Galaxies and Extragalactic Astrophysics

9. Clusters of Galaxies

Clusters of galaxies

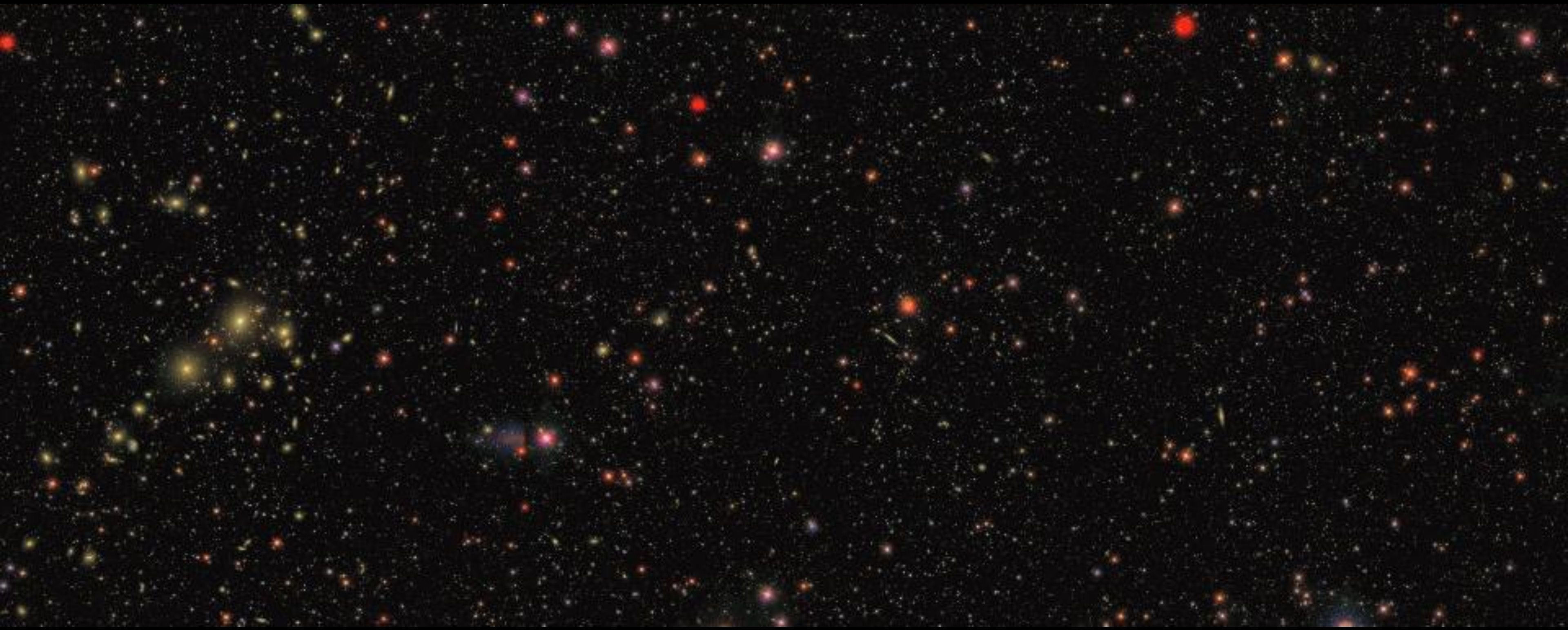
9.1 Introduction

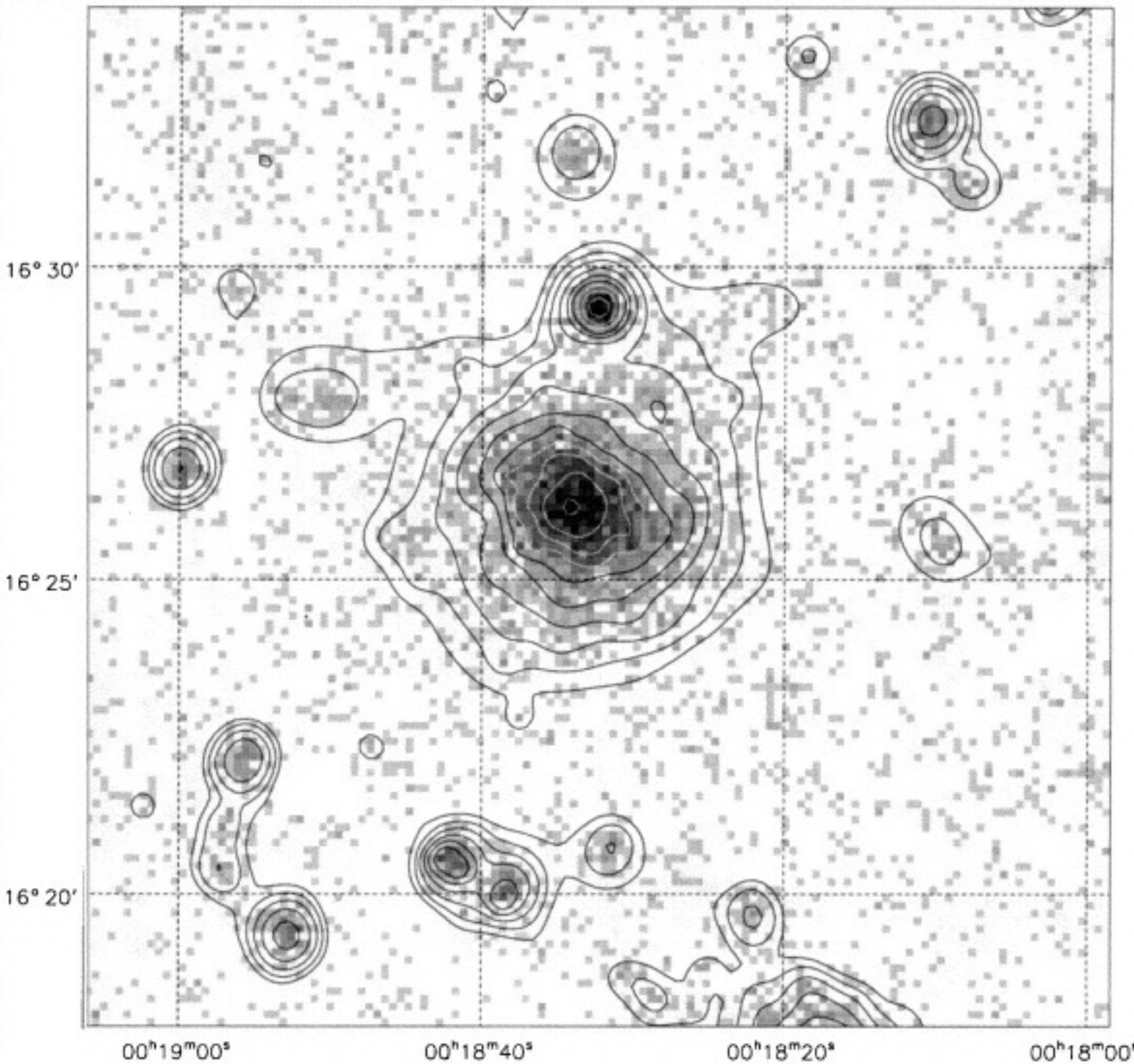
- In the standard CDM cosmological scenario, structure grows from primordial density fluctuations due to the effect of gravity
- Clusters of Galaxies constitute the largest gravitationally collapsed structures in the universe
- Clusters are composed mainly of galaxies, hot gas and dark matter
- Clusters are important: cosmological probes, galaxy evolution, physics of the intracluster medium
- Cluster detection/study: optical/NIR, radio, X-rays, lensing

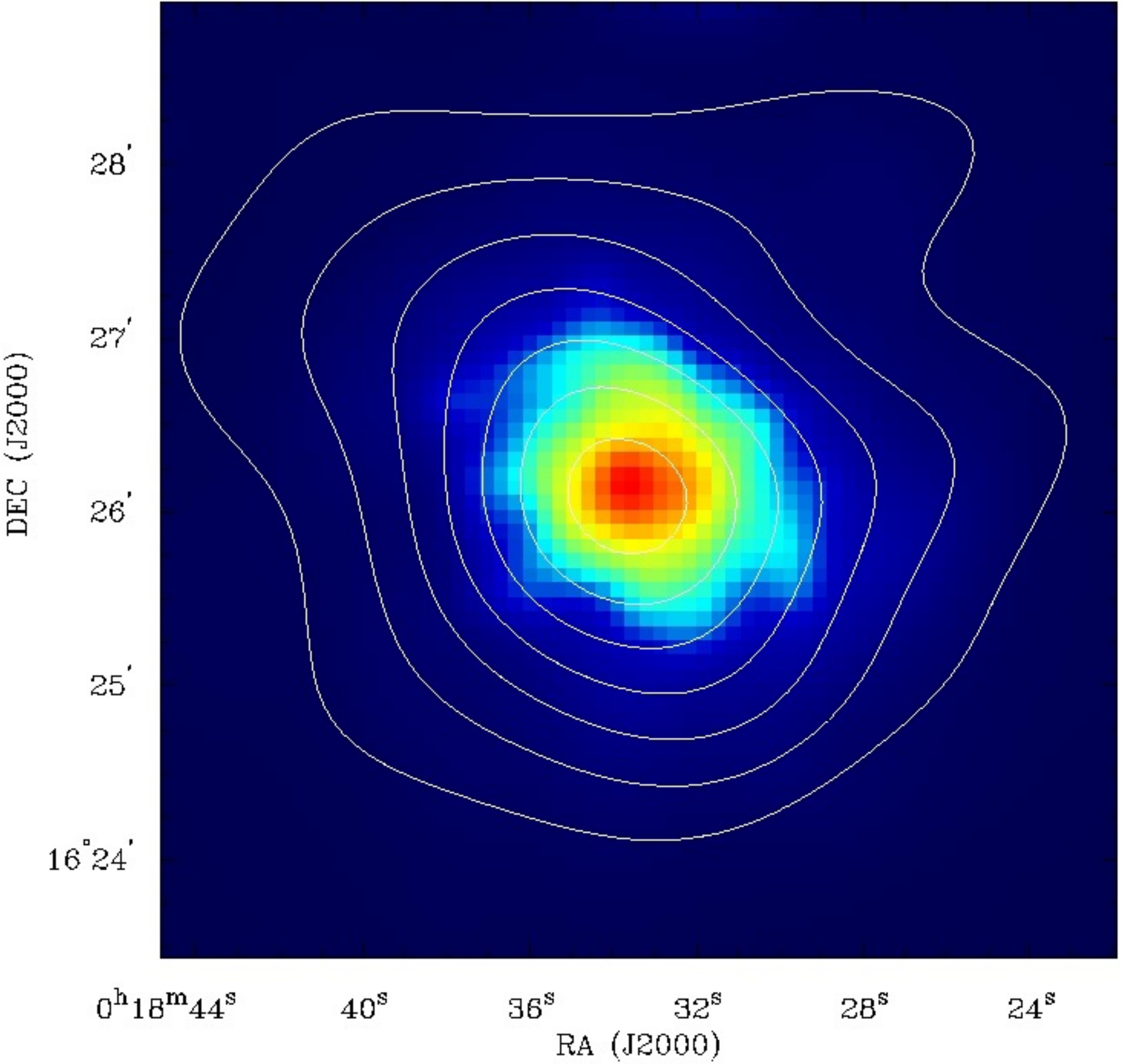
Clusters of galaxies

9.1 Introduction

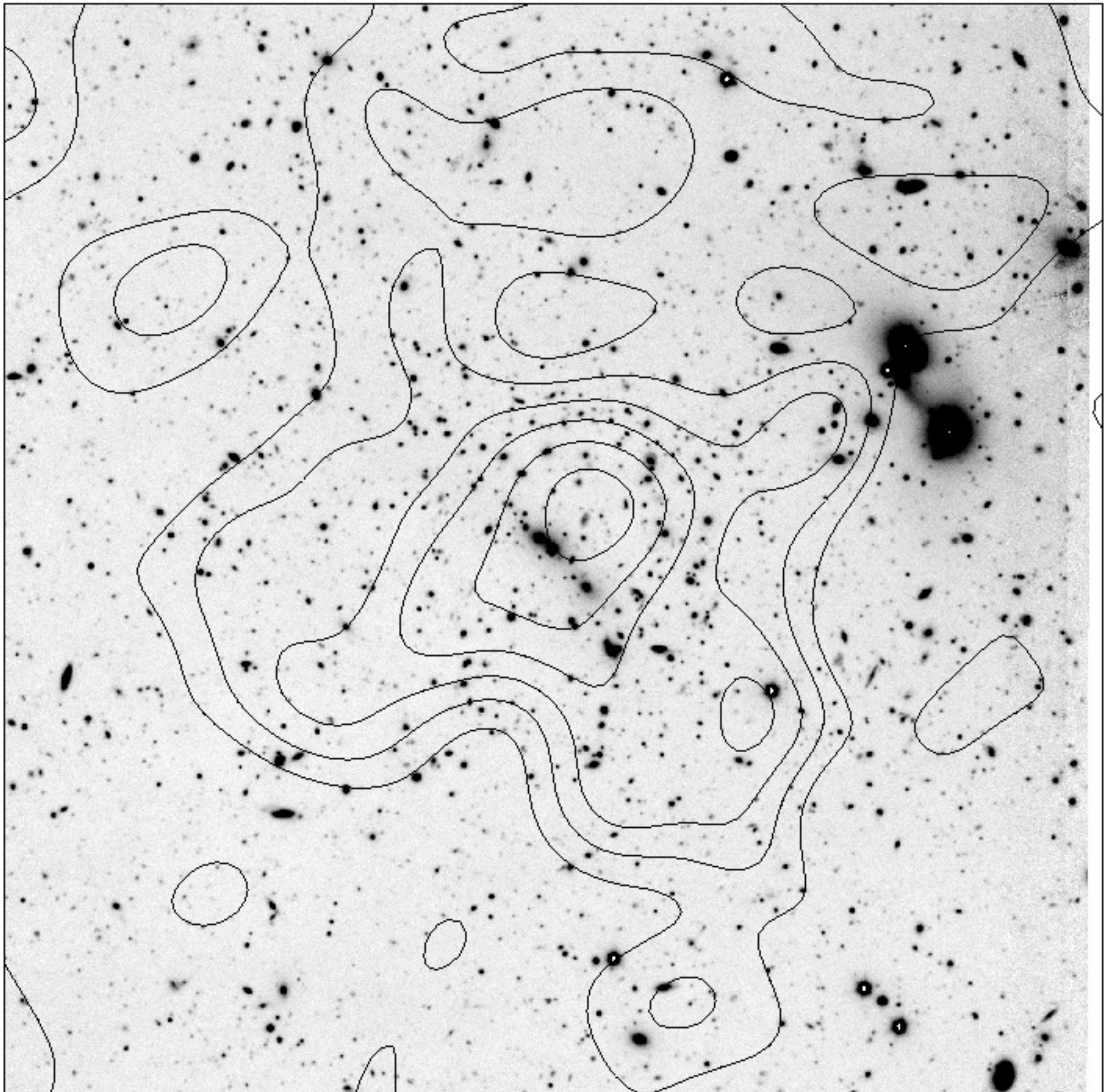
- The first systematic study was carried out by Abell (1958) who compiled an extensive, statistically complete catalogue of rich clusters that has been one of the basics tools to study clusters.
- Clusters of galaxies were first detected in X-ray in the early 70s with the large sky area observations of the Uhuru X-ray satellite (Giaconni et al, 1972).
- The hot gas was detected in the 90's in radio (SZ effect)




16° 30′
16° 25′
16° 20′
00h19m00s
00h18m40s
00h18m20s
00h18m00s


28′
27′
26′
25′
16°24′
DEC (J2000)
0h18m44s
40s
36s
32s
28s
24s
RA (J2000)

MS0016+16



Clusters of galaxies

9.2 Optical Properties

- Galaxy members ~ 1000
- Size: R ~ 1.5 Mpc
- Mass ~ $10^{13\text{-}15}$ Msolar
- baryon fraction: ~ 10-20 %
- Proportion of universe galaxies: ~ 10%
- Galaxy types: E, S0, S

Clusters of galaxies

9.2 Optical Properties: Catalogues

- The most extensive and more widely used catalogues of rich clusters are those of Abell (1958) and Abell et al 1989 and Zwicky et al 1961-68.
- Selected by visual inspection of photographic plates
- Clusters are selected as overdensities compared to a background
- Abell's criteria: (1) at least 50 galaxies in the magnitude range m_3 to m_3+2, (2) contained in a radius $R_A=1.7/z$ arcmin; (3) estimated cluster redshift $0.02 < z < 0.20$

9 Clusters of galaxies

9.2 Optical Properties: Catalogues

- With the advent of high QE CCDs in the early 90s, optical cluster catalogues revived.

- Automated searches:

- Match Filter: Palomar Distant Cluster Survey (Postman et al 1996): selection filtering the data with a model of the spatial and luminosity distribution.

- Voronoid tesselation: (Kim et al 2002)

- Colour selection: Red Cluster Sequence (Gladders & Yee 2000), RedMaPPer (Rykoff, Rozo et al 2014)

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9.2 Optical Properties: Richness

- Number of galaxies in the cluster
- Statistical measure depending on membership criteria

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9.2 Optical Properties: Luminosity Function

- Gives the number distribution of the luminosities of the galaxies
- Schechter luminosity function
- parameters

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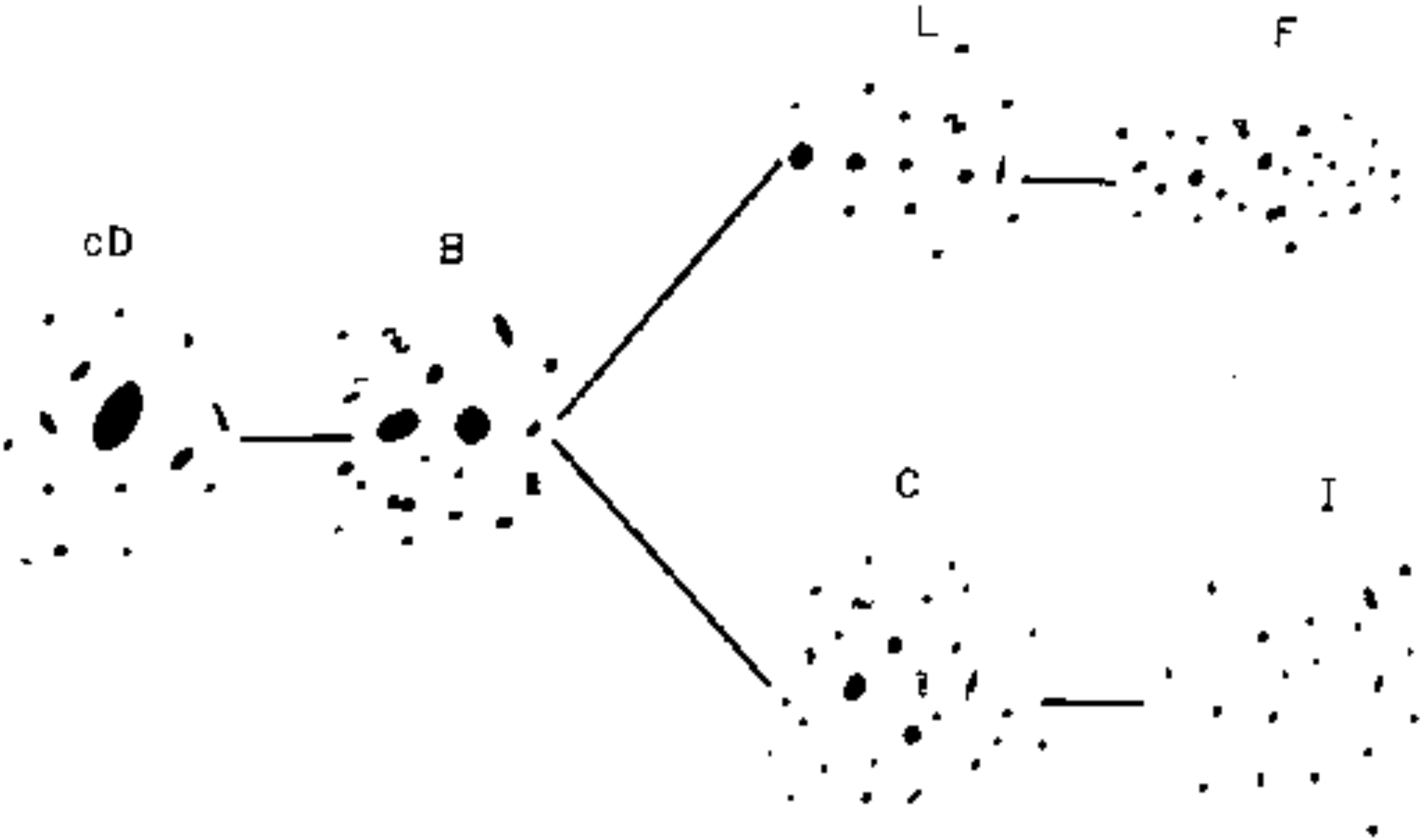
Morphological classification

