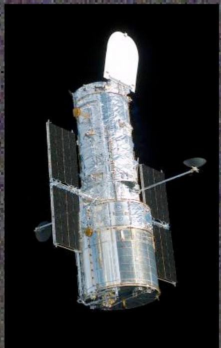
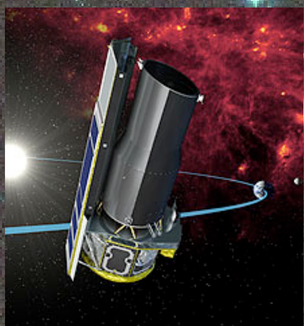


Cold and Hot Baryons in the Most Distant Galaxy Clusters



Piero Rosati (ESO)

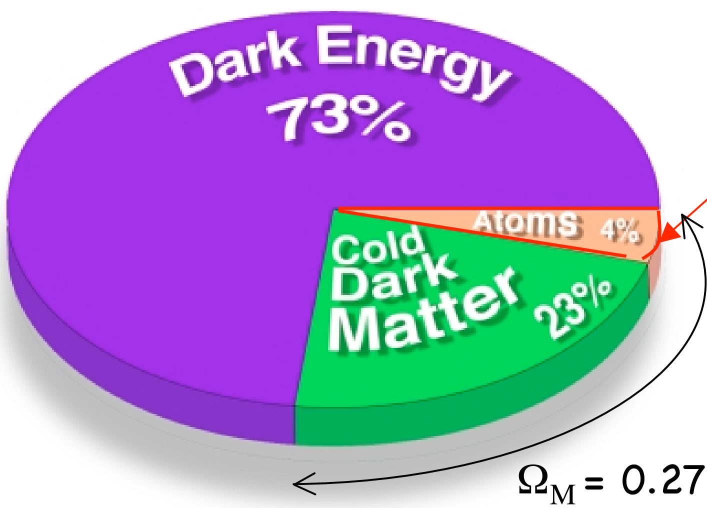
Collaborators

R.Demarco (JHU)
C.Lidman (ESO)
M.Nonino (Trieste)
A.Stanford (LLNL)
P.Eisenhardt (JPL)
V.Mainieri (MPE)
P.Tozzi (Trieste)
S.Ettori (ESO)
S.Borgani (Trieste)

…and The ACS GTO Science Team (H.Ford et al.)

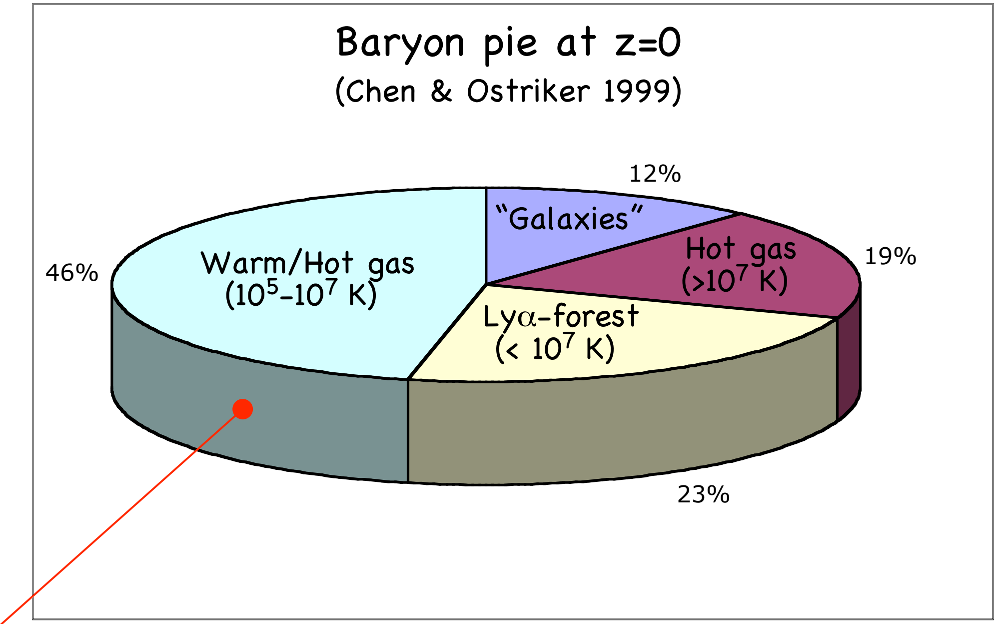
KITP (UCSB) - Nov 8, 04

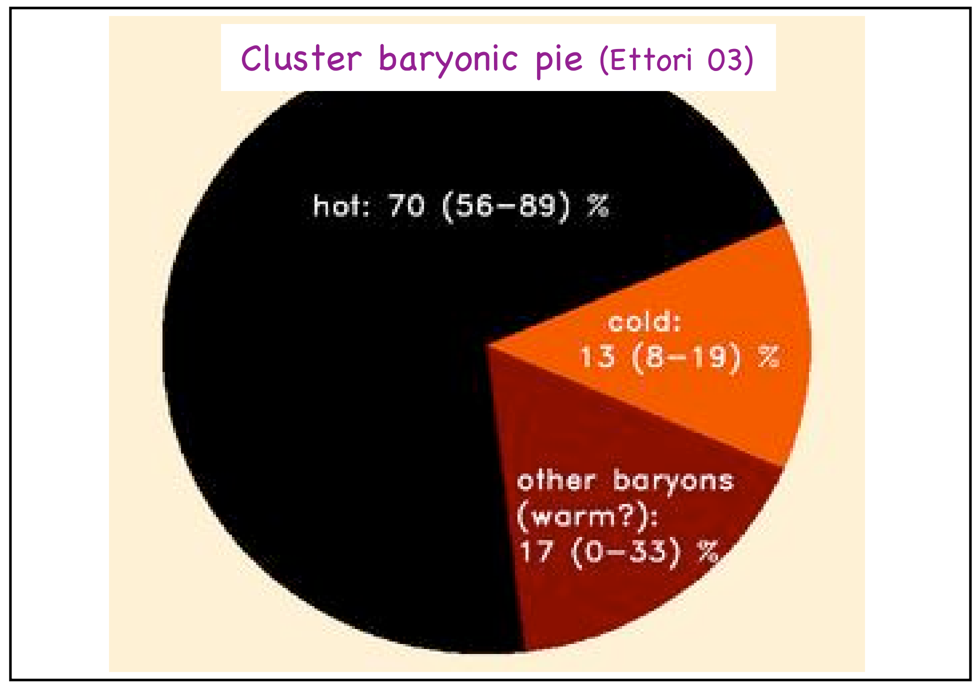
Mass-Energy density budget



$\Omega_M = 0.27$

$\Omega_b/\Omega_M = 0.17$





Towards understanding the formation and evolution of baryonic matter

Some key questions:

a) when and how most of the stellar mass was assembled in cluster galaxies ? is this process different in lower density environments (e.g. the field) ?

b) when did the first clusters form ? i.e. when most of the mass in its dark and baryonic components (gas & gals) were assembled and thermalized in the cluster potential well

c) when and how was the gas pre-heated and polluted with metals ?

