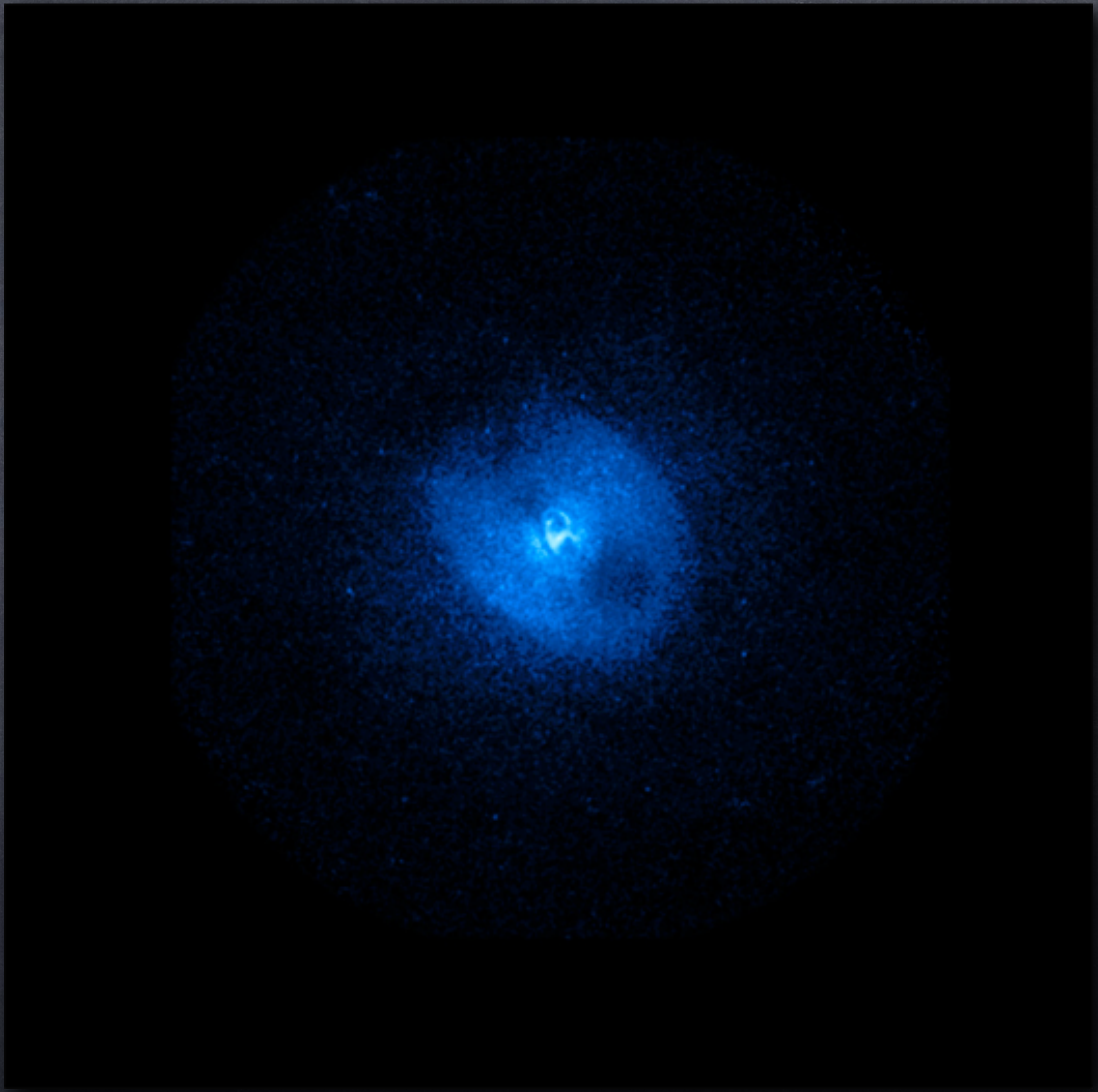
MS0735.6+7421 AT Z=0.22;
NASA, ESA, AND B. MCNAMARA



M84 AT Z=0.0034
C. JONES

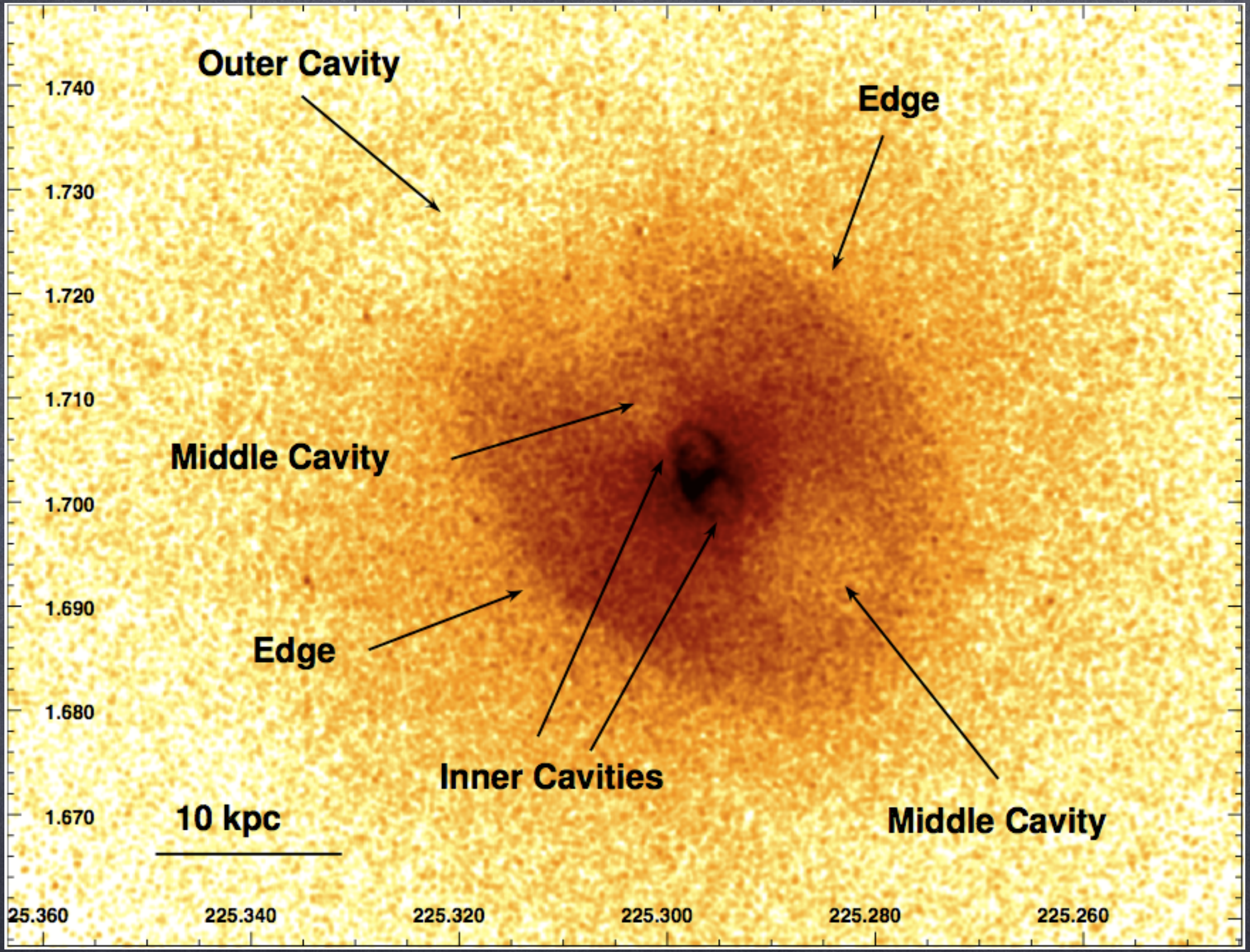
- High-resolution Chandra observations of interaction between AGN and ICM in many systems at all scales

NGC 5813 (Virgo)



RANDALL ET AL 2011 (CHANDRA)

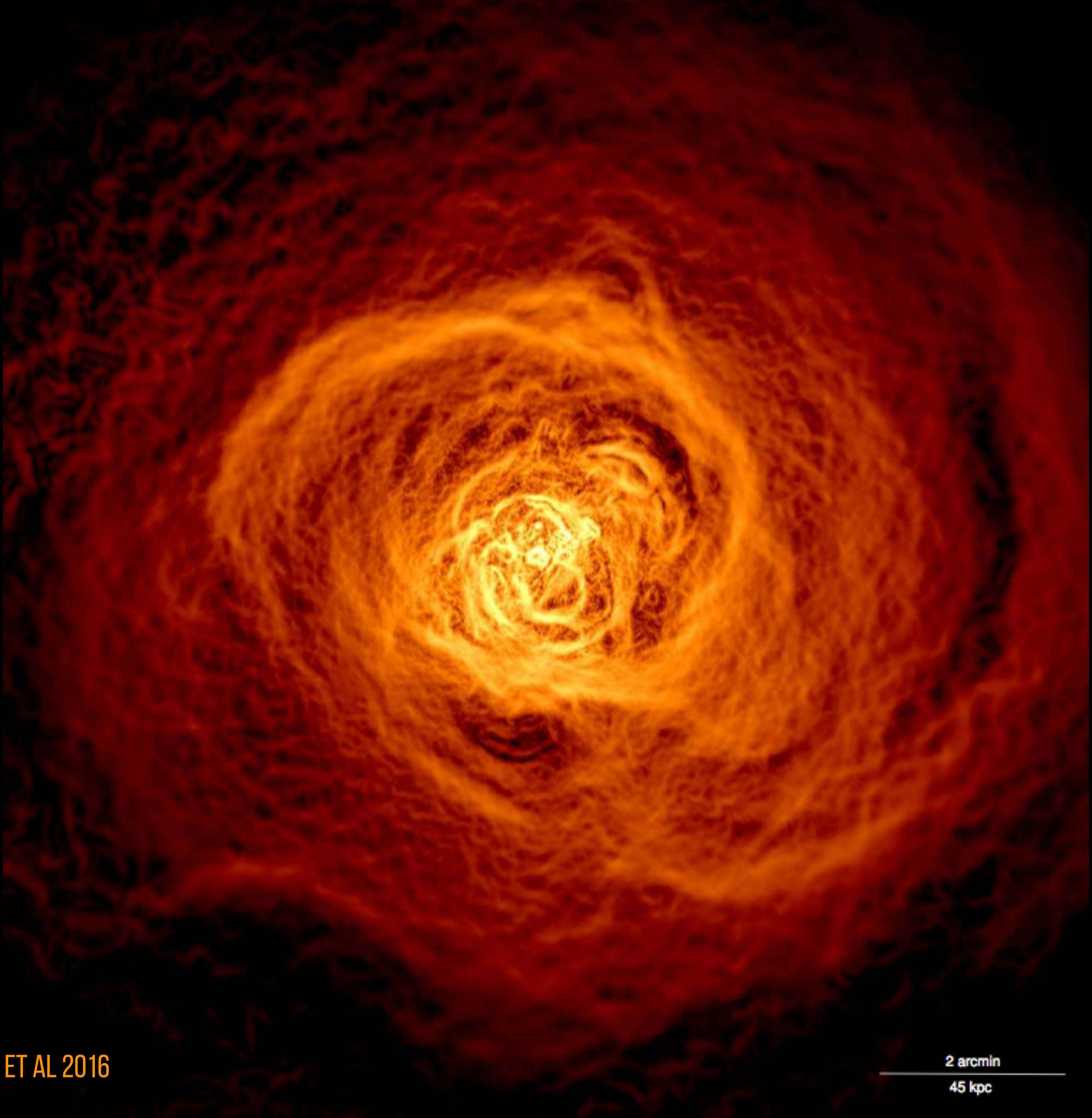
NGC 5813 (Virgo)



RANDALL ET AL 2011 (CHANDRA)

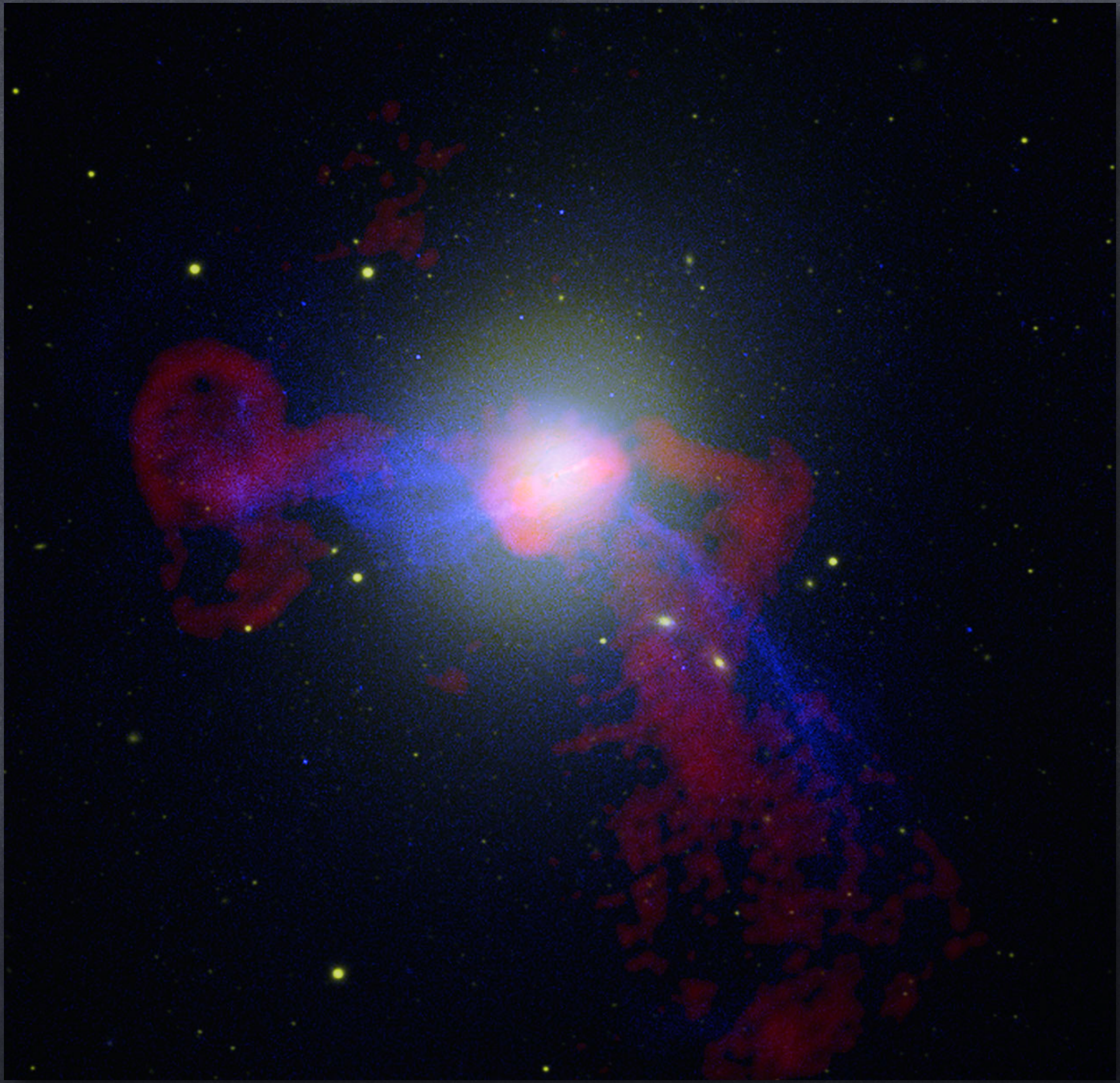
Evidence for several eruptions

- Constraints on eruption timescales (10^6 - 10^8 yr)

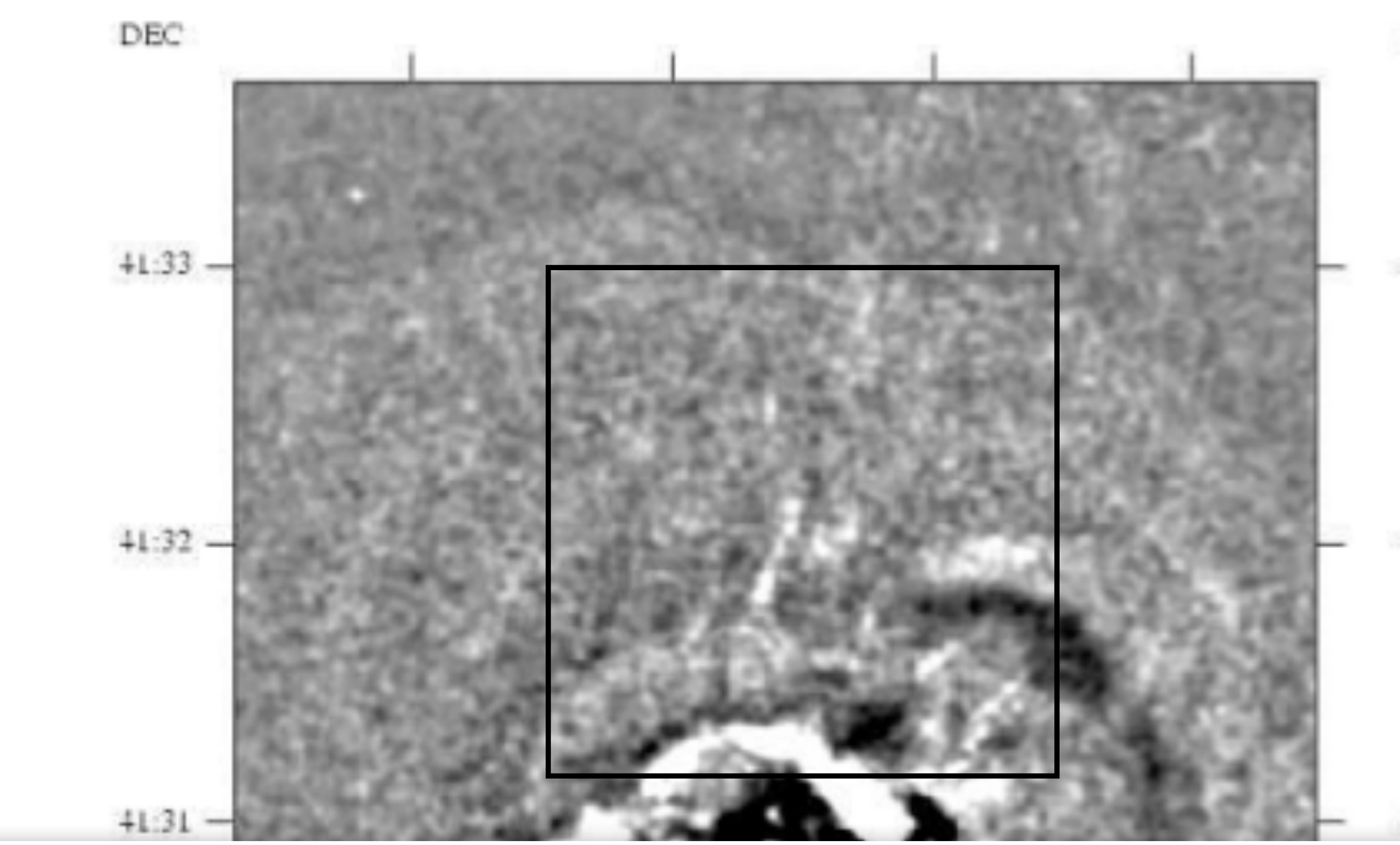


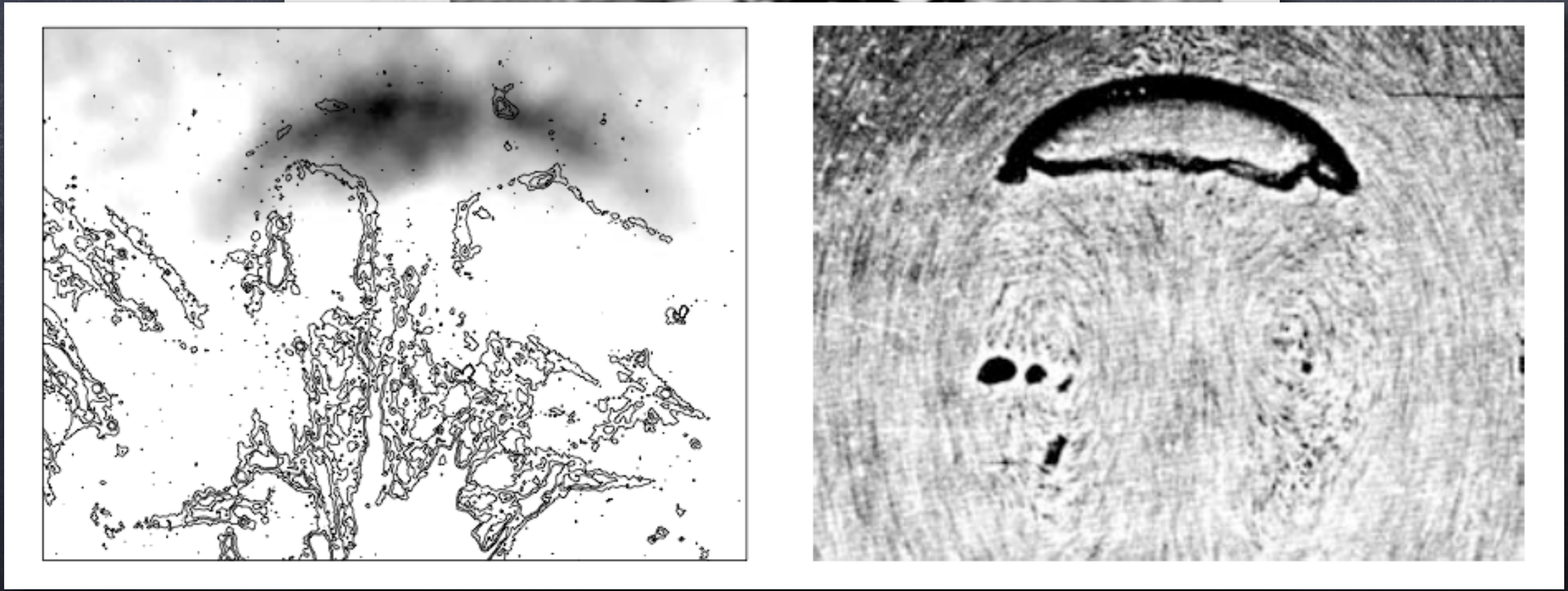
PERSEUS; SANDERS ET AL 2016

Bubbles in M87



M87 OPTICAL, RADIO, X-RAY: FORMAN ET AL





PERSEUS, X-RAY, Hα: FABIAN ET AL

Heating mechanisms

IDEA FROM PRESENTATION BY E. CHURAZOV

BUBBLES

Isothermal

$$\frac{\delta T}{T} \sim 0 \times \frac{\delta n}{n}$$

SUBSONIC DISPLACEMENT

Isobaric

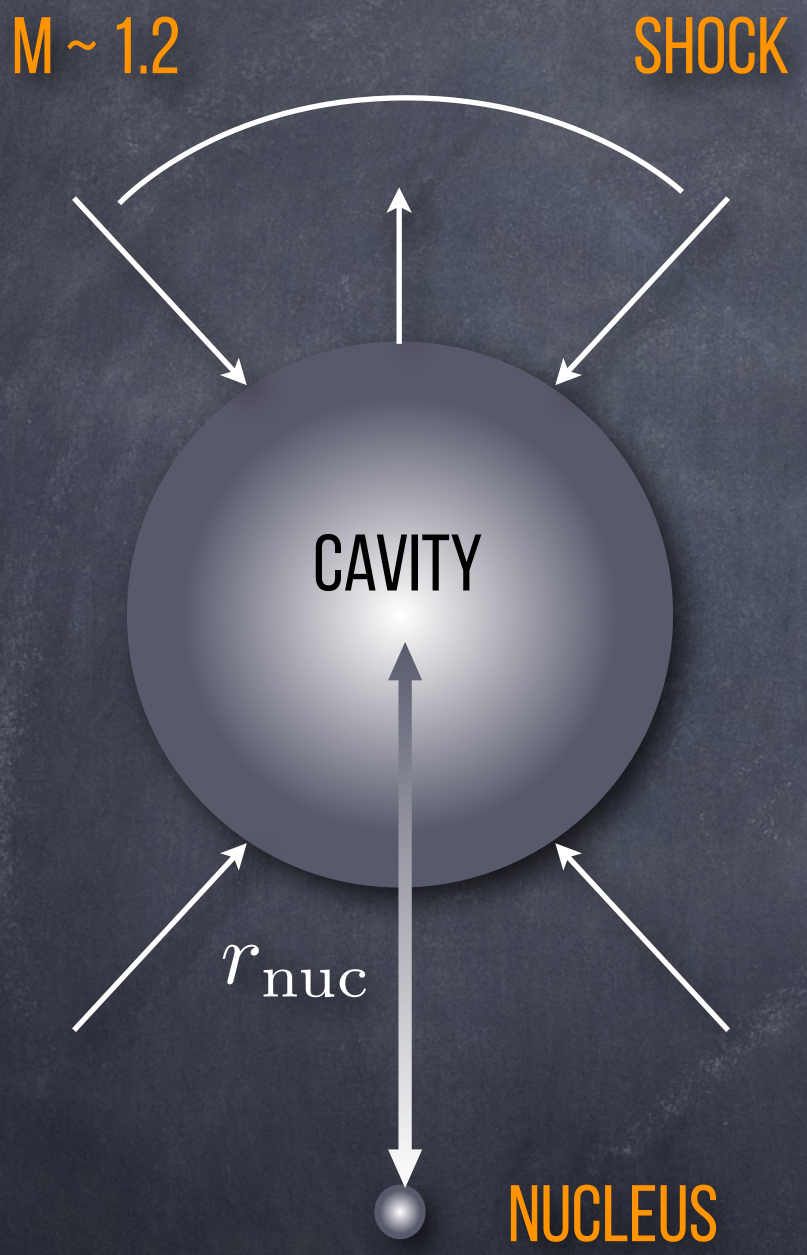
$$\frac{\delta T}{T} \sim -1 \times \frac{\delta n}{n}$$