- Based on different properties
- Zwicky: compact, medium compact, open
- Bautz-Morgan: Type I, II, III
- Rood-Sastry: cD, B, L, C, F, I


cD
B
L
F
C
I

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9.2 Optical Properties: Velocity distribution

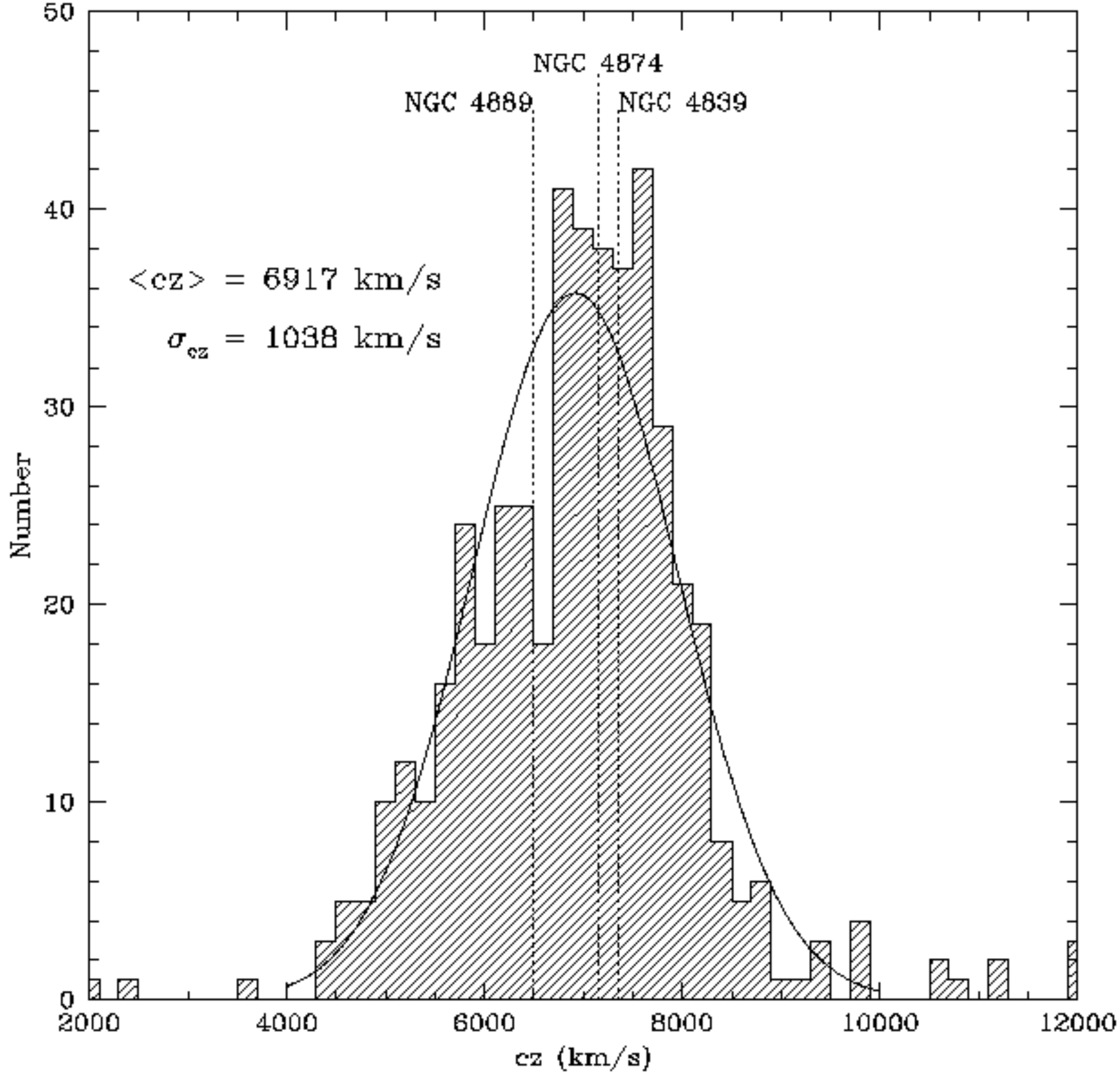
- Existence of morphological sequence from irregular to regular suggests that regular clusters may have undergone some sort of relaxation

- The redshift of a cluster is determined from the mean radial velocity of galaxies in a cluster

- Normally, the velocity distribution is characterized by the dispersion of radial velocities around the mean. The velocity dispersion completely characterizes the radial distribution function of velocities if it is Gaussian

- Radial velocity distribution are found to be close to Gaussian suggesting that they are at least partly relaxed systems in which one can define a "temperature"

$$\sigma_r = (kT/m)^{1/2}$$



Colless 1996

9 Clusters of galaxies

9.2 Optical Properties: Spatial distribution

- The most regular clusters show a smooth galaxy distribution with a concentrated core
- Normally five parameters: position, central projected density, core scale and maximum radial extent

9 Clusters of galaxies

9.2 Optical Properties: Cluster masses

- Assuming that cluster are bound, self-gravitating system one can calculate their masses
- If clusters were not bound they would disperse as their crossing times ($t_{cr} \sim 10^9$ years) are shorter than their ages
- Virial theorem
- M/L ratios
- Missing mass: Dark Matter

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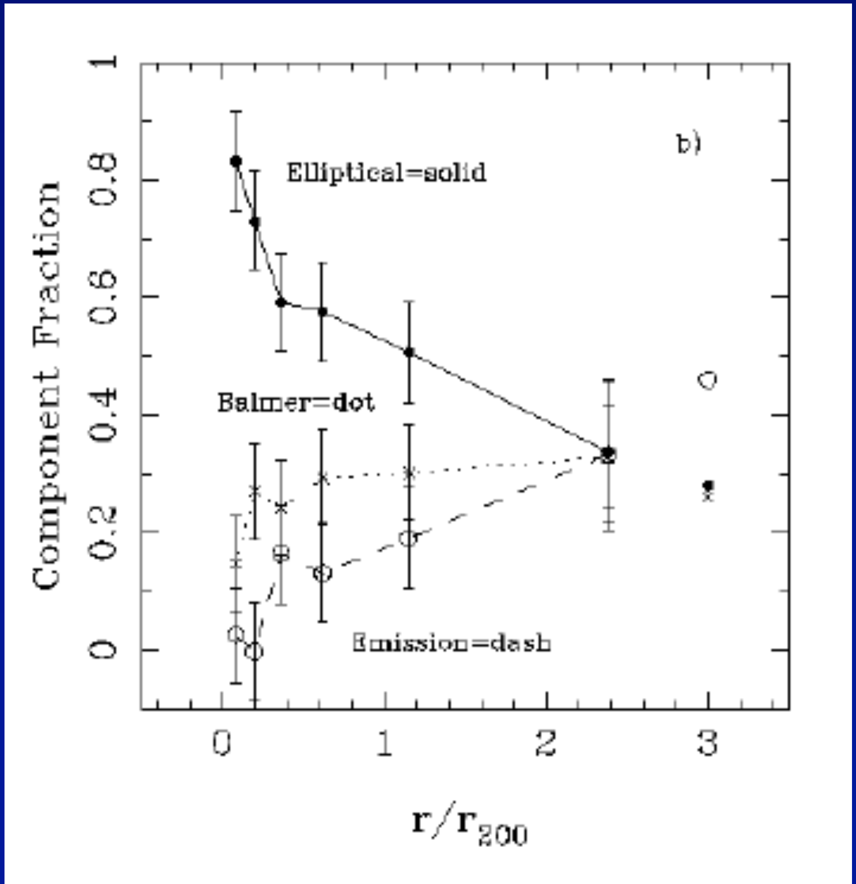
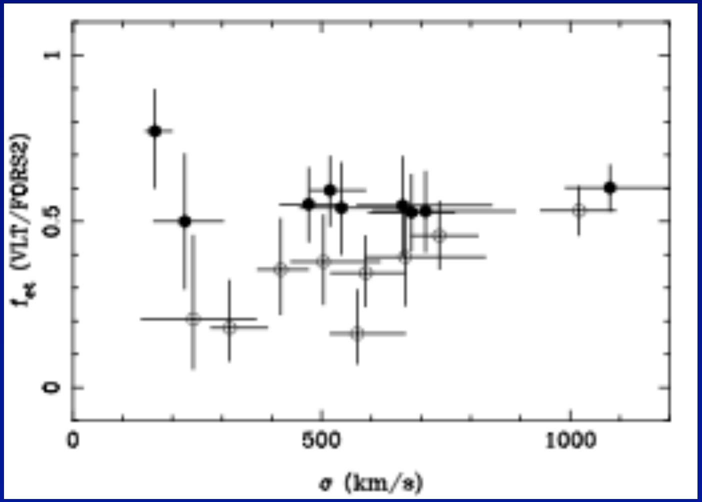
9.2 Optical Properties: Galactic Content

- cD
- Proportion of E, S0, Sp



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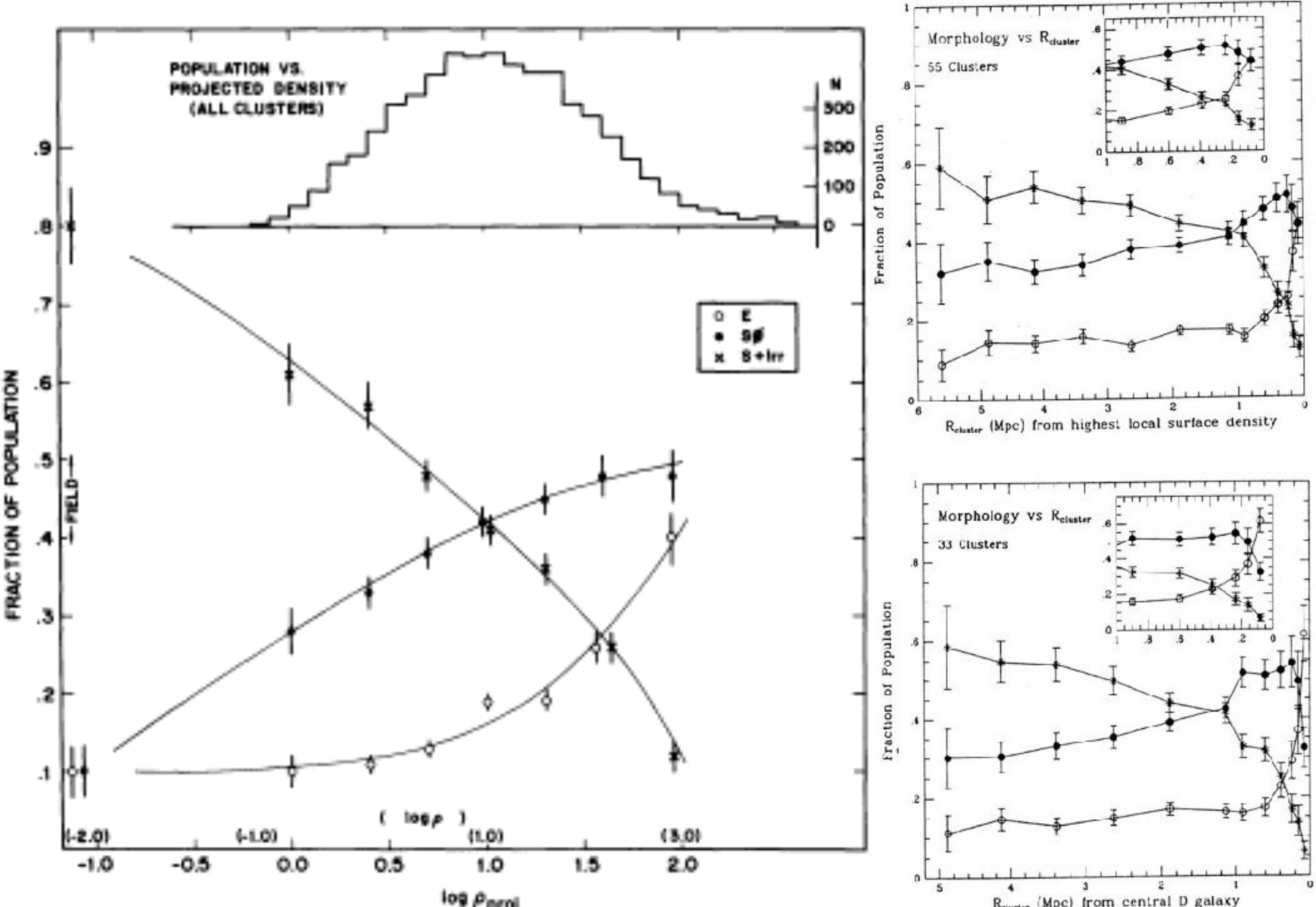
cD Galaxy in Abell496 Field (MPG/ESO 2.2-m + WFI)

ESO PR Photo 46h/99 (21 December 1999)



Dressler 1980: Morphology-density relation

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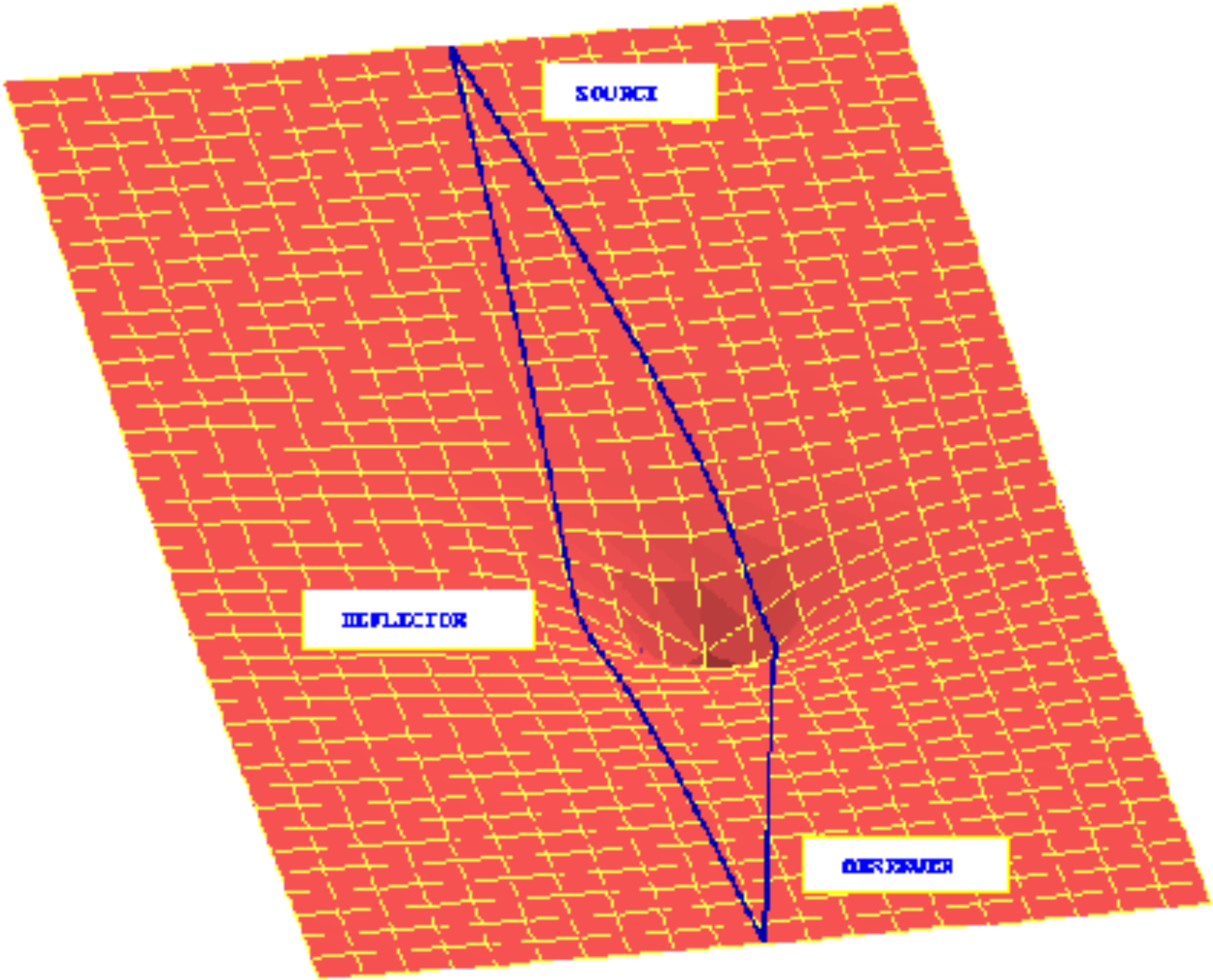
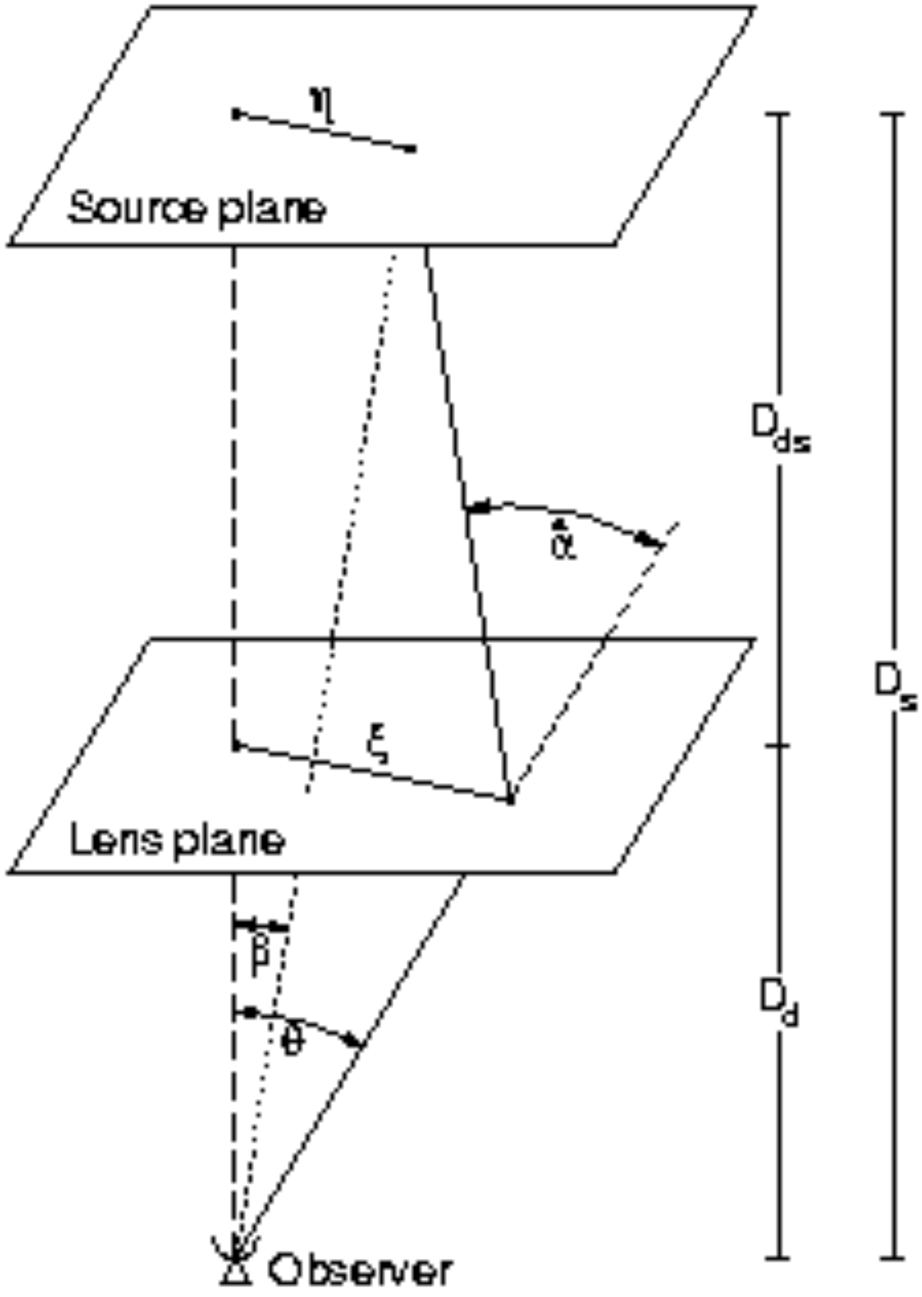
9.2 Optical Properties: Gravitational lensing