Key requirements:

1) probe the largest look-back times (i.e. z>~ 1) in order to approach the formation epoch

2) study the physical properties of both the gas and the galaxy populations ➡ multi-wavelength observations (X-ray + UV→IR)

3) (ideally) measure masses (for both member galaxies and clusters) over a large z range

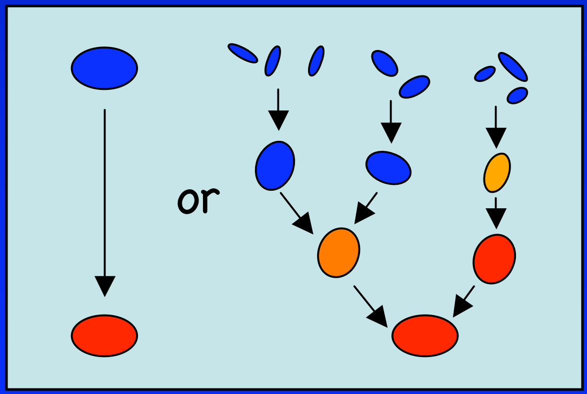
4) model the cold and hot phase of cosmic structure in a self-consistent way…

Most distant clusters ⇒ strongest leverage on models of structure formation

- ICM thermodynamics and metallicity at z~1 probe early feedback mechanisms (energy injection, entropy production) and star formation
- Massive early-type galaxies (highest halo/stellar masses), at large look back times (z>~1) provide the strongest constraints on galaxy evolution models

In hierarchical models stellar mass is built up through mergers and SF ⇒ most massive gals form more recently !

Early types: current competing models…



- Cluster mass function at z>~1 constrains cosmological paramaters

Observational Probes of Cluster Evolution

Galaxies/Stellar Mass Assembly

- Spectrophotometry, line diagnostics
- Red Sequence of Early types: normalization, scatter, slope
- Luminosity Function of cluster galaxies
- M/L (fundamental plane), Stellar Mass Function

⇔ stellar synthesis + semi-analytical models (SAM) + hydro simulations

baryons

Intra-Cluster Medium (ICM)

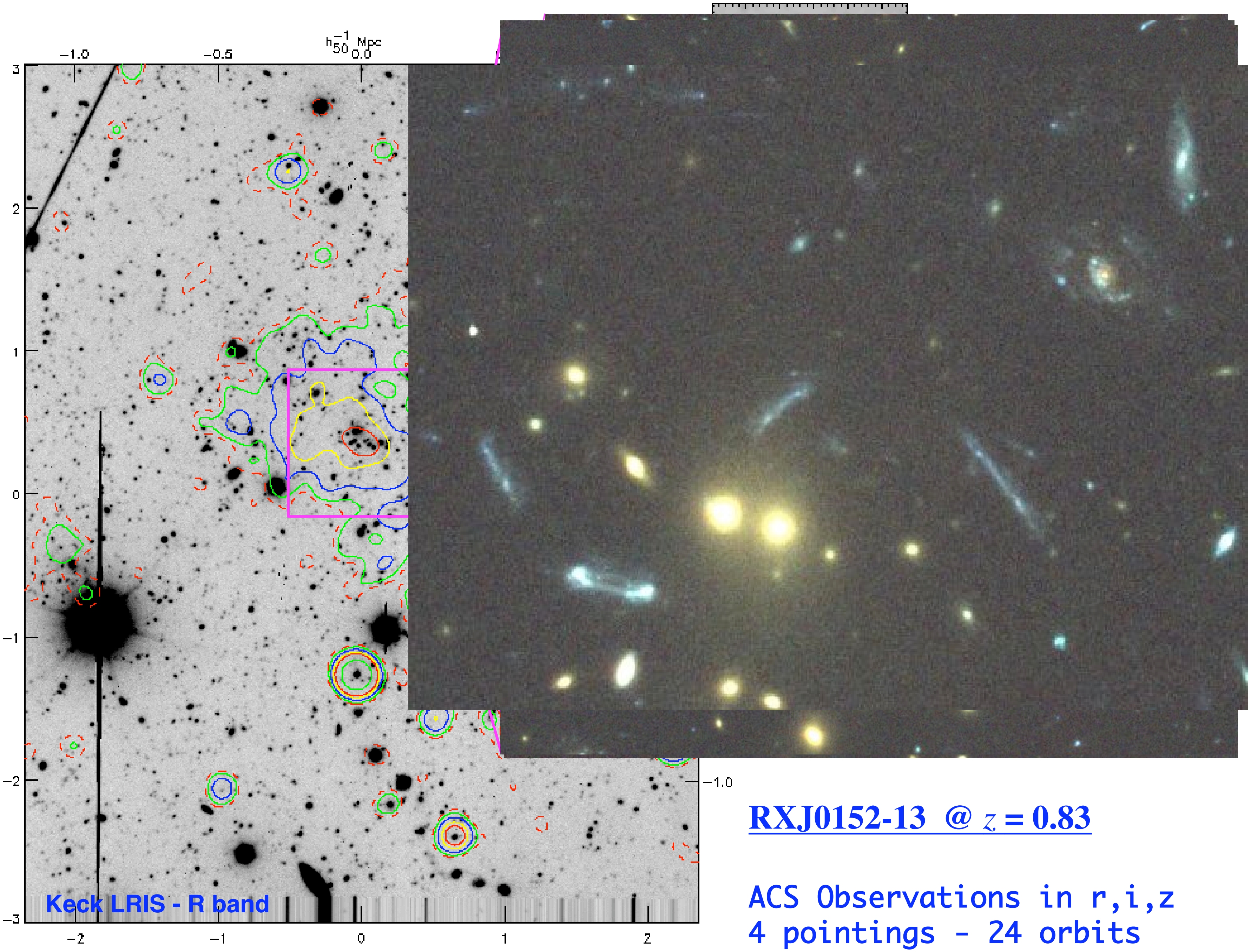
- Cluster Scaling Relations (L_X-T, M-T, Entropy, f_{gas})
- Gas Metallicity

⇔ hydro cosmo simulations + SAMs + chemical evolution

Cluster Mass (DM)

- Mass Function (e.g. from X-ray) ⇔ N-body simulations, Extended PS
- Mass Distribution (inner cores from Lensing) ⇔ CDM simulations