SOUND WAVES

Adiabatic

$$\frac{\delta T}{T} \sim \frac{2}{3} \times \frac{\delta n}{n}$$

Energetics



1. pV work due to expansion

$$E_{\rm cav} = H = E + pV = \frac{\Gamma}{\Gamma - 1} pV$$

$$H = 4pV$$ relativistic particles

$$H = 2.5pV$$ non-relativistic particles

$$t_{\rm cav} \sim r_{\rm nuc}/v$$

2. Energy of weak shock

$$E_{\rm shock} \sim \Delta\, pV$$

$$t_{\rm shock} \sim r_{\rm shock}/c_s$$

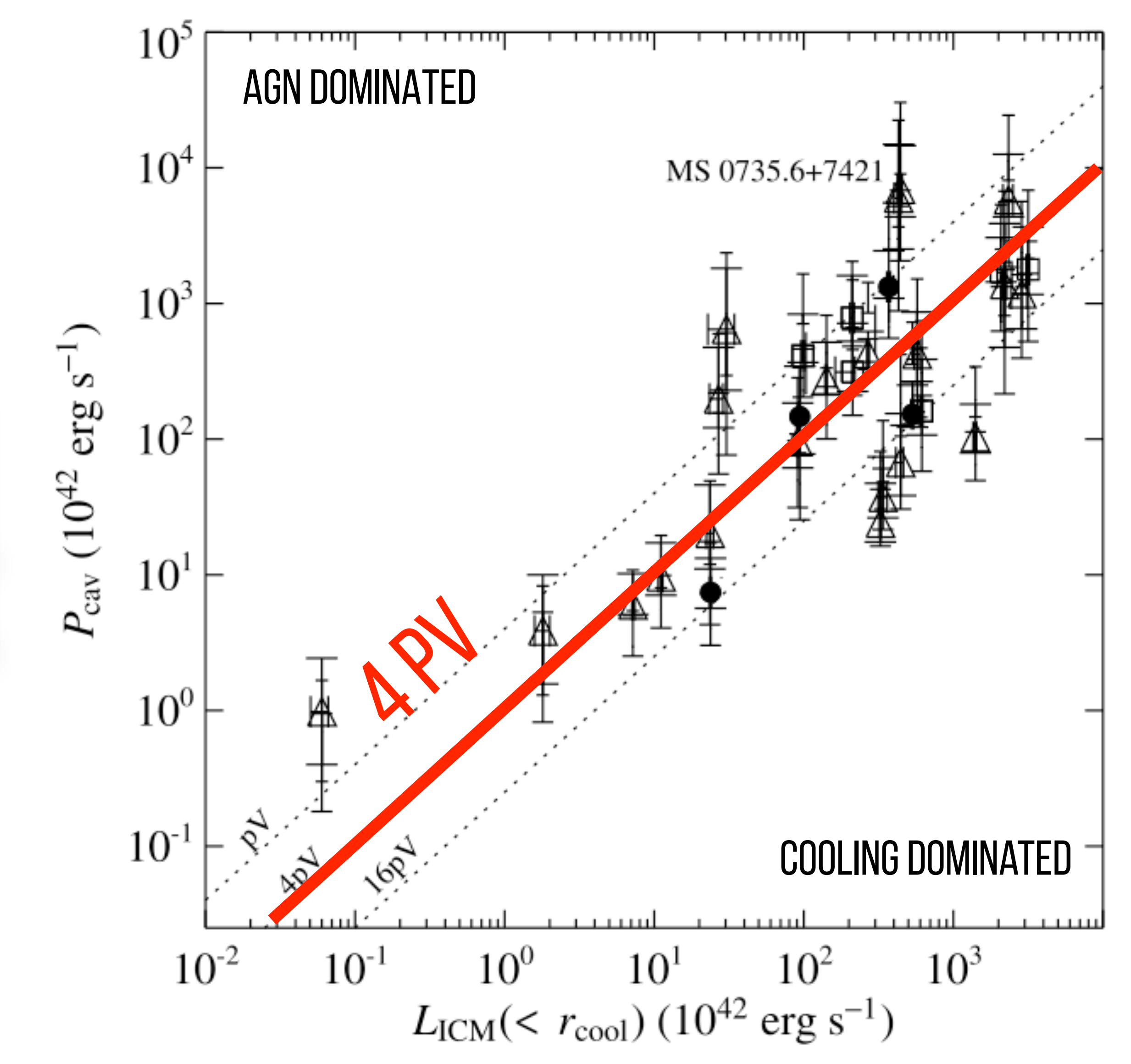
3. Total energy

$$E_{\rm tot} = E_{\rm cav} + E_{\rm shock} + (E_{\rm photon})$$

$$\sim 10^{55} - 10^{62} {\rm erg}$$

Energetic equilibrium

Jet power

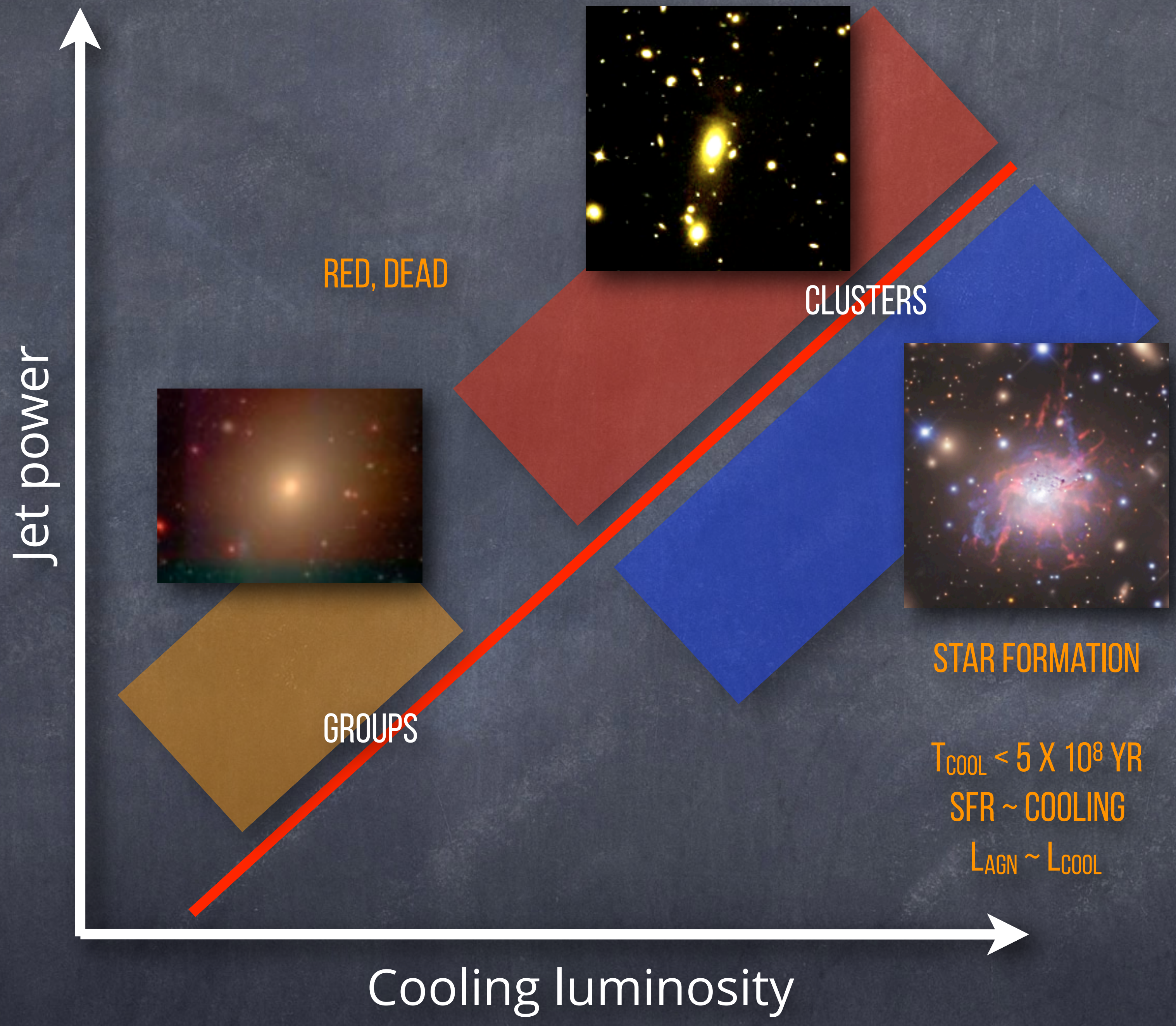


Cooling luminosity

RAFFERTY ET AL 2008

$\langle$heating$\rangle$ ~ cooling

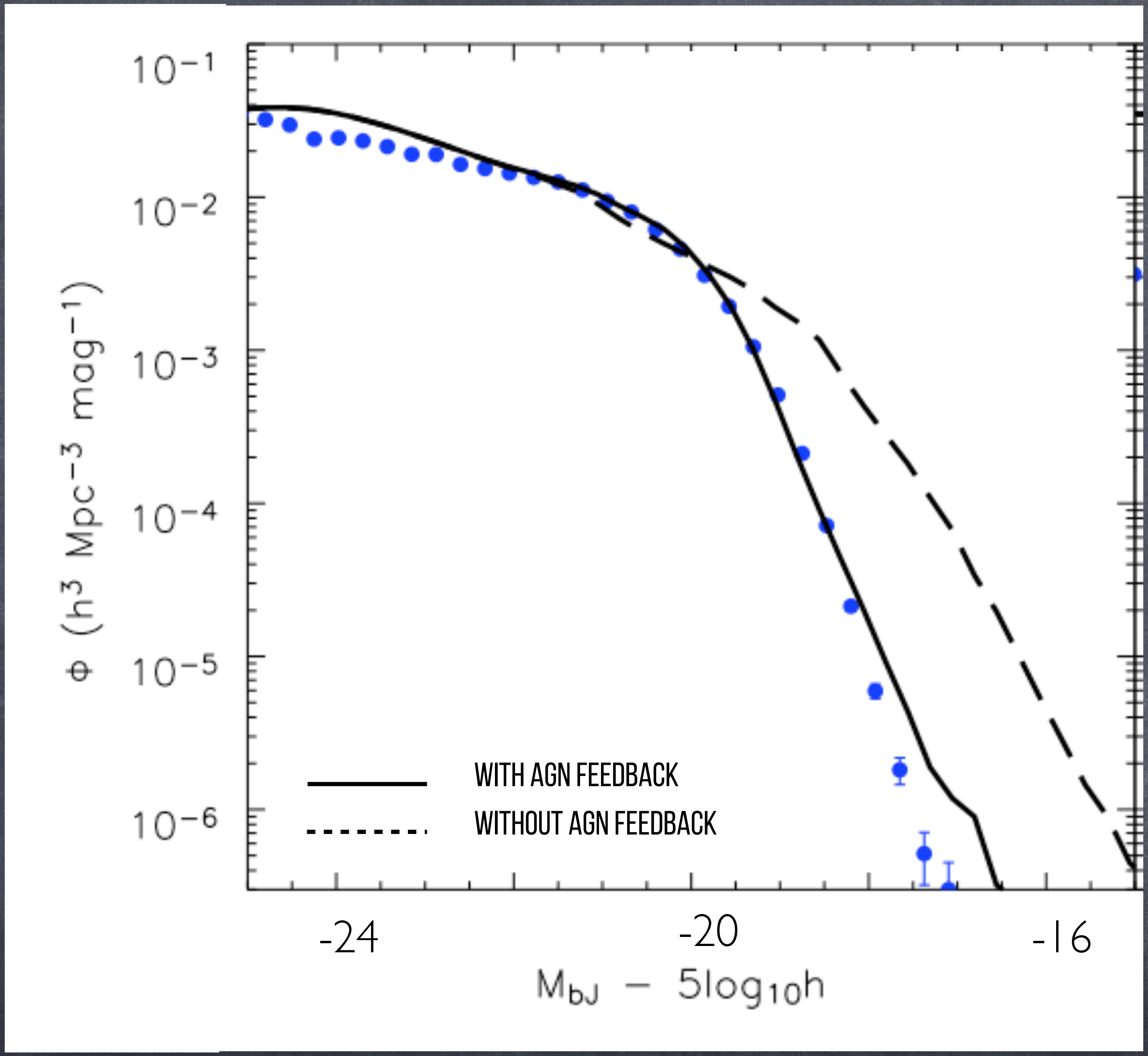
Consequences for central galaxies



$T_{COOL} < 5 \times 10^8$ YR
SFR ~ COOLING
$L_{AGN} \sim L_{COOL}$

$\langle$heating$\rangle$ ~ cooling

Consequences for central galaxies

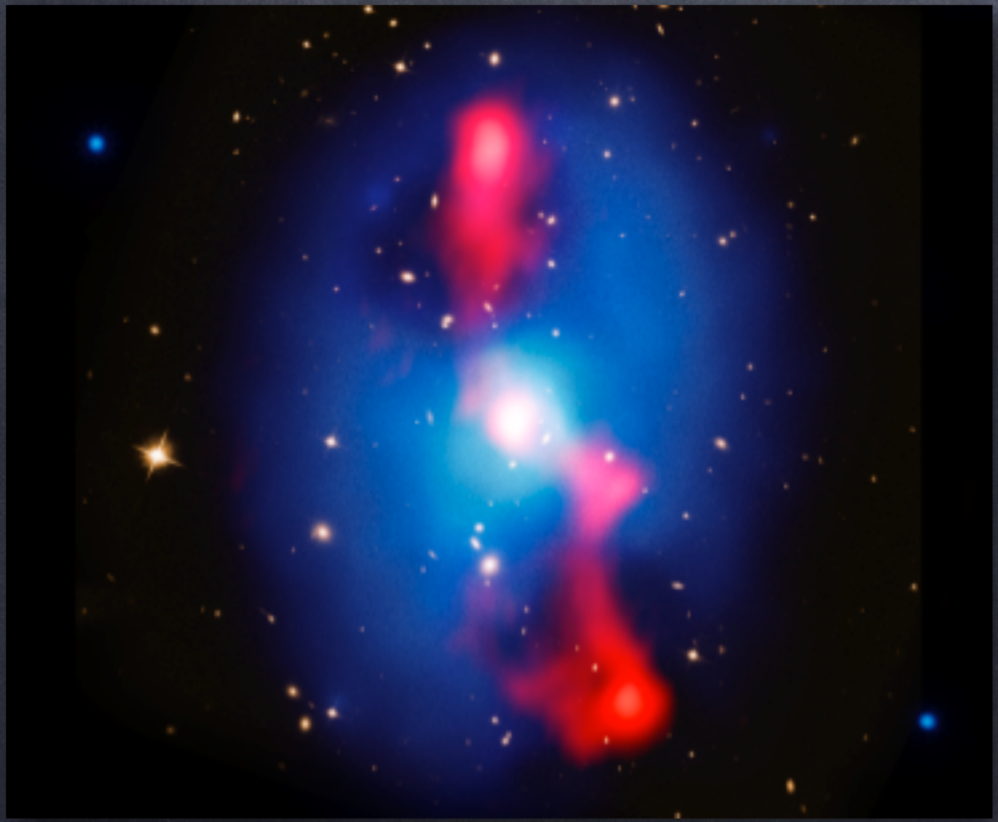


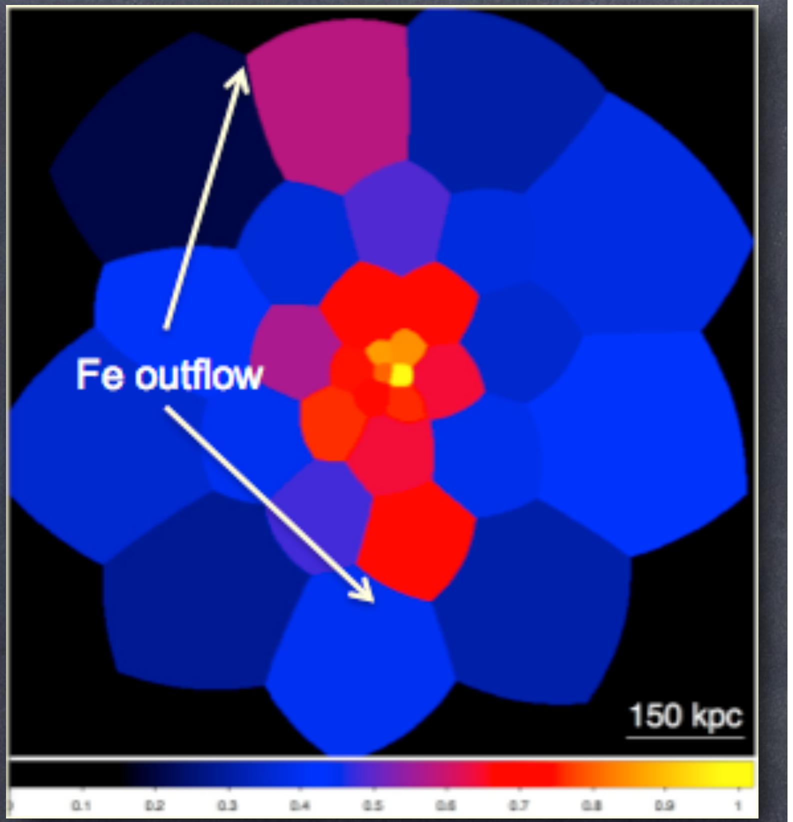
CROTON ET AL 2006

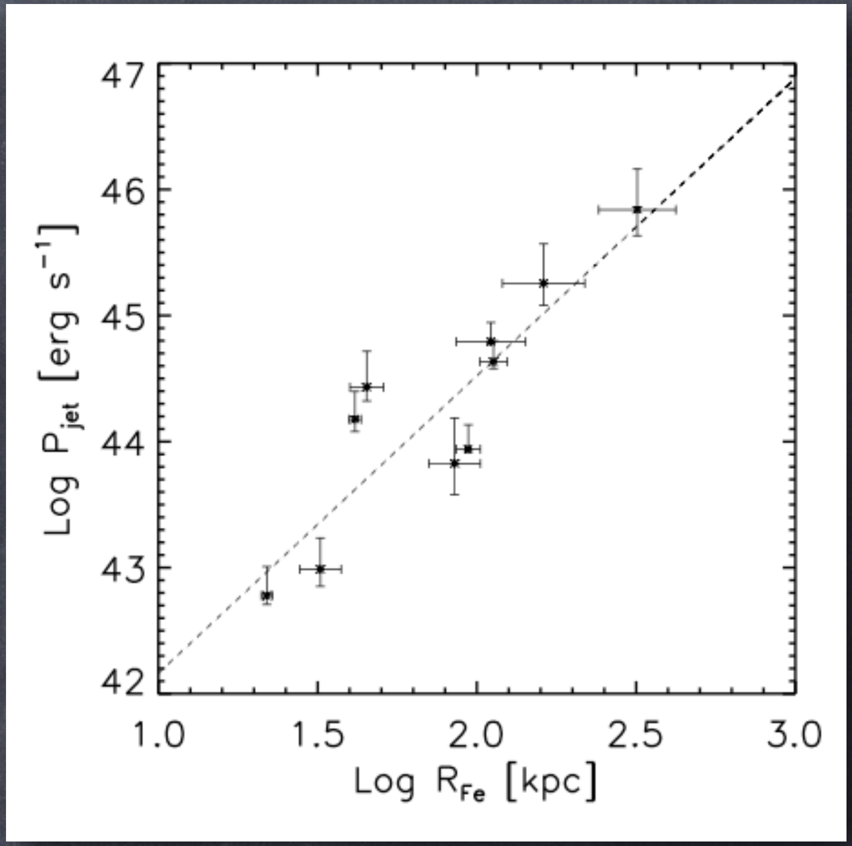
Feedback necessary to reproduce observed galaxy luminosity fn