- Gravitational lensing is the deflection of light due to gravitational potentials
- Normally, two regimes are considered
  - Strong lensing
  - Weak lensing


SOURCE
DEFLECTOR
OBSERVER



η
Source plane
D_{ds}
$\hat{\alpha}$
D_s
ξ
Lens plane
β
θ
D_d
Observer

Clusters of galaxies

9.2 Optical Properties: Gravitational lensing

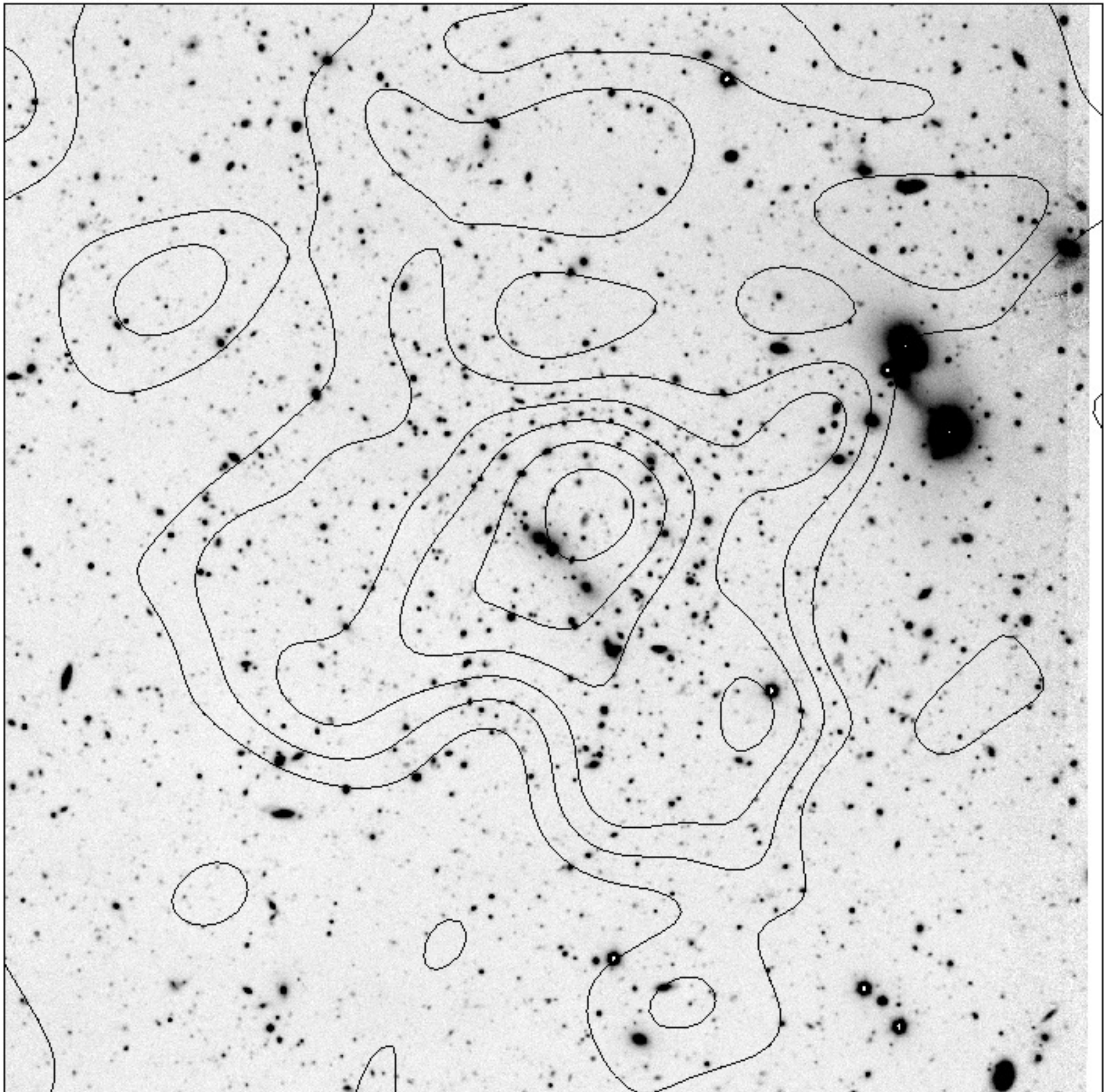
- Strong lensing: Multiple images of the lensed background objects are produced

Clusters of galaxies

9.2 Optical Properties: Gravitational lensing

- Weak lensing: Background galaxies are distorted and magnified/demagnified due to the large cluster gravitational potential

MS0016+16



Clusters of galaxies

9.2 Optical Properties: Gravitational lensing equations

$$\vec{\eta} = \frac{D_s}{D_d}\vec{\xi} - D_{ds}\hat{\vec{\alpha}}(\vec{\xi}) \, .$$

$$\vec{\beta} = \vec{\theta} - \frac{D_{ds}}{D_s}\hat{\vec{\alpha}}(D_d\vec{\theta}) \equiv \vec{\theta} - \vec{\alpha}(\vec{\theta})$$

$$\partial\vec{\beta} = \mathcal{A}\,\partial\vec{\theta}$$

$$\mathcal{A}(\vec{\theta}) = \left(\delta_{ij} - \frac{\partial^2\psi(\vec{\theta})}{\partial\theta_i\partial\theta_j}\right) = \begin{pmatrix} 1-\kappa-\gamma_1 & -\gamma_2 \\ -\gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix} ,$$

$$\Sigma(\vec{\xi}) \equiv \int dr_3\, \rho(\xi_1, \xi_2, r_3)$$

$$\kappa(\vec{\theta}) = \frac{\Sigma(D_d\vec{\theta})}{\Sigma_{cr}}$$

$$\Sigma_{cr} = \frac{c^2}{4\pi G}\frac{D_s}{D_d\, D_{ds}}$$

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9.3 X-ray Properties

• Clusters of Galaxies form from gravitational collapse of high density peaks

• Cluster collapse dominated by dark matter with baryons following the potential wells dominated by dark matter

• During collapse the baryons suffer adiabatic compression and heating by gravitationally induced shocks, resulting in the formation of a hot intracluster medium

• For typical cluster masses ($\sim 10^{15}$ $M_\odot$) the gas reaches temperatures of several 10^7 ^oK and becomes fully ionized.

• 10-15% cluster mass is hot gas trapped in the cluster potential well

Clusters of galaxies

9.3 X rays properties

- If gas dynamics corresponds to galaxy dynamics:

$k_B T \sim \mu m_p \sigma_v^2 \sim 6\ (\sigma_v / 1000\ \mathrm{kms}^{-1})^2$ keV

- The hot fully ionized ICM emits thermal bremsstrahlung in X-rays

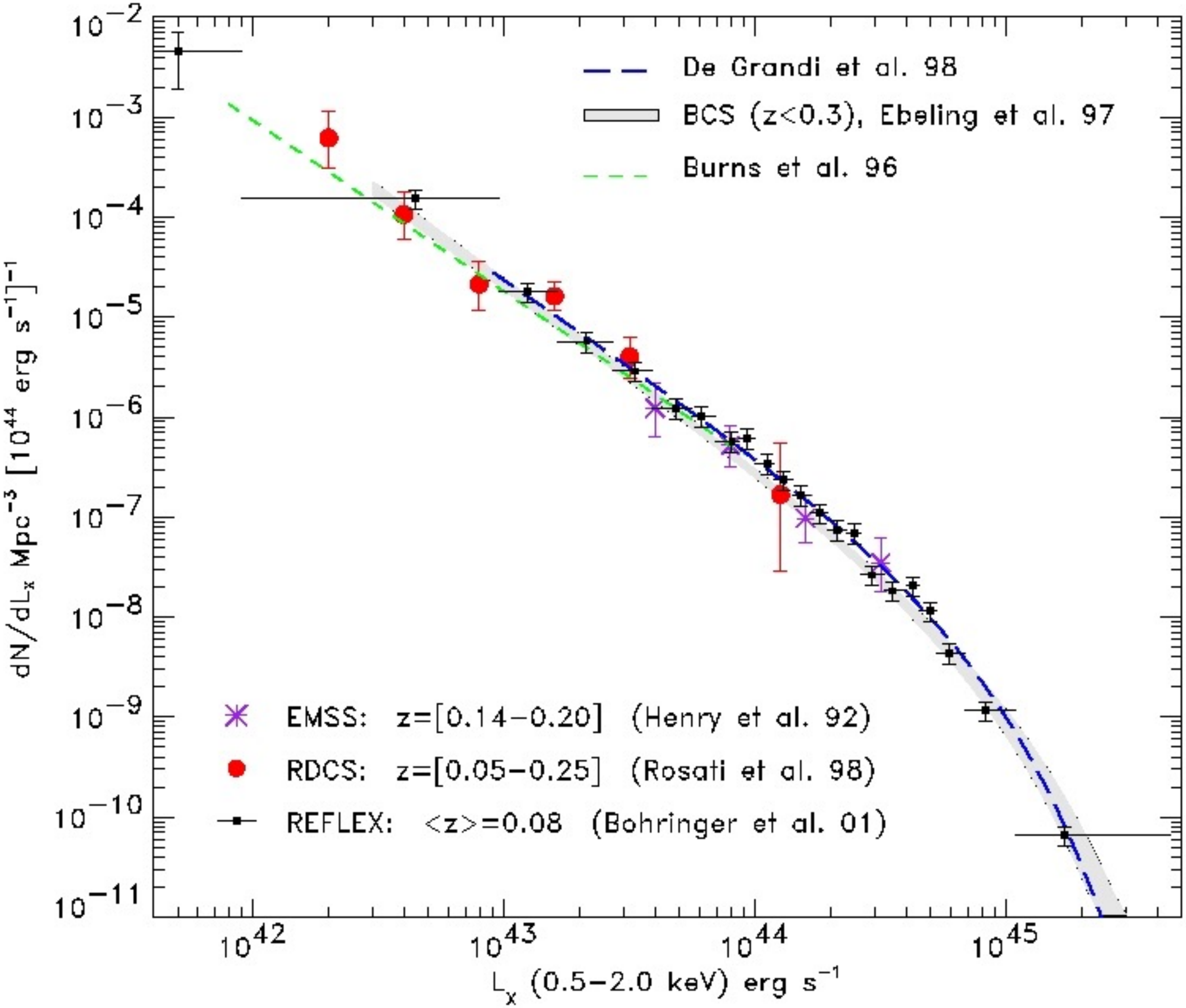
- The spectrum can be characterized by Raymond-Smith (1977) spectrum: thermal bremsstrahlung, lines and edges. Further refinements: Mekal (Mewe et al 1985, Kaastra 1992 & Liehdal 1995)

Clusters of galaxies

9.3 X ray Properties: X-ray luminosity & luminosity function

- Observe count-rates => flux => luminosity
- They are extremely luminous $L_x \sim 10^{43\text{-}45}$ erg/s
- The luminosity function is the number of clusters per unit volume with X-ray luminosities in the range of L_x to $L_x + dL_x$: $f(L_x)dL_x$
- The observed luminosity function is well-fit to a Schechter function

$$f(L_x) = A\,(L/L_*)^{\alpha} \exp(-L/L_*)$$



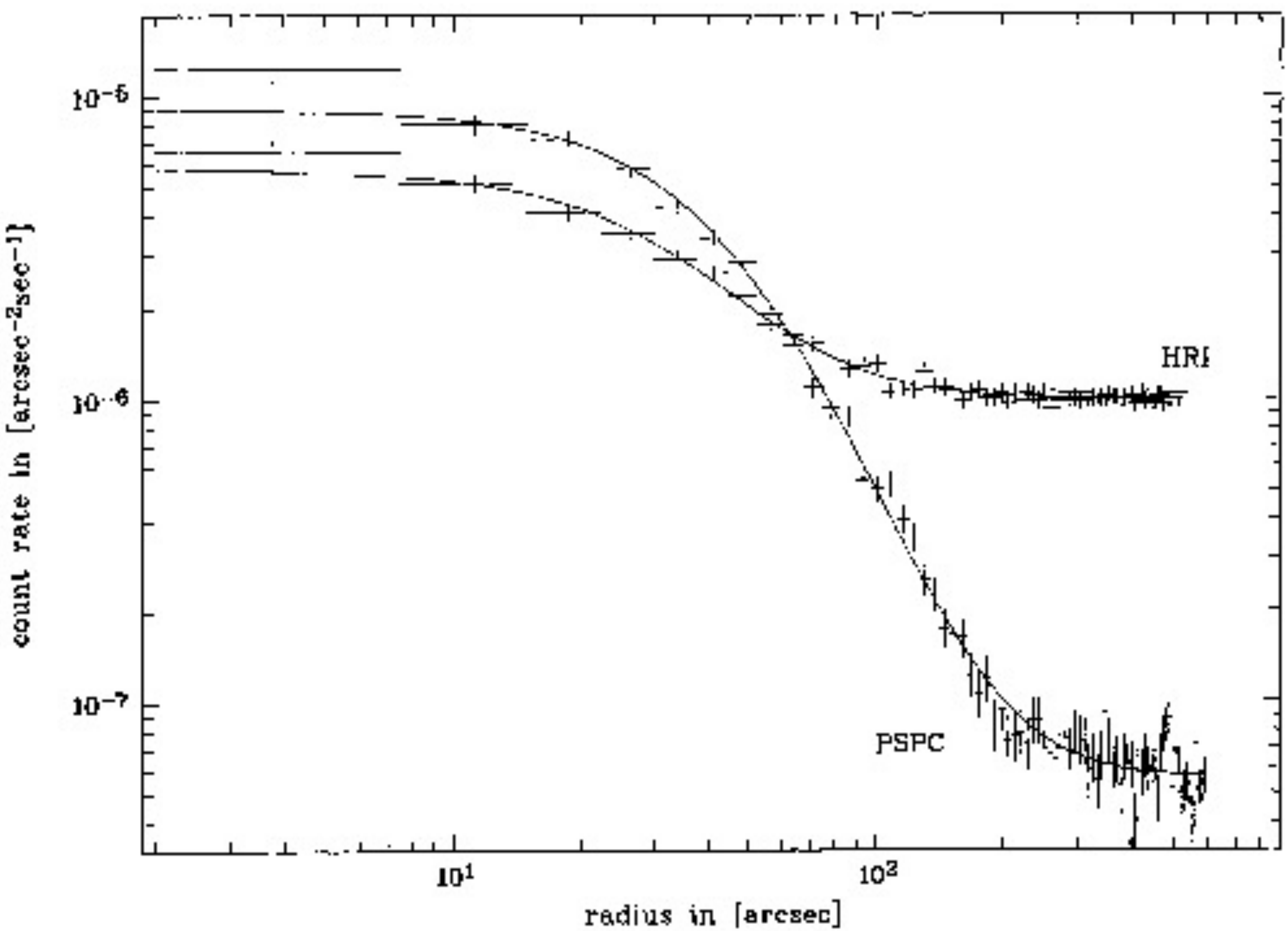
De Grandi et al. 98
BCS (z<0.3), Ebeling et al. 97
Burns et al. 96
EMSS: z=[0.14-0.20] (Henry et al. 92)
RDCS: z=[0.05-0.25] (Rosati et al. 98)
REFLEX: <z>=0.08 (Bohringer et al. 01)
dN/dL_X Mpc^{-3} $[10^{44}$ erg $s^{-1}]^{-1}$
L_X (0.5-2.0 keV) erg s^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{42}
10^{43}
10^{44}
10^{45}

9 Clusters of galaxies

9.3 X-ray Properties: Spatial distribution of X-ray emission

- Extended emission
- The surface brightness is well fit in the majority of cases by the so-called beta model profile

$$S_x = S_{xo}\,[1 + (r/r_c)^2]^{-3\beta+1/2}$$

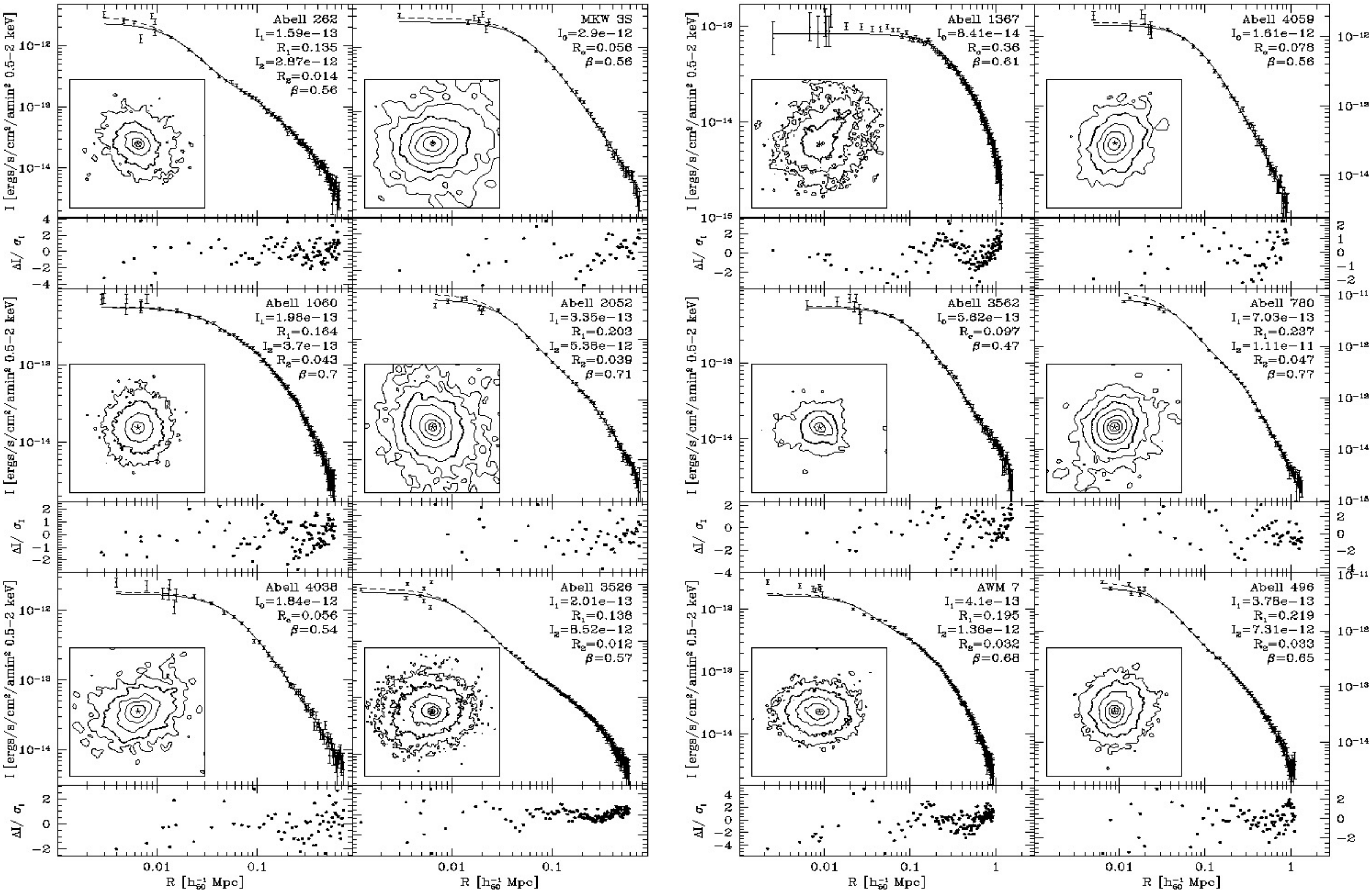


count rate in [arcsec^{-2}sec^{-1}]
10^{-5}
10^{-6}
10^{-7}
HRI
PSPC
10^{1}
10^{2}
radius in [arcsec]