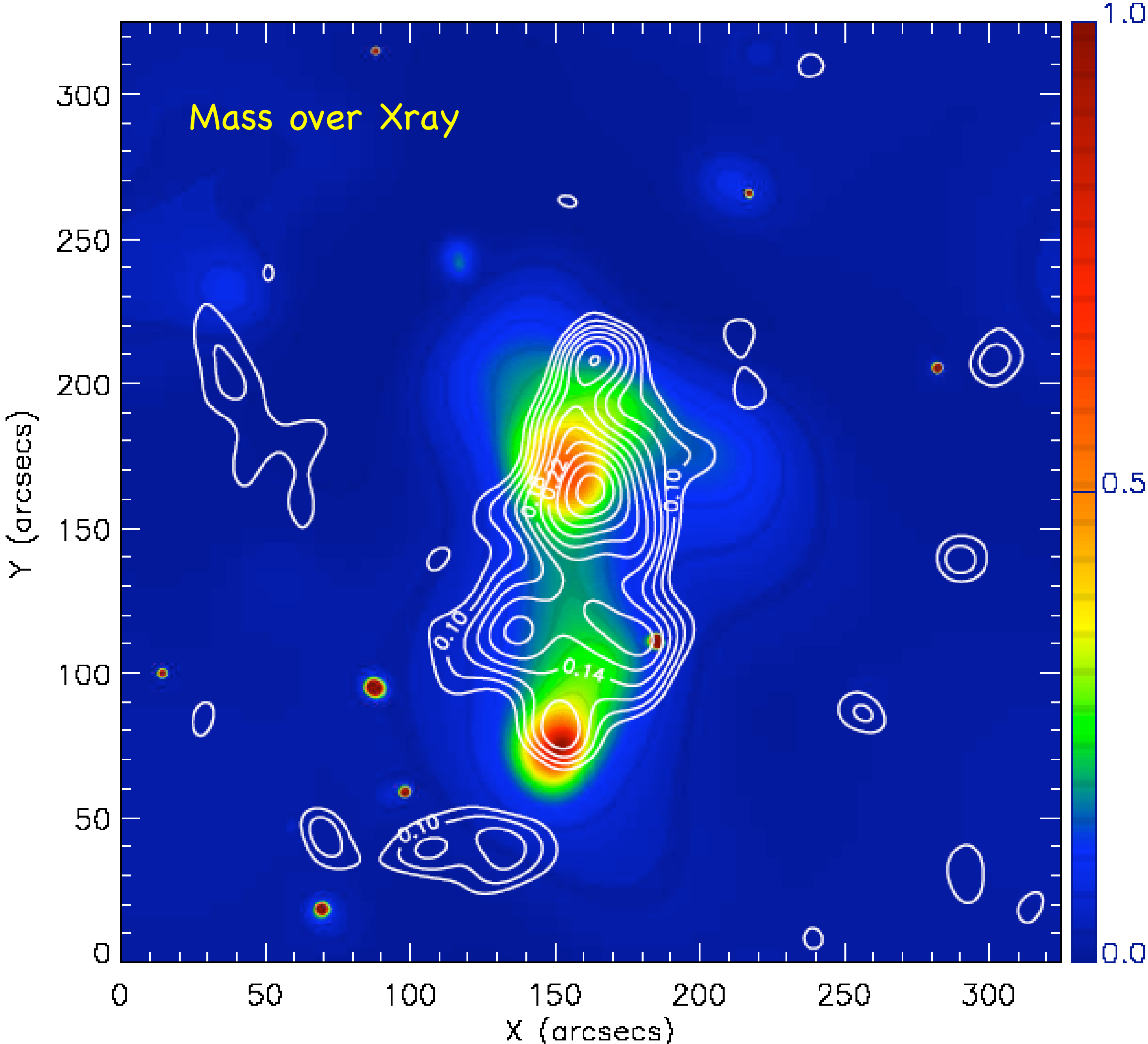
RXJ0152 - z=0.83: distant merging massive cluster