Enrichment

Consequences for metal distribution





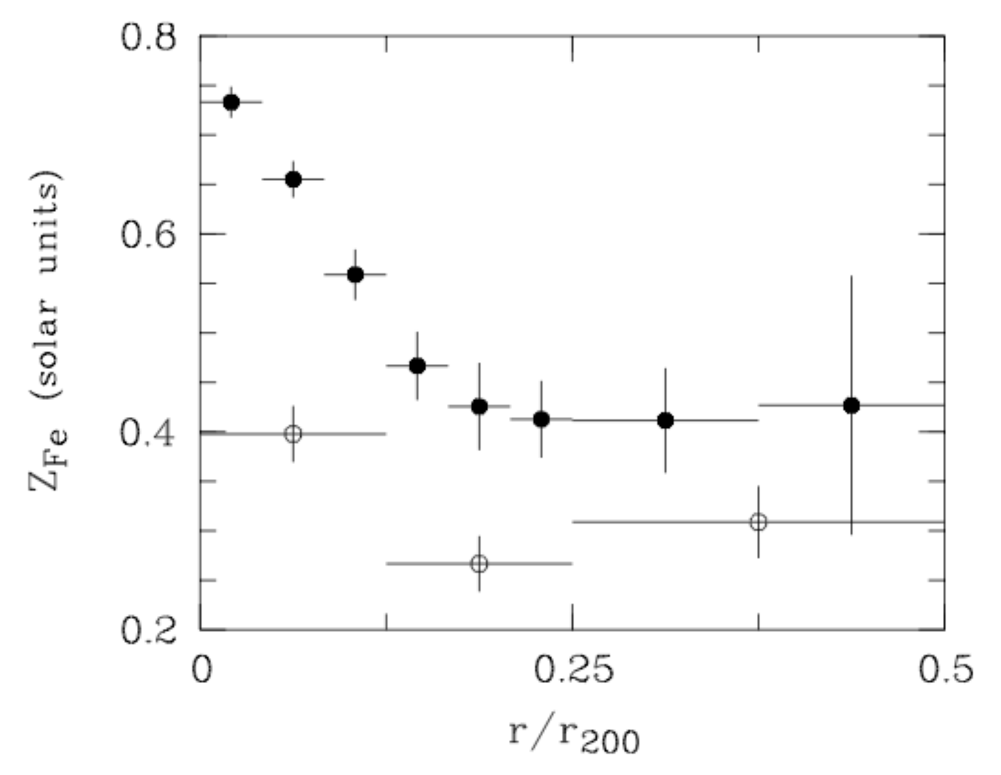


MCNAMARA ET AL 2011, KIRKPATRICK ET AL 2011

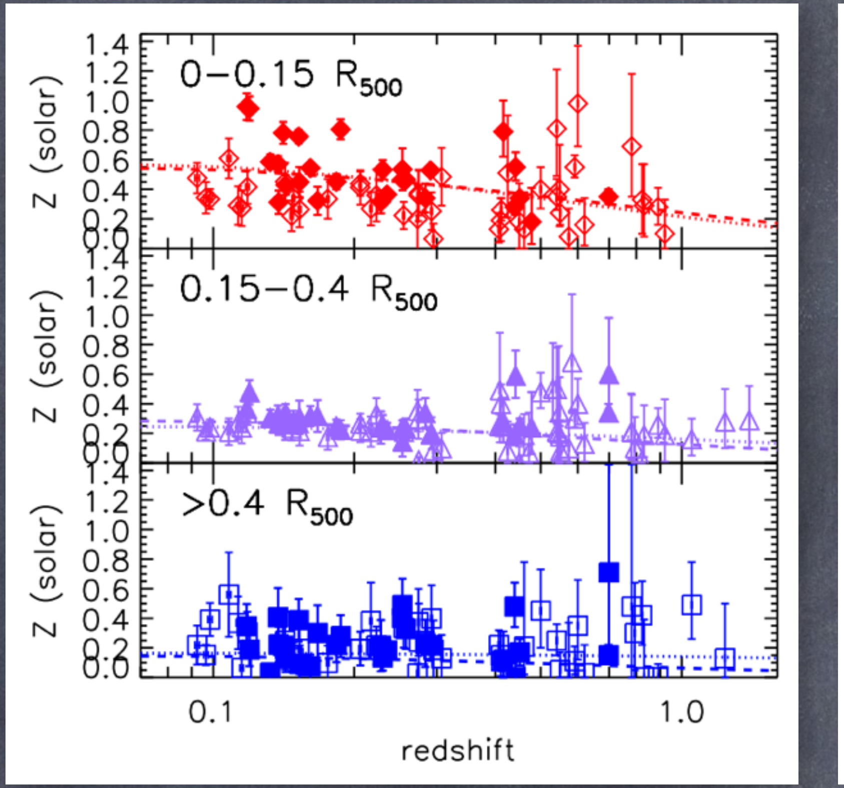
Entrainment of metals to larger radius

- Correlation with jet power

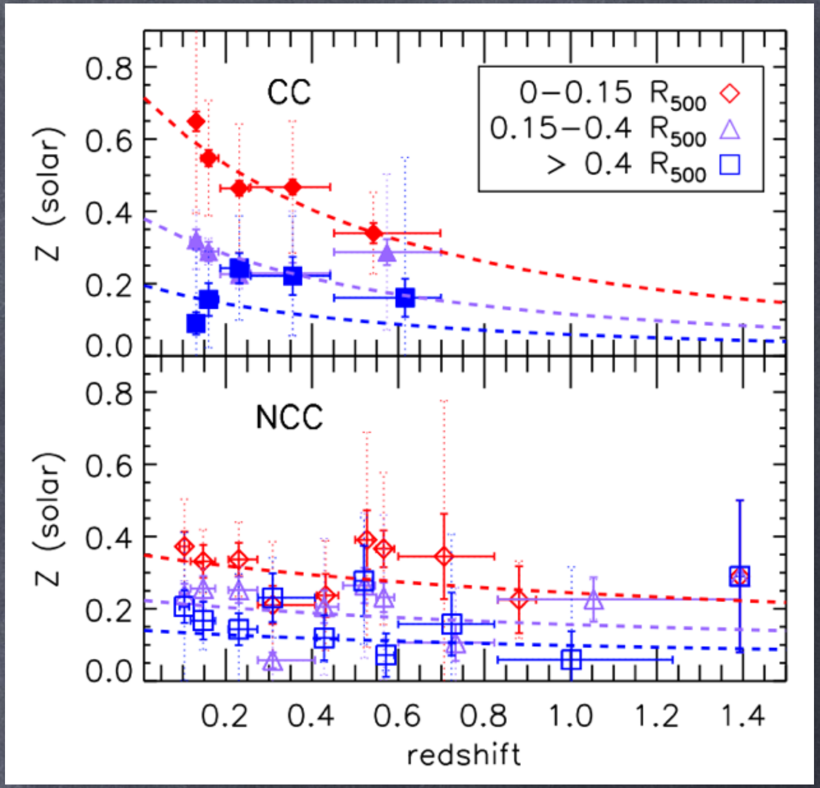
Metallicity distribution and evolution



DE GRANDI & MOLENDI 2004



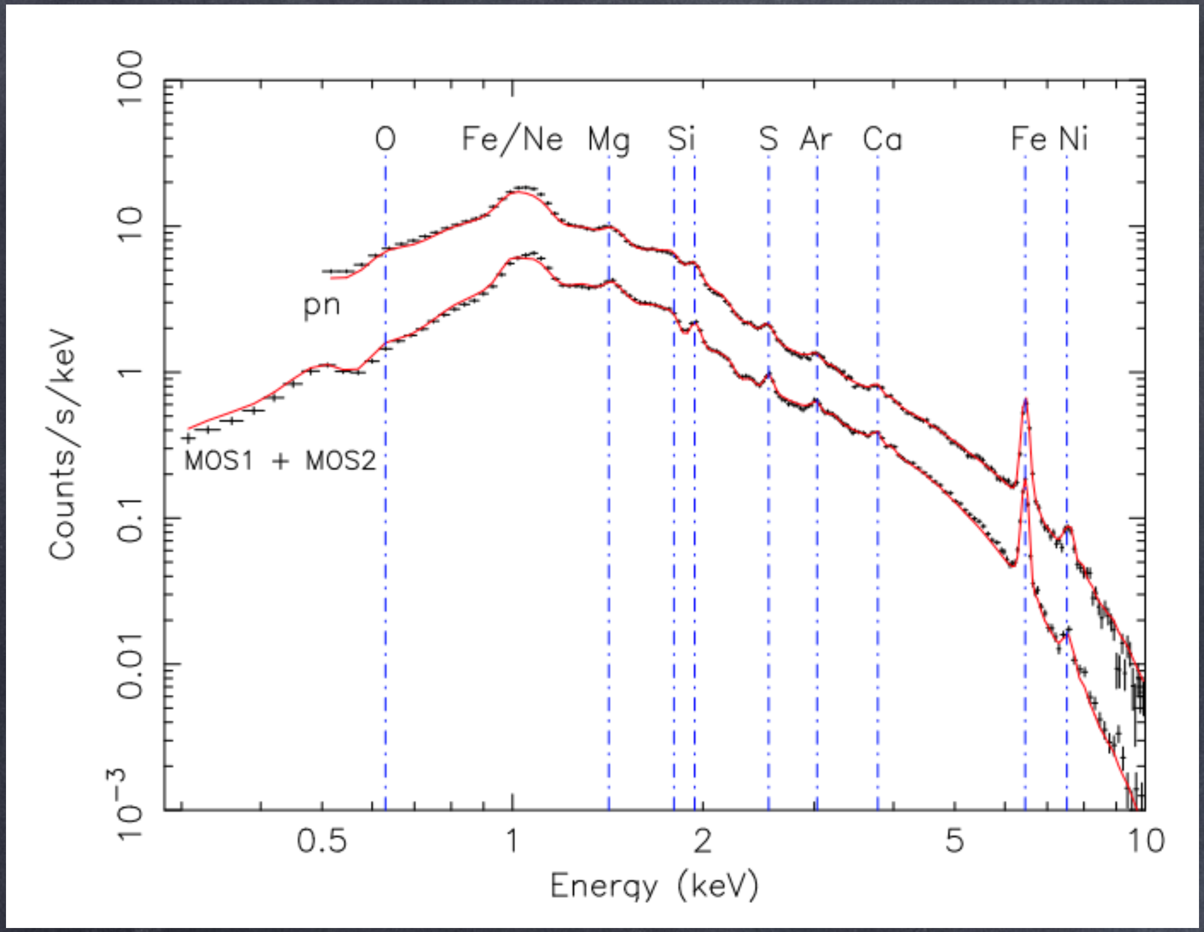
ETTORI ET AL 2016

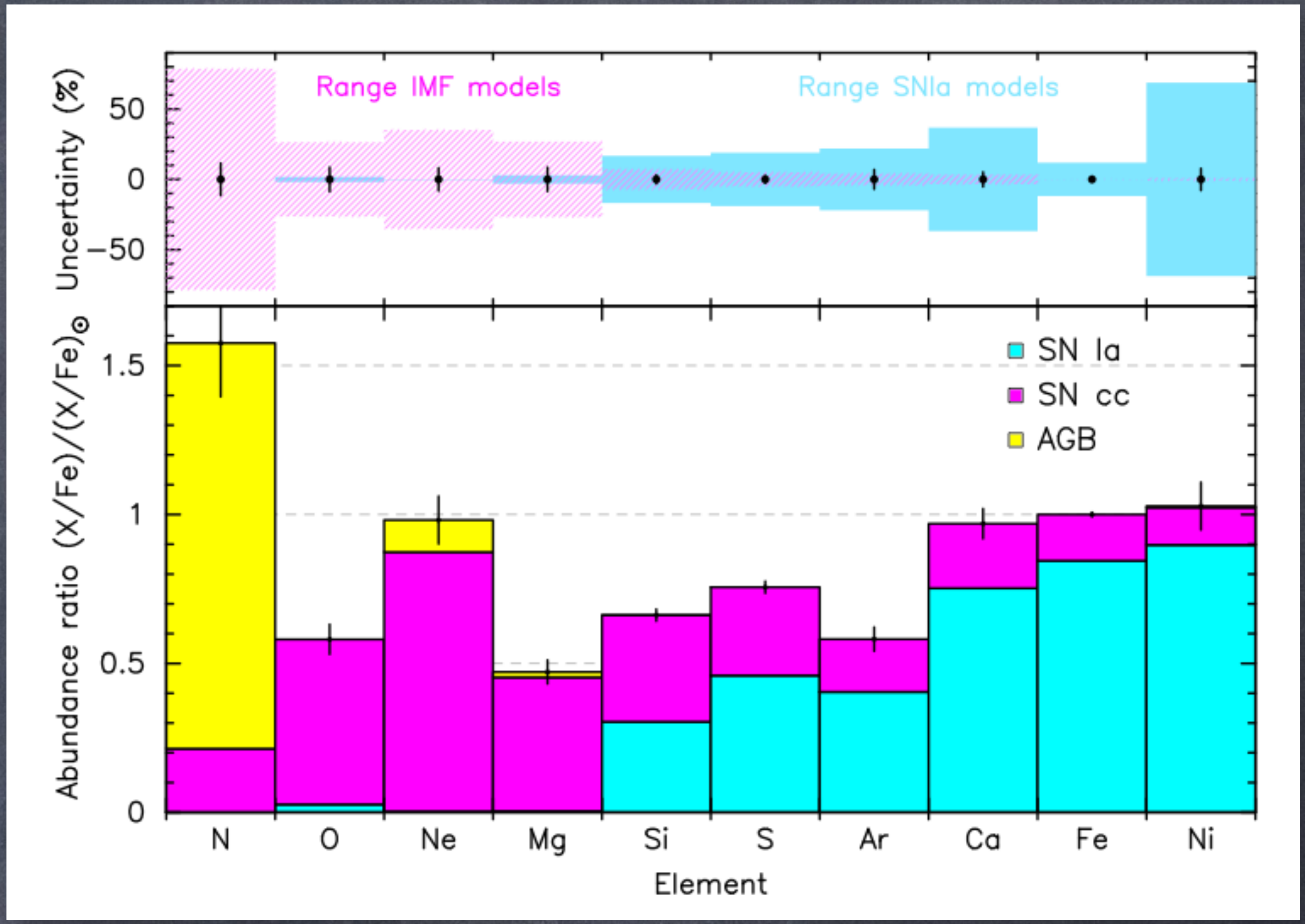


ETTORI ET AL 2016

- Cool cores have central abundance peaks
- Central abundance evolves with redshift
- Abundance outside core constant to z>1
- Consistent with early enrichment scenario

Enrichment



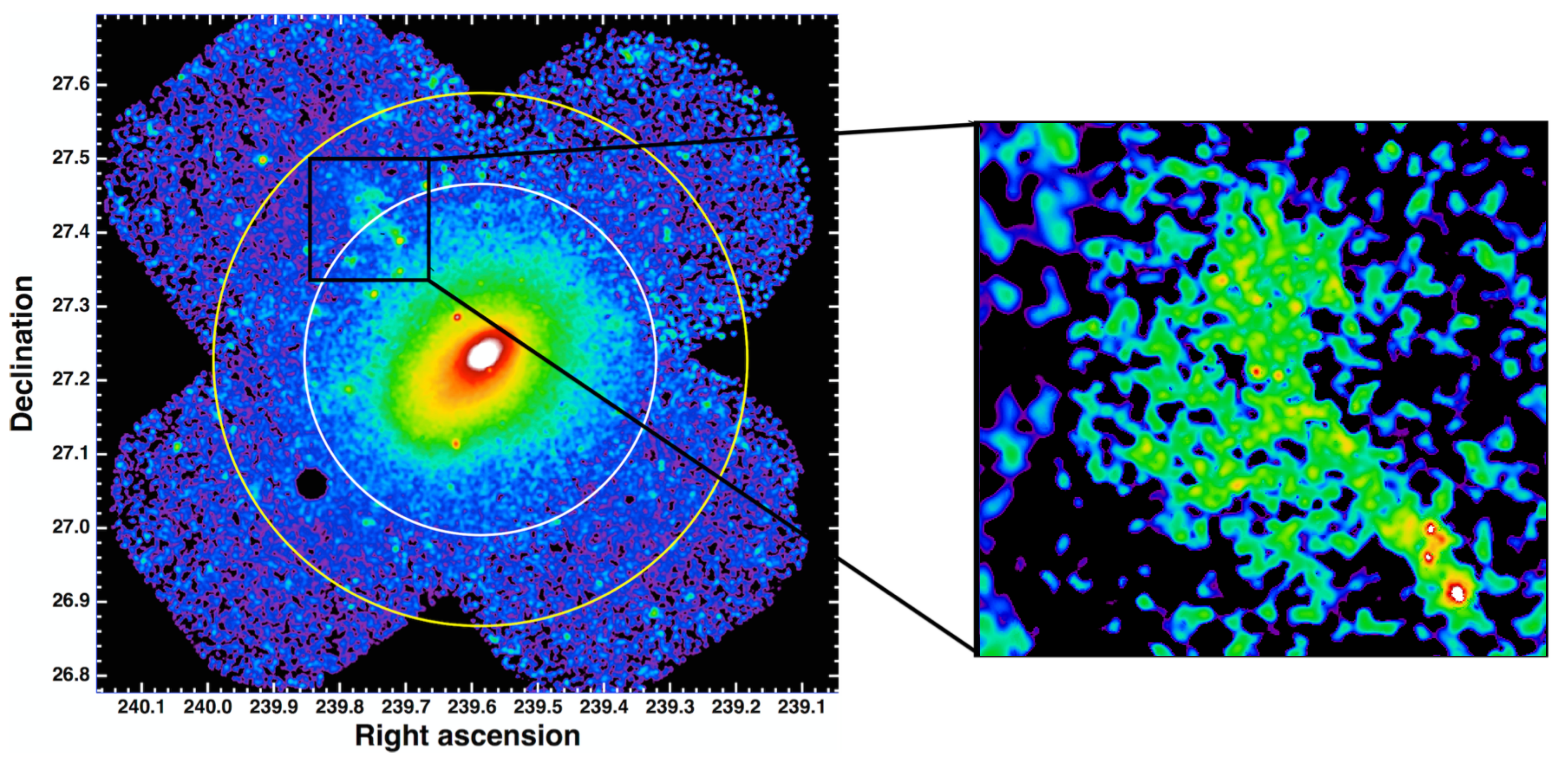


DE PLAA 2013

- Can measure (central) abundance *ratios* using CCD spectroscopy
- O-Si mainly generated in SNII; Si-Ni generated in SNIa
- Core: production by cD (SNIa+SNII)
- Outside core: higher contribution from SNII
- Compare these to supernova detonation models to give yields

Enrichment

Accreting substructure in A2142



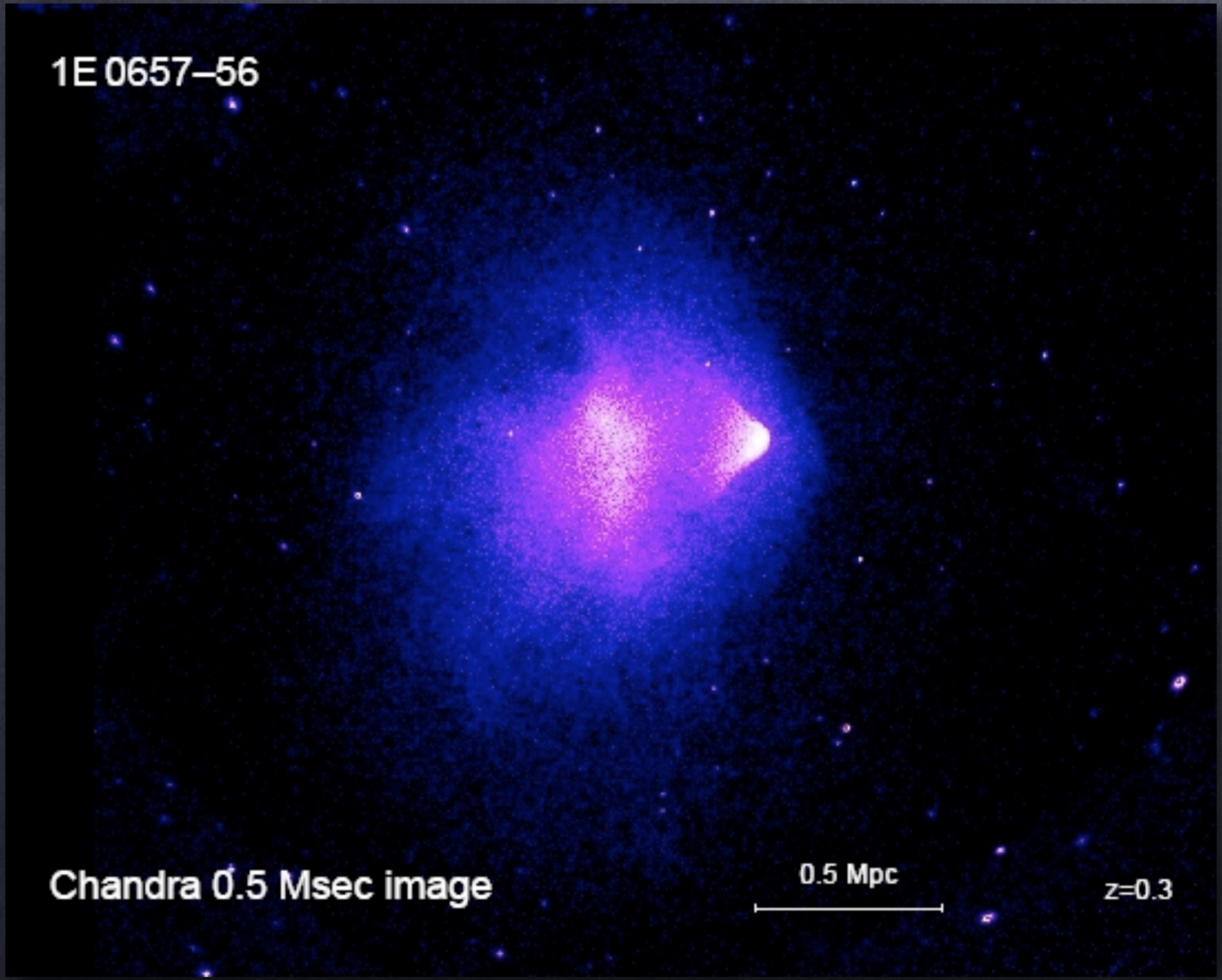
ECKERT ET AL 2014

Statistical properties

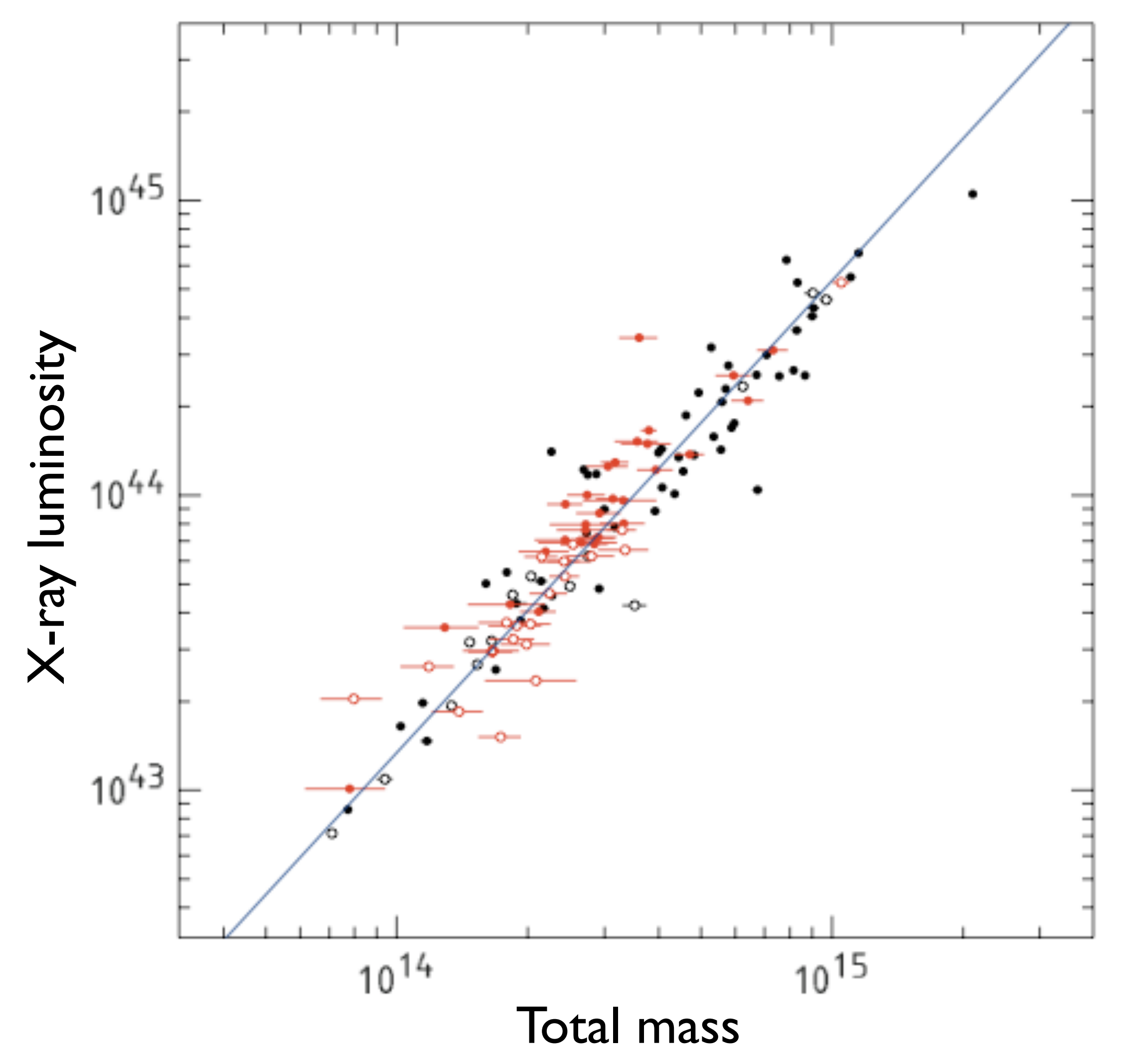
Galaxy clusters

Are *individually* complex…

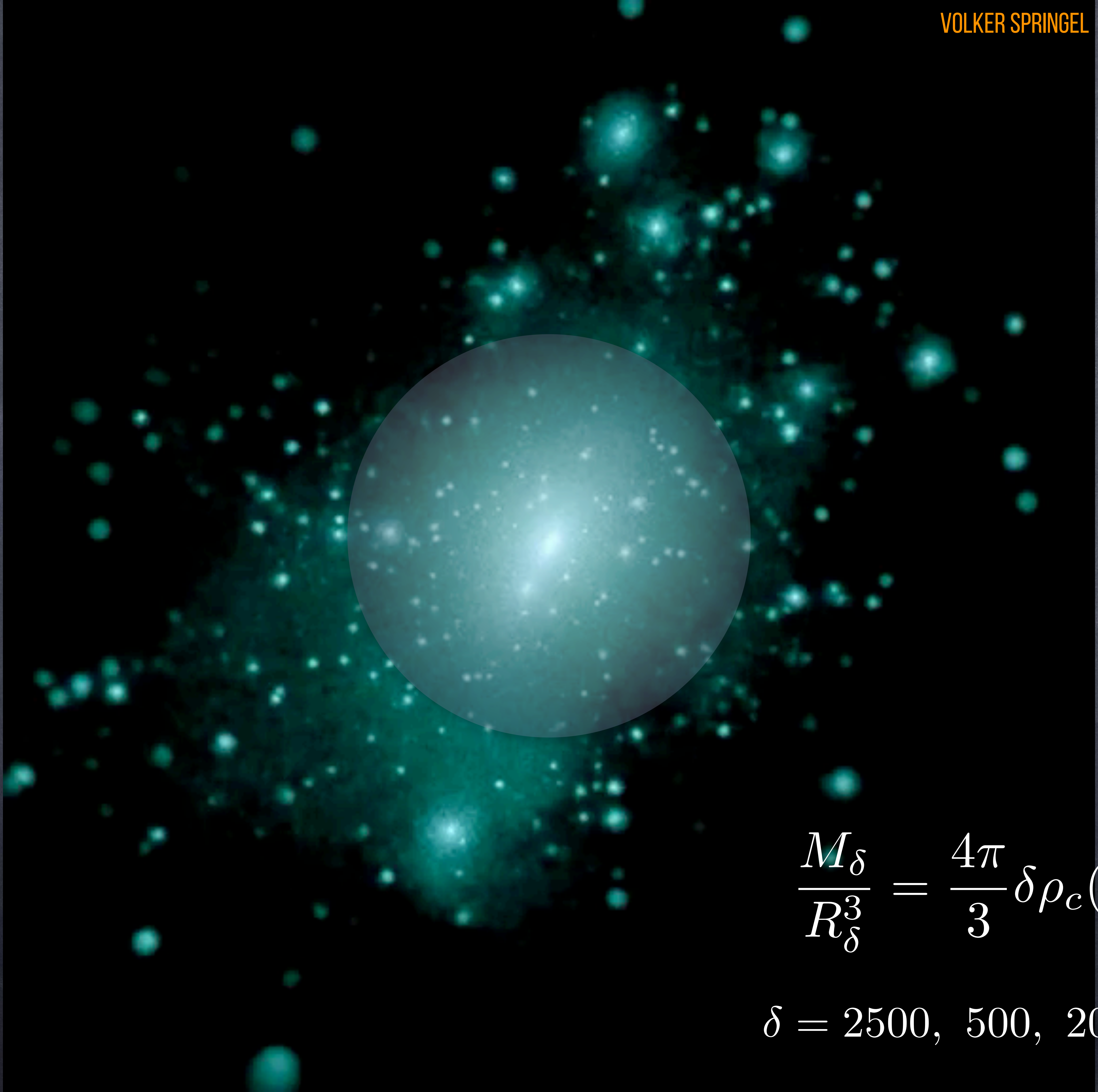
…but *globally* simple



MARKEVITCH ET AL 2002, 2004



VIKHLININ ET AL 2009



VOLKER SPRINGEL

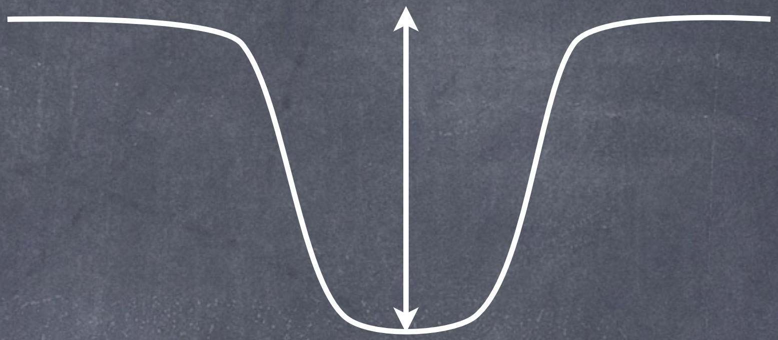
$$\frac{M_\delta}{R_\delta^3} = \frac{4\pi}{3}\delta\rho_c(z)$$

$$\delta = 2500,\ 500,\ 200\ldots$$

Scaling laws

- Virial theorem:
  - X-ray temperature reflects depth of potential

$$\frac{GM_\delta}{R_\delta} \propto kT$$



- Constant gas mass fraction:
  - Clusters are essentially closed boxes

$$f_{\rm gas} = \frac{M_{{\rm gas},\delta}}{M_\delta} = {\rm const}$$

- Evolution via mean dark matter (gas) density

$$\overline{\rho_{\rm gas}} \propto \overline{\rho_{\rm DM}} \propto \rho_{\rm c}(z) \propto E^2(z)$$

⇒ Scaling laws for global properties:

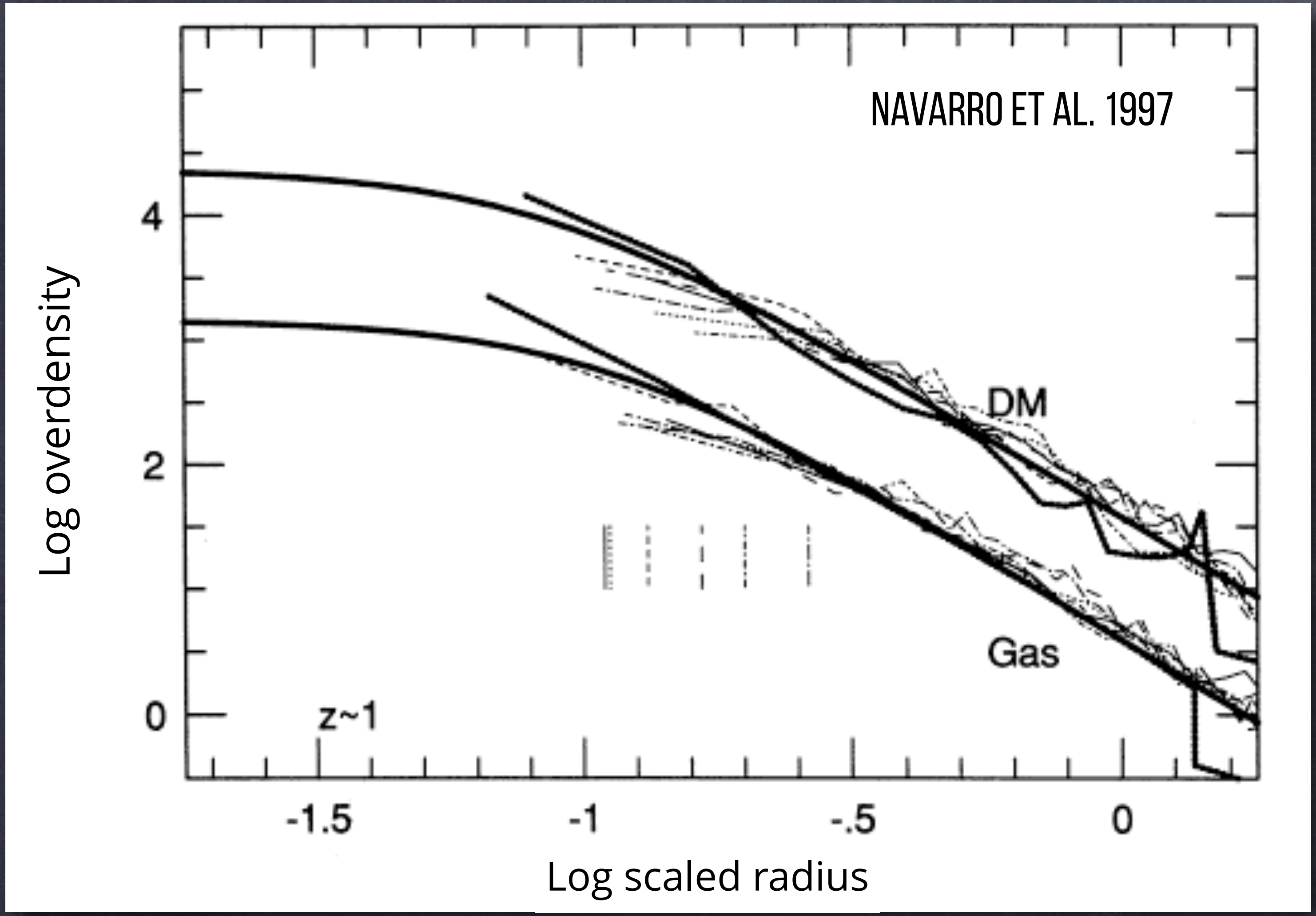
$$T_\delta \propto M\delta/R_\delta \propto E(z)R_\delta^2 \propto E(z)M_\delta^{2/3}$$