9 Clusters of galaxies

9.3 X-rays Properties: ICM Morphology

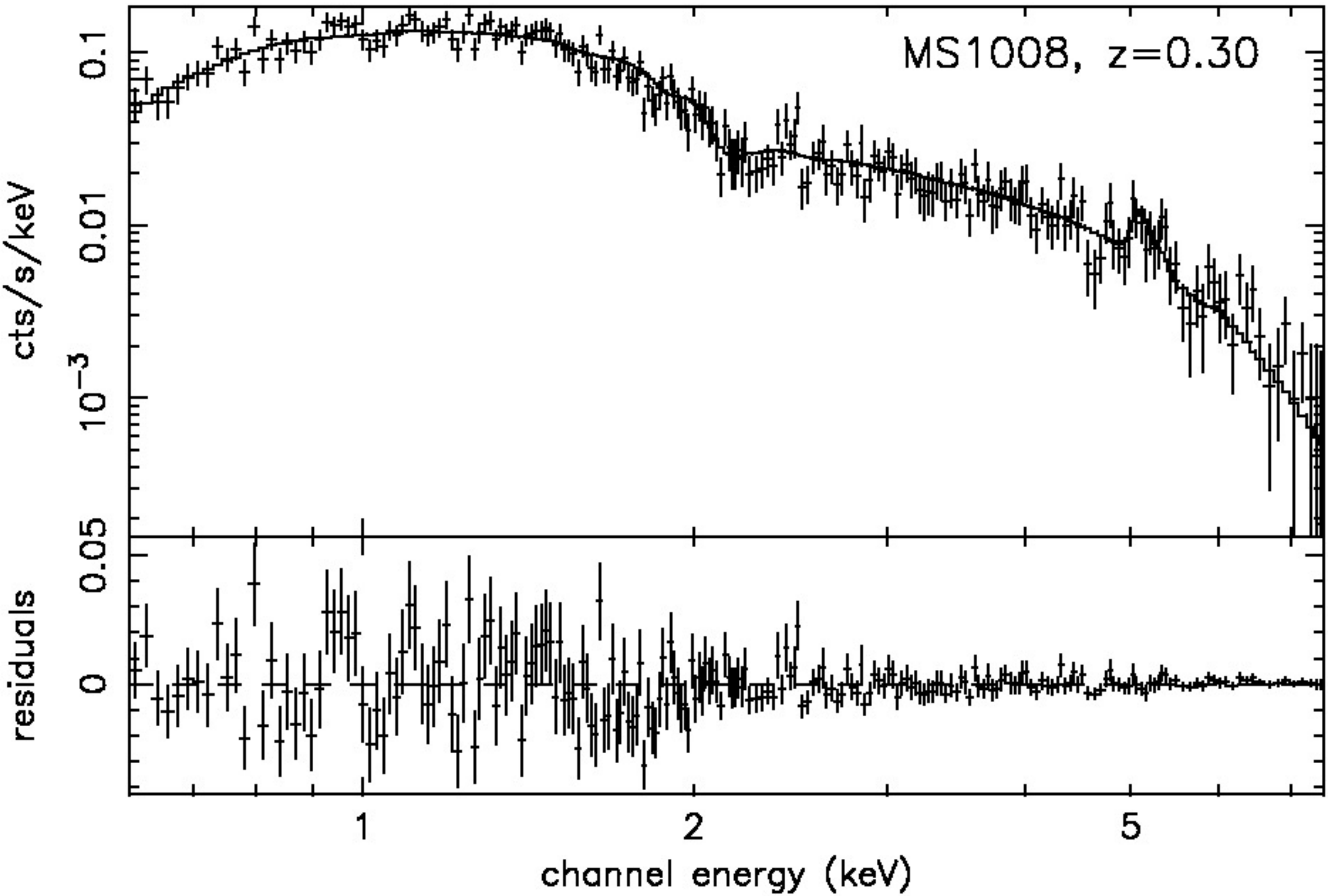
- Clusters present varied morphologies although they are mostly ellipsoids
- Forman & Jones (1982) proposed a two-dimensional scheme for the X-ray morphology. First they are irregular ('early') or regular ('evolved'). Secondly, the presence or absence of a dominant galaxy in the center: X-ray dominant (XD) or non X-ray dominant (nXD).
- Evolutionary sequence
- Evolution of X-ray morphology => Cosmology

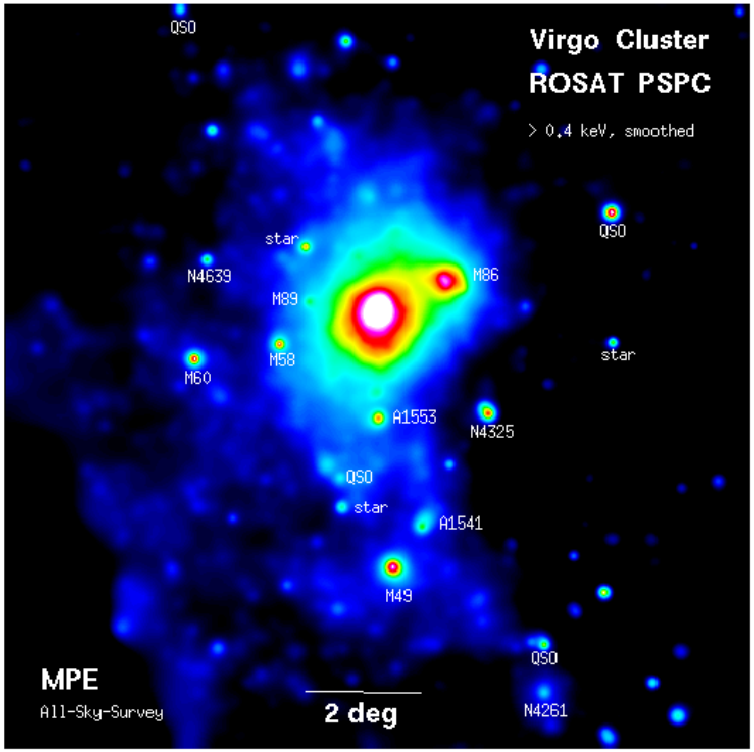

Abell 262
I_1=1.59e-13
R_1=0.135
I_2=2.87e-12
R_2=0.014
β=0.56
MKW 3S
I_0=2.9e-12
R_c=0.056
β=0.56
Abell 1367
I_0=8.41e-14
R_c=0.36
β=0.61
Abell 4059
I_0=1.61e-12
R_c=0.078
β=0.56
Abell 1060
I_1=1.98e-13
R_1=0.164
I_2=3.7e-13
R_2=0.043
β=0.7
Abell 2052
I_1=3.35e-13
R_1=0.203
I_2=5.38e-12
R_2=0.039
β=0.71
Abell 3562
I_0=5.62e-13
R_c=0.097
β=0.47
Abell 780
I_1=7.03e-13
R_1=0.237
I_2=1.11e-11
R_2=0.047
β=0.77
Abell 4038
I_0=1.84e-12
R_c=0.056
β=0.54
Abell 3526
I_1=2.01e-13
R_1=0.138
I_2=5.52e-12
R_2=0.012
β=0.57
AWM 7
I_1=4.1e-13
R_1=0.195
I_2=1.36e-12
R_2=0.032
β=0.68
Abell 496
I_1=3.78e-13
R_1=0.219
I_2=7.31e-12
R_2=0.033
β=0.65
I [ergs/s/cm^2/amin^2 0.5−2 keV]
$\Delta I/\sigma_I$
R [h_{50}^{-1} Mpc]

9 Clusters of galaxies

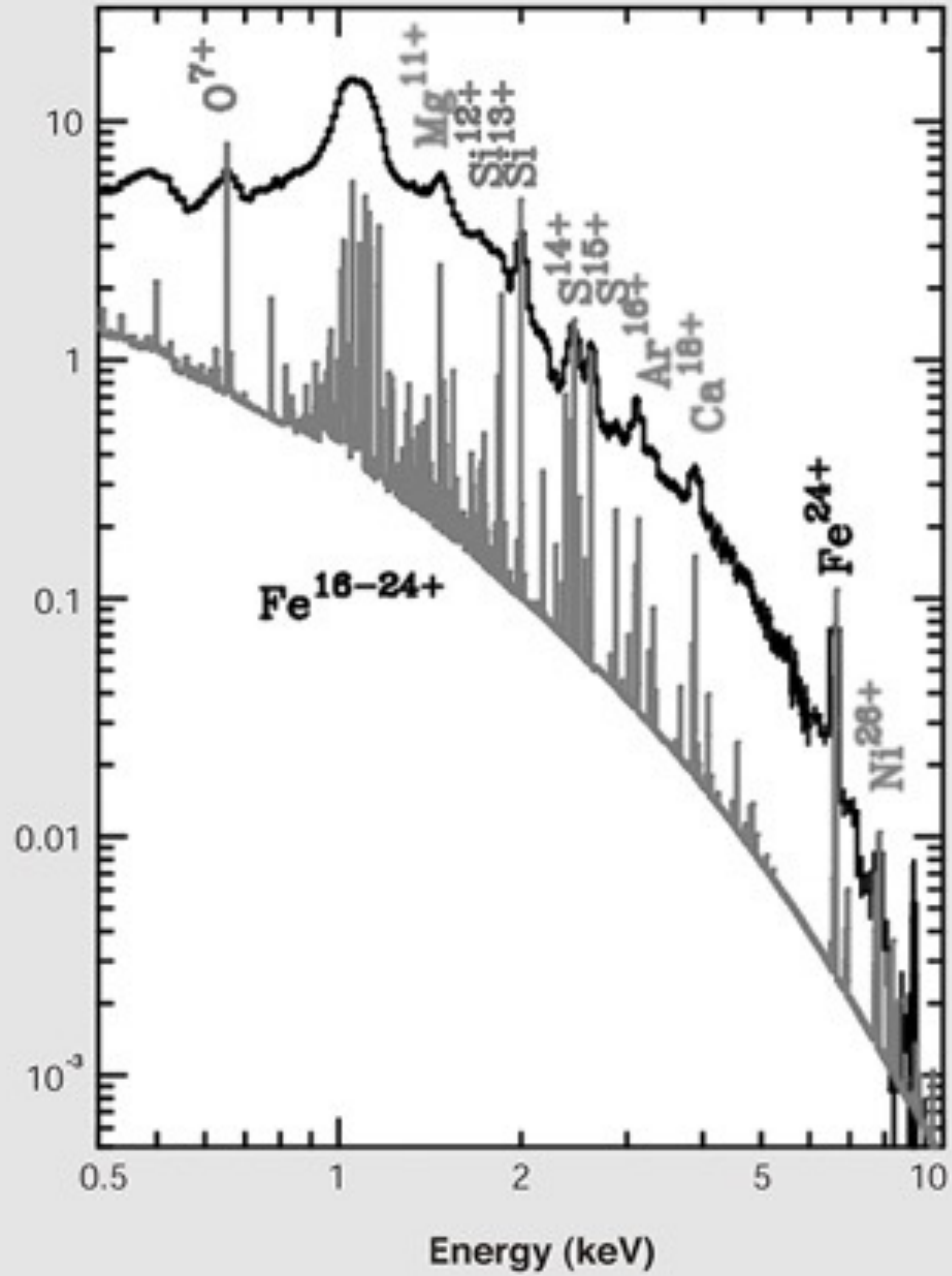
9.3 X-ray Properties: X-ray Spectra

- Clusters exhibit thermal bremsstrahlung spectra from their thin, high temperature, highly ionized intracluster medium
- Typical temperatures are of the order of a few keV
- Typical metallicities are of the order of 1/3 solar
- Spectra show α-element enhancement
- In most (non-cooling flow) clusters there is negligible low energy absorption
- Cooling flows

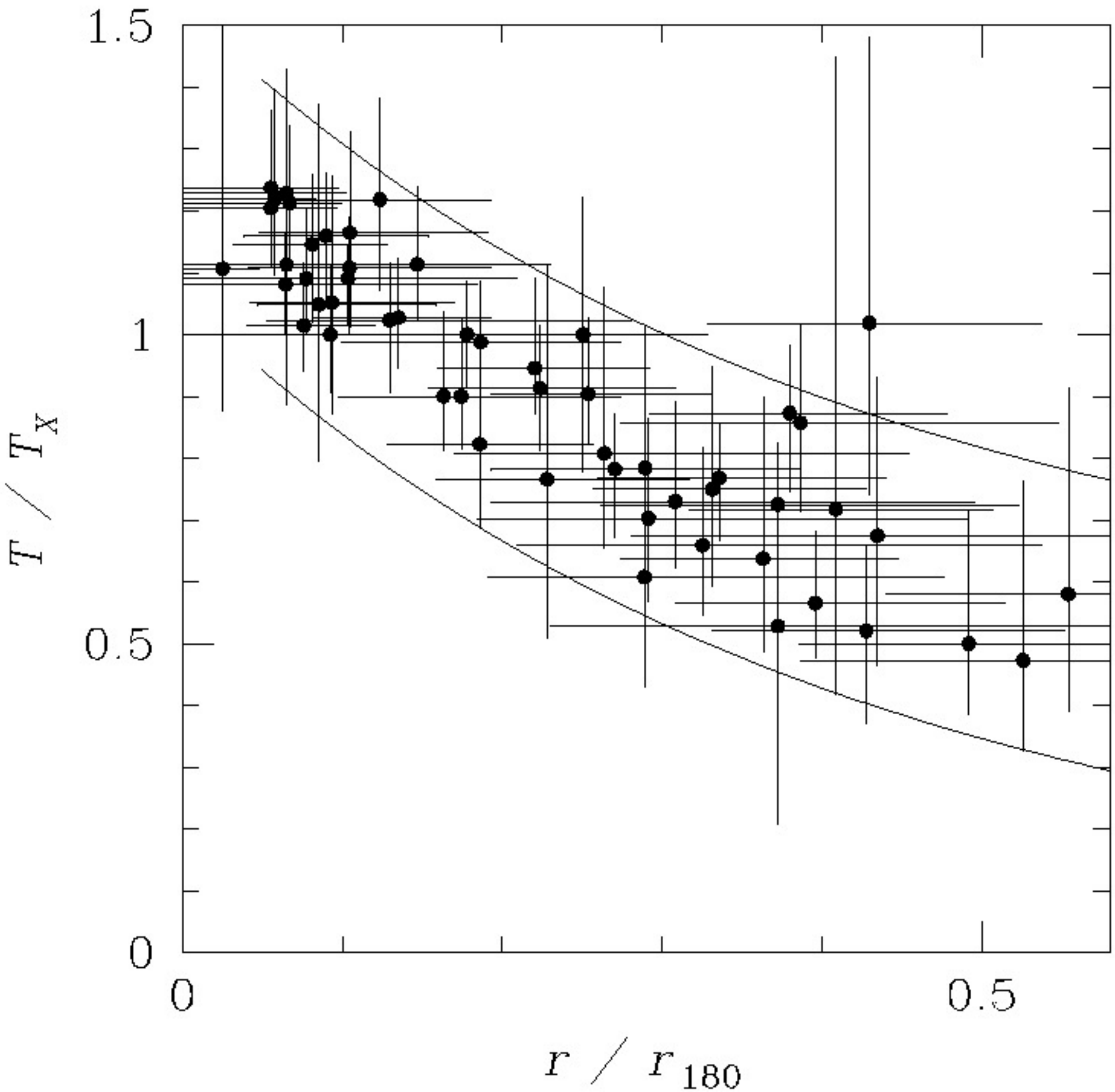

MS1008, z=0.30
cts/s/keV
0.1
0.01
10^{-3}
0.05
residuals
0.05
0
1
2
5
channel energy (keV)



Virgo Cluster
ROSAT PSPC
> 0.4 keV, smoothed
QSO
star
N4639
M89
M86
M60
M58
A1553
N4325
QSO
star
A1541
M49
QSO
MPE
All-Sky-Survey
2 deg
N4261



O^{7+}
Mg^{11+}
Si^{12+}
Si^{13+}
S^{14+}
S^{15+}
Ar^{16+}
Ca^{18+}
Fe^{16-24+}
Fe^{24+}
Ni^{26+}
10
1
0.1
0.01
10^{-3}
0.5
1
2
5
10
Energy (keV)



1.5
1
0.5
0
0
0.5
T / T_X
r / r_180

Metallicity profiles: Mernier et al arXiv: 1703.01183

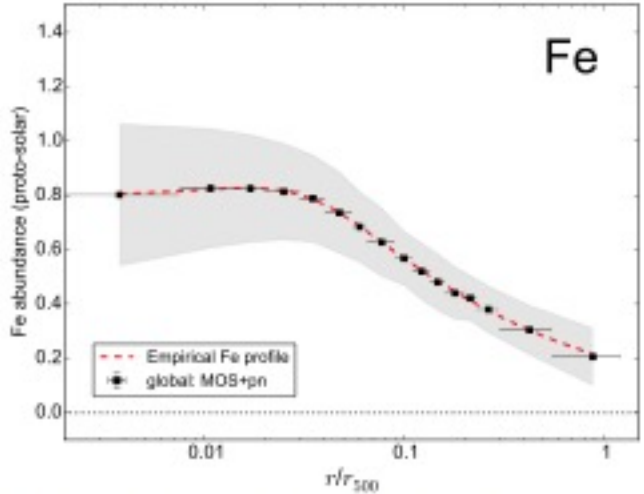


Fig. 1. Average radial Fe abundance profile for the full sample. Data points show the average values and their statistical uncertainties (σ_{stat}, barely visible on the plot). The shaded area shows the scatter of the measurements ($\sigma_{scatter}$, see text).