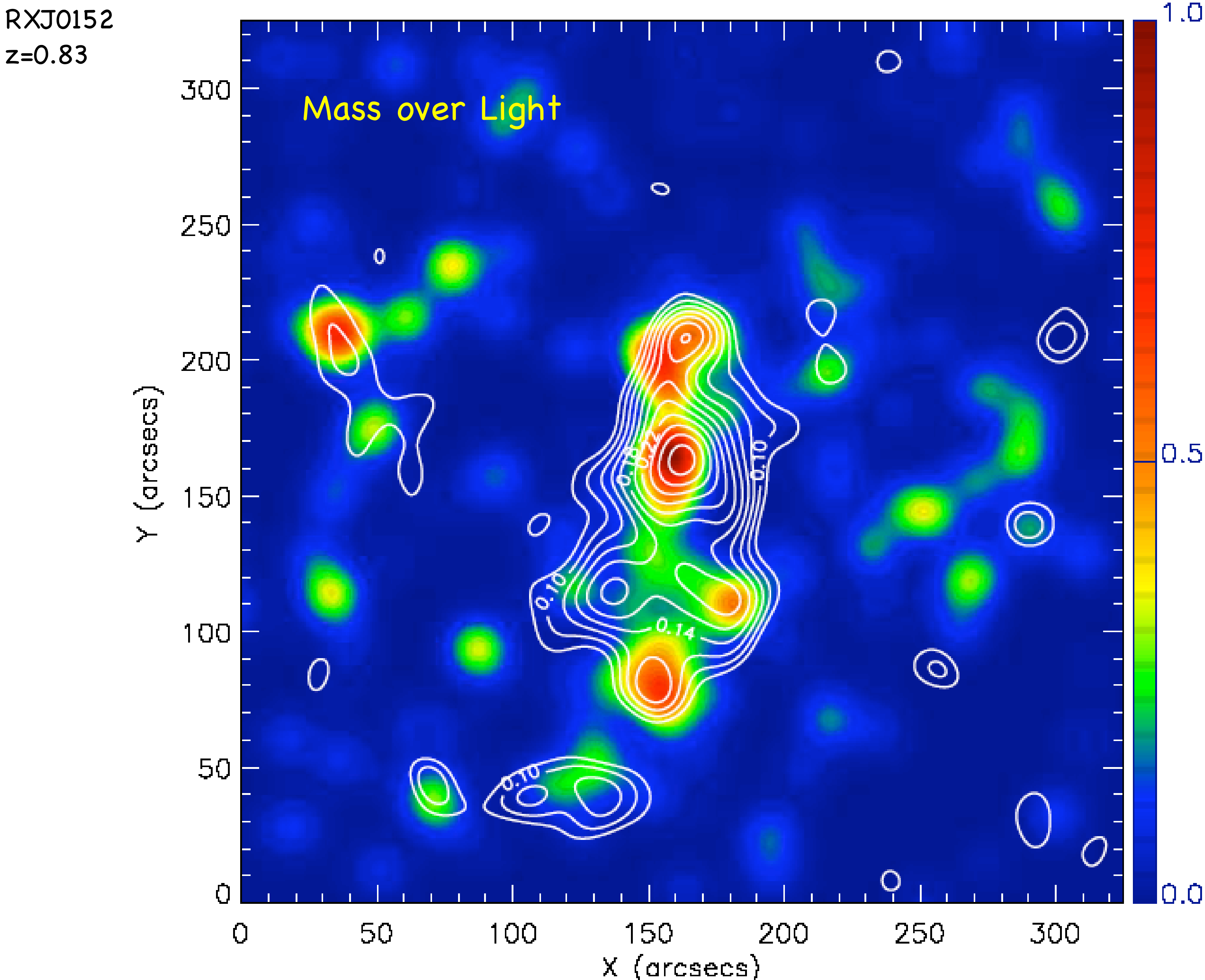
RXJ0152-13 @ $z = 0.83$

ACS Observations in r,i,z
4 pointings - 24 orbits

RXJ0152
z=0.83

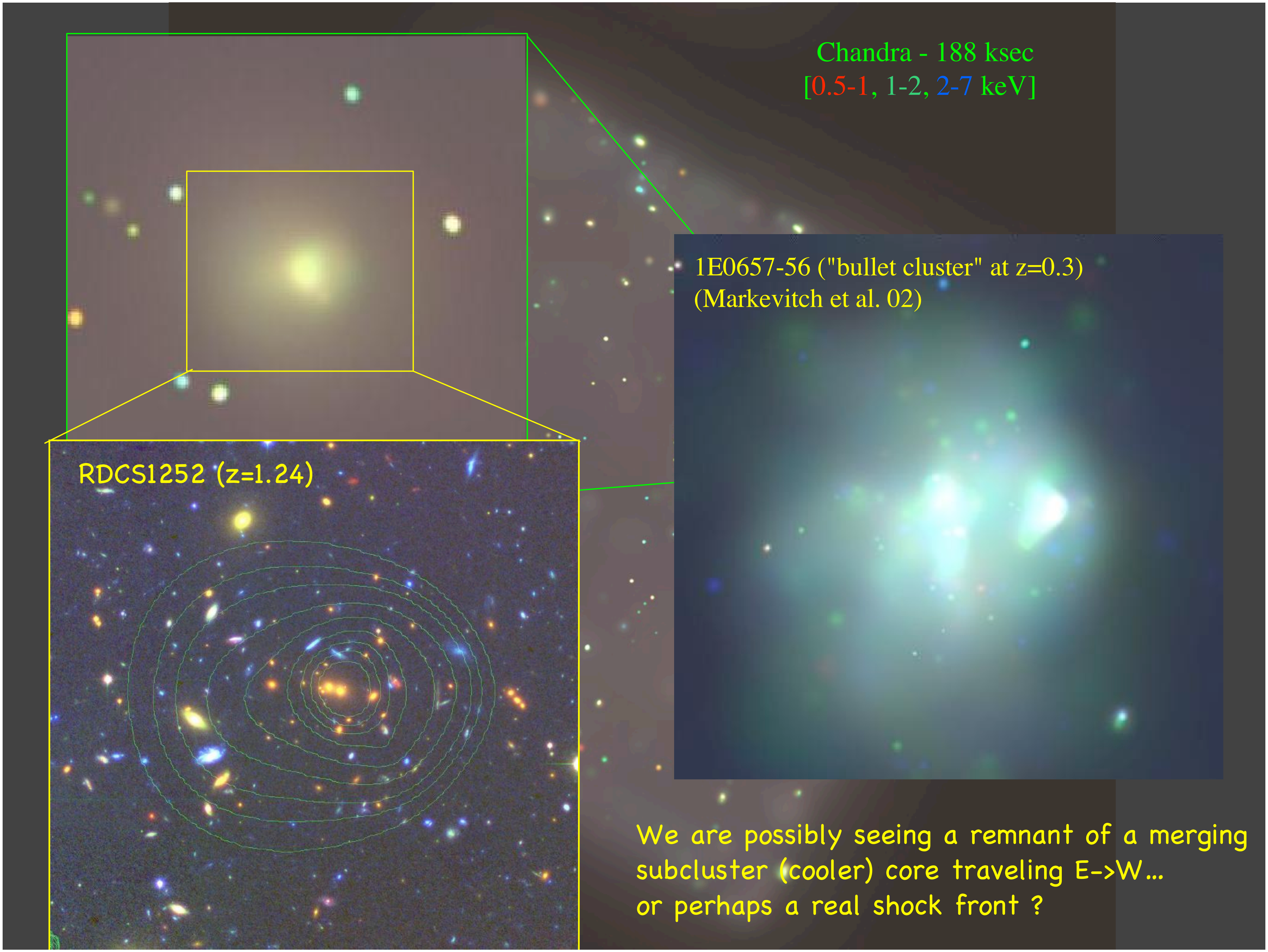


(Jee et al. 04)


RXJ0152
z=0.83
Mass over Light
Y (arcsecs)
X (arcsecs)
0.10
0.12
0.14
1.0
0.5
0.0

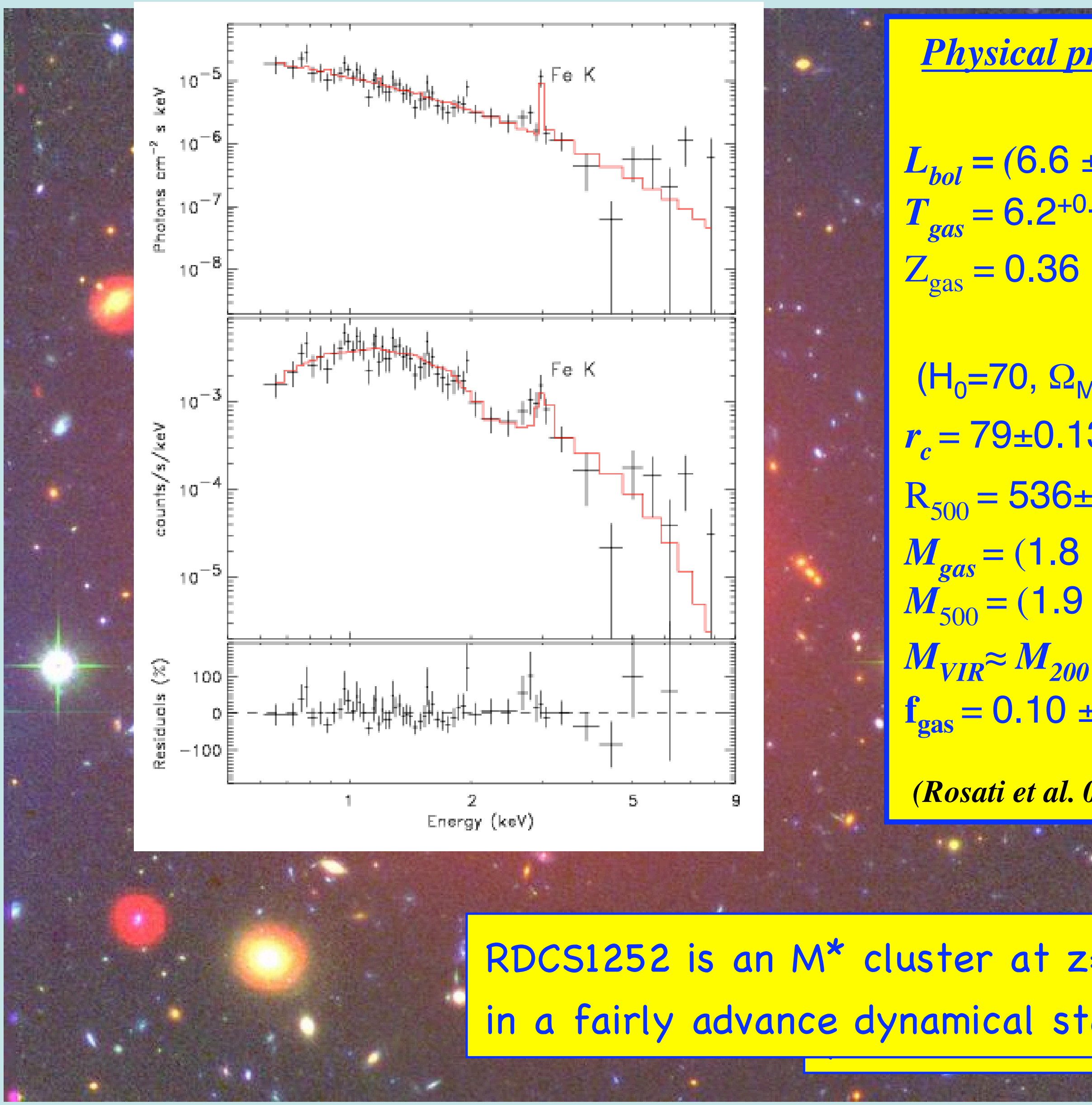
(Jee et al. 04)

A Deep Look at the ICM and cluster DM at the Largest Look-back time (accessible to date)



Chandra - 188 ksec
[0.5-1, 1-2, 2-7 keV]
1E0657-56 ("bullet cluster" at z=0.3)
(Markevitch et al. 02)
RDCS1252 (z=1.24)
We are possibly seeing a remnant of a merging
subcluster (cooler) core traveling E->W...
or perhaps a real shock front ?