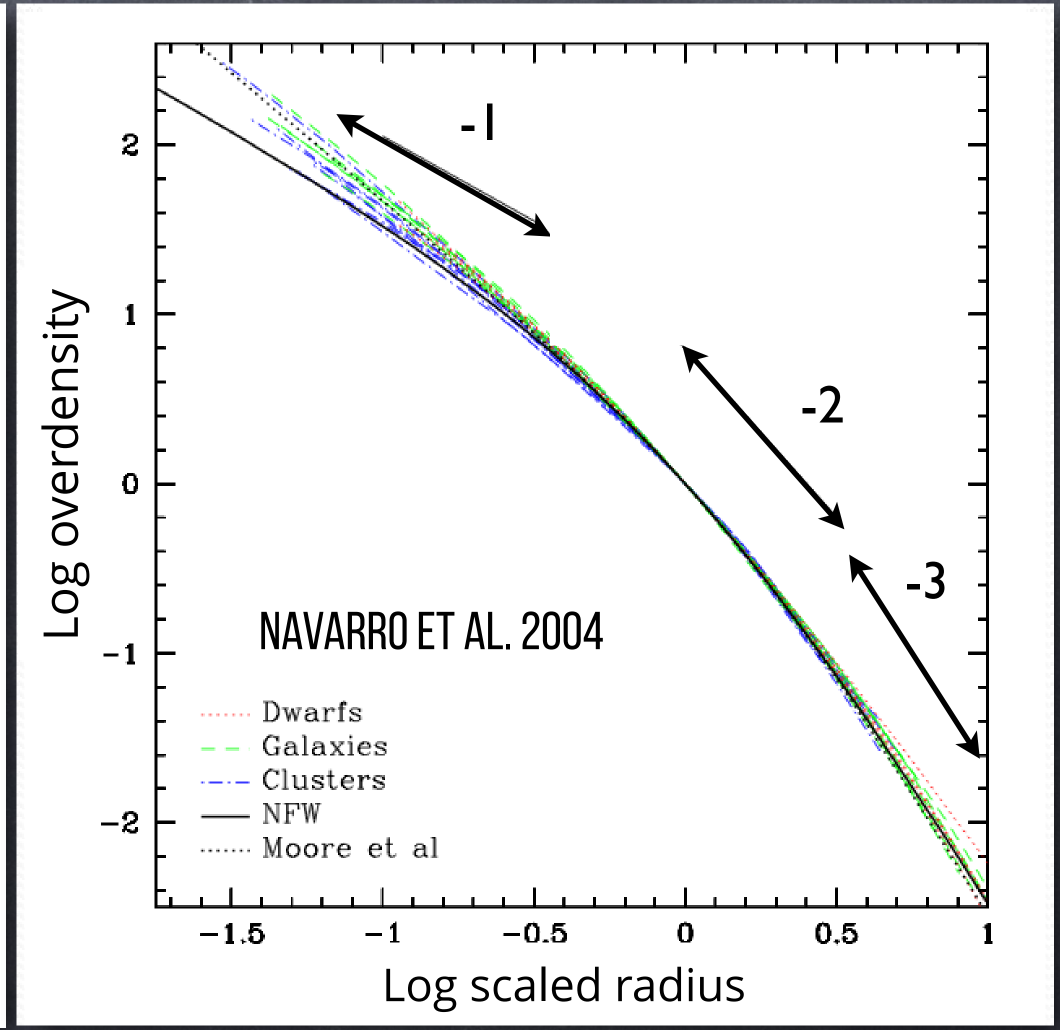
$$L_\delta \propto E(z)\,T_\delta^2 \quad ; \quad L_\delta \propto M_\delta^{4/3}$$

(assuming Bremsstrahlung)

+ optical richness, Y_{SZ}, etc

CDM haloes are structurally (self-)similar



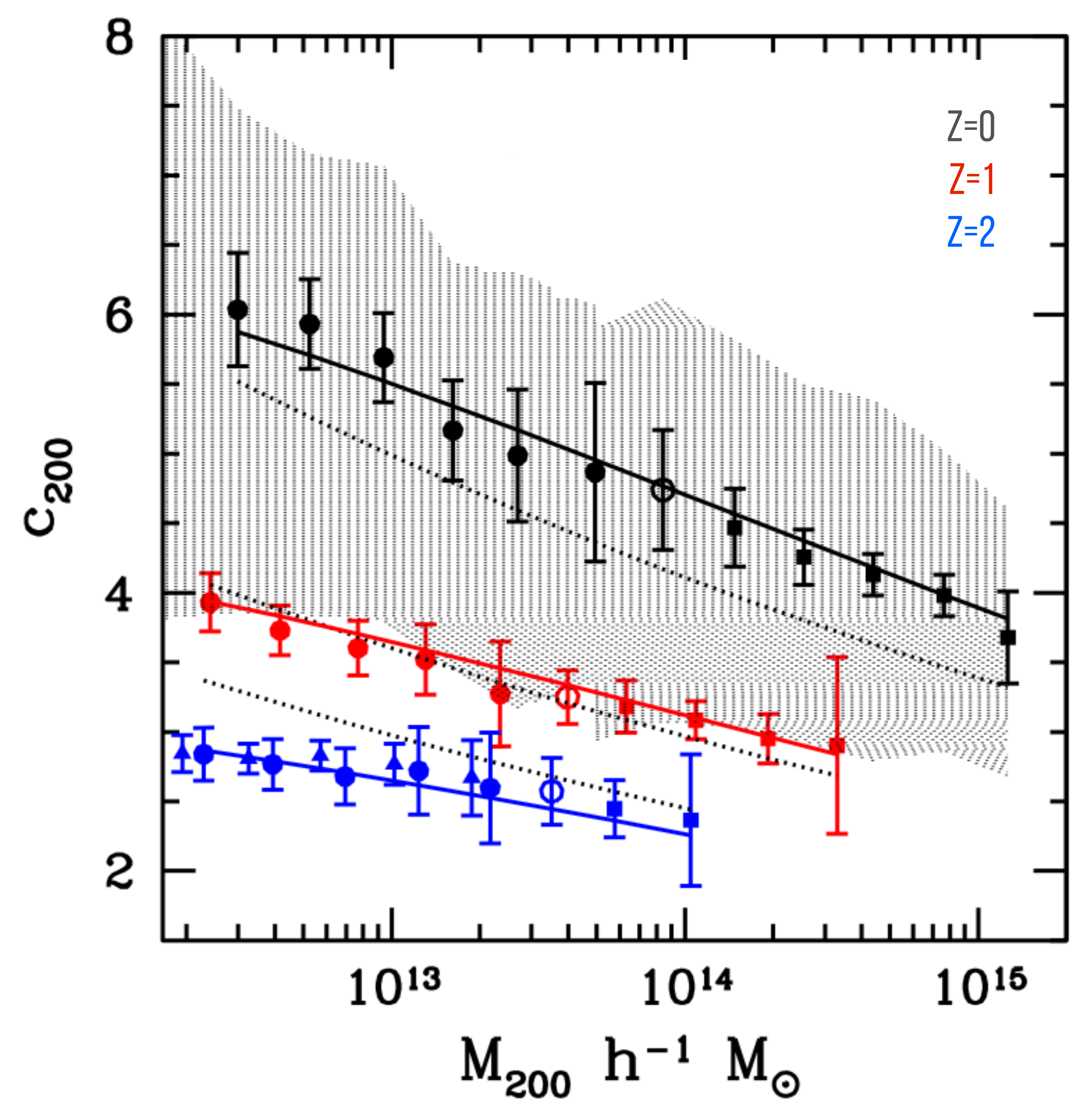


Universal density profile of CDM haloes:

$$\rho_r = \frac{\rho_c(z)\delta_c}{(r/r_s)(1+r/r_s)^2}$$

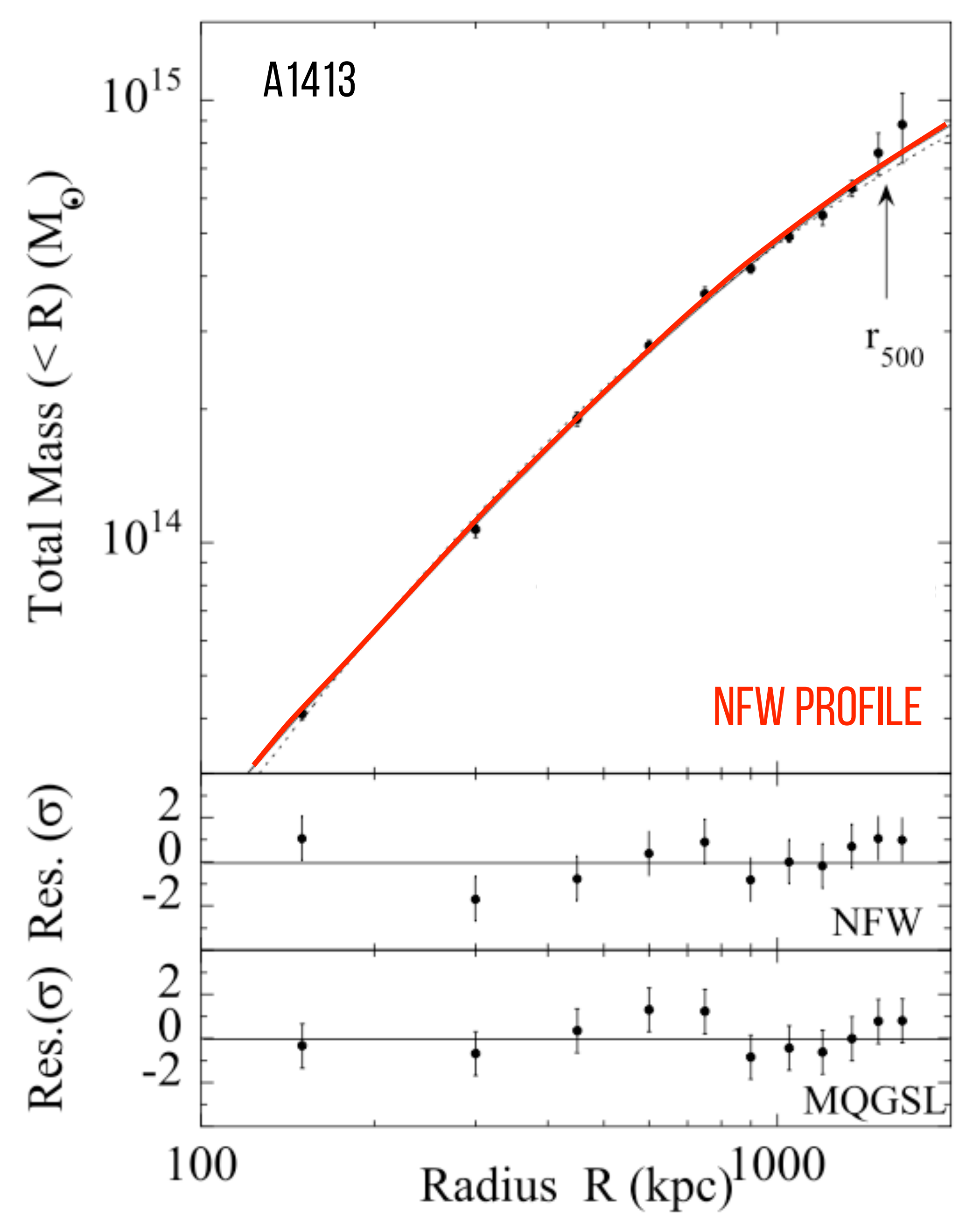
$$\left[\ \delta_c = \frac{200}{3}\frac{c^3}{[\ln(1+c) - c/(1+c)]} \quad ; \quad r_\delta = c_\delta r_s\ \right]$$

CDM halo concentration

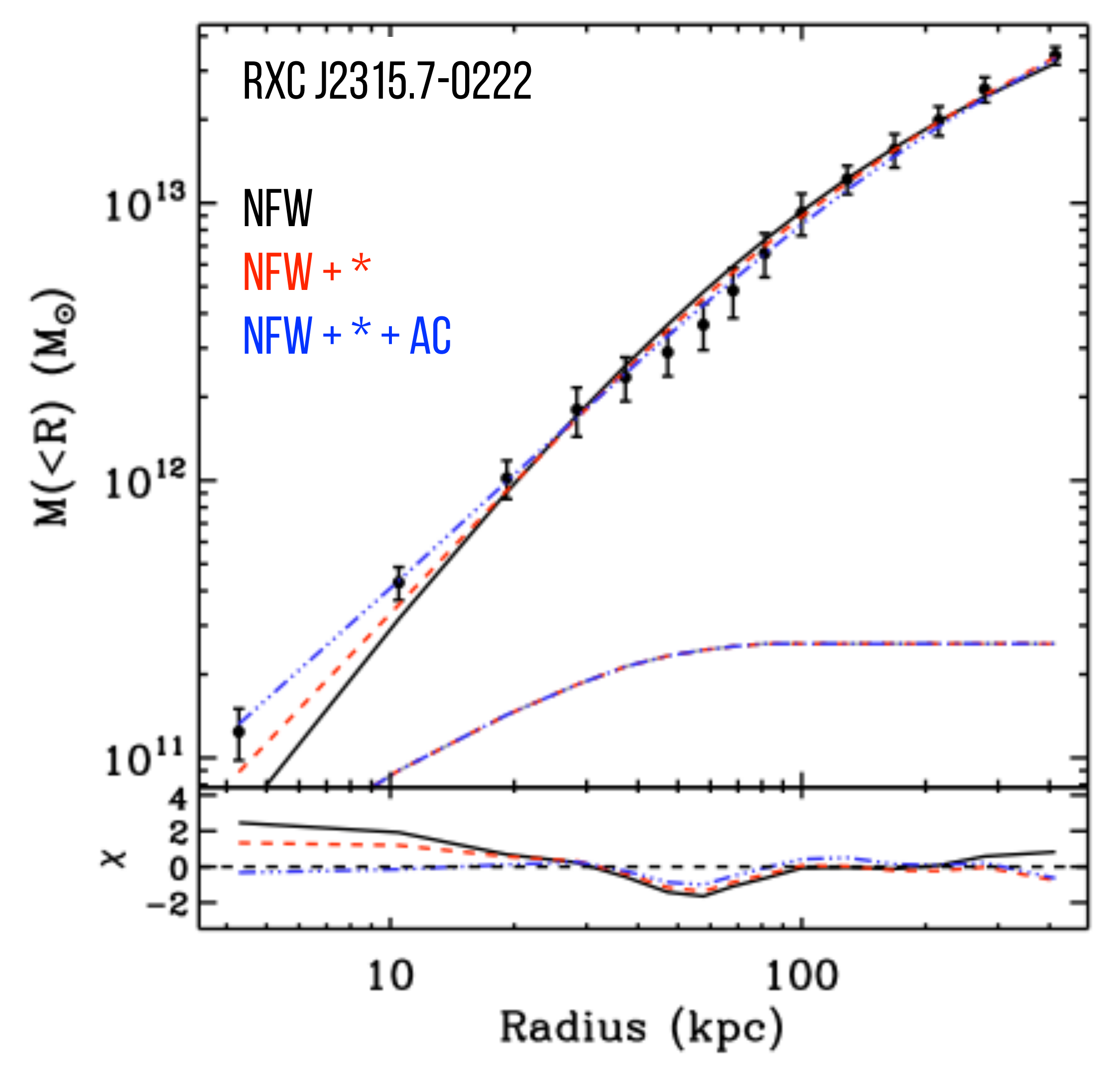


BHATTACHARYA ET AL 2013
ALSO E.G., DOLAG ET AL 2004 AND MANY OTHERS

Dark matter distribution



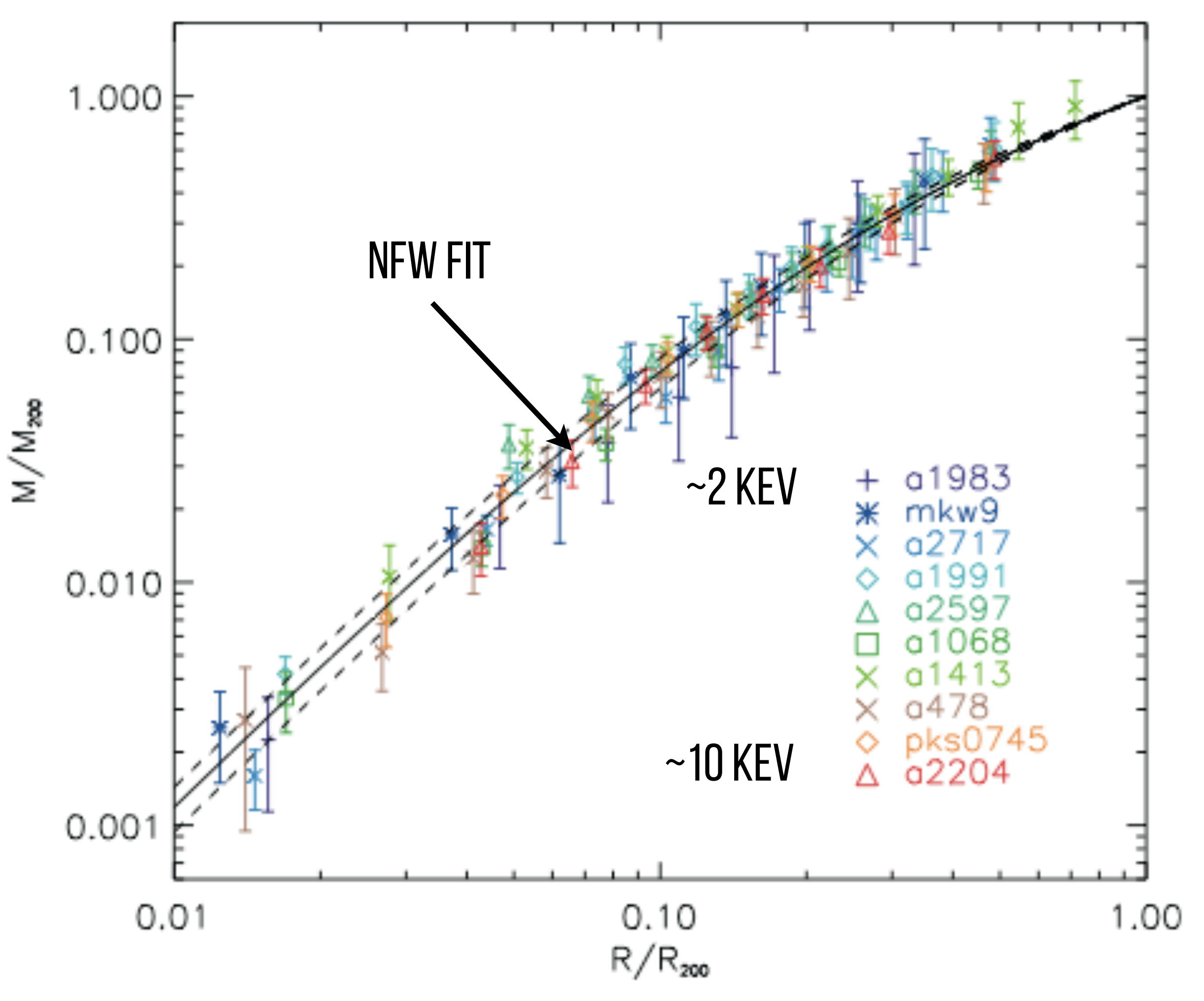
PRATT & ARNAUD 2002
(XMM OBSERVATIONS)



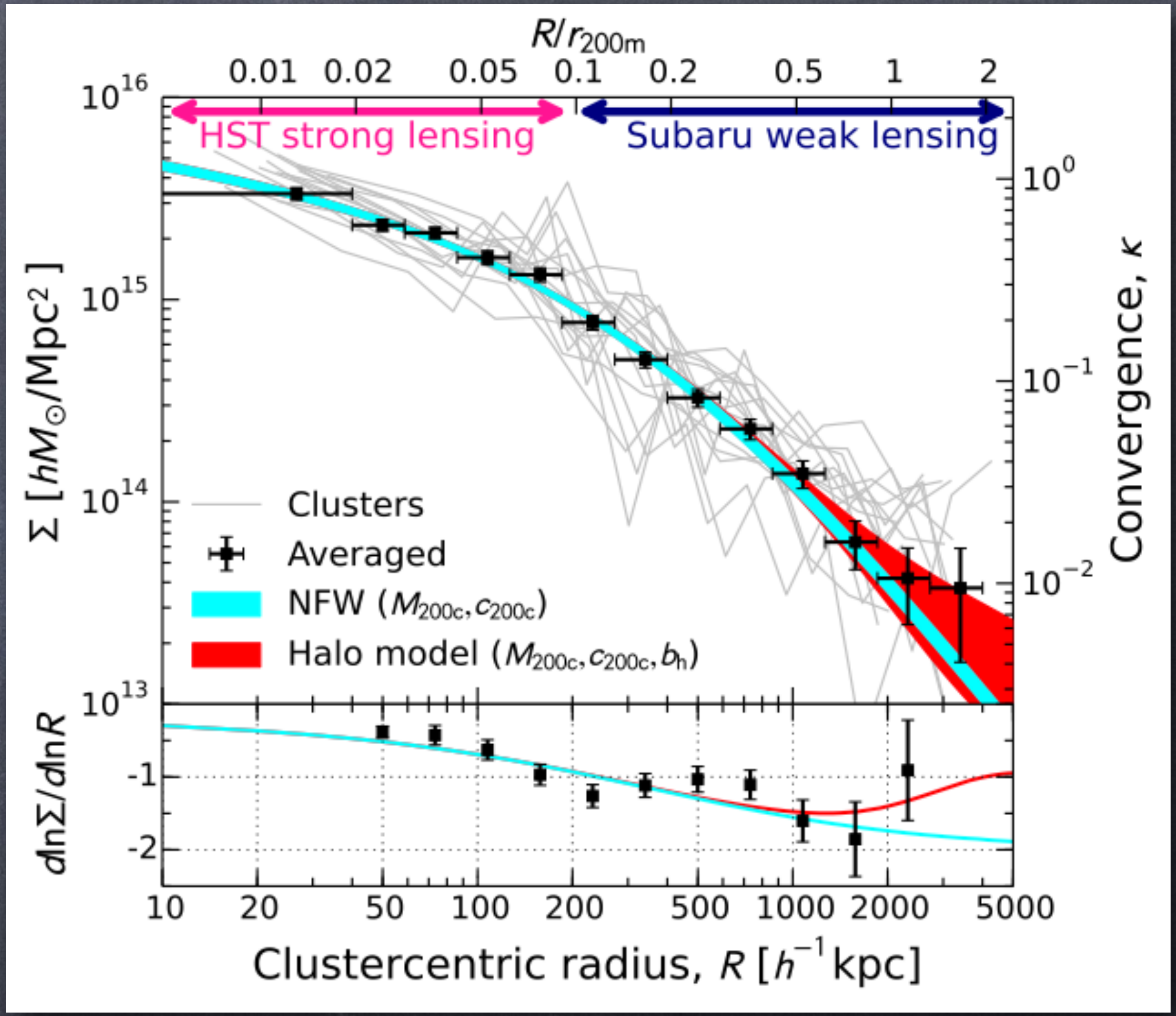
DÉMOCLÈS, PRATT ET AL 2010

Mass distributions are similar

And agree with NFW

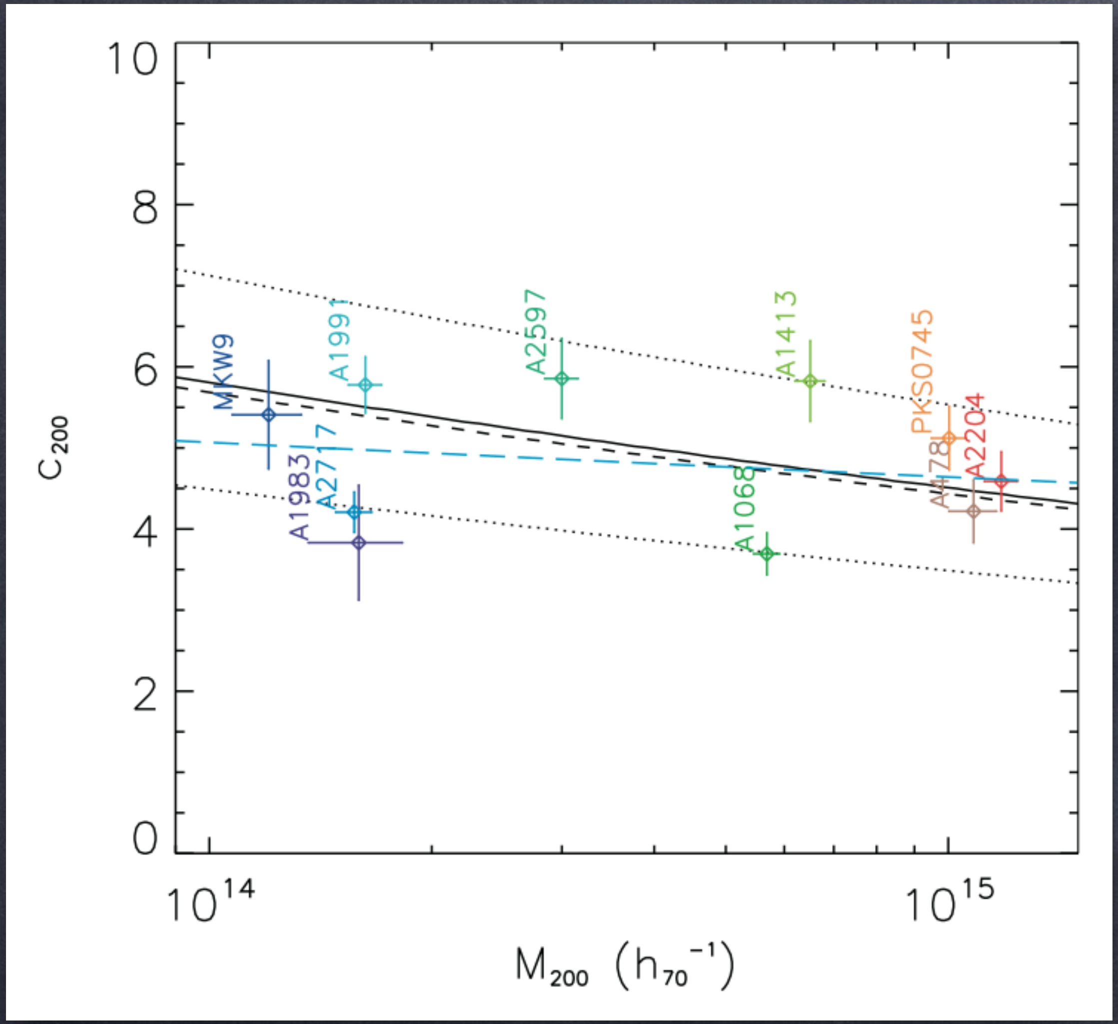


POINTECOUTEAU, ARNAUD & PRATT 2005
(XMM OBSERVATIONS)