9 Clusters of galaxies

9.4 Radio Properties

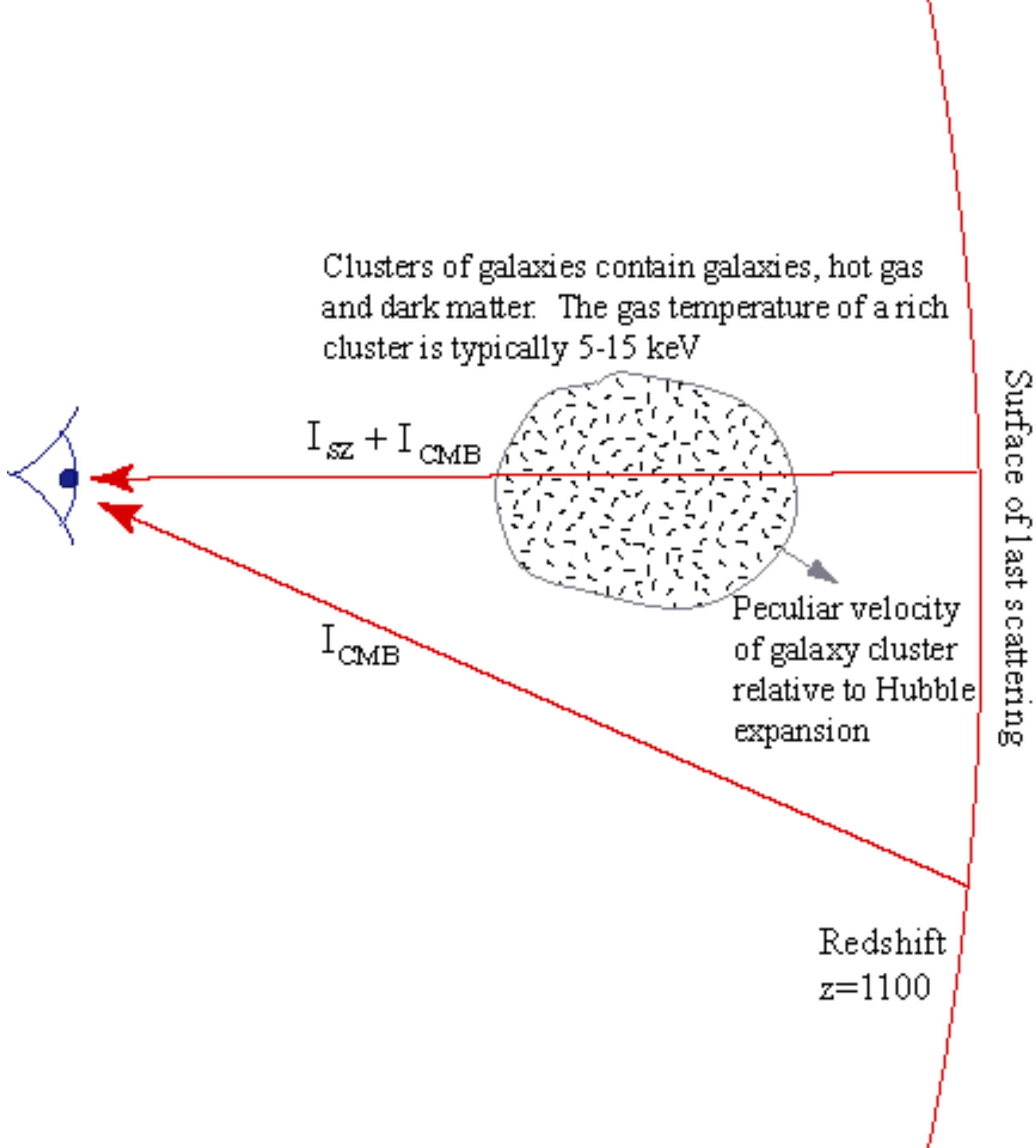
- Emission from galaxies within the cluster
- Head-tail and wide-angle-tail radio sources
- Radio haloes

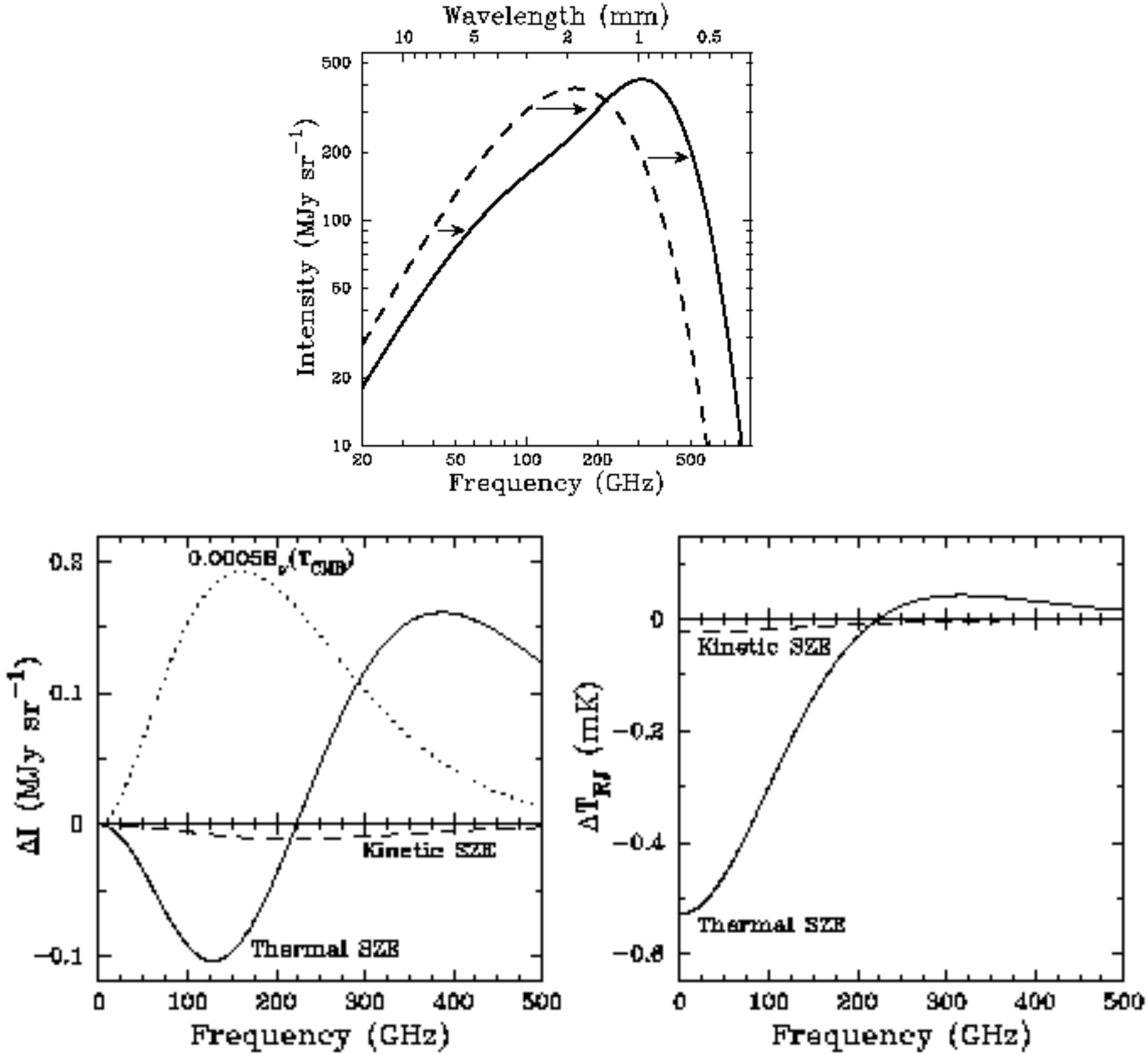
9 Clusters of galaxies

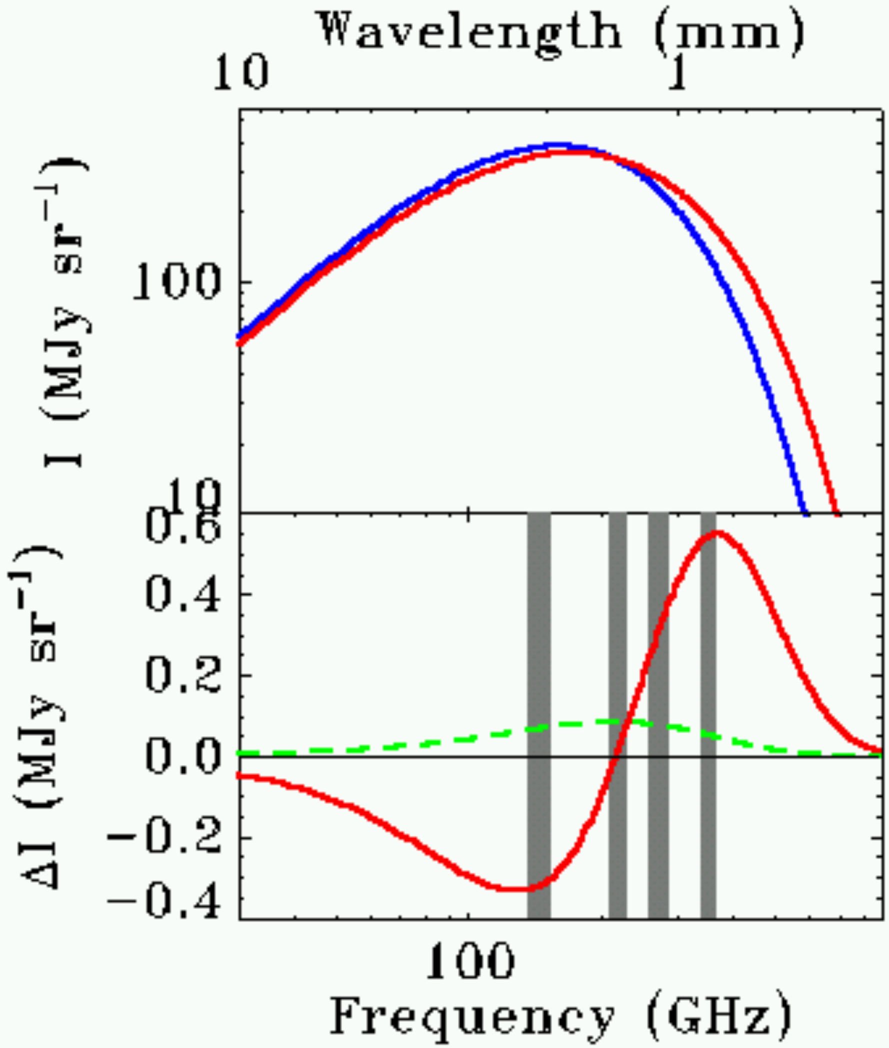
9.4 Radio Properties: Sunyaev-Zeldovich (SZ) effect

- The free electrons in the ICM (inverse Compton) scatter low energy photons from the Cosmic Microwave Radiation

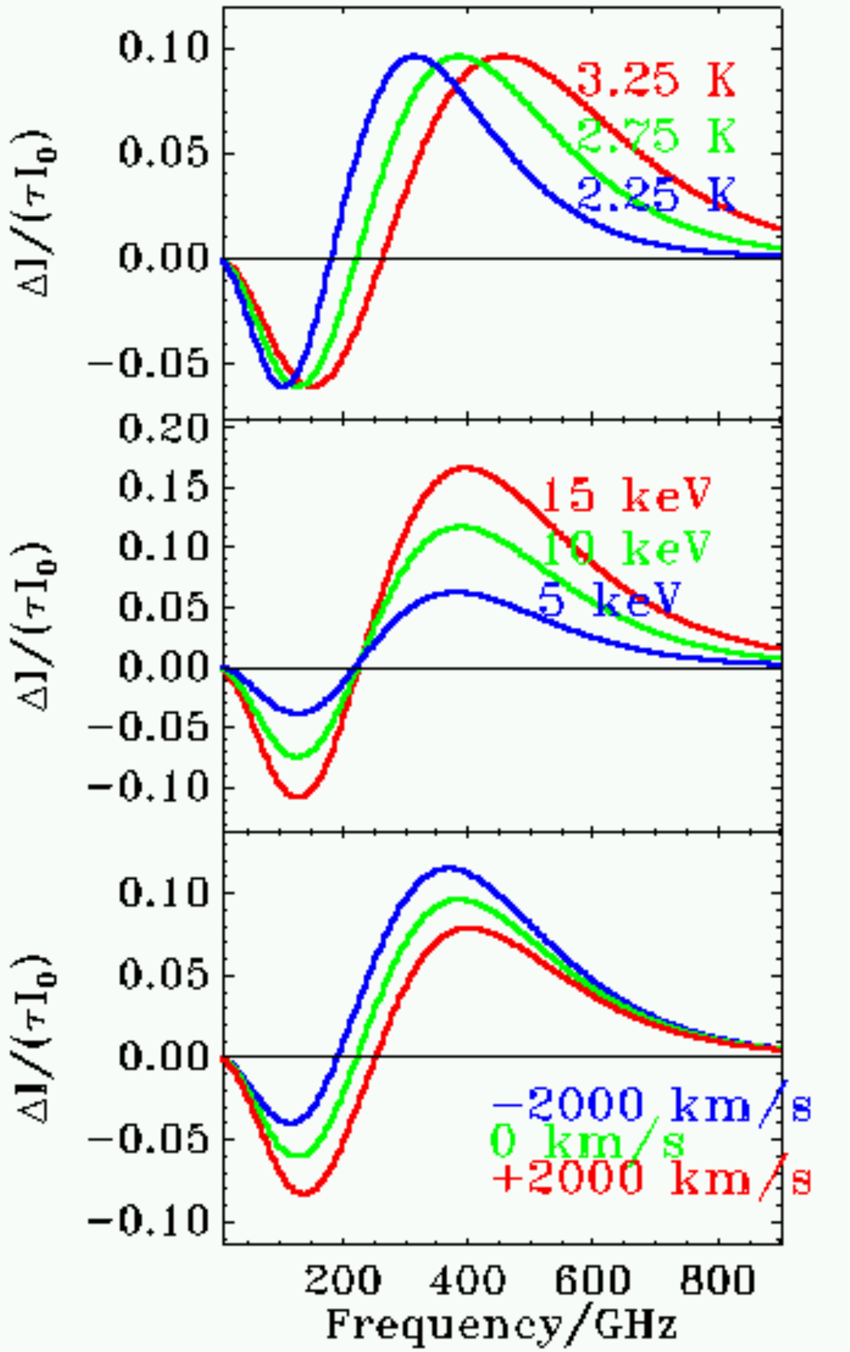
$$\Delta T/T \propto \rho T$$


Clusters of galaxies contain galaxies, hot gas and dark matter. The gas temperature of a rich cluster is typically 5-15 keV
$I_{SZ} + I_{CMB}$
I_{CMB}
Peculiar velocity of galaxy cluster relative to Hubble expansion
Surface of last scattering
Redshift z=1100

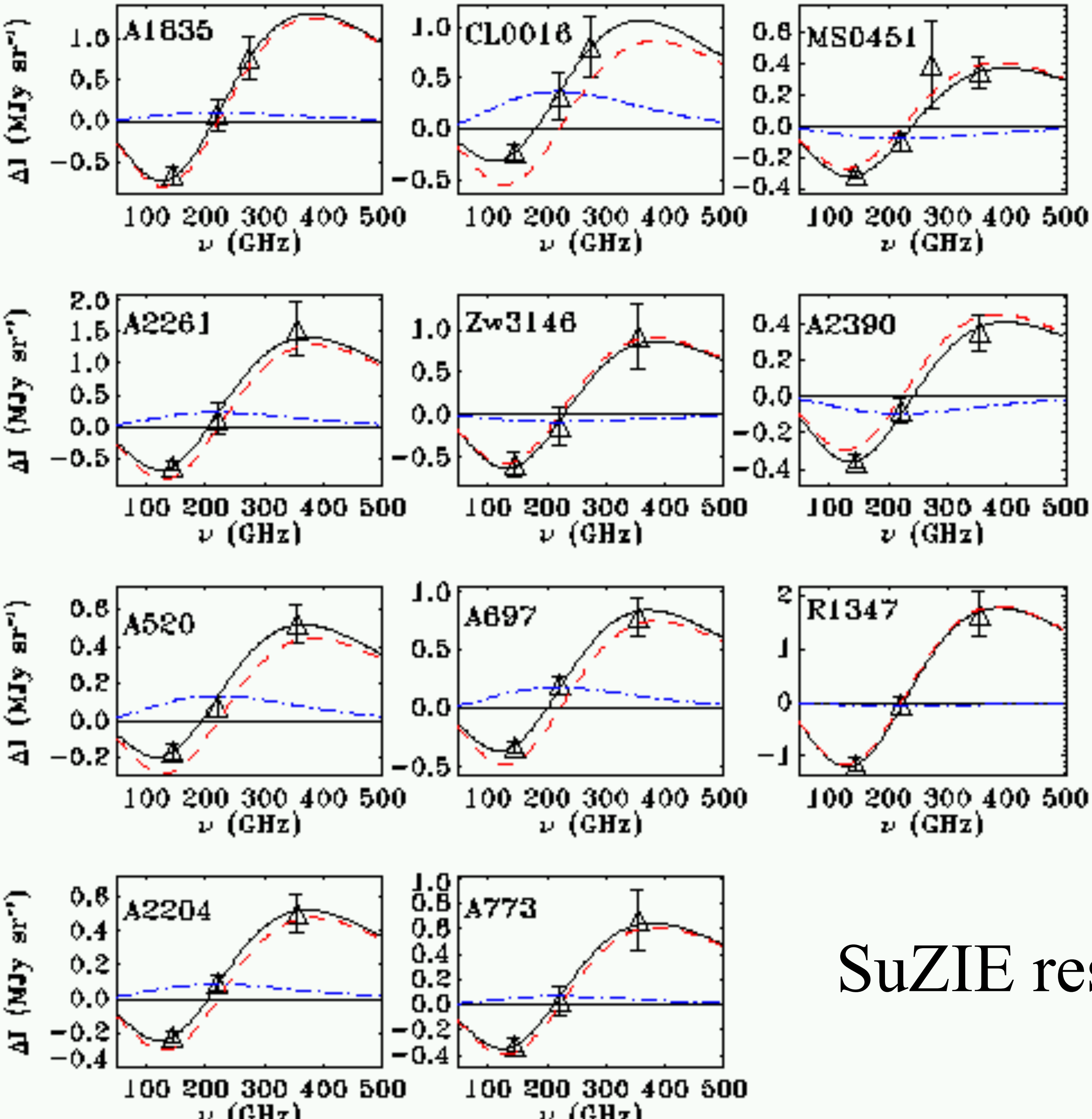

Wavelength (mm)
10
5
2
1
0.5
Intensity (MJy sr^{-1})
500
200
100
50
20
10
20
50
100
200
500
Frequency (GHz)
0.0005B$_\nu$(T$_{CMB}$)
ΔI (MJy sr^{-1})
0.2
0.1
0
−0.1
Kinetic SZE
Thermal SZE
0
100
200
300
400
500
Frequency (GHz)
ΔT$_{RJ}$ (mK)
0
−0.2
−0.4
−0.6
Kinetic SZE
Thermal SZE
0
100
200
300
400
500
Frequency (GHz)



Wavelength (mm)
10
1
I (MJy sr^{-1})
100
10
0.6
0.4
0.2
0.0
−0.2
−0.4
ΔI (MJy sr^{-1})
100
Frequency (GHz)

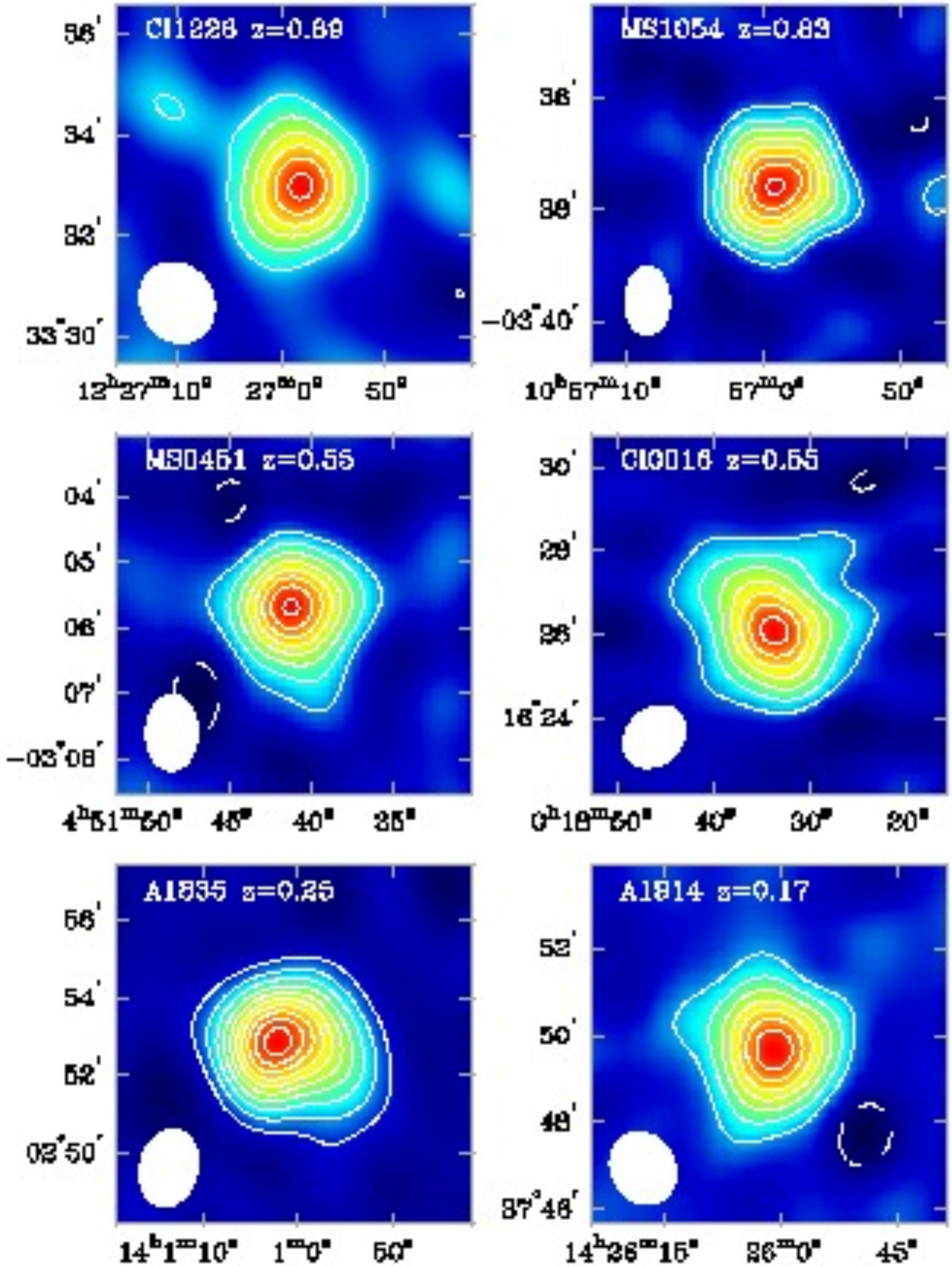


0.10
0.05
0.00
−0.05
ΔI/(τI$_0$)
3.25 K
2.75 K
2.25 K
0.20
0.15
0.10
0.05
0.00
−0.05
−0.10
15 keV
10 keV
5 keV
0.10
0.05
0.00
−0.05
−0.10
−2000 km/s
0 km/s
+2000 km/s
200
400
600
800
Frequency/GHz