Distribution of baryons and DM in a distant cluster (z=1.24)



Physical properties of RDCS1252

(z=1.237)

L_{bol} = (6.6 ±0.1) x10^{44} erg/s

T_{gas} = $6.2^{+0.7}_{-0.5}$ keV

Z_{gas} = 0.36 ± 0.11 $Z_{\odot}$ ⇐

(H_0=70, Ω_M=0.3, Ω_Λ=0.7)

r_c = 79±0.13 kpc, β= 0.53±0.03

R_{500} = 536±40 kpc

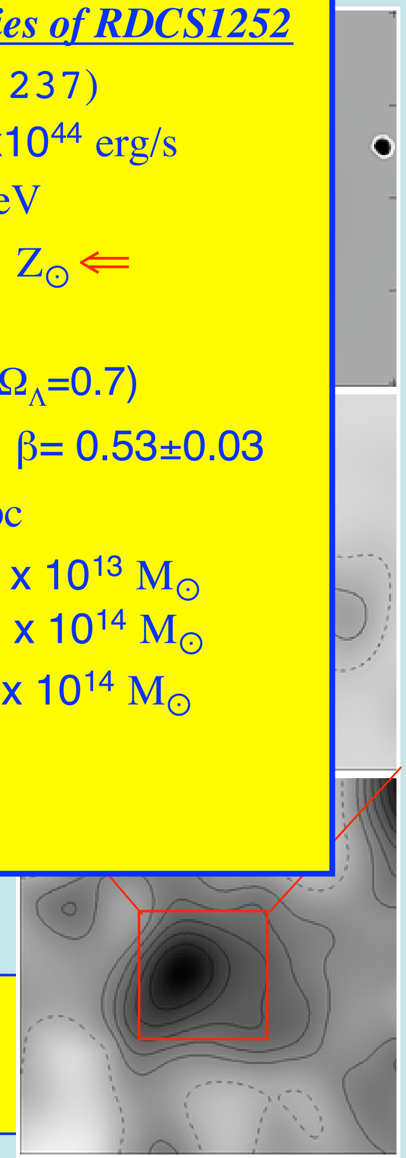
M_{gas} = (1.8 ± 0.3) x 10^{13} $M_{\odot}$

M_{500} = (1.9 ± 0.3) x 10^{14} $M_{\odot}$

$M_{VIR} \approx M_{200} \approx$ 2.7 x 10^{14} $M_{\odot}$

f_{gas} = 0.10 ± 0.04

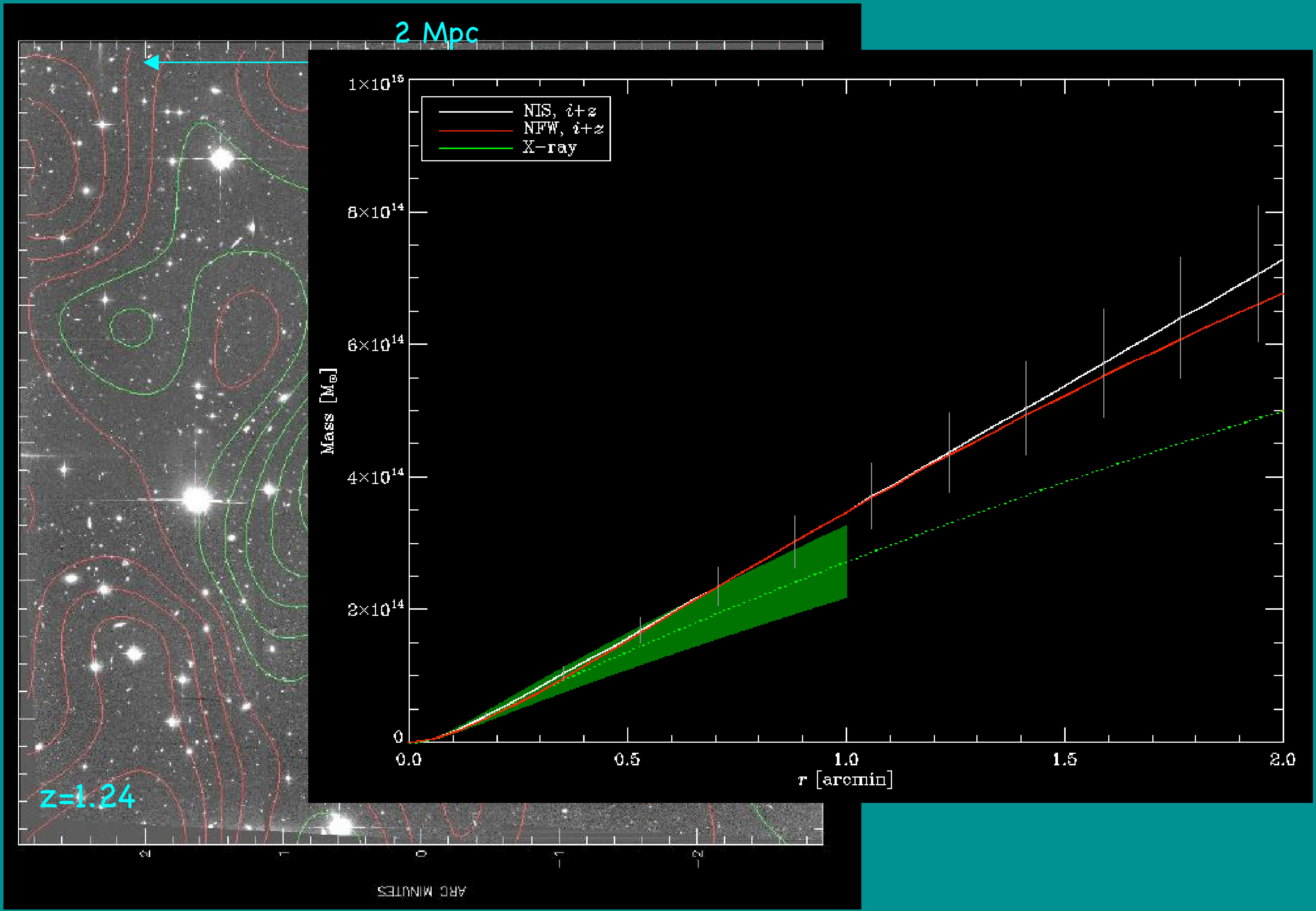
(Rosati et al. 03)