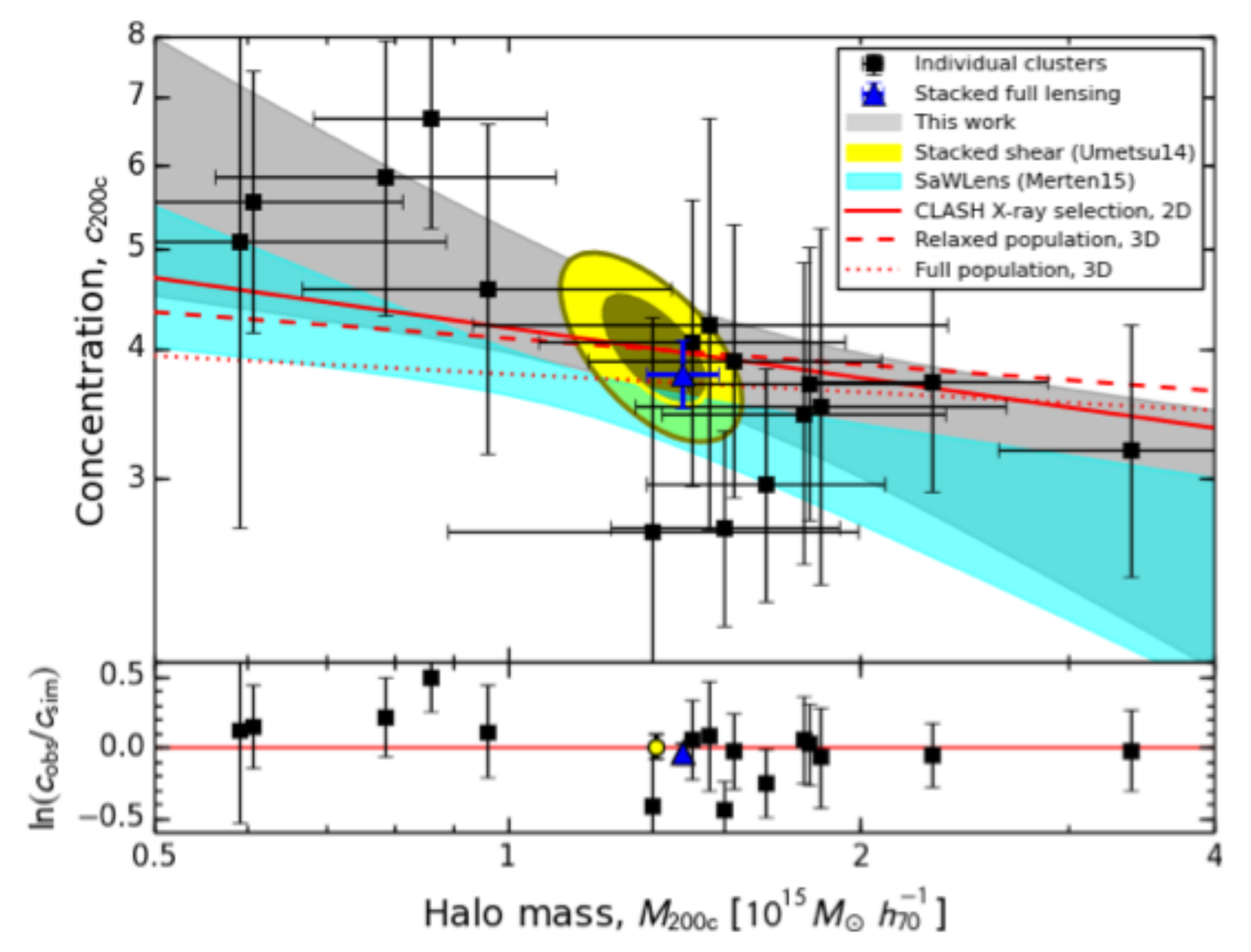


UMETSU ET AL 2016
(HST+SUBARU OBSERVATIONS)

Concentration behaves as expected

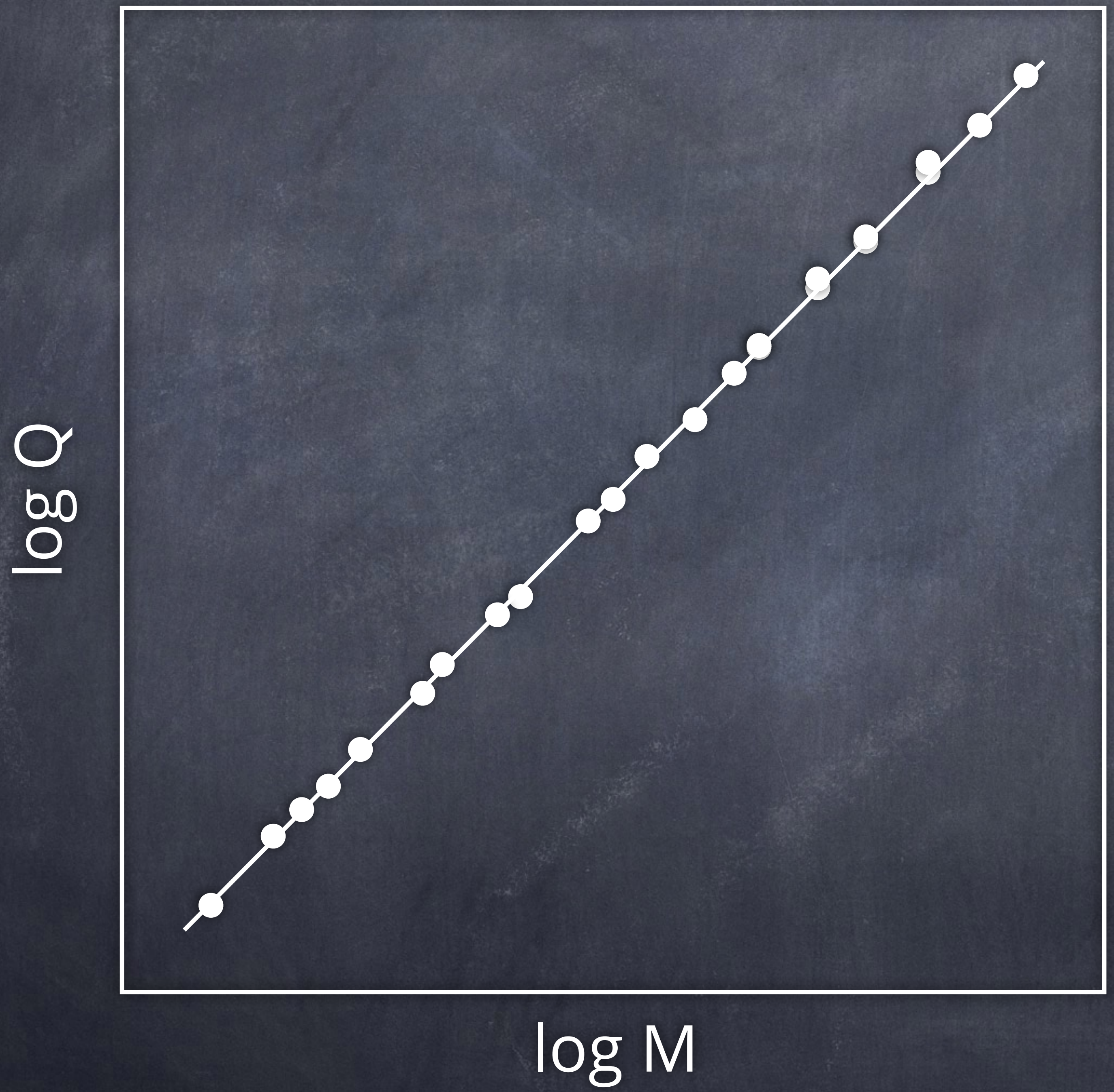


POINTECOUTEAU, ARNAUD & PRATT 2005
(XMM OBSERVATIONS)



UMETSU ET AL 2016
(HST+SUBARU OBSERVATIONS)

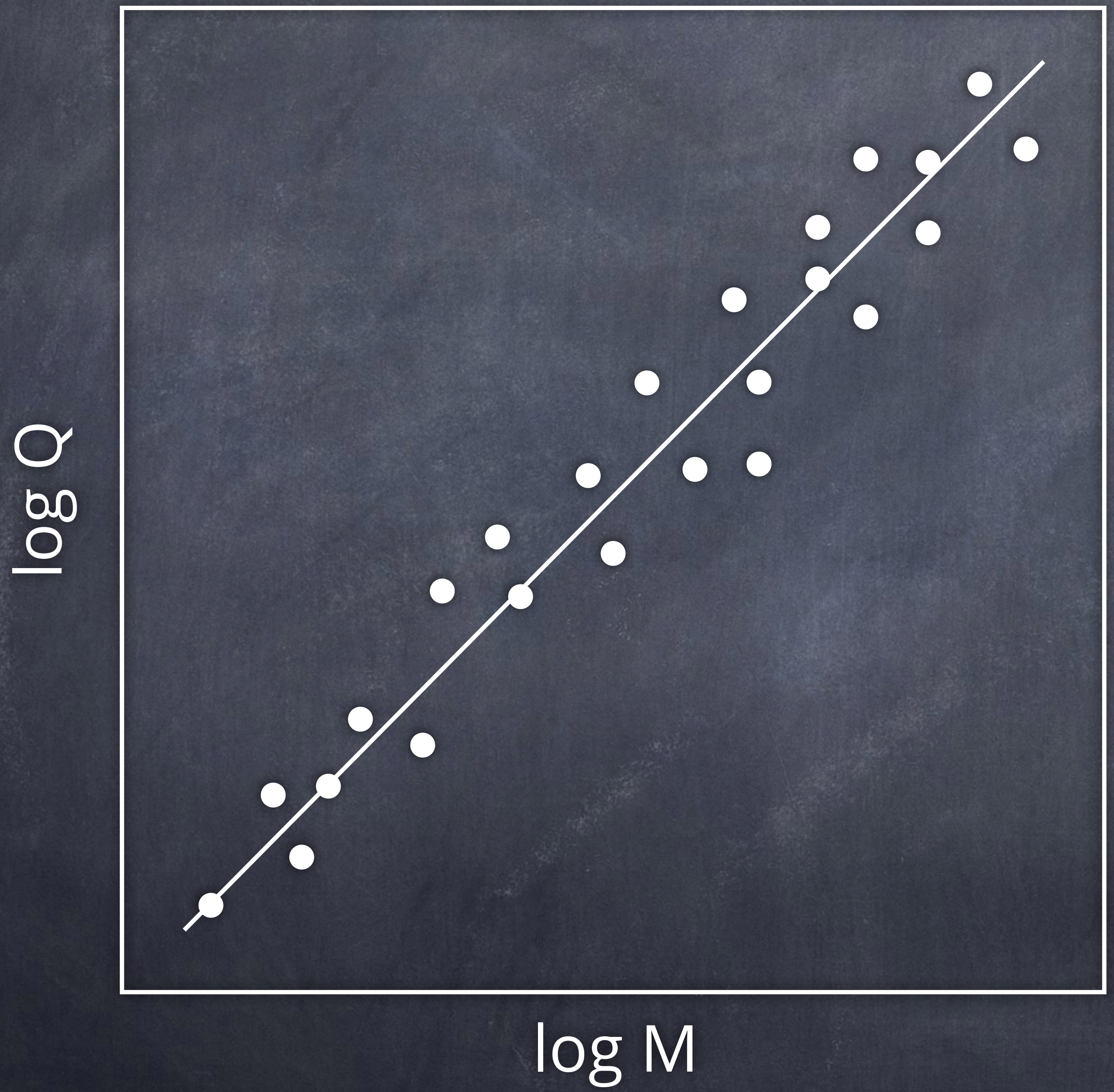
Scaling law "Theory"



- Similar internal structure
- Power-law relations between observables Q and mass (and redshift)

"Theoretical reality"

Dispersion



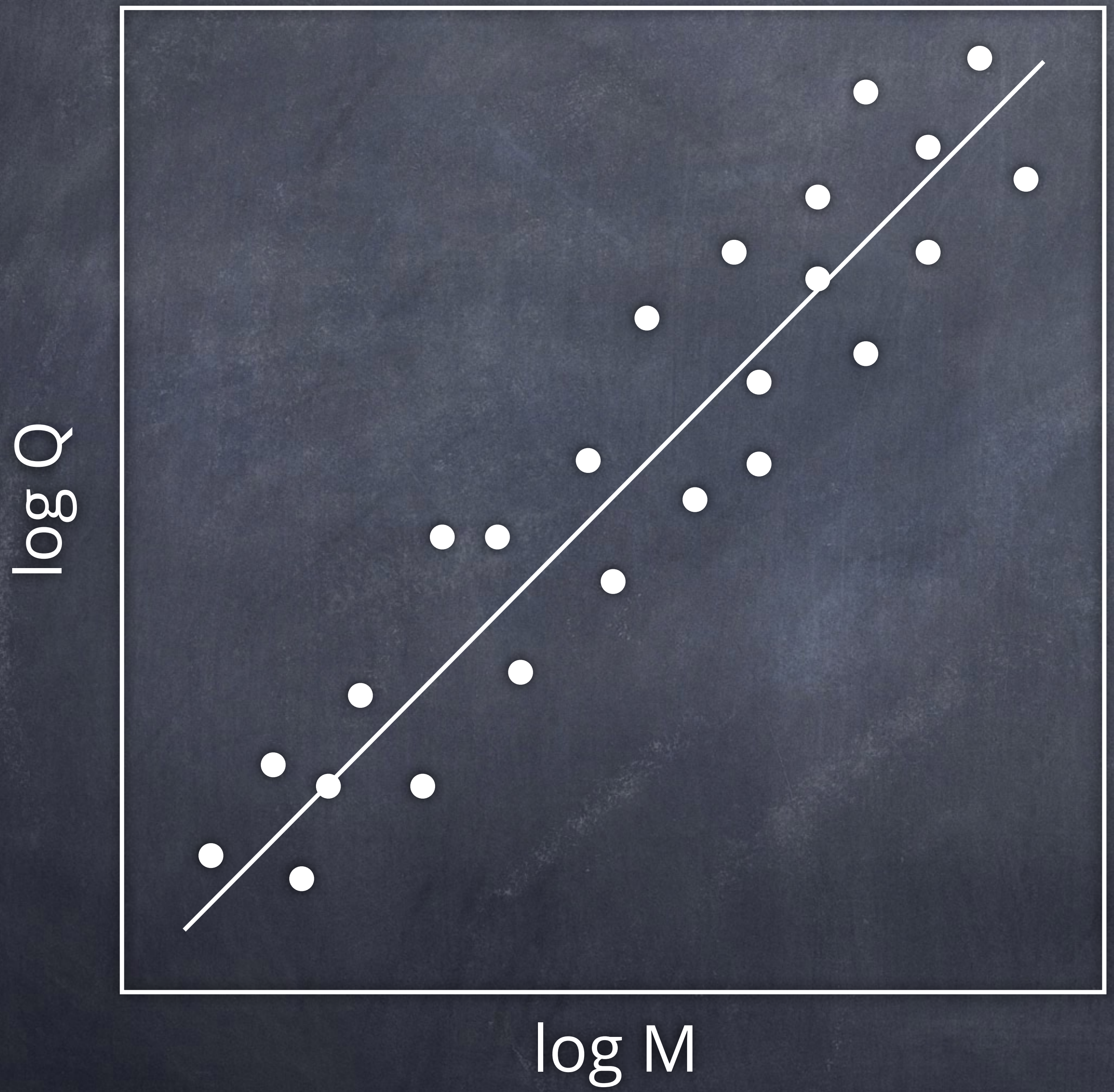
Dispersion due to differences in:

- Internal structure
- Orientation
- Large-scale environment
- Projection effects

These deviations are ~lognormal (Central Limit Theorem)

Observational reality

Additional sources of dispersion

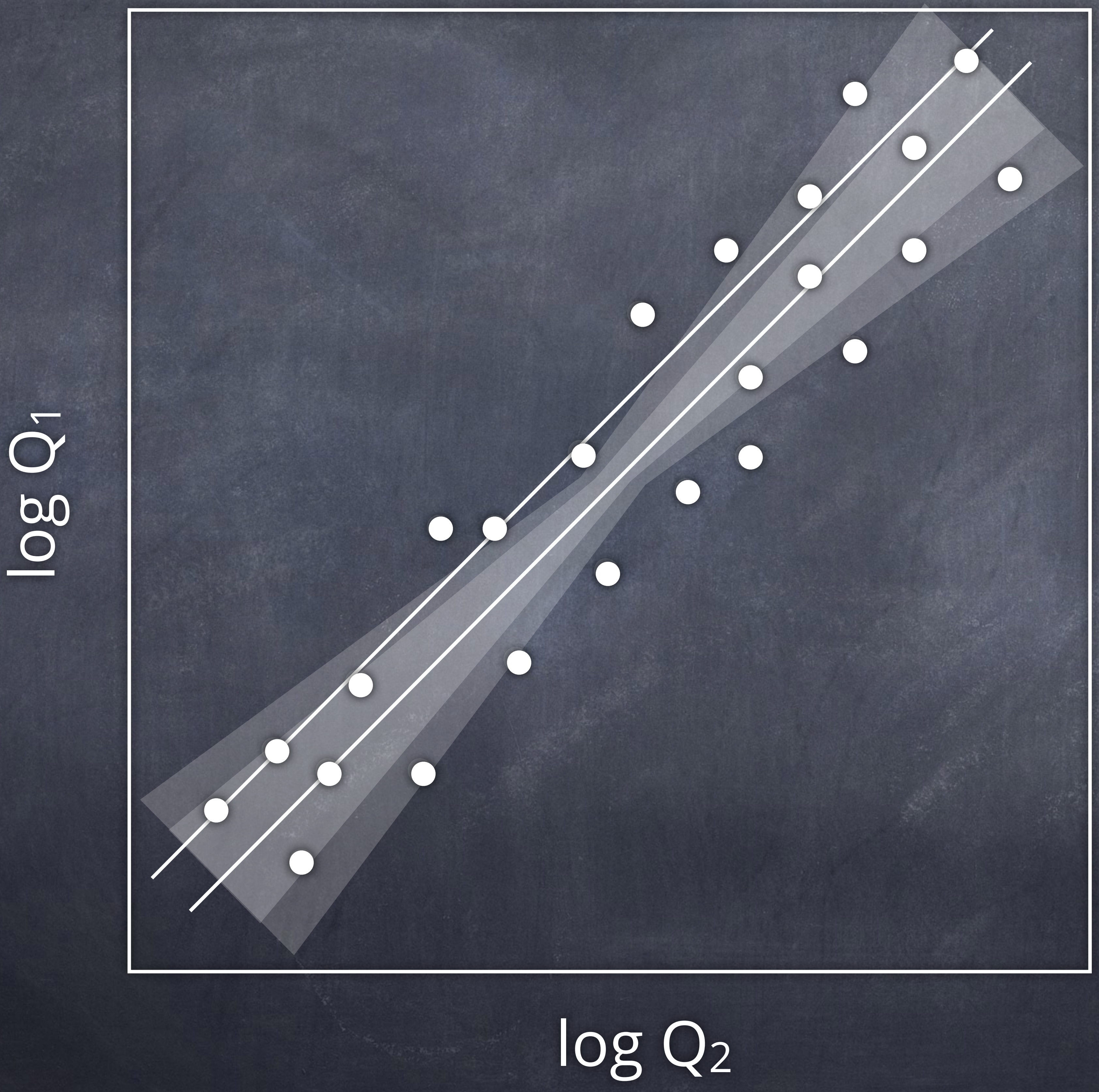


Additional dispersion due to:

- Non-gravitational astrophysics
- Evolutionary effects
- Observational error

These deviations are *not* lognormal

Effect of non-gravitational processes



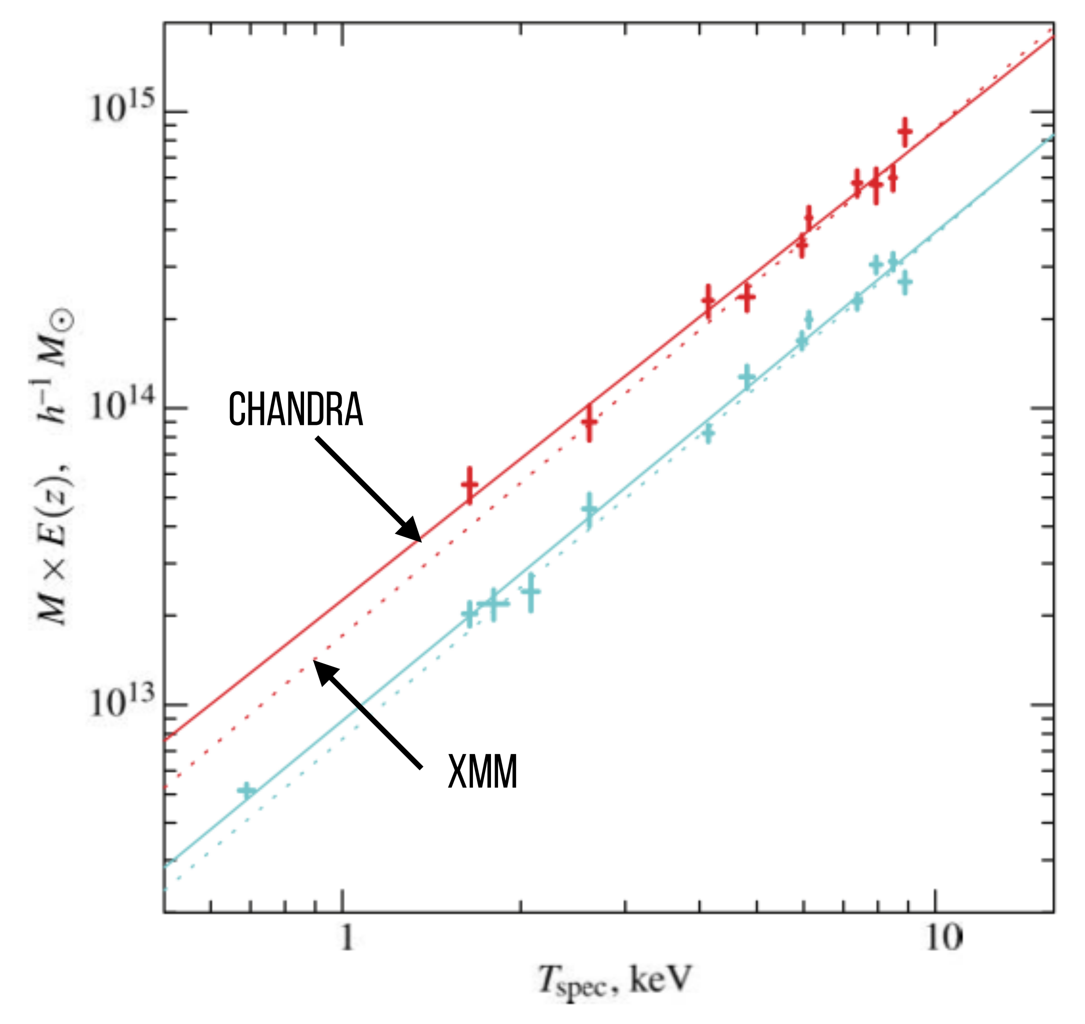
Dispersion

Normalisation

Slope

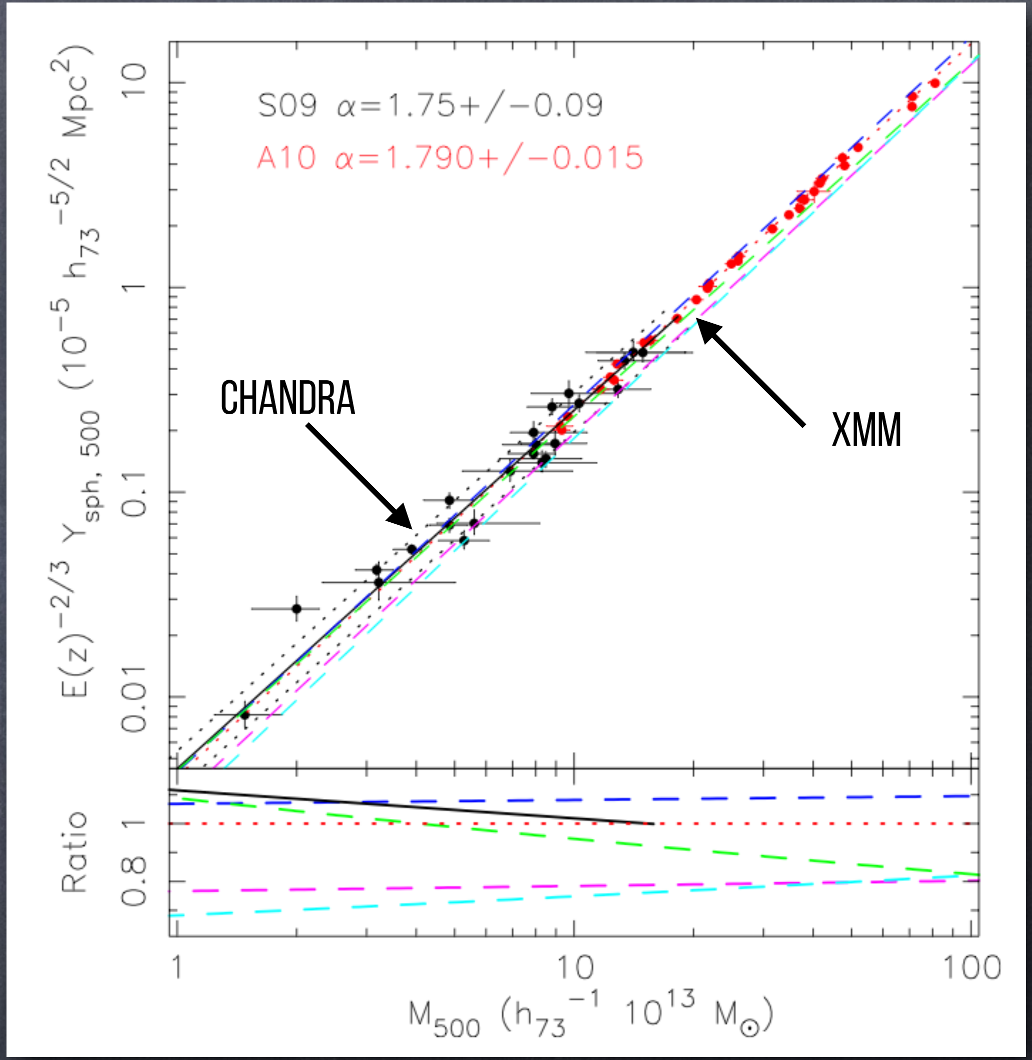
Converging local X-ray scaling relations