SuZIE results

Carlstrom et al 2004



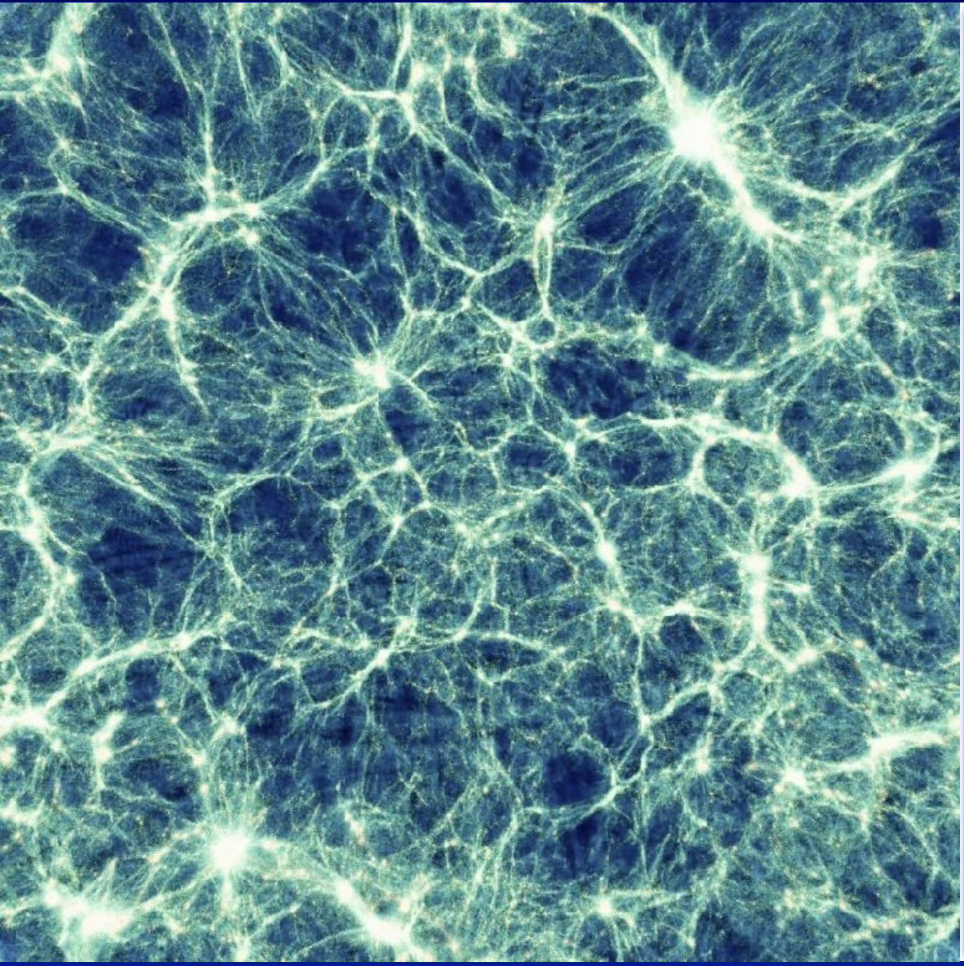
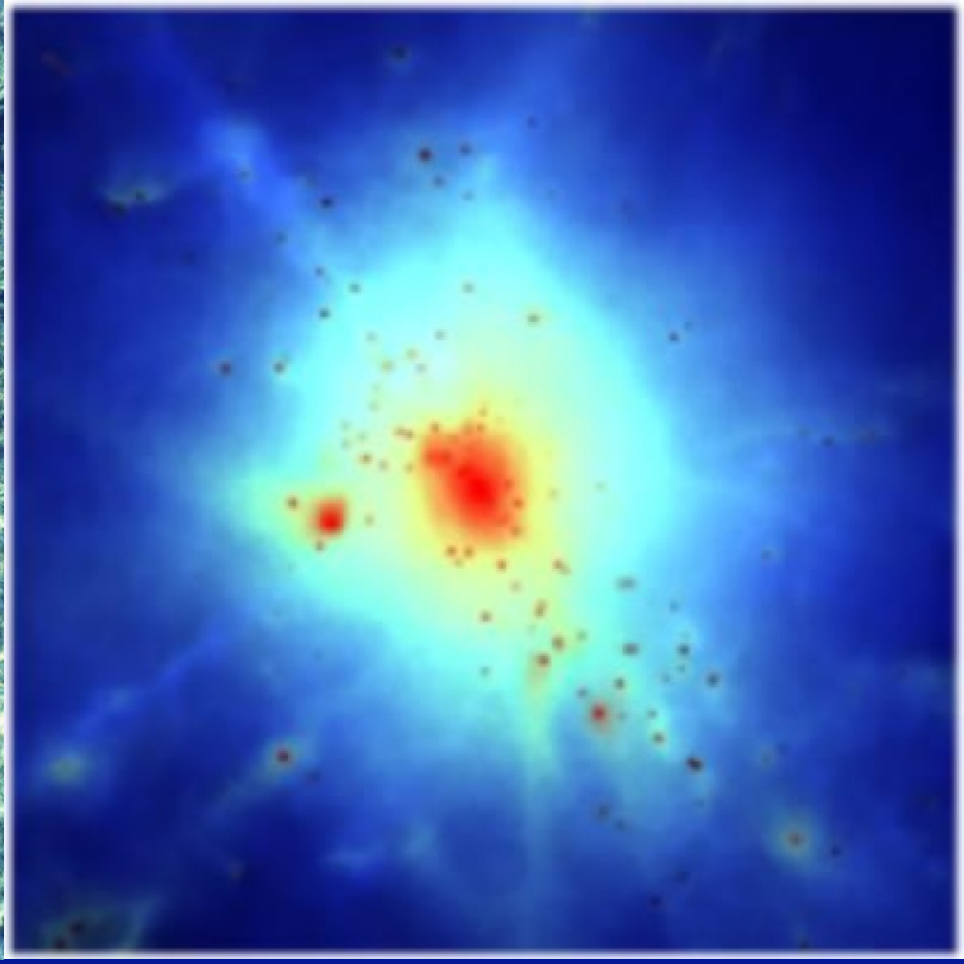
Clusters of galaxies

9.5 Simulations

- A fundamental tool to try to understand

  the abundance and evolution of the cluster population

  the physical processes that take part in clusters of galaxies
- N-body simulations (cluster evolution)
- Hydrodynamic simulations (gas physics, scaling relation)
- Problem: dynamical range



Clusters of galaxies

9.6 Cosmology with clusters

- **Cluster Mass: cosmological “observable”**
- **Cluster Observables:**
  - Richness: N_g
  - Velocity dispersion: z,σ
  - X-rays: S_x α ρ^2 $T^{1/2}$, Tx
  - Lensing: ε,m => g, μ
  - Sunyaev-Zeldovich: ΔT α ρT

Clusters of galaxies

9.6 Cosmology with clusters

- Clustering: clusters are highly biased tracers of the underlying mass distribution

  power spectrum, correlation functions

- Abundances: count how many clusters are above a certain mass threshold imposed by your observable

  mass function

- Baryon fraction: clusters are fair samples of the overall mass composition of the universe

  $f_B = \Omega_B/\Omega_M \quad \Rightarrow \Omega_M = \Omega_B/f_B$

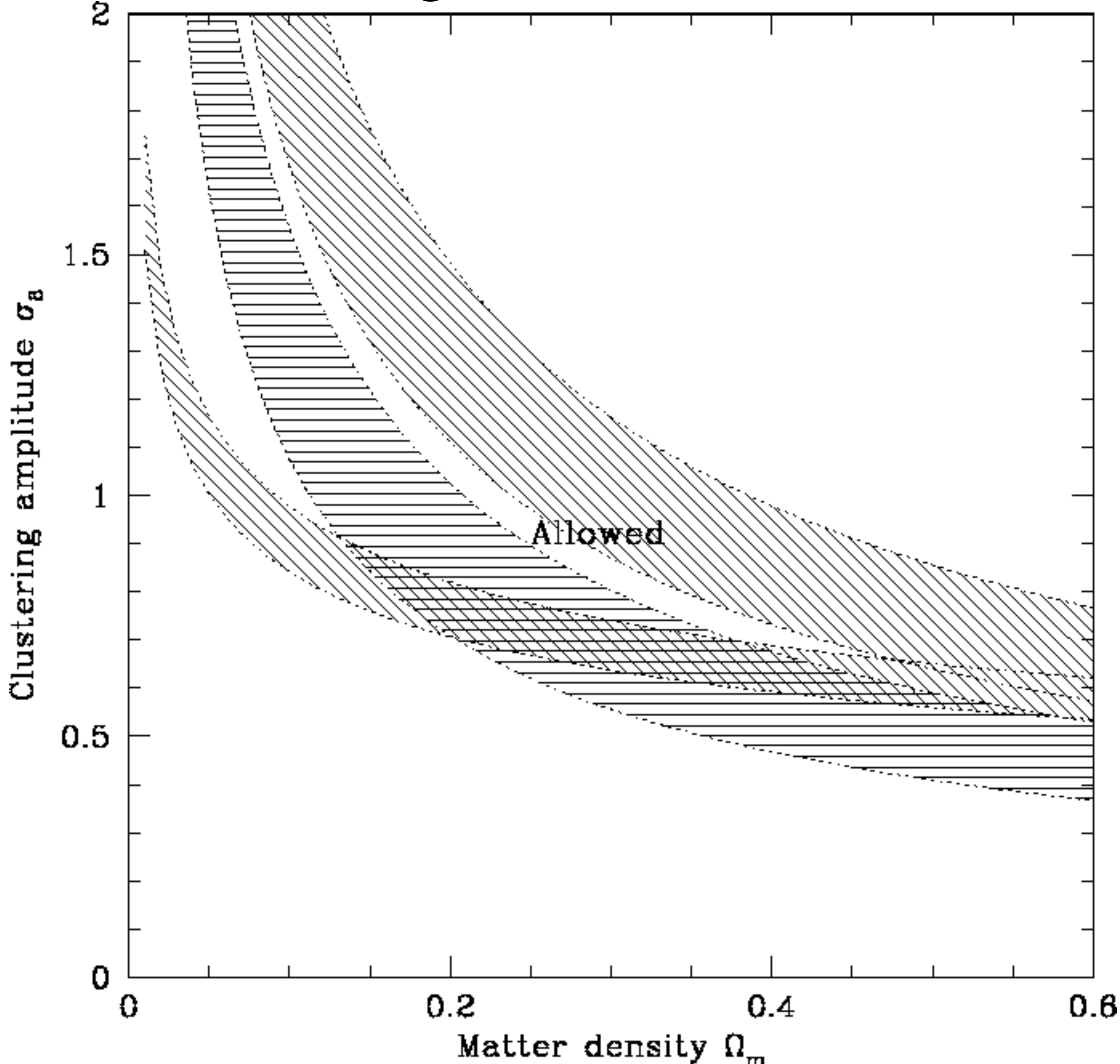
Clusters of galaxies

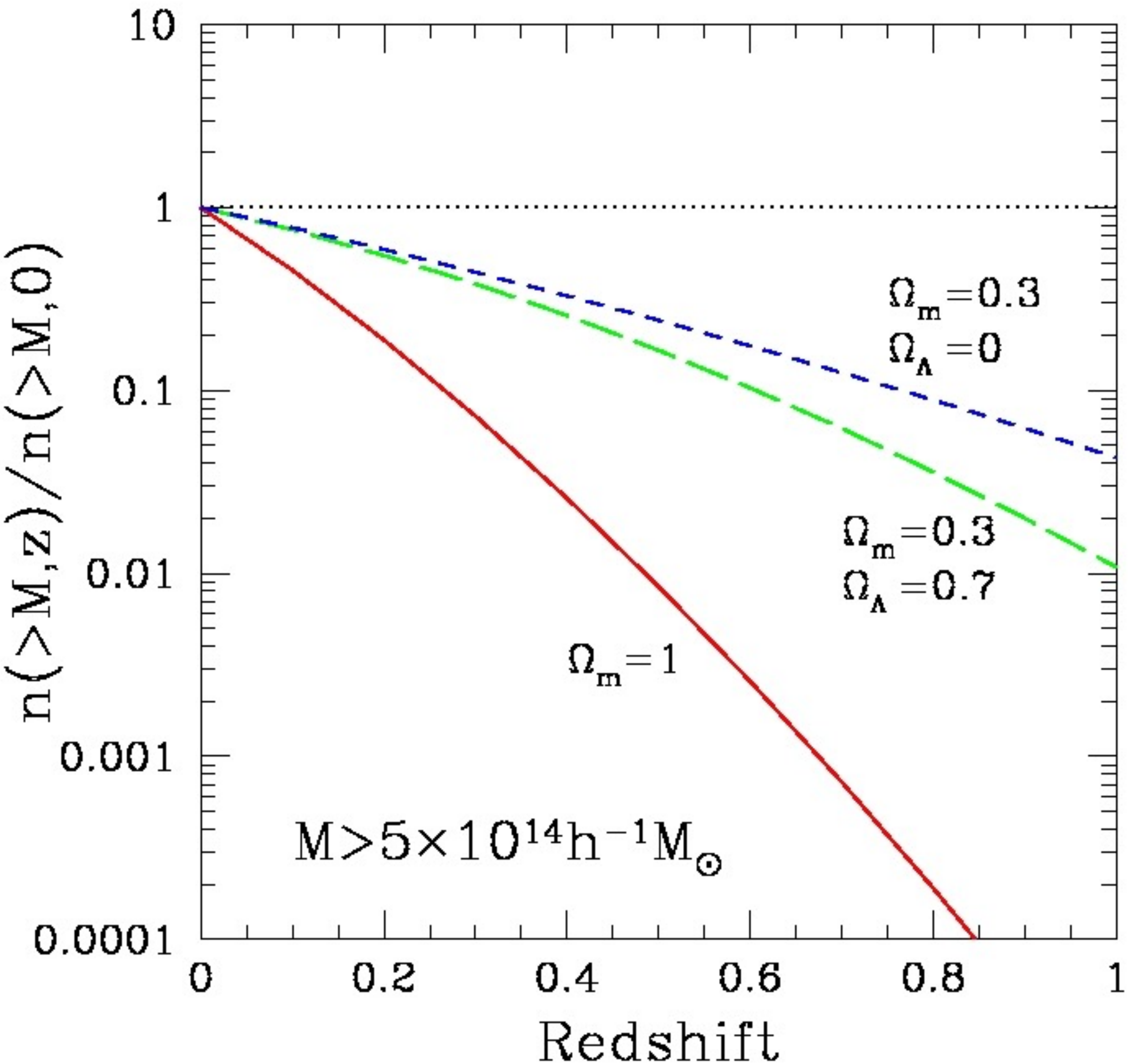
9.6 Cosmology with clusters: Abundance and evolution

- The cluster abundance at a given epoch is a function of Ω_m and σ_8
- The evolution of the cluster abundance depends on Ω_m
- Theoretically, one can predict the mass function
- X-rays studies more widely used due to its nicer selection function
- Observationally in X-rays, one find clusters due to their surface brightness and measures their Lx

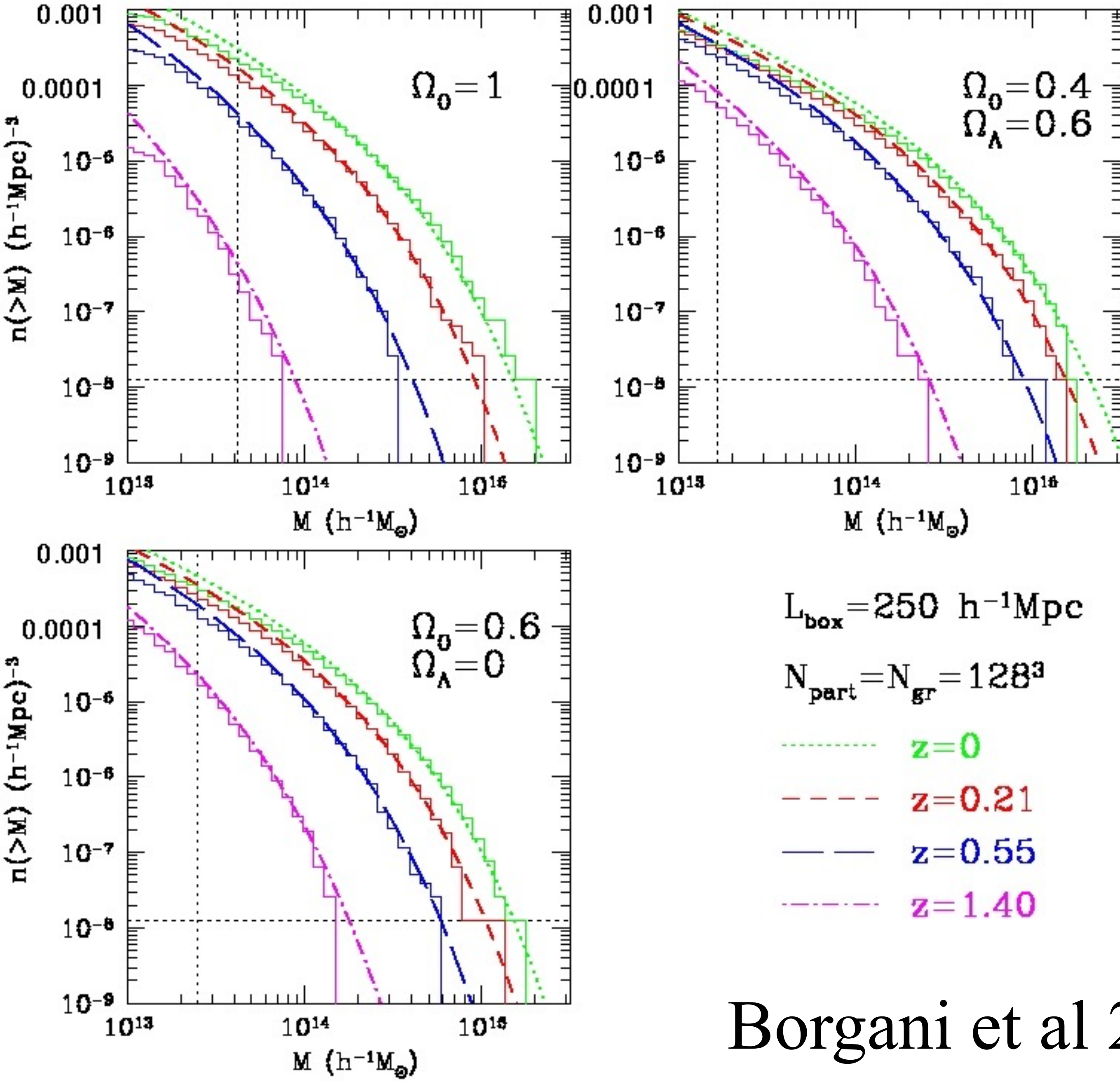
$$\frac{d^2N}{dz\,d\Omega}(z) = \frac{d^2V}{dz\,d\Omega}(z)\,n_{com}(z) = \frac{c}{H(z)} D_A^2 (1+z)^2 \int_0^\infty dM\, f(M,z) \frac{dn}{dM}(z)$$