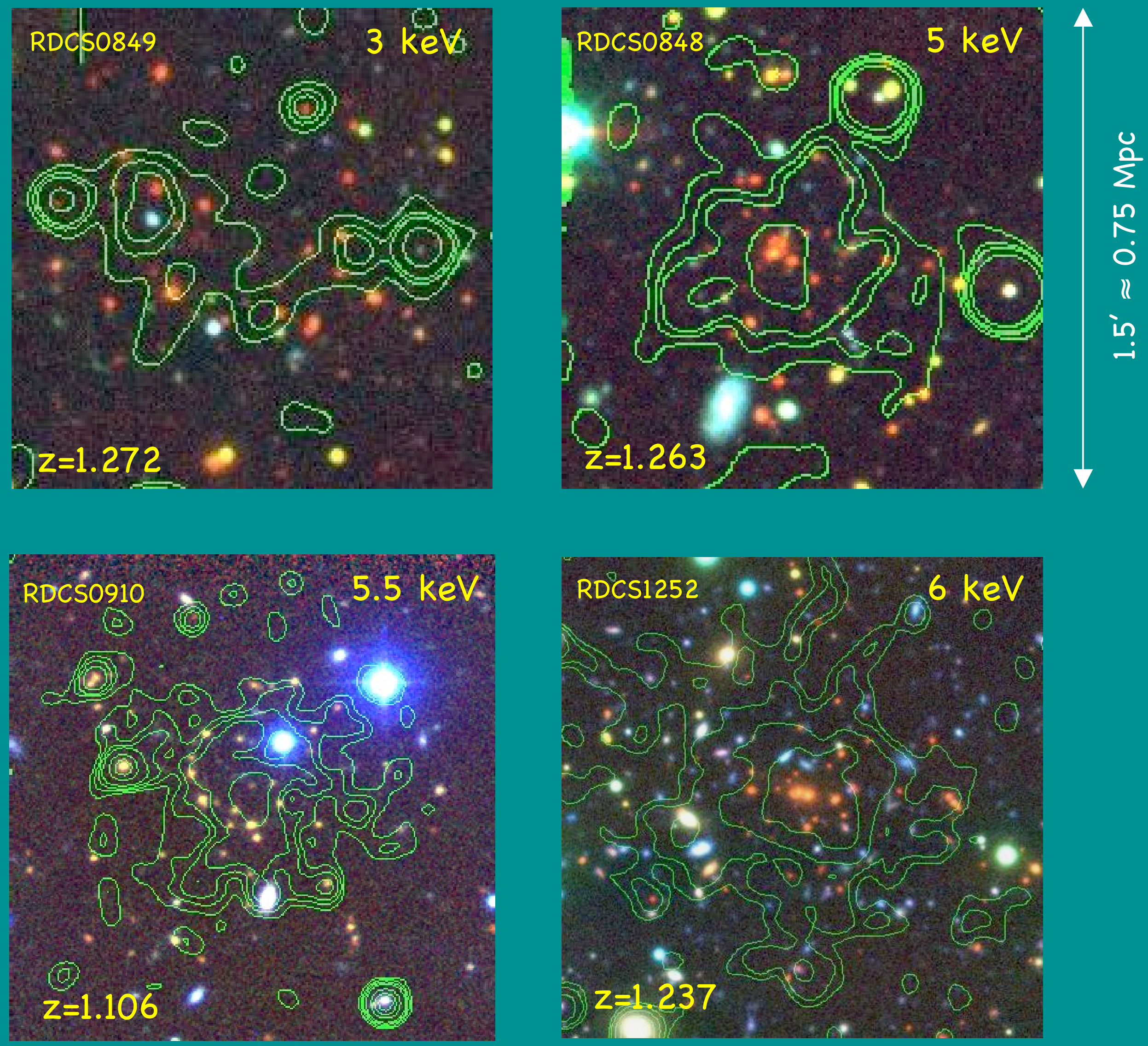
RDCS1252 is an M* cluster at z=1.24
in a fairly advance dynamical state

Probing the DM mass distribution of most distant systems:

First detection of weak lensing at z > 1 with ACS (Lombardi et al. 04)

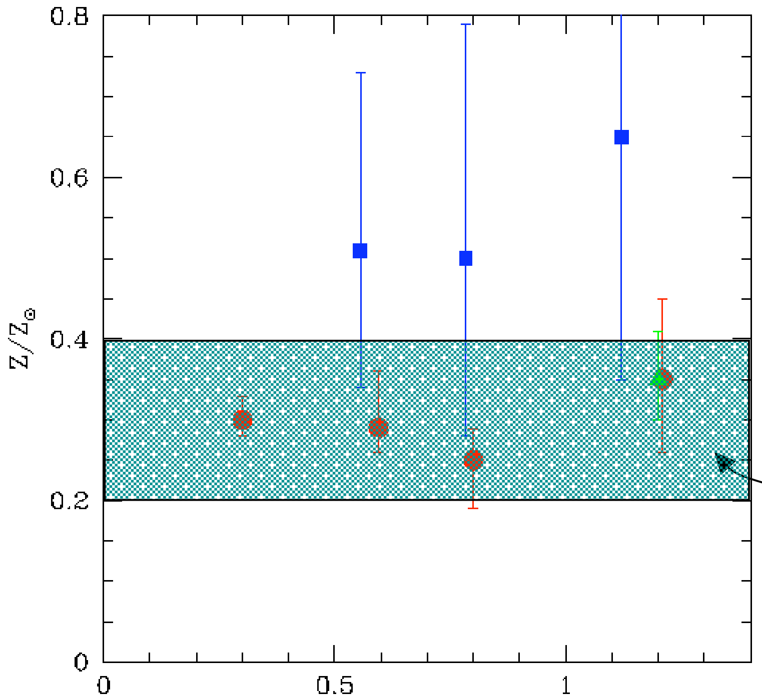


Baryon distribution in clusters at z>1



(Rosati et al. 1999; Stanford et al. 2001, 2002; Rosati et al. 2003)

Evolution of ICM metallicity from Chandra Observations of distant clusters
(Tozzi et al 03)



Method:
stacking spectral analysis of a sample of 20 high-z clusters (0.3<z<1.2)

Metallicity of local (z< 0.2) clusters

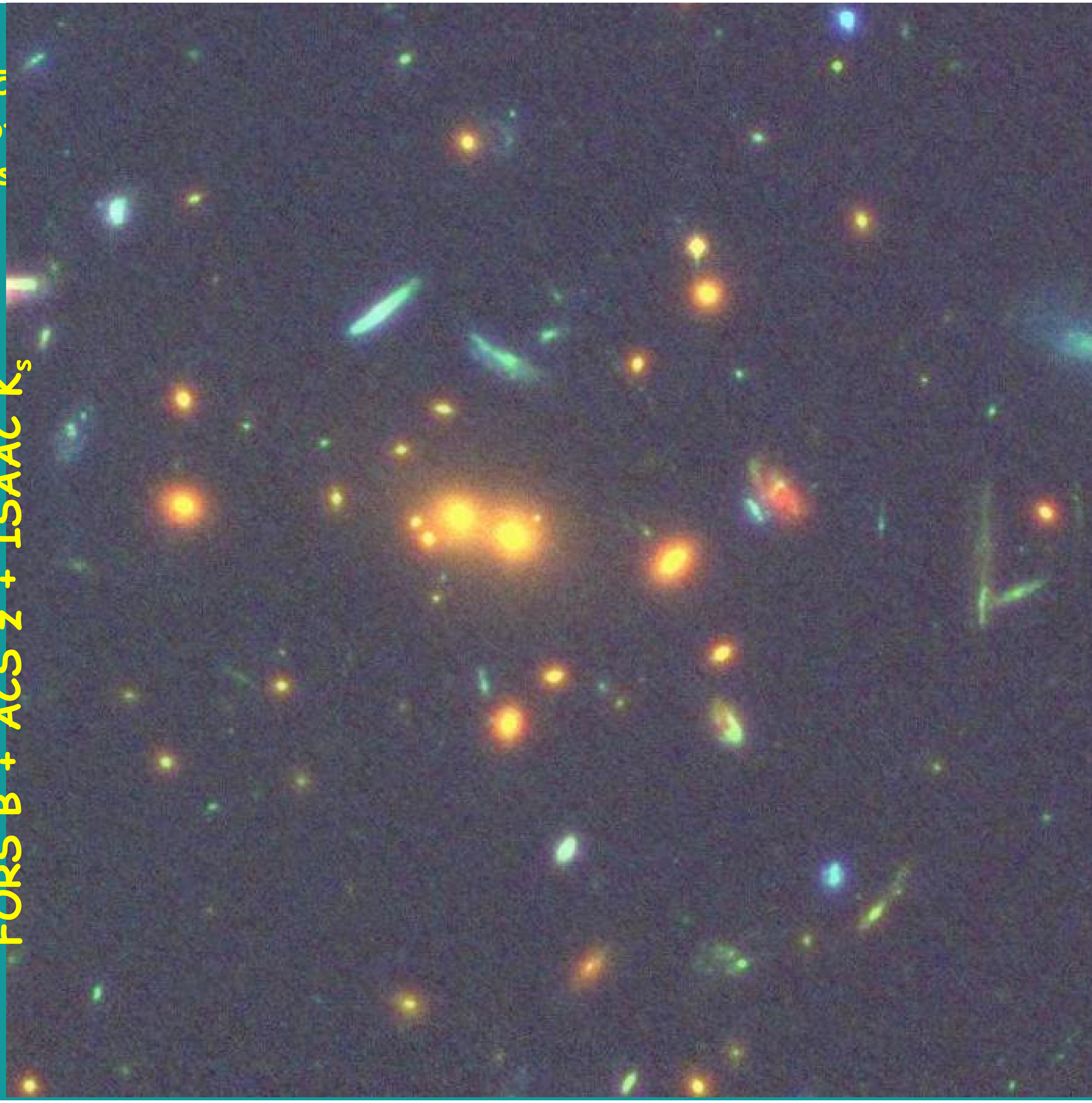
ICM enrichment complete by $T_{z=1.2}+T_{cross}$ i.e. $z\approx 2$!