$M - T$



VIKHLININ ET AL 2006;
ARNAUD ET AL 2005

$Y_{\rm sph} - M$

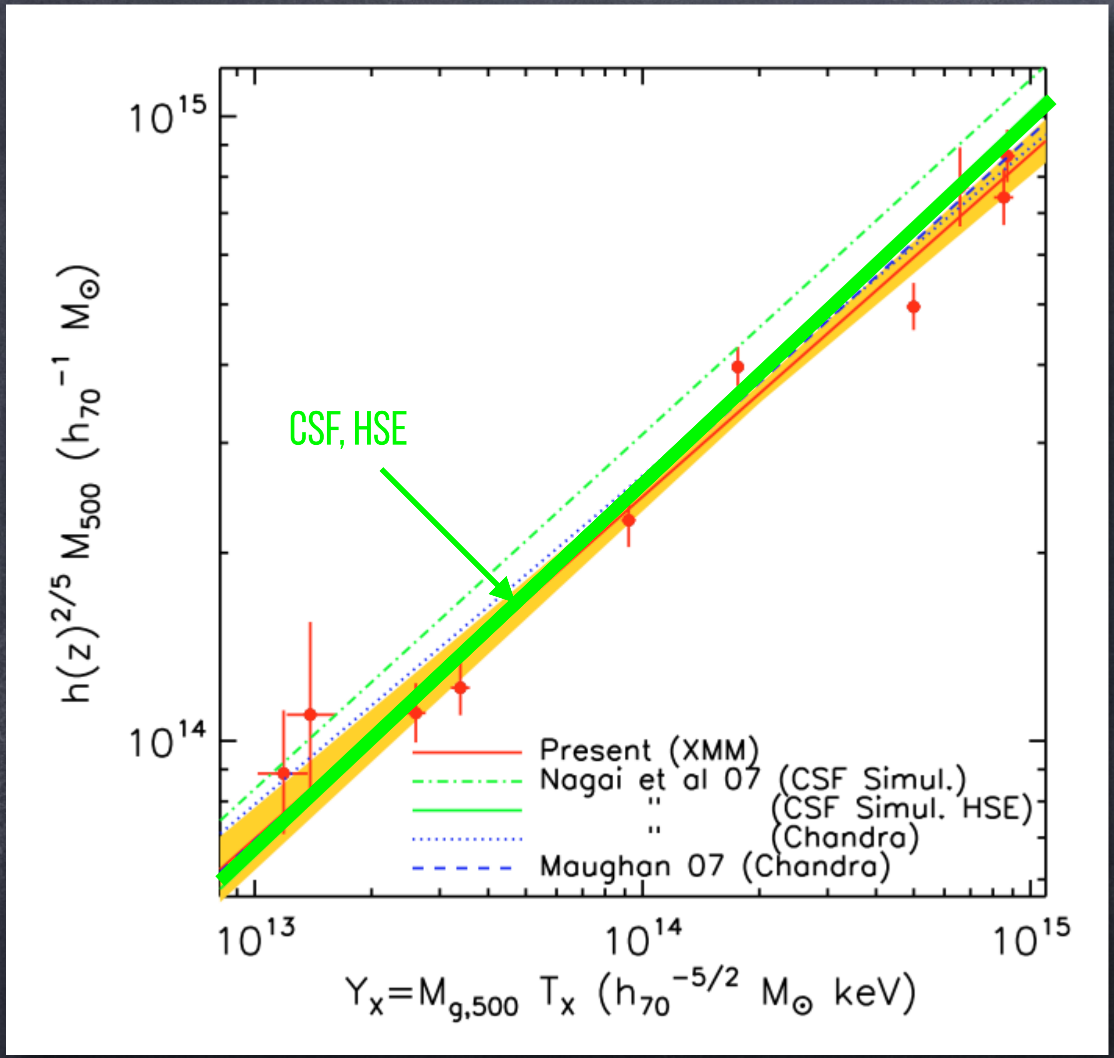


SUN ET AL 2011;
ARNAUD ET AL 2010

- Huge improvement in recent years

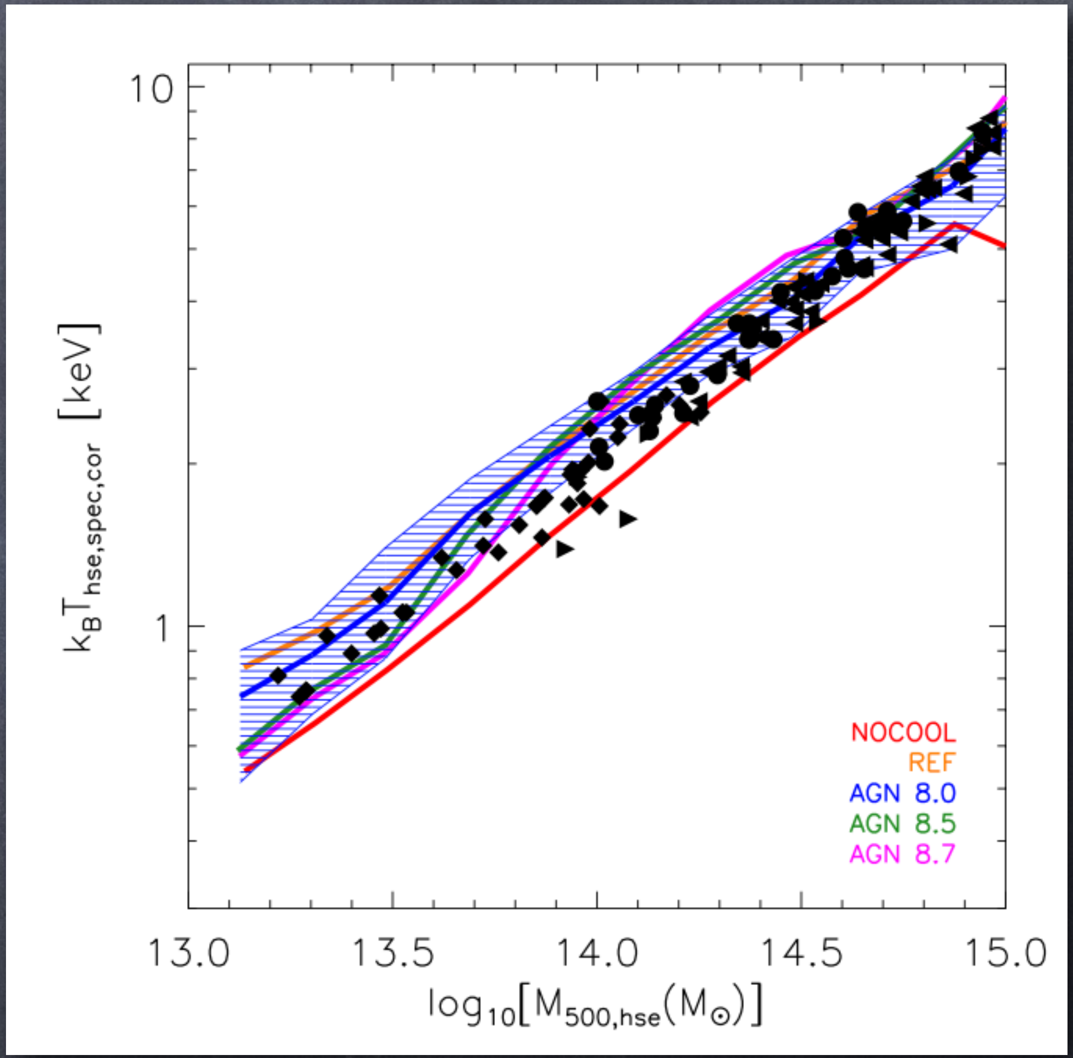
Converging agreement with simulations

$Y_{\mathrm{X}} - M_{\mathrm{HSE}}$



ARNAUD ET AL 2007 ;
SEE ALSO PLANELLES ET AL 2014

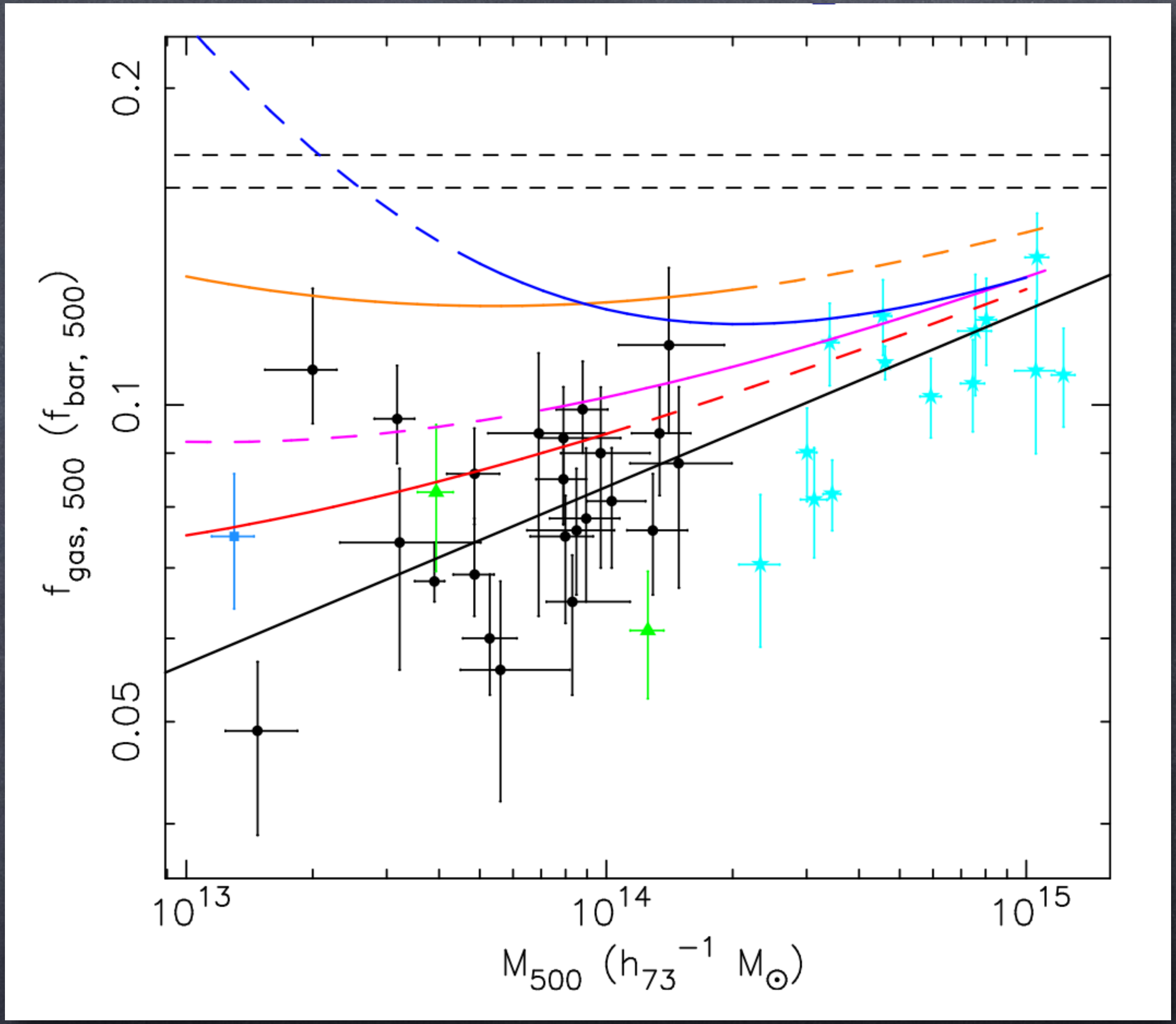
$M_{\mathrm{HSE}} - T$



LE BRUN ET AL 2014, OBSERVATIONAL DATA FROM
SUN ET AL 2009, VIKHLININ ET AL 2009, PRATT ET AL 2009

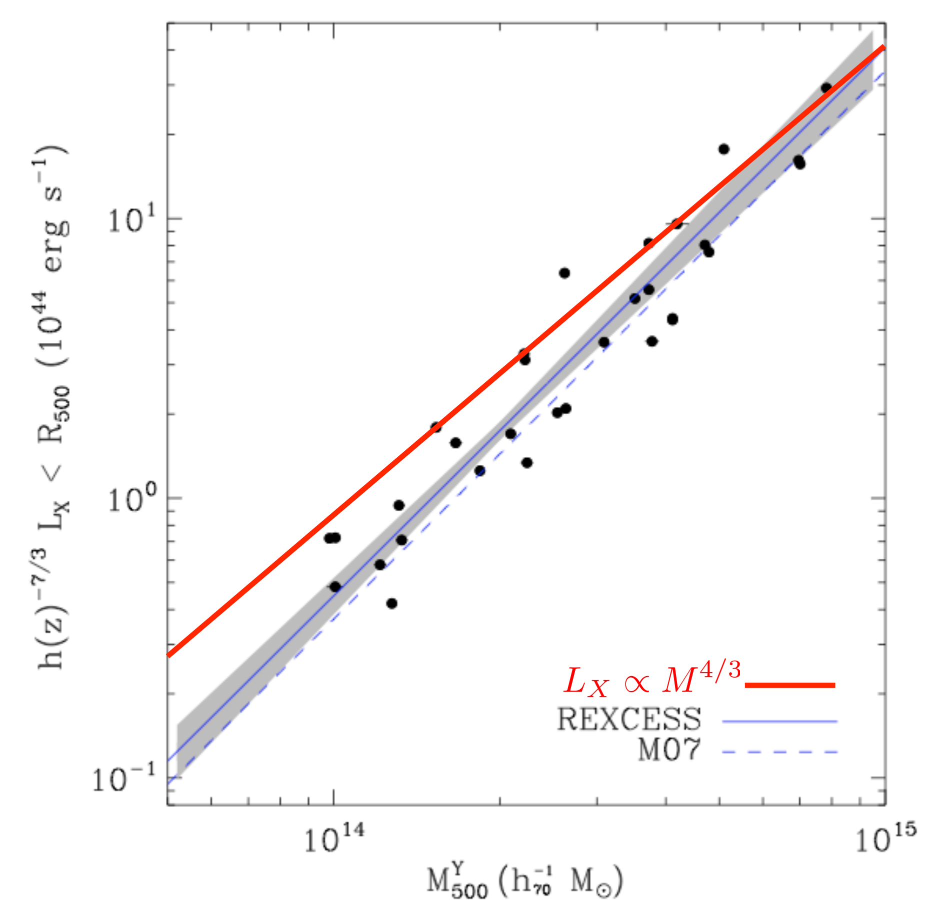
- Improved modelling of non-gravitational processes in simulations
- Use of synthetic X-ray analyses (e.g., to measure T_{spec} and M_{HSE})

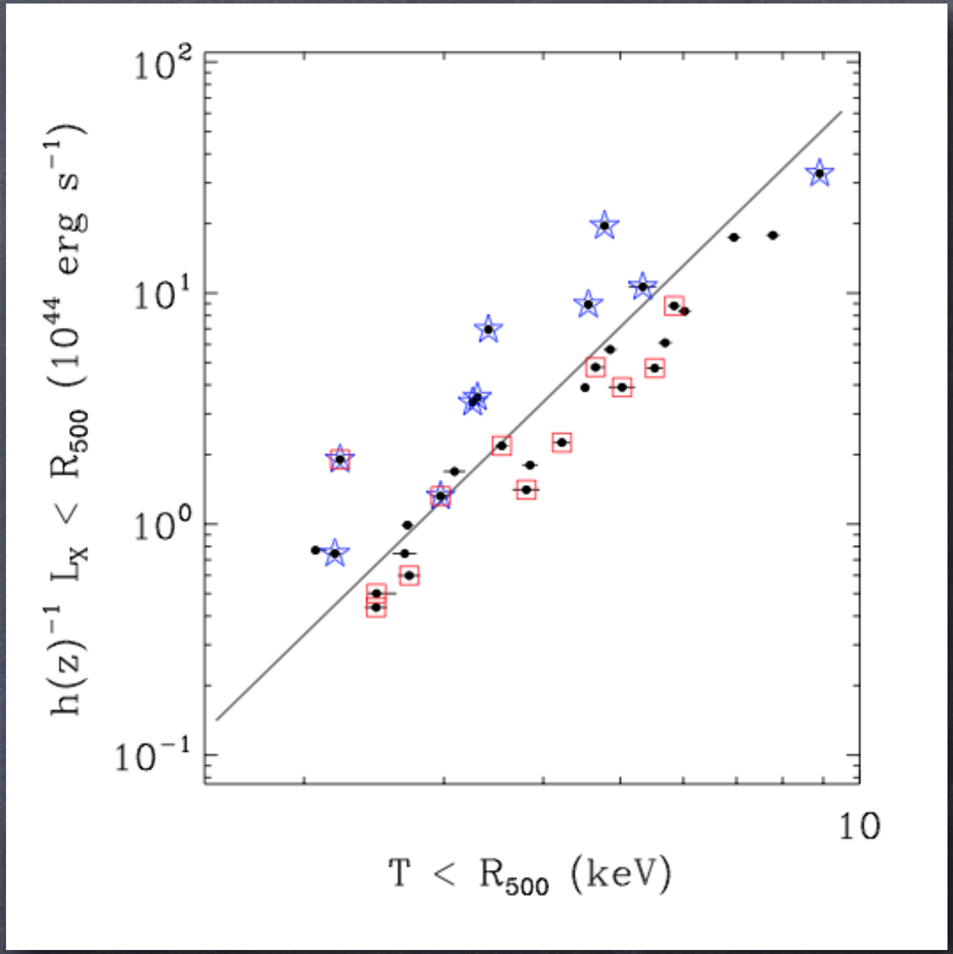
f_{gas} varies substantially with mass



SUN 2012, COMPILING DATA FROM
SUN ET AL 2009, VIKHLININ ET AL 2006, DÉMOCLÈS ET AL 2010, RASMUSSEN ET AL 2009

Effect of feedback on scaling relations



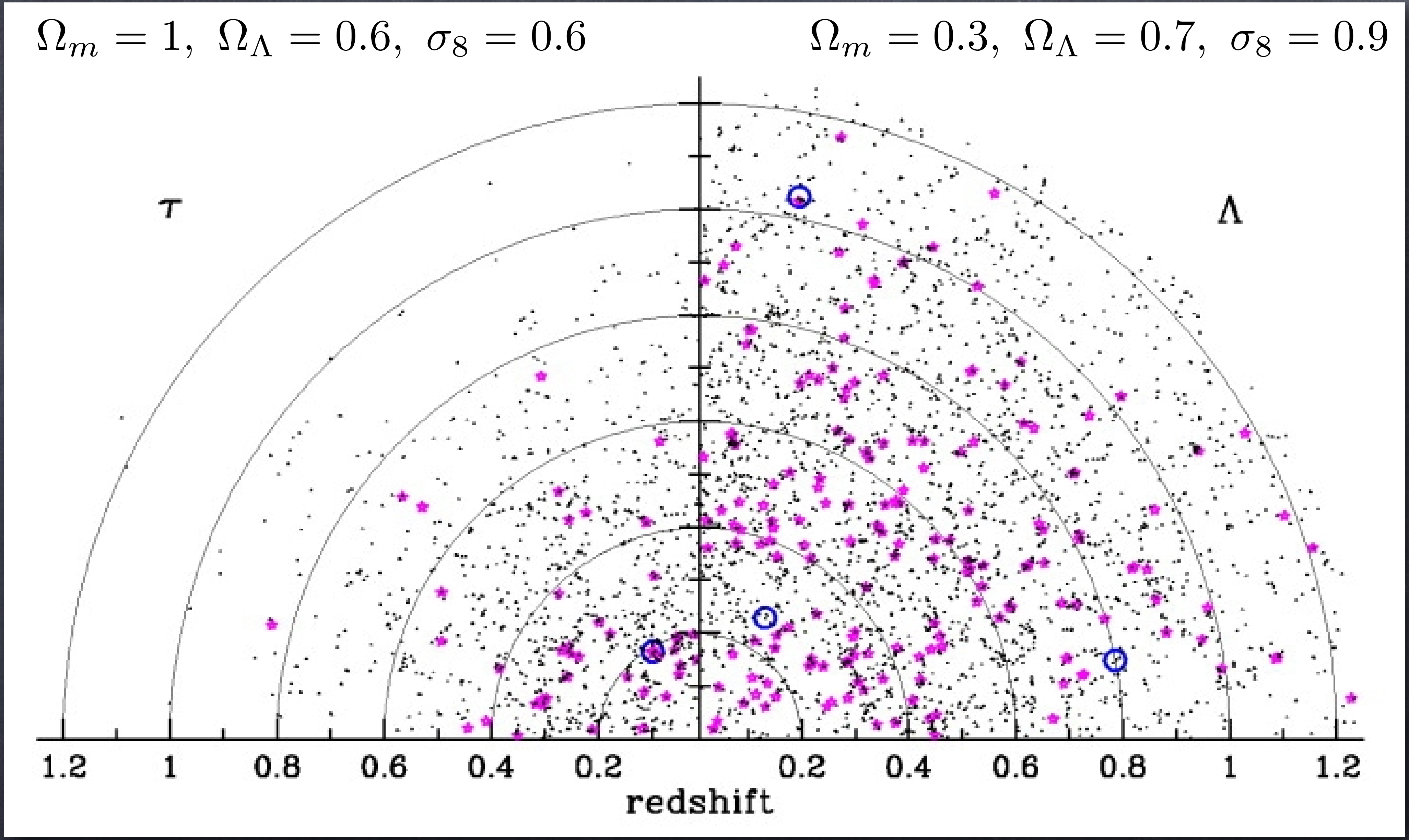


- In local systems, the trend is mass-dependent
- The scatter comes mostly from cool cores

- No evidence for ‘catastrophic’ AGN feedback in local population
- Gas was pushed beyond R_{500} some time ago, or had a higher entropy when accreted

Cosmology

Cosmology with clusters

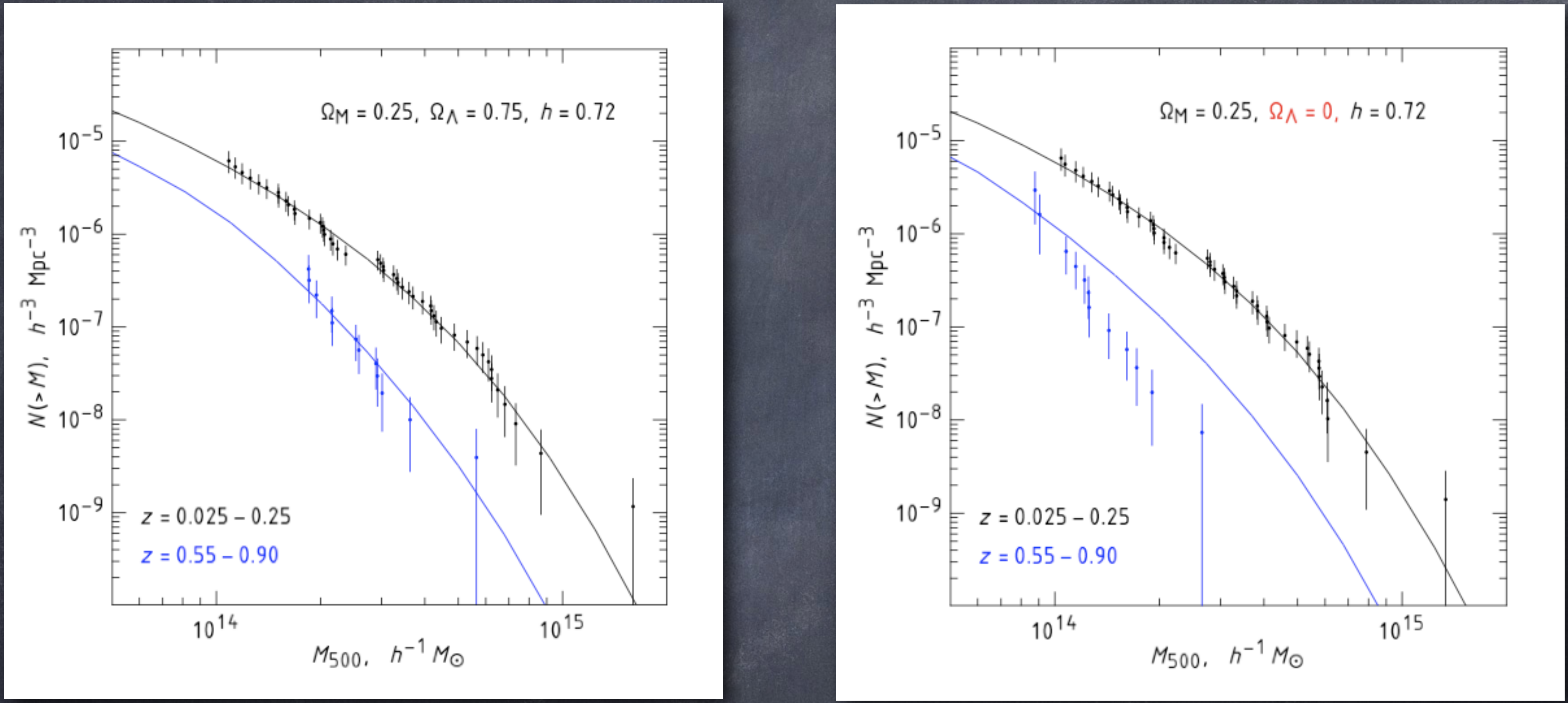


EVRARD ET AL. 2002

- $N(M, z)$ depends on $\Omega_m,\ \sigma_8\ [\Omega_b, n, h, \Omega_\Lambda]$
- Evolution strongly depends on Ω_m