Tegmark et al 2003

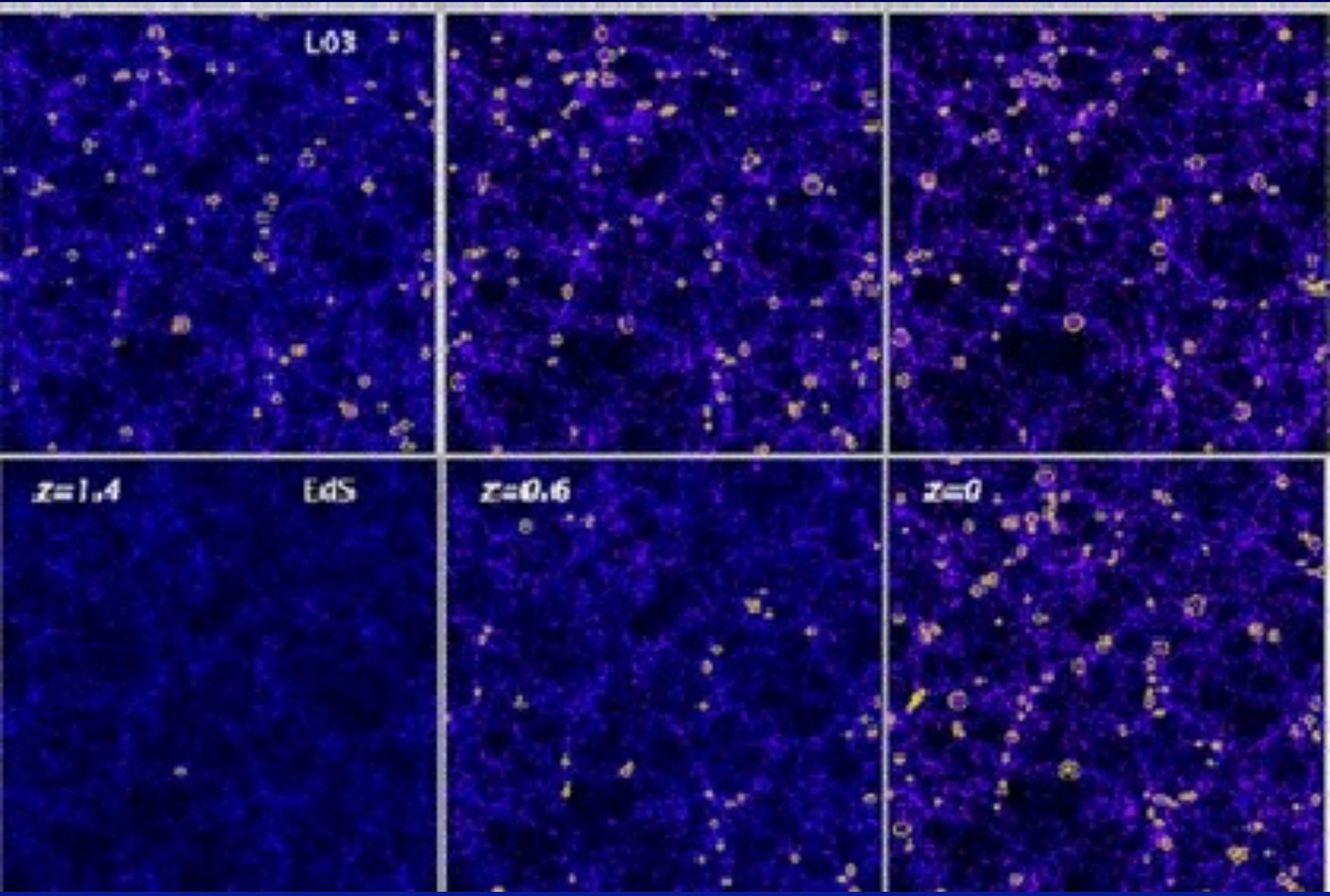




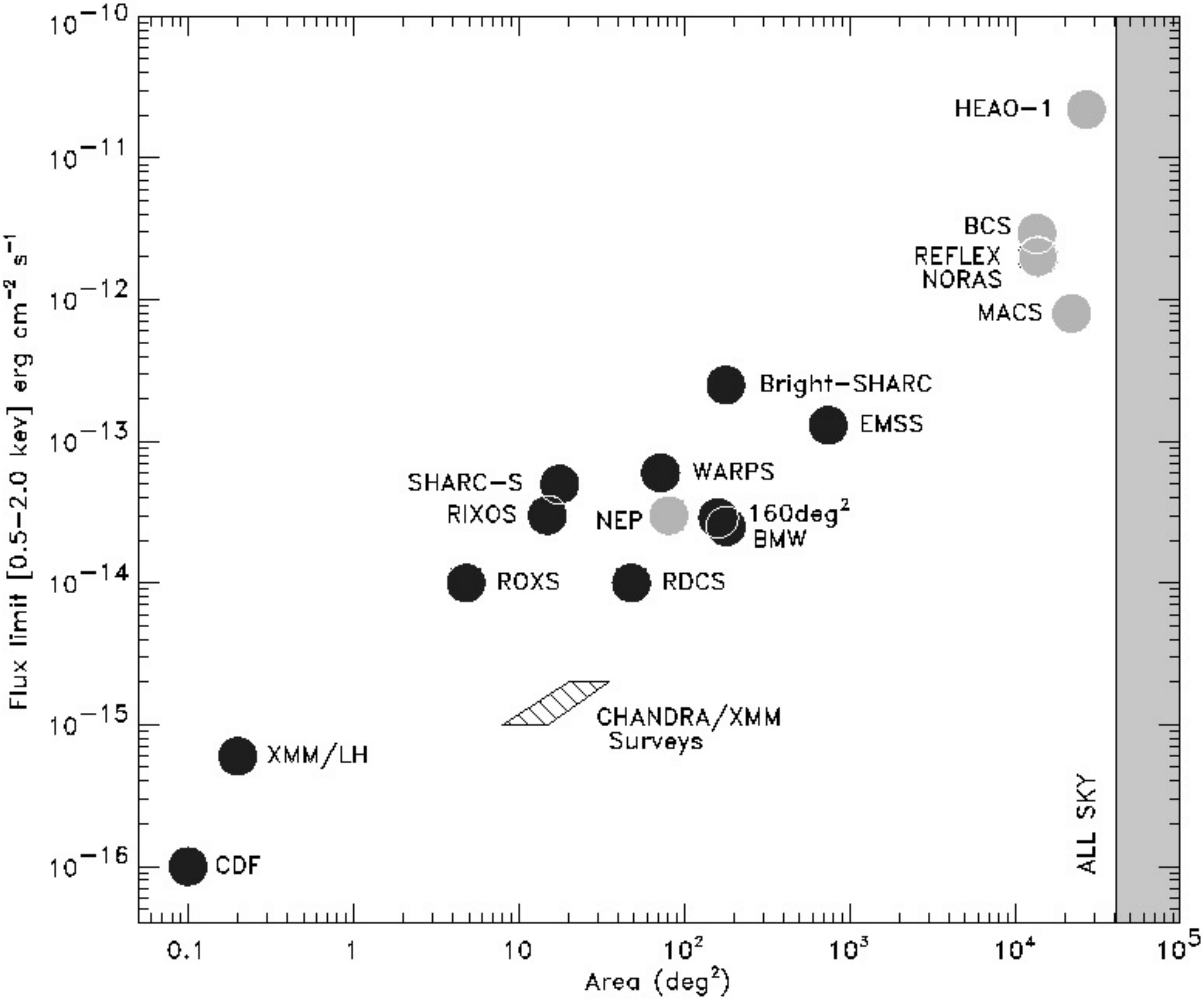
10
1
0.1
0.01
0.001
0.0001
0
0.2
0.4
0.6
0.8
1
n(>M,z)/n(>M,0)
Redshift
$\Omega_m=0.3$
$\Omega_\Lambda=0$
$\Omega_m=0.3$
$\Omega_\Lambda=0.7$
$\Omega_m=1$
$M>5\times10^{14}h^{-1}M_\odot$



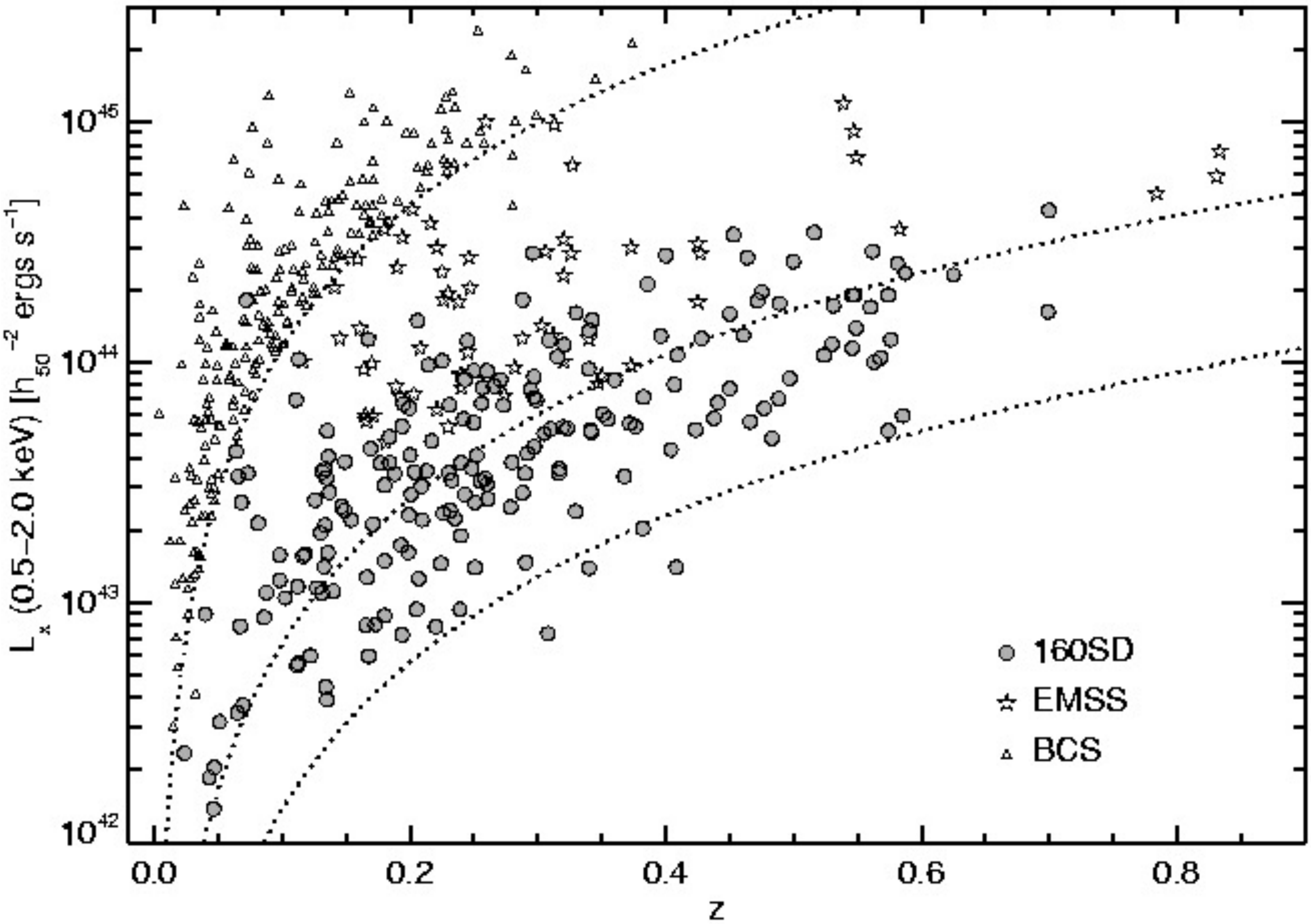
Borgani et al 2001



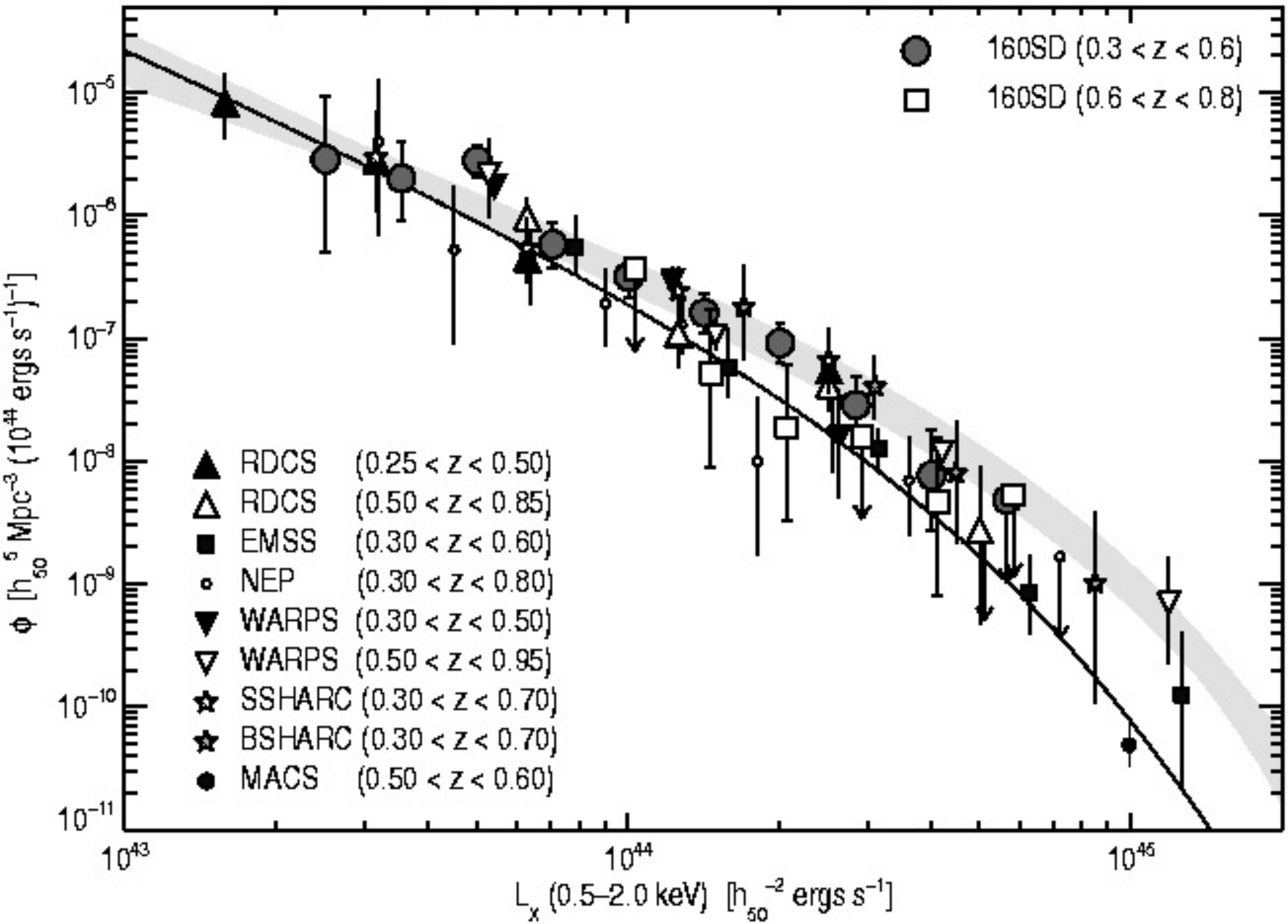
L03
z=1.4
EdS
z=0.6
z=0



HEAO-1
BCS
REFLEX
NORAS
MACS
Bright-SHARC
EMSS
WARPS
SHARC-S
RIXOS
NEP
$160 deg^2$
BMW
ROXS
RDCS
CHANDRA/XMM
Surveys
XMM/LH
CDF
ALL SKY
Flux limit [0.5-2.0 kev] erg cm^{-2} s^{-1}
Area (deg^2)
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
0.1
1
10
10^2
10^3
10^4
10^5

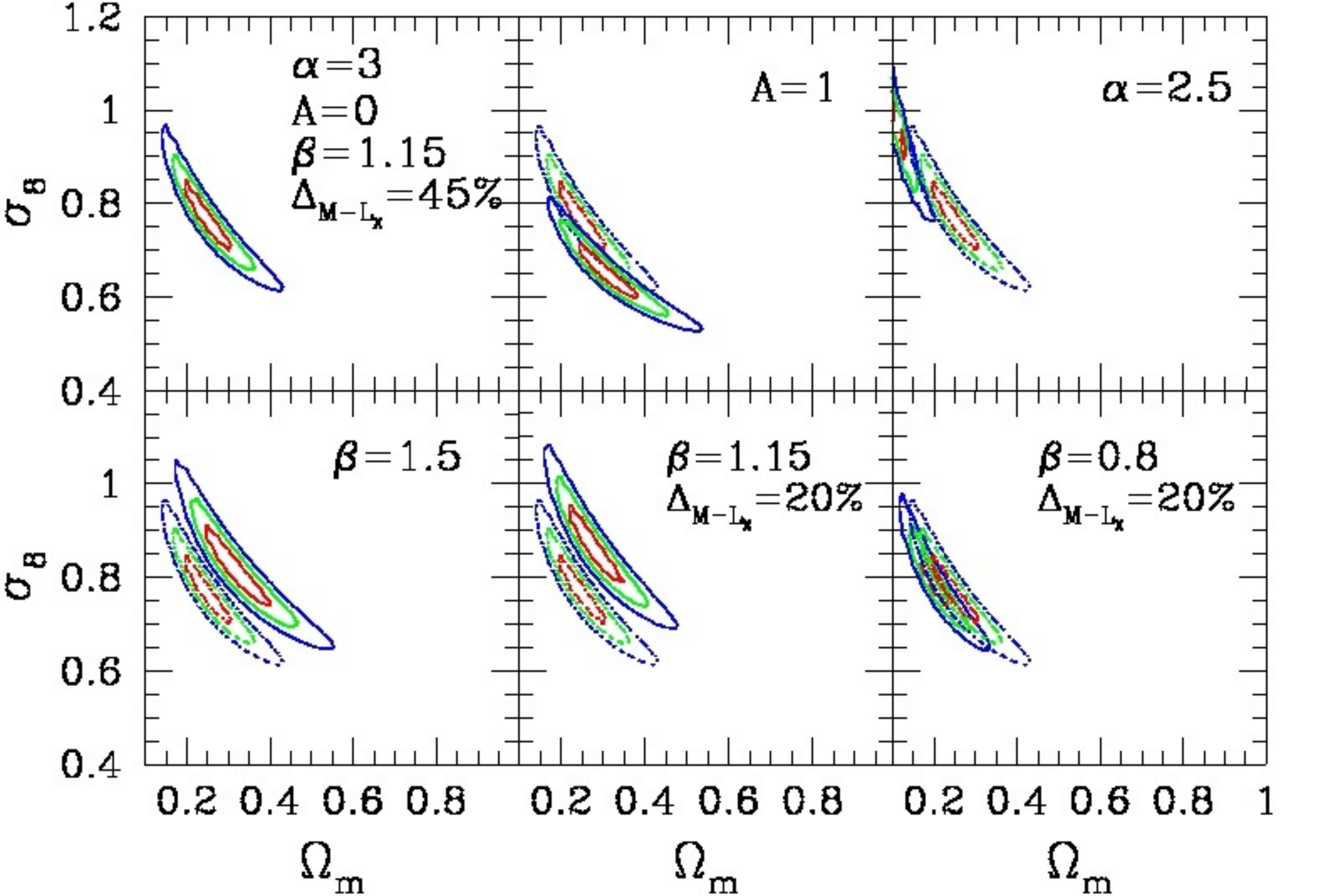


L_x (0.5–2.0 keV) [h_{50}^{-2} ergs s^{-1}]
10^{42}
10^{43}
10^{44}
10^{45}
0.0
0.2
0.4
0.6
0.8
z
160SD
EMSS
BCS