Much SF at high-z and/or efficient/fast mechanism to circulate metals

(>~50% of the present day stellar mass density assembled by z~1 (Dickinson+ 03, Rudnick+ 03))

A Deep Look at the Cluster Galaxy Populations at the Largest Look-back time

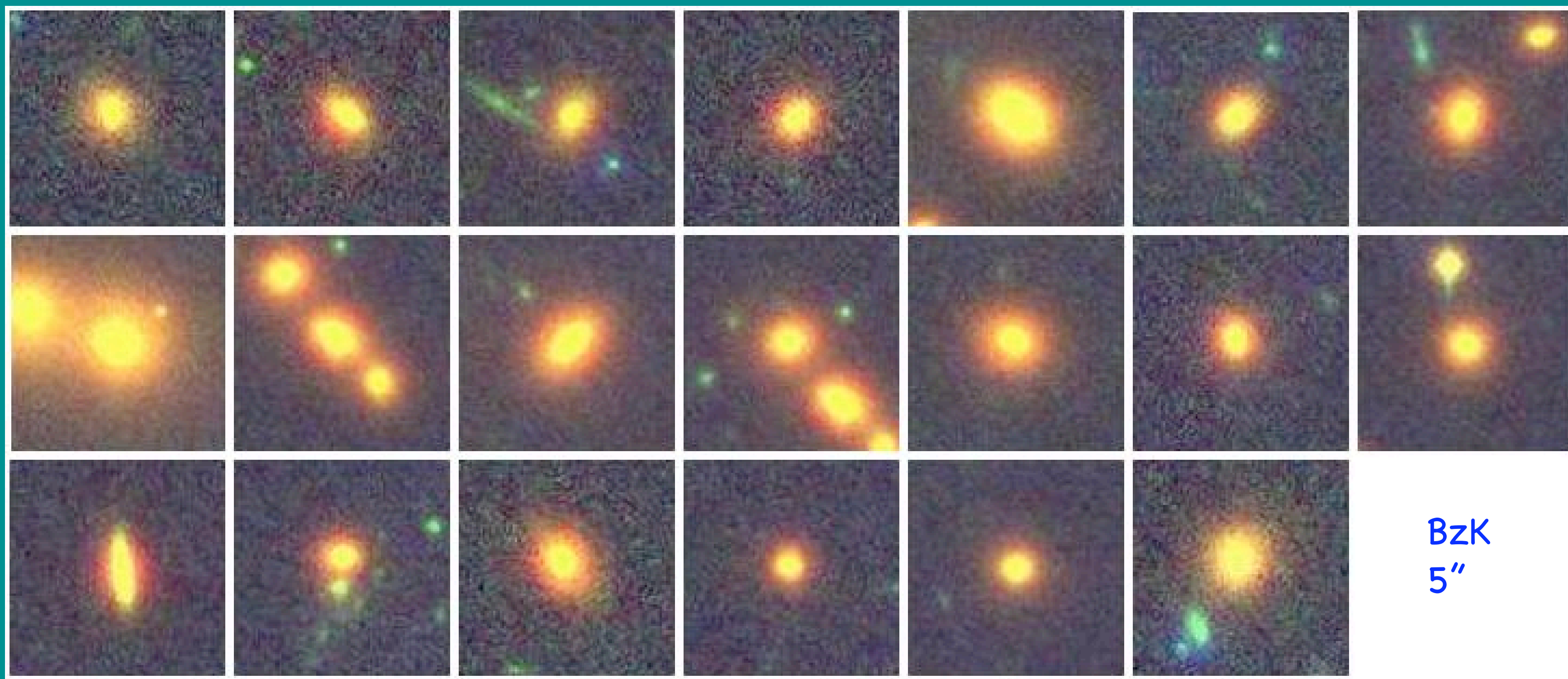
RDCS125
Mosaic o
12 orbits



Cluster members in RDCS1252-29 with HST/ACS

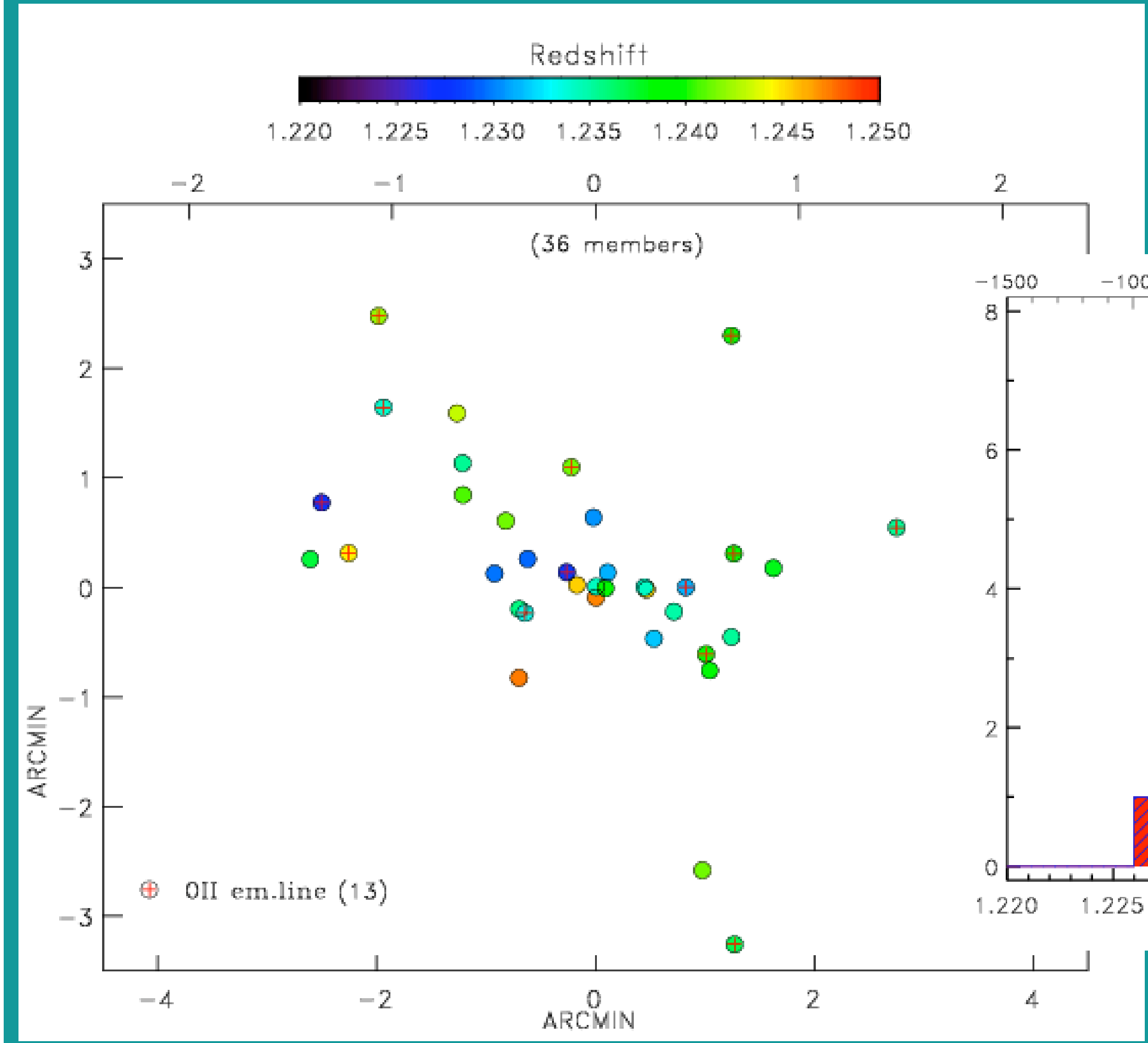
(Rosati et al. 04)