Cosmology with the cluster mass function

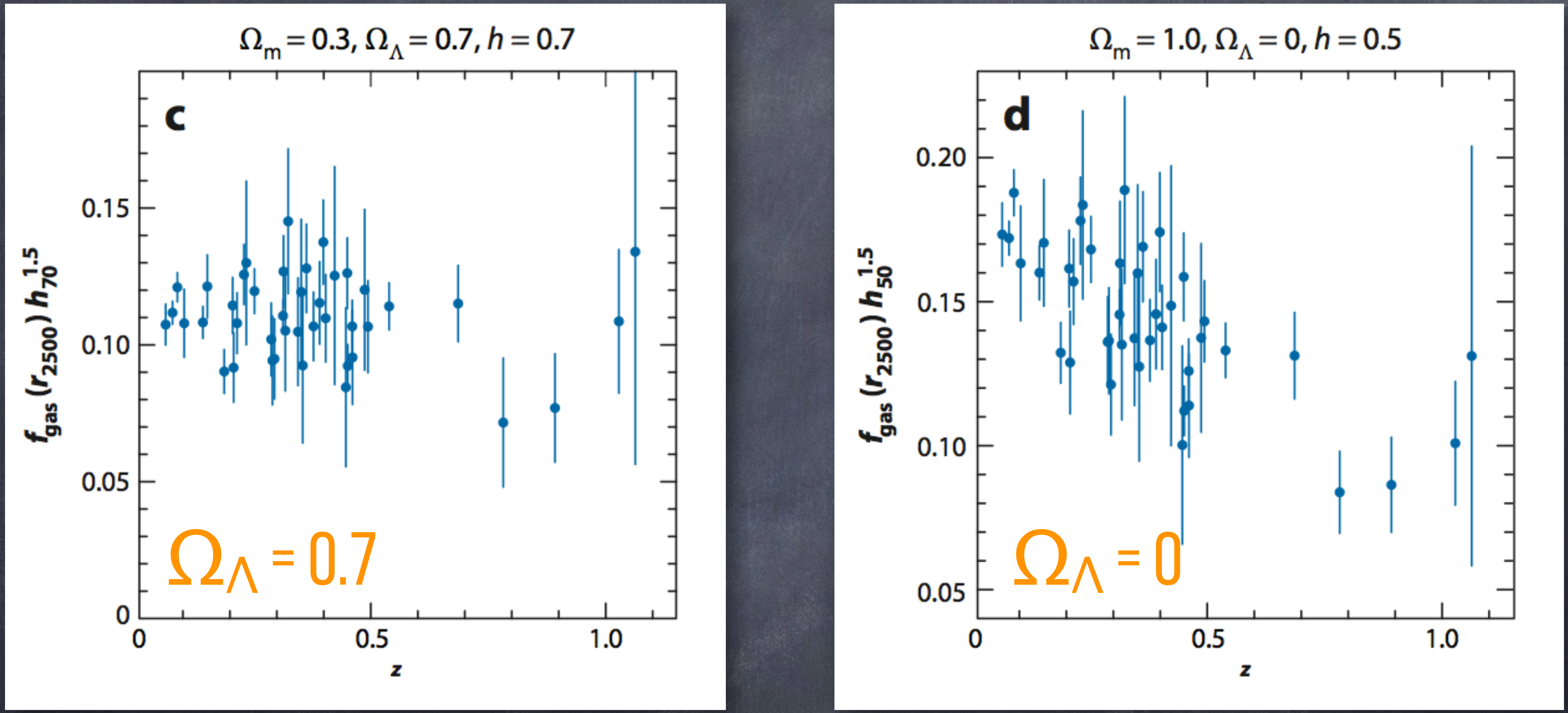
Sensitivity to cosmological parameters



CHANDRA/ROSAT OBSERVATIONS VIKHLININ ET AL 2009

- L_X → M_{500} + selection function, i.e. scaling laws + scatter
- Compare to mass function N(z, M) from simulations
- High-mass systems most sensitive to cosmology
- High redshift needed to probe growth of structure

Cosmology with f_{gas}

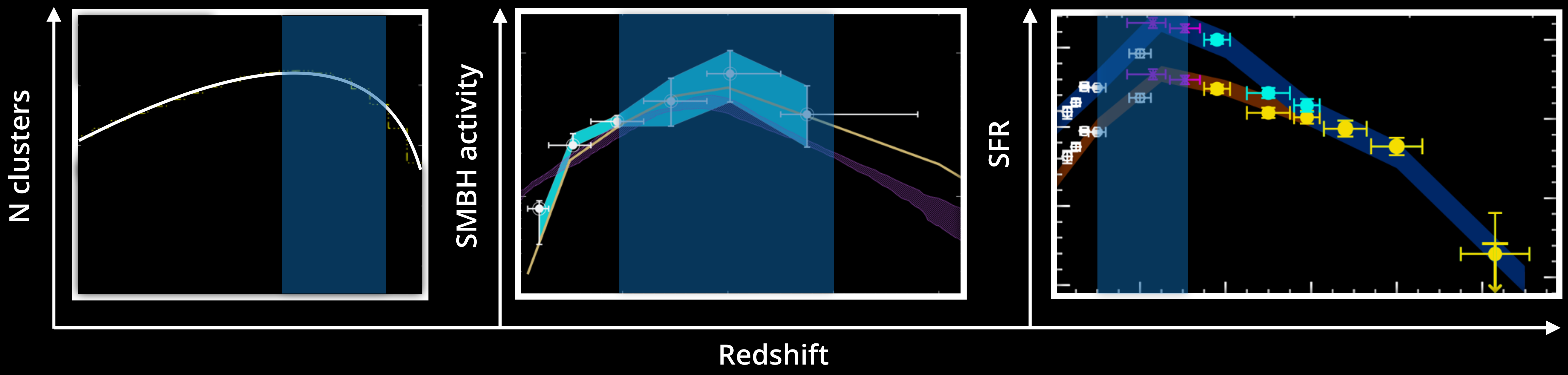


CHANDRA/ROSAT OBSERVATIONS ALLEN ET AL 2008

- Assumes f_{gas} (z, M) = const, but f_{gas} = f_{gas}(M), so high mass only
- $f_{\rm gas} \propto \Omega_{\rm b}/\Omega_{\rm m}; \quad f_{\rm gas}(z) \propto d_{\rm A}(z)^{3/2}$
- Needs only the most relaxed clusters

X-ray perspectives

Overall context: evolution



COURTESY F. PACAUD

DELVECCHIO ET AL 2014

BOUWENS ET AL 2011

- Growth of structure, BH
- AGN feedback
- Enrichment of IGM and ICM

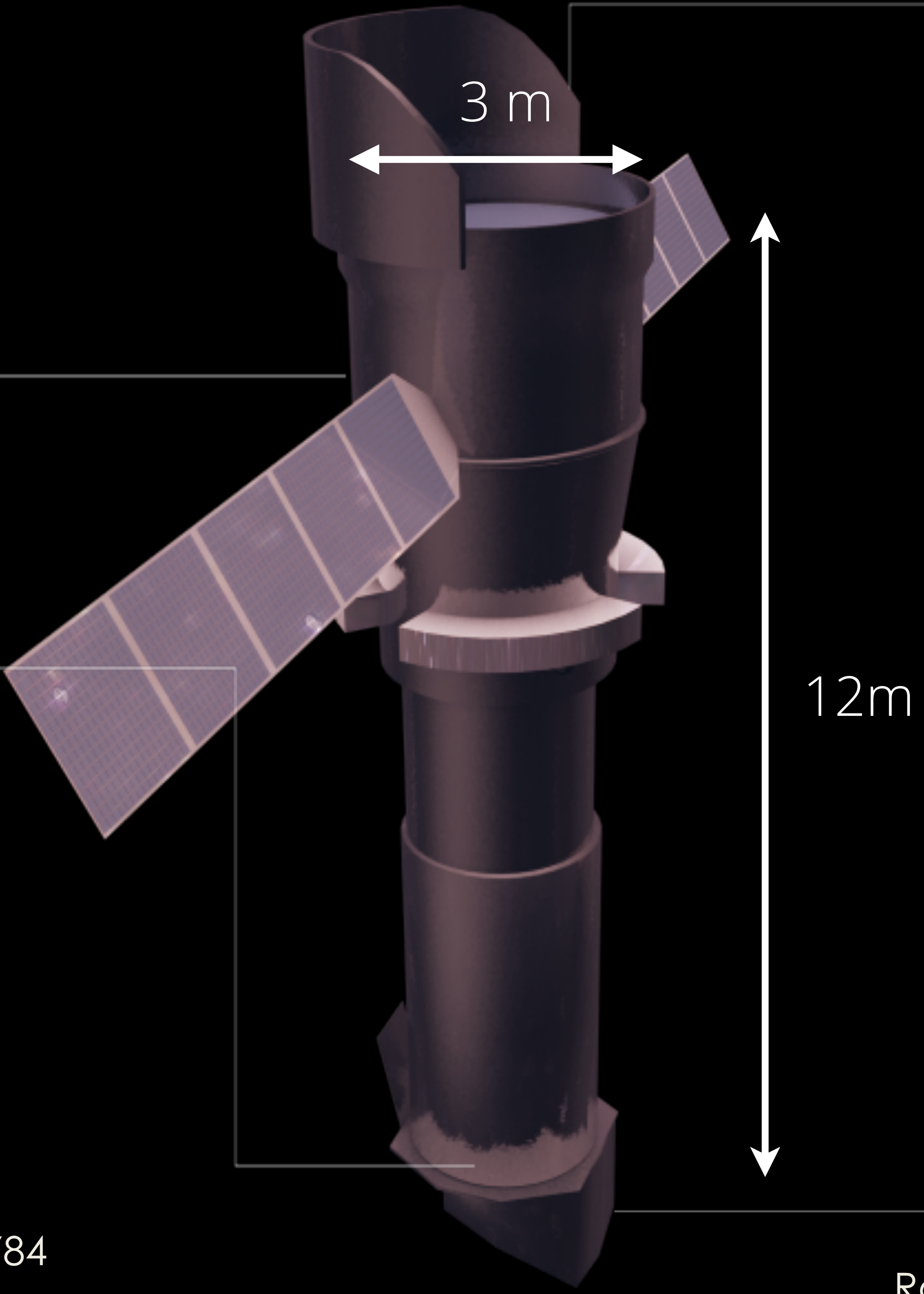
… and their evolution

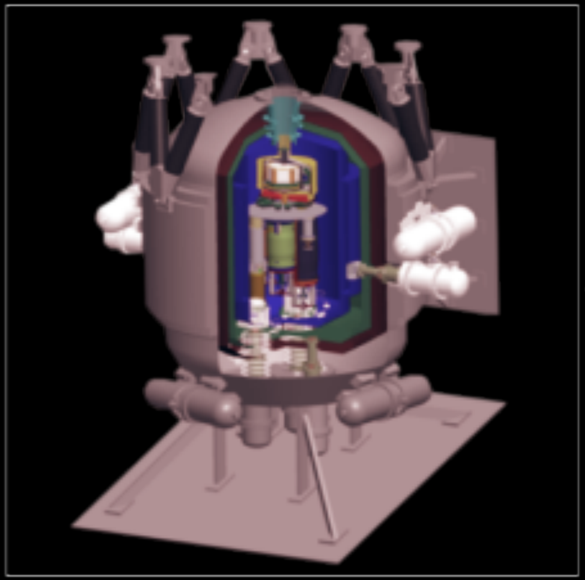
What's needed

1. More throughput (photons)
2. Higher spatial resolution (microphysics, distant objects)
3. Higher spectral resolution (the third dimension)

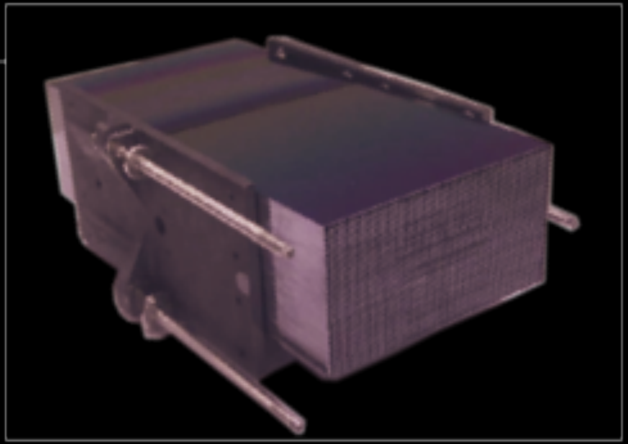
The Advanced Telescope for High ENergy Astrophysics

L2 orbit Ariane V
Mass < 5100 kg
Power 2500 W
5 year mission

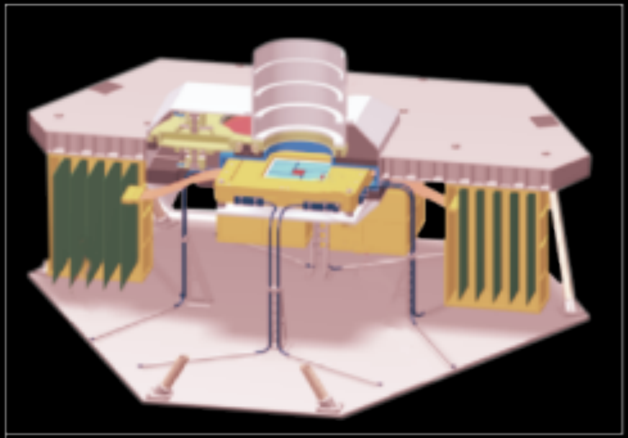




X-ray Integral Field Unit:
ΔE: 2.5 eV
Field of View: 5 arcmin
Operating temp: 50 mk



Silicon Pore Optics:
2 m^2 at 1 keV
5 arcsec HEW
Focal length: 12 m
Sensitivity: 3 10^{-17} erg cm^{-2} s^{-1}

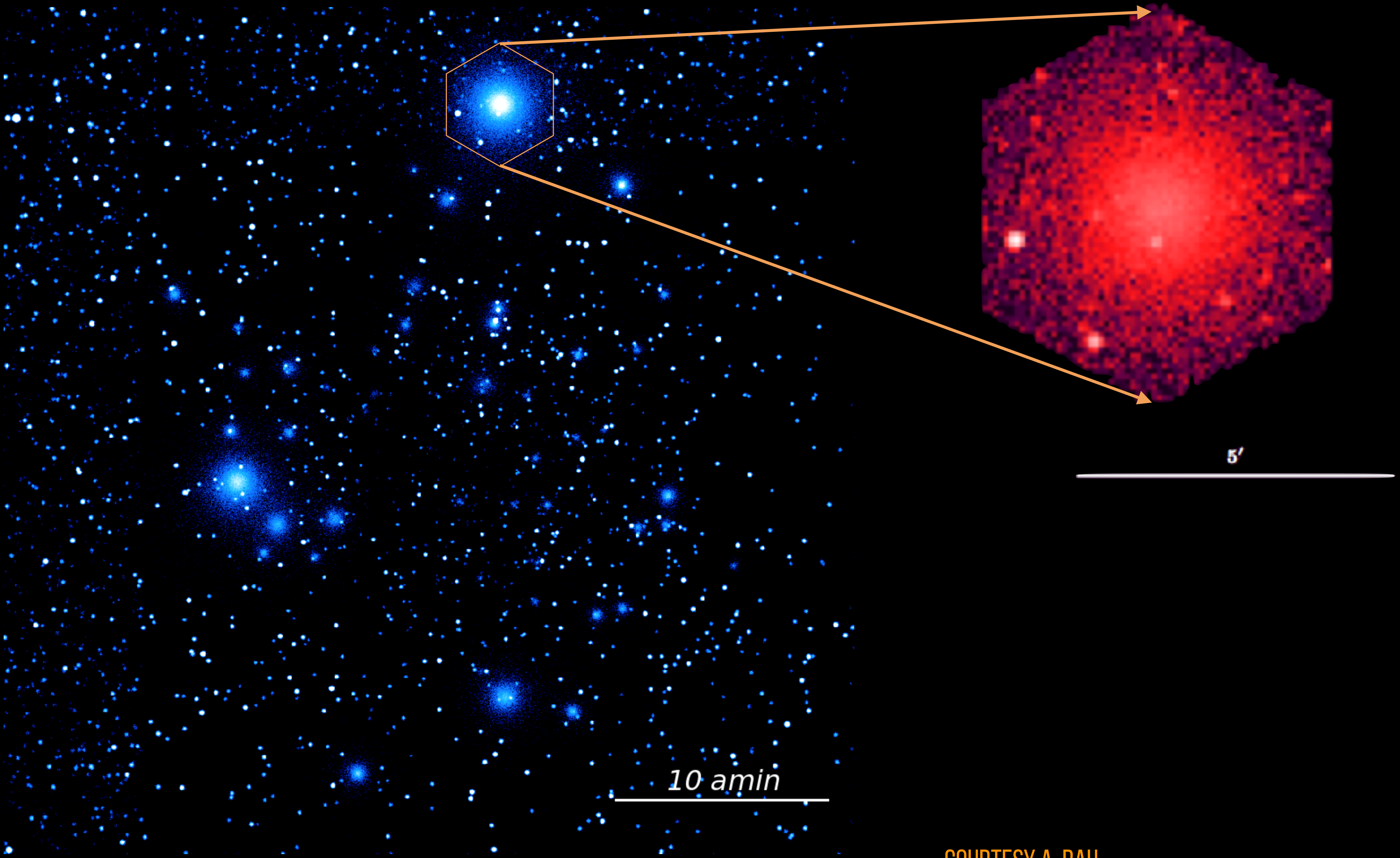


Wide Field Imager:
ΔE: 125 eV
Field of View: 40 arcmin
High countrate capability

Barret et al., 2013 arXiv:1308.6784

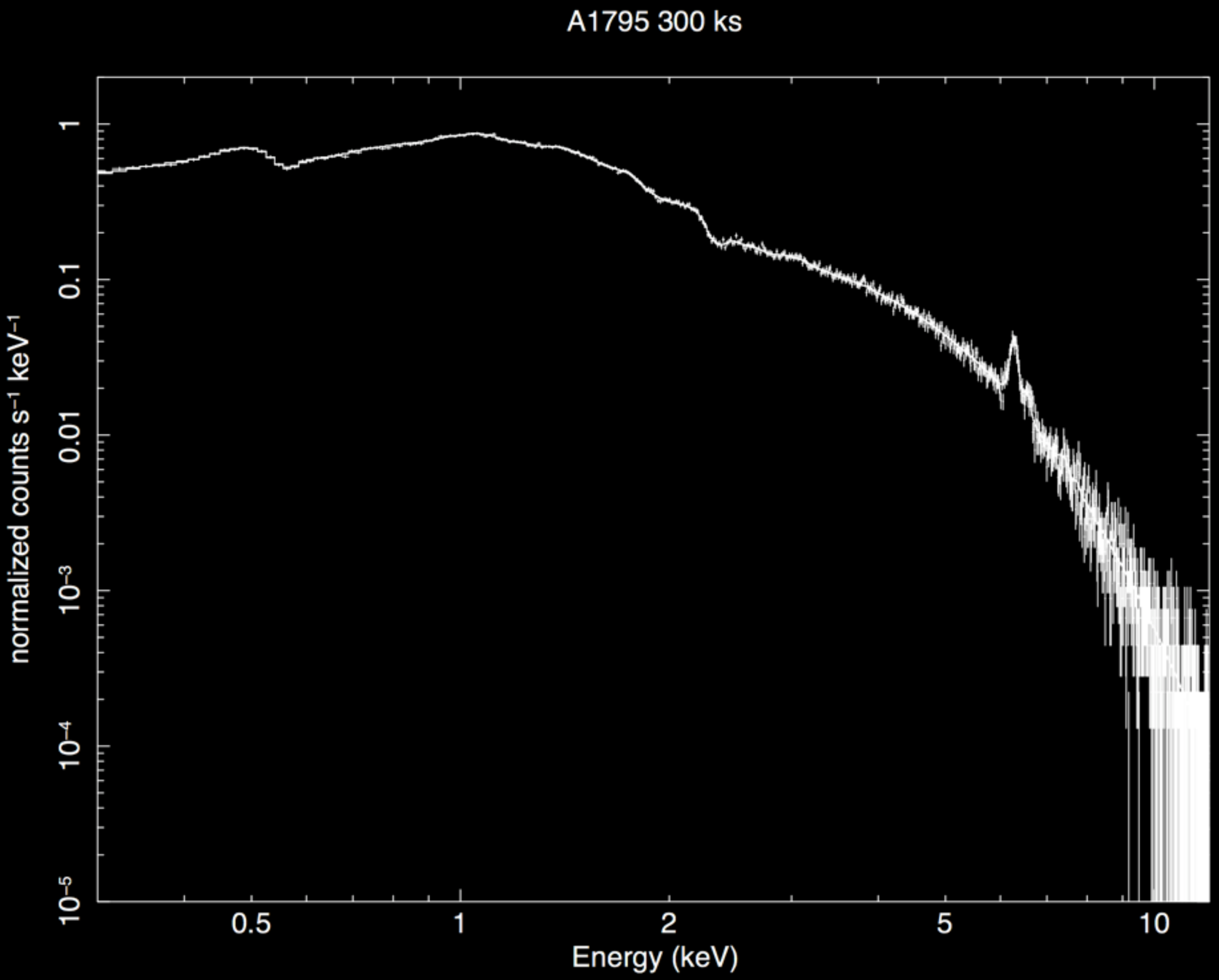
Rau et al. 2013 arXiv1307.1709

E2E simulations



COURTESY A. RAU
T. DAUSER / J. WILMS / T. BRAND

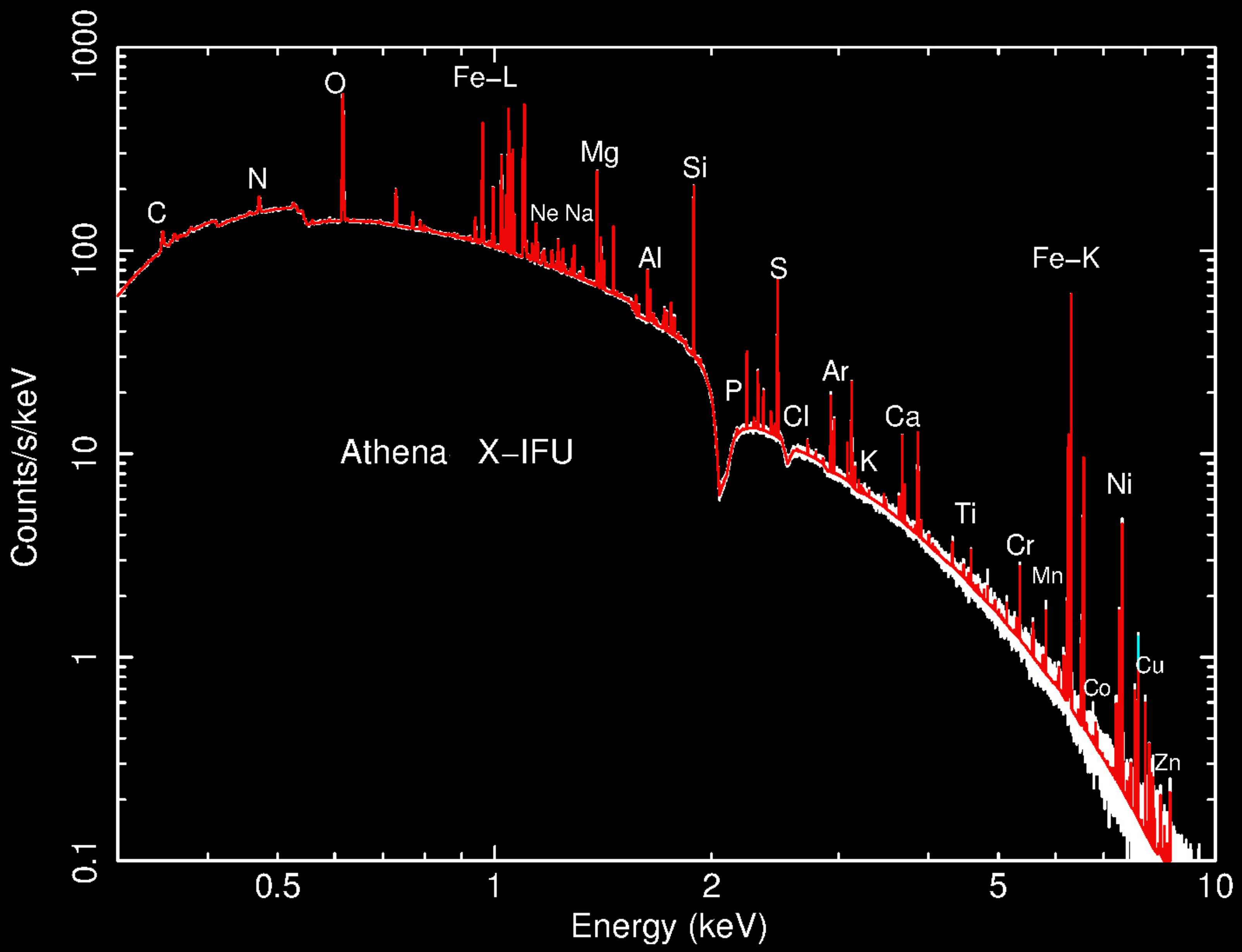
XMM-Newton EPIC EMOS



- Typical current CCD resolution (~ 150 ev)