160SD (0.3 < z < 0.6)
160SD (0.6 < z < 0.8)
RDCS (0.25 < z < 0.50)
RDCS (0.50 < z < 0.85)
EMSS (0.30 < z < 0.60)
NEP (0.30 < z < 0.80)
WARPS (0.30 < z < 0.50)
WARPS (0.50 < z < 0.95)
SSHARC (0.30 < z < 0.70)
BSHARC (0.30 < z < 0.70)
MACS (0.50 < z < 0.60)
ϕ [h_{50}^{5} Mpc^{-3} (10^{44} ergs s^{-1})$^{-1}$]
L_X (0.5–2.0 keV) [h_{50}^{-2} ergs s^{-1}]
10^{43}
10^{44}
10^{45}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}

Borgani et al 2001



9 Clusters of galaxies

9.6 Cosmology with clusters: baryon fraction

- Baryon fraction: clusters are fair samples of the overall mass composition of the universe

$f_B = \Omega_B/\Omega_M \quad \Rightarrow \Omega_M = \Omega_B/f_B$

Clusters of galaxies

9.7 Ingredients of cluster physics

Hydrostatic Equilibrium

$$\frac{1}{\rho_{gas}} \nabla P_{gas} = -\nabla \Phi$$

Poisson's Equation

$$\nabla^2 \Phi = 4\pi G \rho_{grav}$$

Equation of State

$$P_{gas} = \frac{\rho_{gas} k T_e}{\mu m_p}$$

$$\rho_{grav} = -\frac{1}{4\pi G} \nabla \left(\frac{1}{\rho_{gas}} \nabla P_{gas} \right)$$

Isothermal

$$\rho_{grav} = -\frac{k T_e}{4\pi G \mu m_p} \nabla^2 \ln \rho_{gas}$$

Hydrostatic Equilibrium

$$\frac{1}{\rho_{gas}} \nabla P_{gas} = -\nabla \Phi$$

Spherical Symmetry

$$\frac{1}{\rho_{gas}} \frac{\mathrm{dP}}{\mathrm{dr}} = -\frac{\mathrm{d}\Phi}{\mathrm{dr}} = -\frac{G M(r)}{r^2}$$

Isothermal

$$\frac{k T_e}{\mu m_p} \frac{\mathrm{d} \ln \rho_{\mathrm{gas}}}{\mathrm{dr}} = -\frac{\mathrm{d}\Phi}{\mathrm{dr}}$$

Clusters of galaxies

9.7 Cluster Physics ingredients: Profiles

NFW Profile

$$\rho(r) = \frac{\delta_c \rho_c}{\frac{r}{r_s}\left(1 + \frac{r}{r_s}\right)^2}$$

$$M(r) = 4\pi\delta_c\rho_c r_s^2 \left[ln\left(1 + \frac{r}{r_s}\right) - \frac{r}{r + r_s}\right]$$

$$\phi(r) = -4\pi G\delta_c\rho_c r_s^2 \left[\frac{ln\left(1 + \frac{r}{r_s}\right)}{\frac{r}{r_s}}\right] \longrightarrow \phi(x)$$

$$\frac{kT_e}{\mu m_p}\frac{\mathrm{d}\ln\rho_{\mathrm{gas}}}{\mathrm{dr}} = -\frac{\mathrm{d}\Phi}{\mathrm{dr}} = -\frac{GM(r)}{r^2}$$

$$\rho_{gas} = \rho_{gas\,o}\mathrm{e}^{-b}\left(1 + \frac{r}{r_s}\right)^{\frac{b}{r/r_s}}$$

(Makino et al 98)

Clusters of galaxies

9.7 Cluster Physics ingredients: profiles

Beta Model

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

$$S_X(x) = S_{X0} \left(1 + \left(\frac{x}{x_c}\right)^2\right)^{-3\beta+\frac{1}{2}}$$

$$\Delta T(x) = \Delta T_0 \left(1 + \left(\frac{x}{x_c}\right)^2\right)^{-\frac{3}{2}\beta+\frac{1}{2}}$$

$$\frac{1}{\rho_{gas}} \nabla P_{gas} = -\nabla\Phi \longrightarrow \frac{kT_e}{\mu m_p}\frac{\mathrm{d}\ln\rho_{\mathrm{gas}}}{\mathrm{dr}} = -\frac{\mathrm{d}\Phi}{\mathrm{dr}} = -\frac{GM(r)}{r^2}$$

$$M(<r) = \frac{kT_e}{\mu m_p}\frac{3\beta}{G} r \frac{\left(\frac{r}{r_c}\right)^2}{1 + \left(\frac{r}{r_c}\right)^2}$$

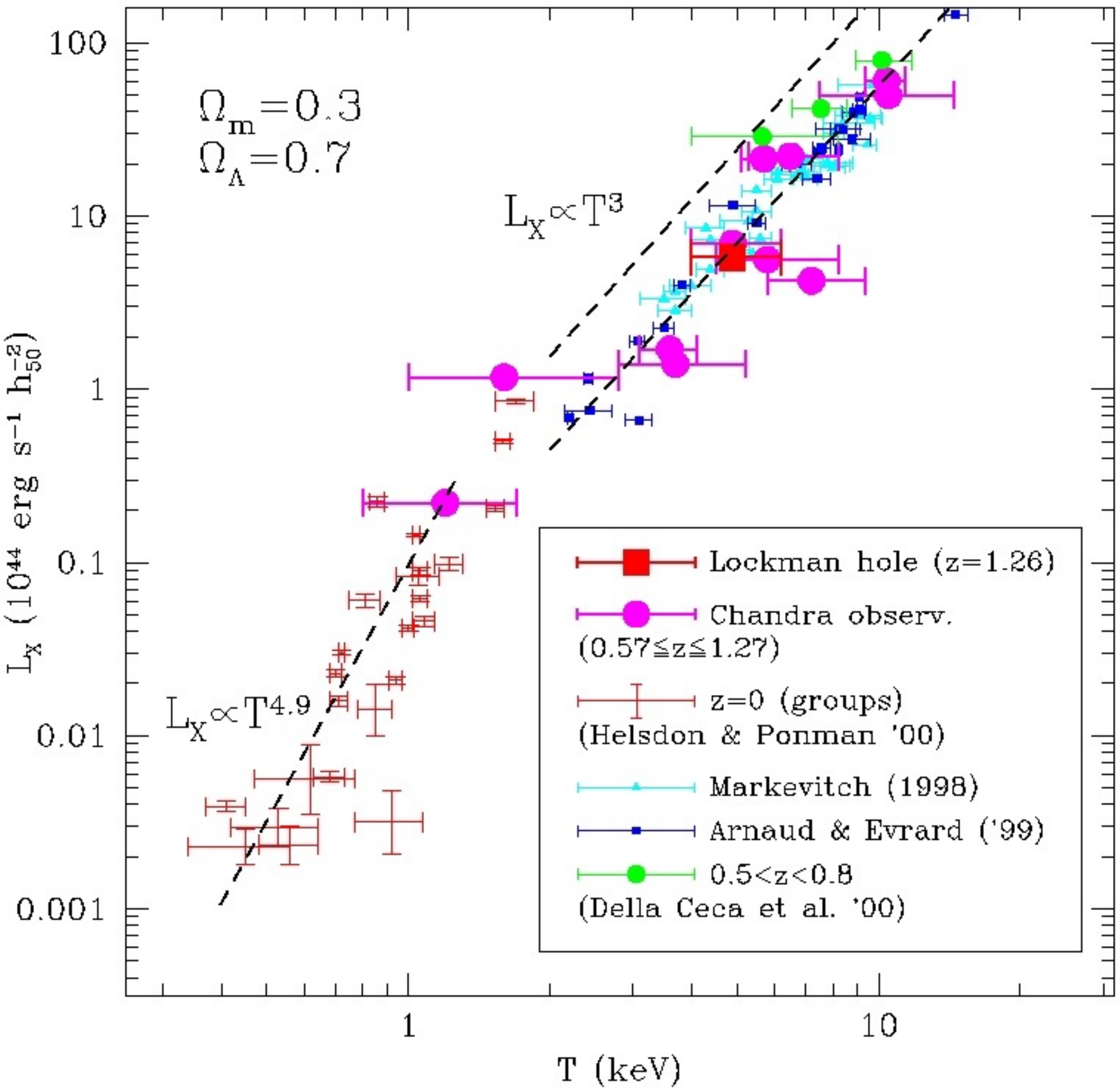
$$\phi(r) = \frac{3}{2}\frac{\beta kT_e}{\mu m_p}\left[ln\left(1 + \left(\frac{r}{r_c}\right)^2\right) - ln\left(1 + \left(\frac{r_{cut}}{r_c}\right)^2\right)\right] \longrightarrow \phi(x)$$

Clusters of galaxies

9.8 Cluster scaling relations

- If cluster gas properties determined only by gravitational collapse then clusters should be scaled versions of each other:
  - $L_x \propto M \rho_{gas} T_x^{1/2}$
  - $L_x \propto T_x^2 (1+z)^{3/2}$
  - $L_x \propto M^{4/3} (1+z)^{7/2}$
  - $S \propto T_x (1+z)^{-2}$
- Observationally these relations do not hold
  - $L_x \propto T_x^3$

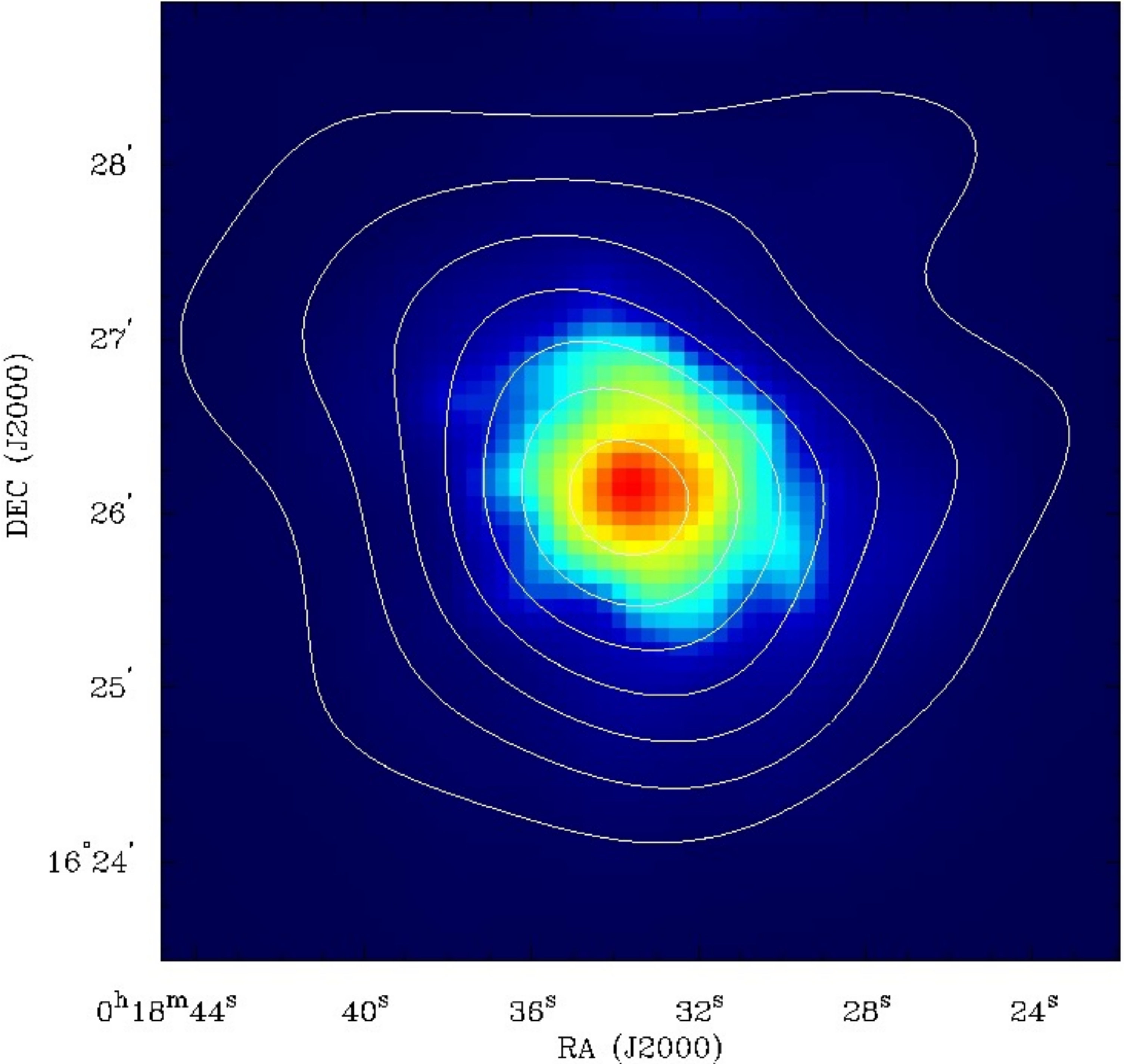
Cluster Scaling Relations



Clusters of galaxies

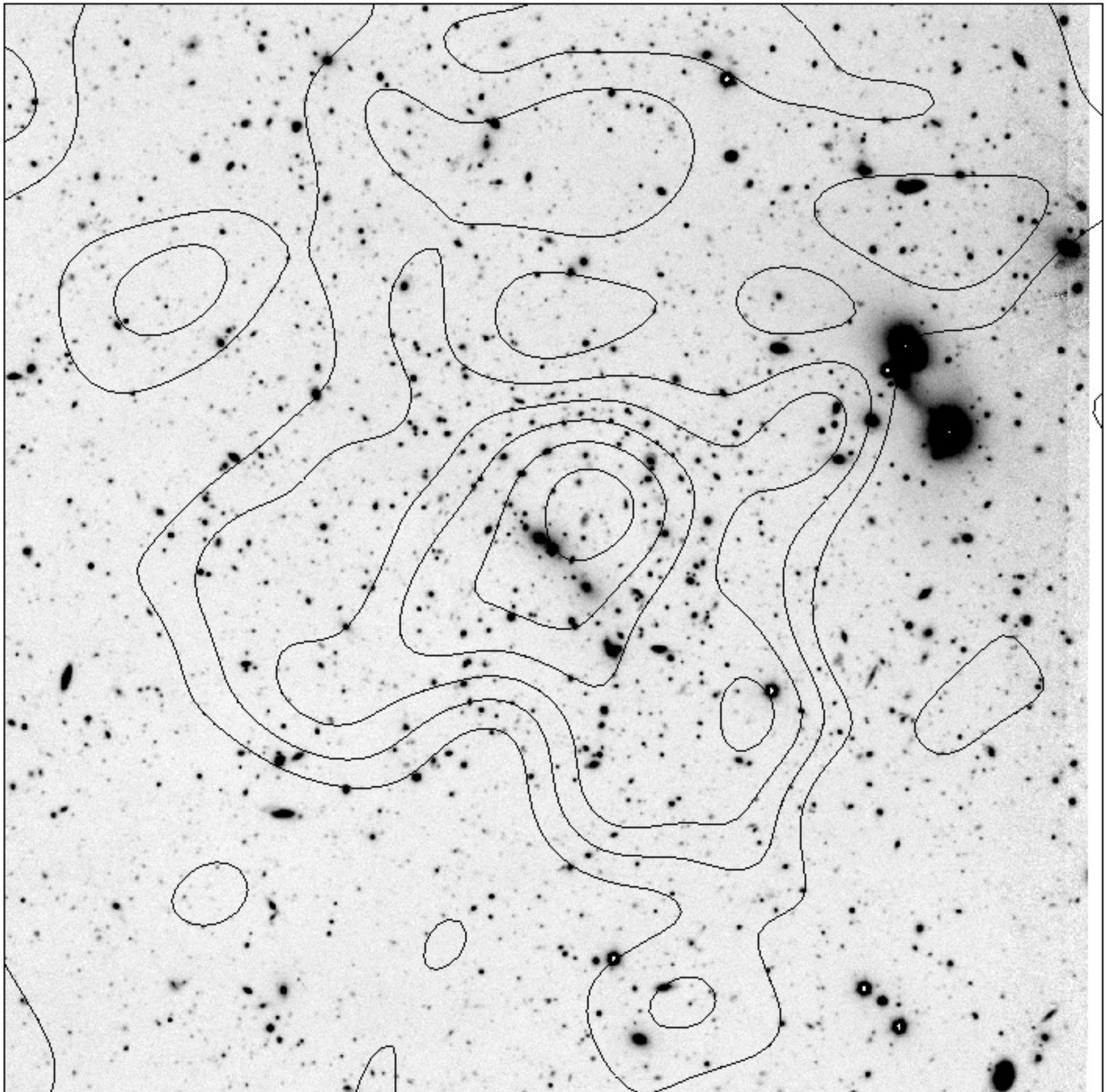
9.9 Multi-wavelength studies

- Obtain as much information as possible in order to understand cluster behaviour (gastrophysics). Such deeper understanding is necessary to use them as precise cosmological tools
- X-ray: gas, potential
- Optical: galaxies, potential
- Radio: gas, potential



28′
27′
26′
25′
16°24′
DEC (J2000)
0h18m44s
40s
36s
32s
28s
24s
RA (J2000)

MS0016+16



Clusters of galaxies

9.9 Multi-wavelength studies

We observe:

- Lensing: e_i (X_i, Y_i)
- X-rays: S_x (X,Y), T_x (X,Y)
- SZ: ΔT (X,Y), I (u,v)

What we want:

- 3-D Physical Quantities: M (x,y,z), T_x (r, θ, φ), ρ (x,y,z),...

Clusters of galaxies

9.9 Multi-wavelength studies

Lensing

- Observable: $\epsilon_i, m_i, a_i \rightarrow g_i, \mu_i \rightarrow \psi, M$

$$g_i = < \epsilon >$$

$$g_i = \frac{\gamma_i}{1-\kappa} \quad \begin{cases} \kappa = \frac{1}{2}\left[\psi_{,11}(\theta) + \psi_{,22}(\theta)\right] \\ \gamma_1 = \frac{1}{2}\left[\psi_{,11}(\theta) - \psi_{,22}(\theta)\right] \\ \gamma_2 = \psi_{,12}(\theta) \end{cases}$$

Clusters of galaxies

9.9 Multi-wavelength studies

X-rays

- Observable: $S_X \propto n_e^2 \Lambda \propto \rho_g^2 T^{\frac{1}{2}} \rightarrow \rho_g \rightarrow \phi$

Beta model: $$S_X = S_{X0} \left(1 + \left(\frac{r}{r_c}\right)^2\right)^{-3\beta+\frac{1}{2}}$$

Clusters of galaxies

9.9 Multi-wavelength studies

Sunyaev-Zeldovich

- Observable: Interferometry: u, v, I_{uv}

  Finite size aperture: I_{uv} α FT(I_{sky}) * FT(beam)

  Low systematics

- Observable: Bolometers: ΔT/T

  ΔT/T α ρT

Clusters of galaxies

9.9 Multi-wavelength studies

Application

- Obtaining the Hubble constant combining X-ray and SZ data

  - X-rays: $S_X \propto D_A n_e^2 T^{1/2}$
  - SZ: $(\Delta T/T) \propto D_A n_e T$

$$D_A \propto (\Delta T/T)^2 / S_X T^{3/2}$$