IFU

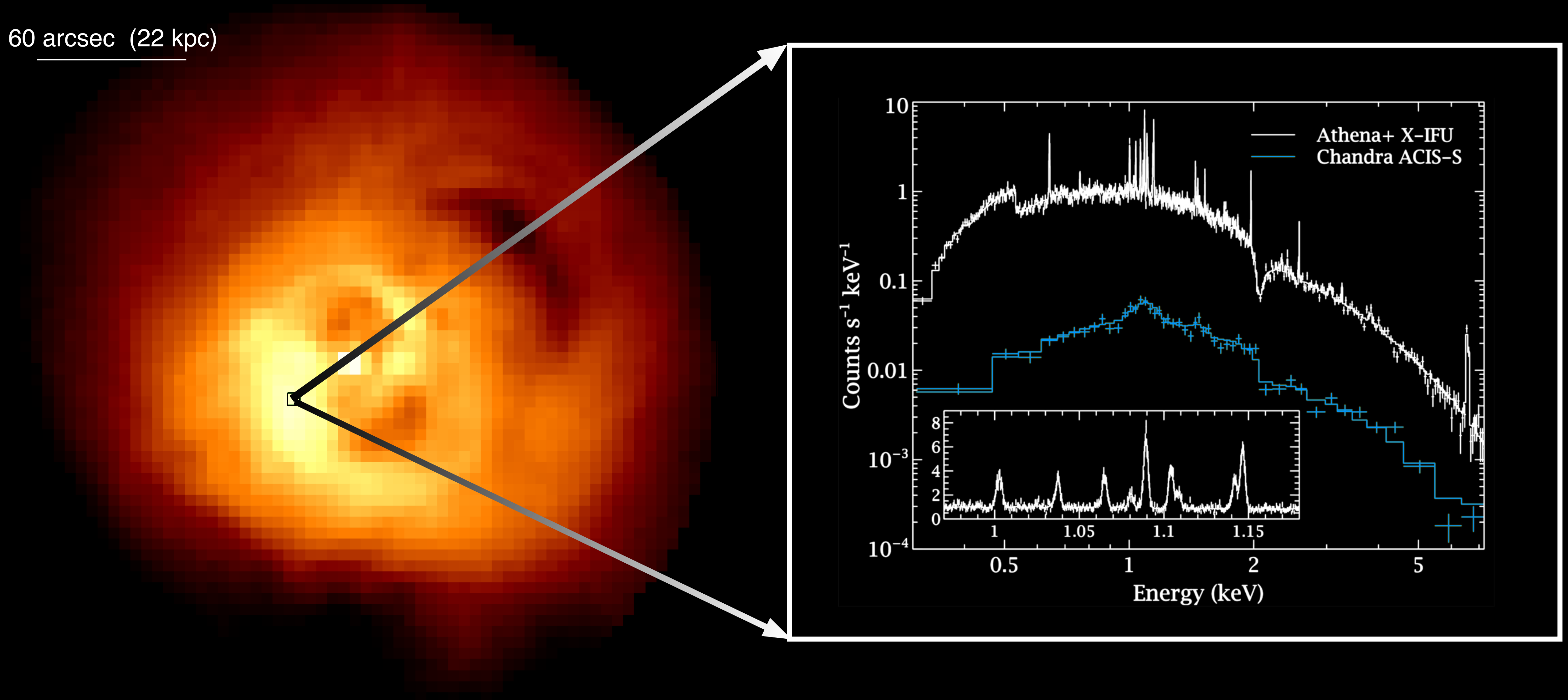
ATHENA X-ray Integral Field Unit


Abell 1795 (300 ks)

- TES sensor array / 2.5 eV resolution / 5′ diameter FoV

Interaction of jets with ICM, heating and cooling

CROSTON, SANDERS ET AL. 2013



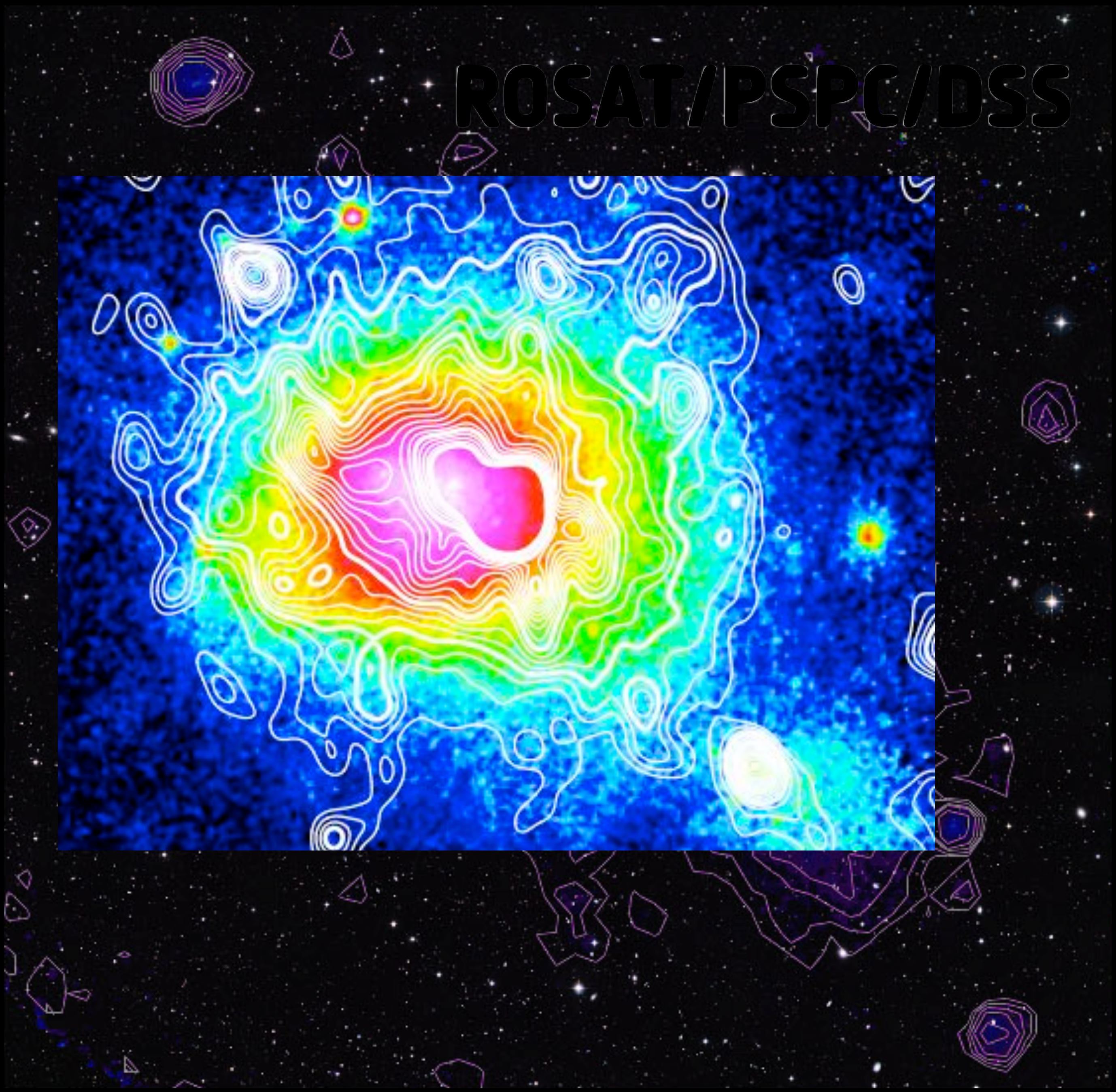
Perseus

- 50 ks observation of core
- One spectrum per 5″ x 5″ pixel

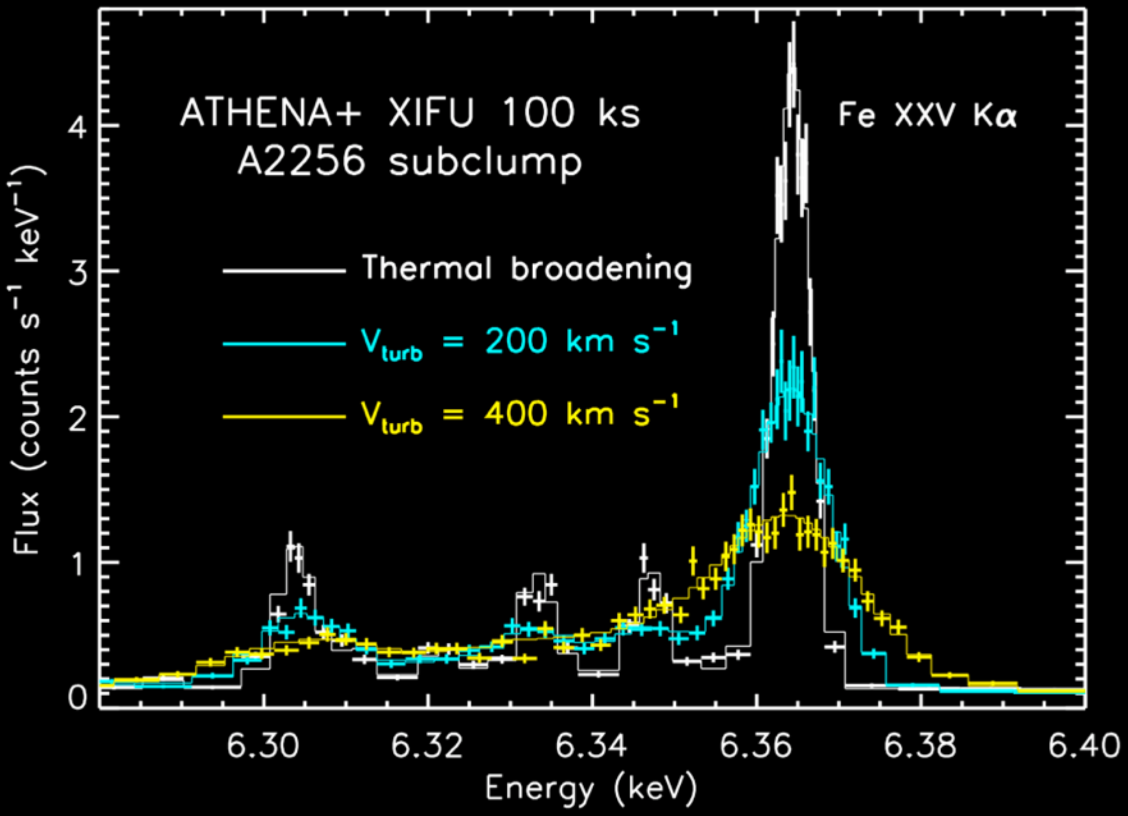
IFU

ATHENA X-ray Integral Field Unit

The halo-turbulence connection



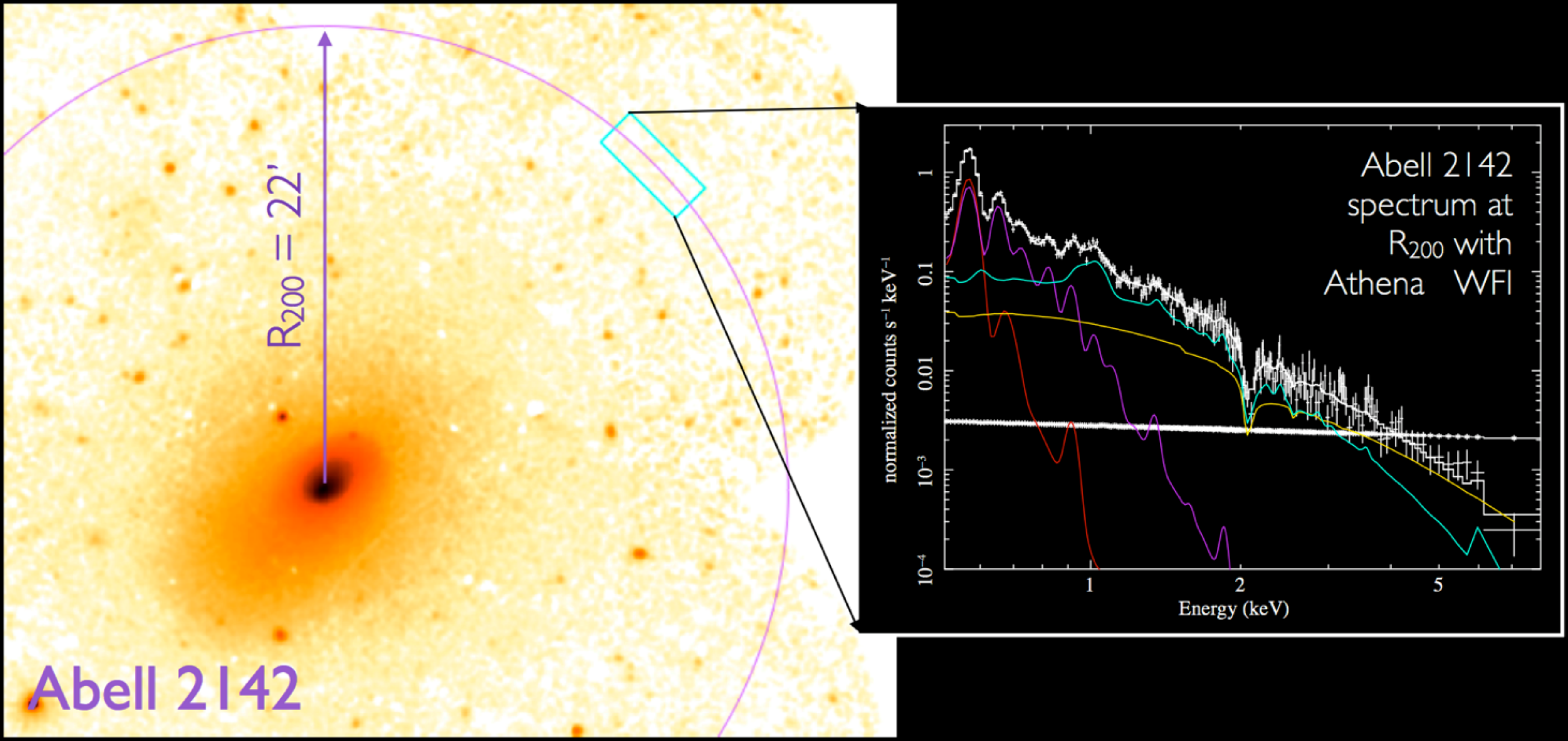
BROWN & RUDNICK 2010



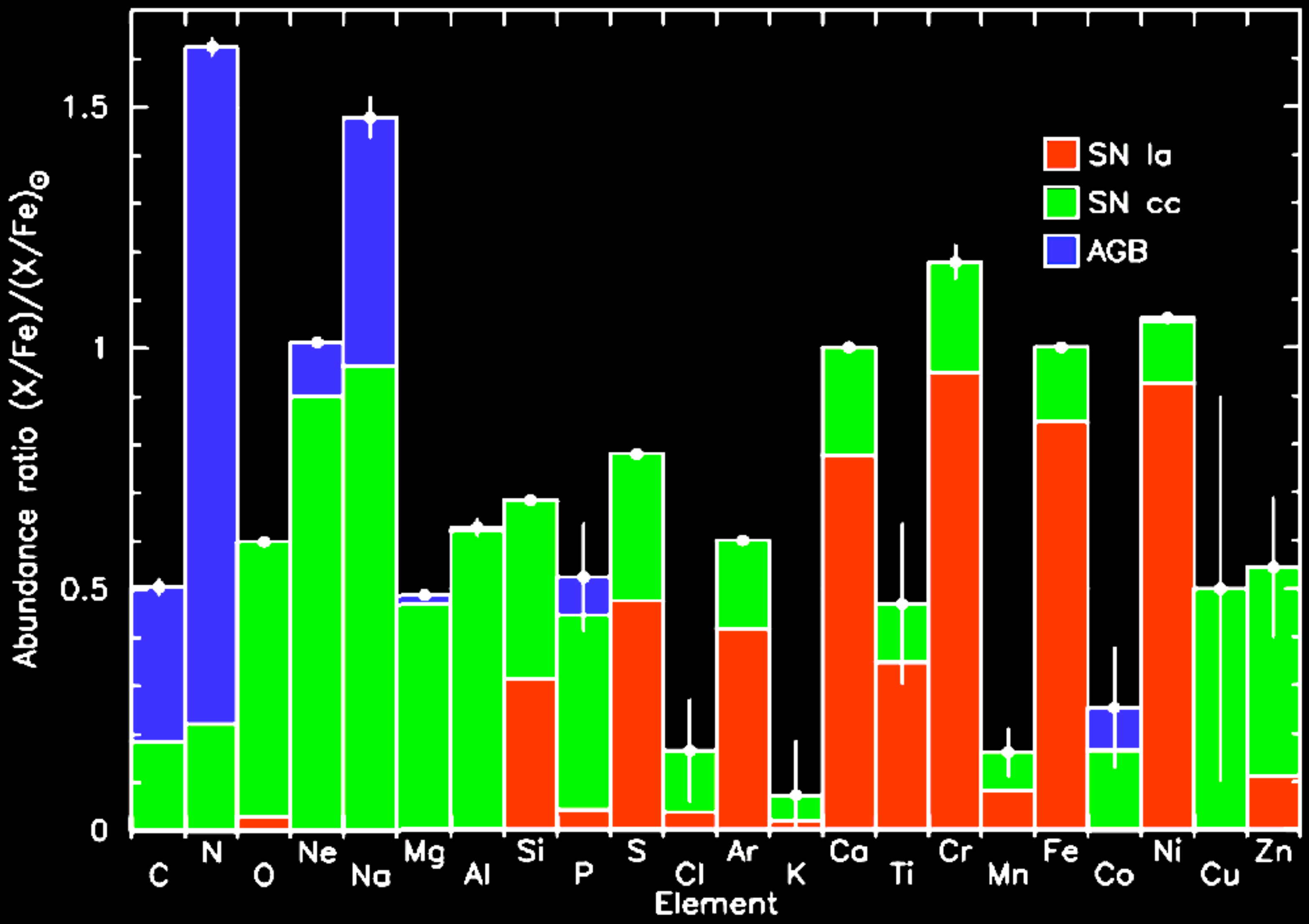
ETTORI, PRATT ET AL. 2013

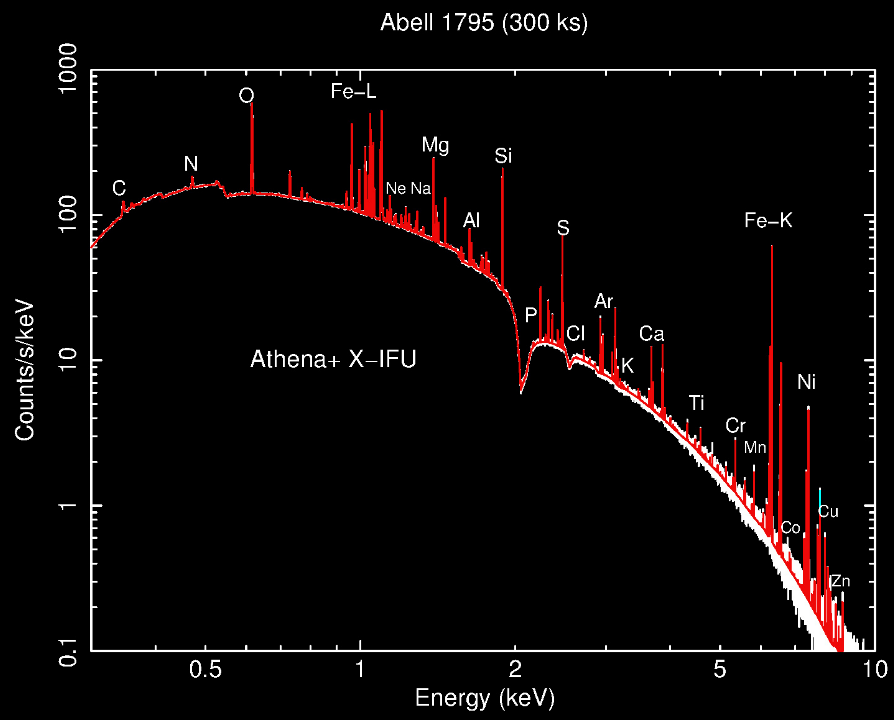
IFU
ATHENA X-ray Integral Field Unit

Thermodynamics of the outskirts



ICM chemistry

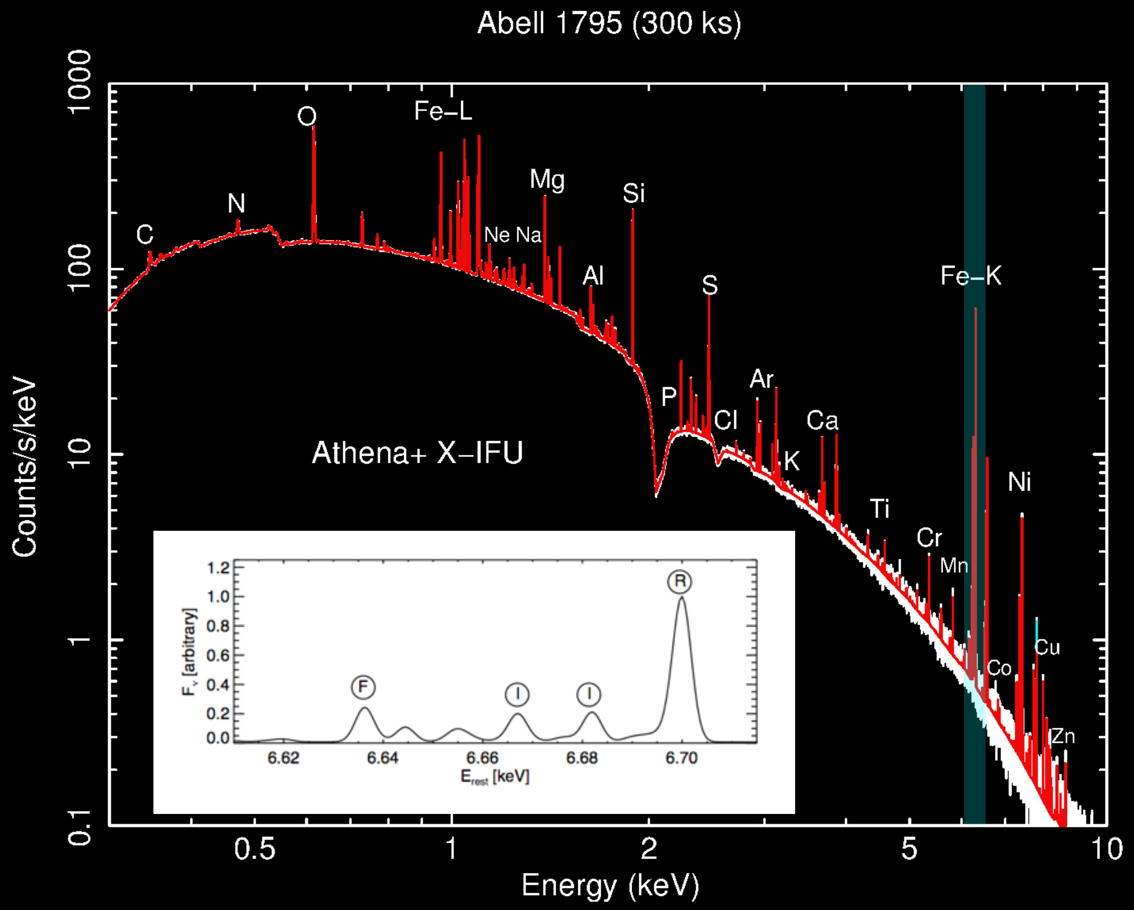




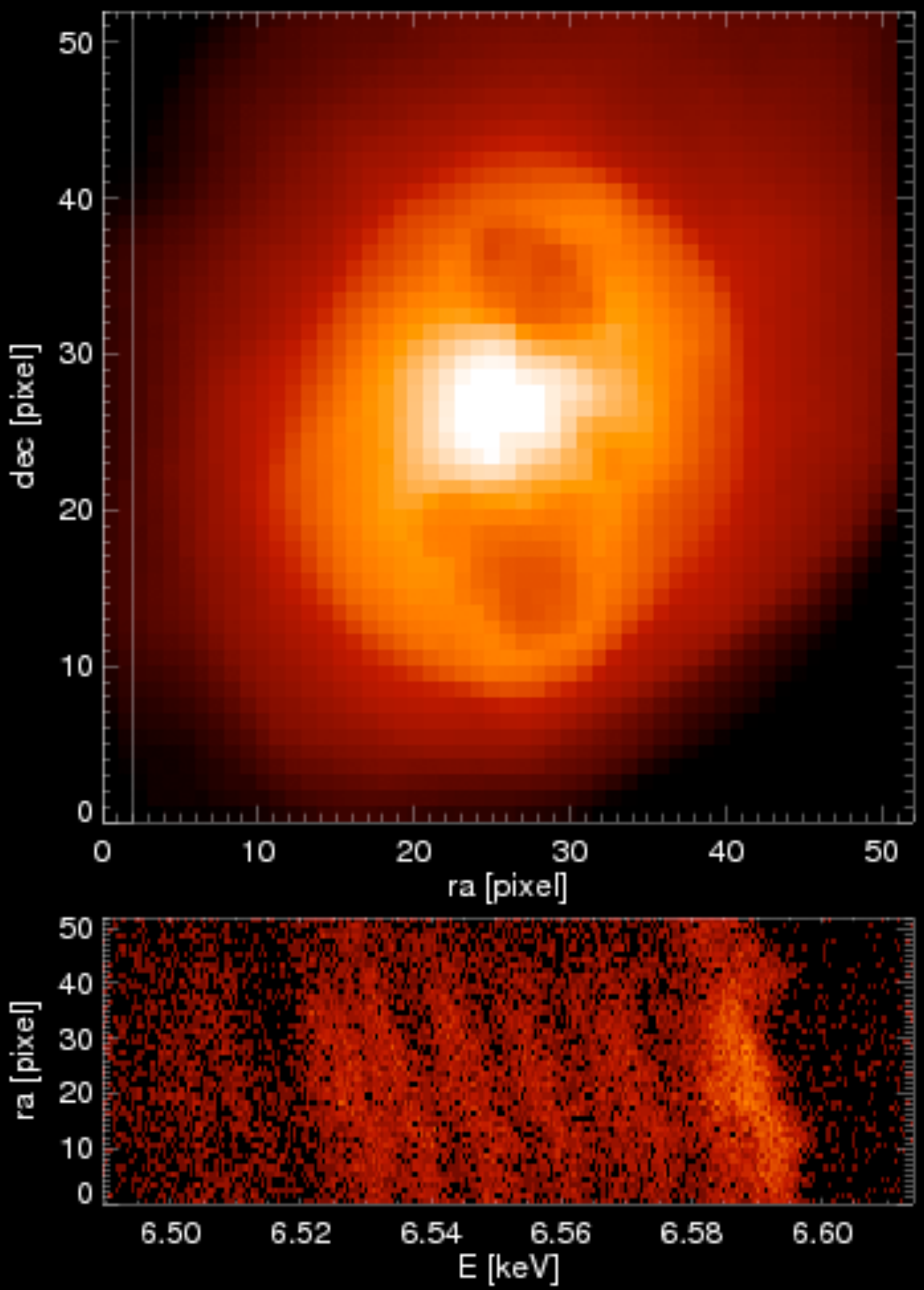
- Much higher precision on yields
- Detection of rare elements

ATHENA X-ray Integral Field Unit

Fe XXV Kα as a kinematic tracer



Simulated Athena image of Perseus



HEINZ ET AL. 2010

Take-home messages

1. Clusters are cosmic laboratories
2. X-ray observations hold the key to understanding many aspects of their formation and evolution