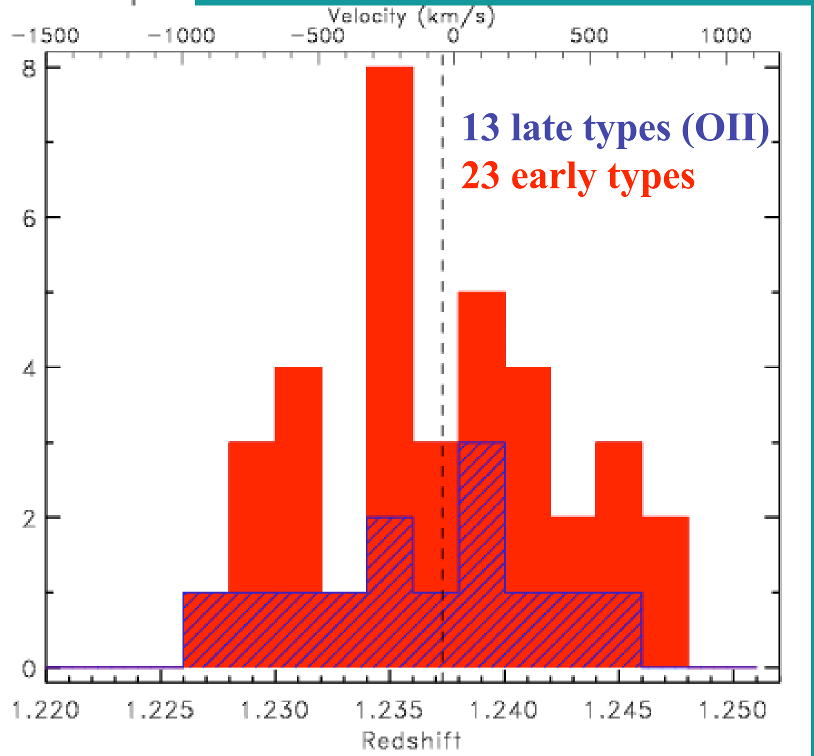
Early-type spectra



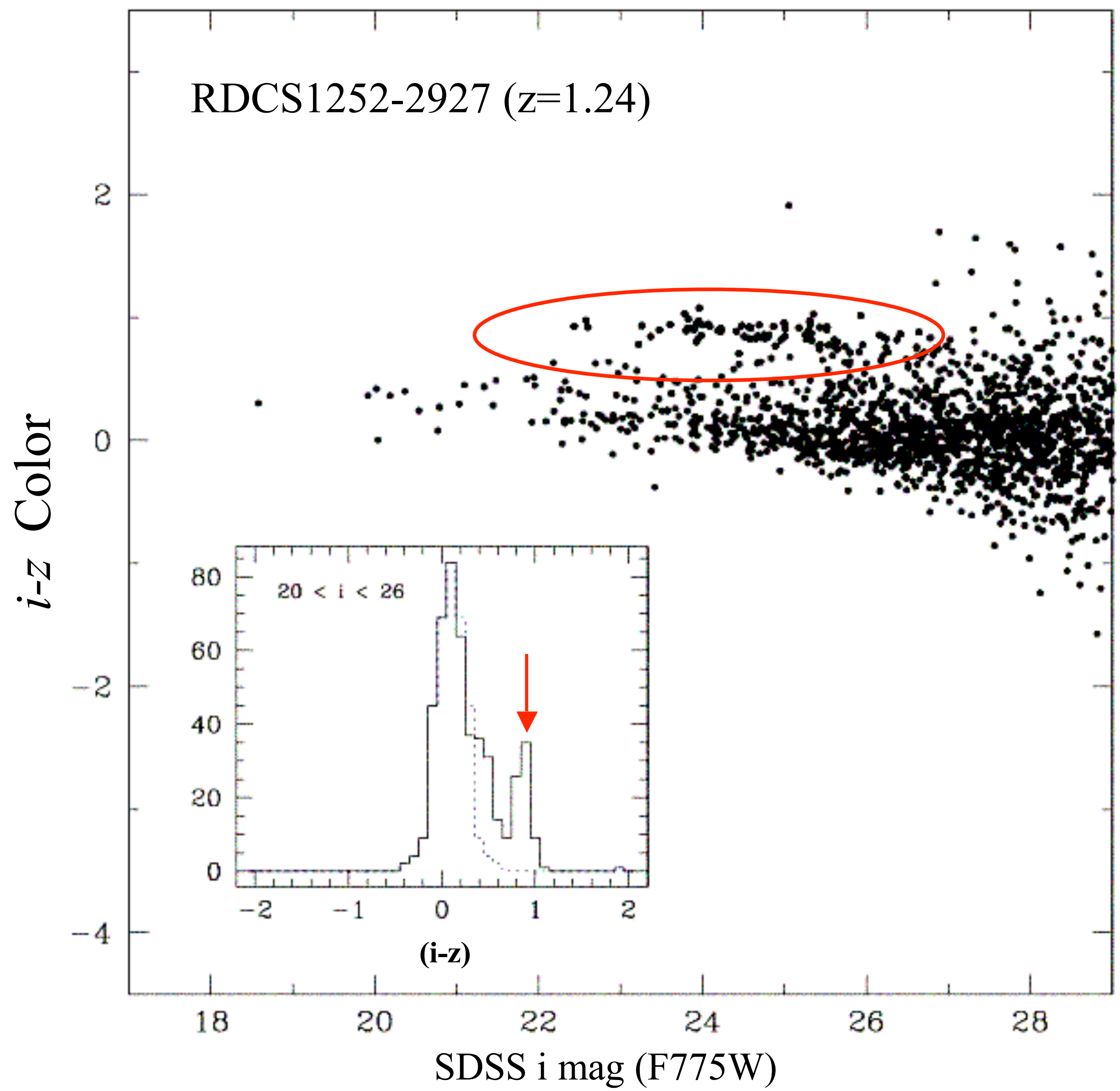
Late-type spectra (OII)

FORS2 Spectroscopy of RDCS1252-29





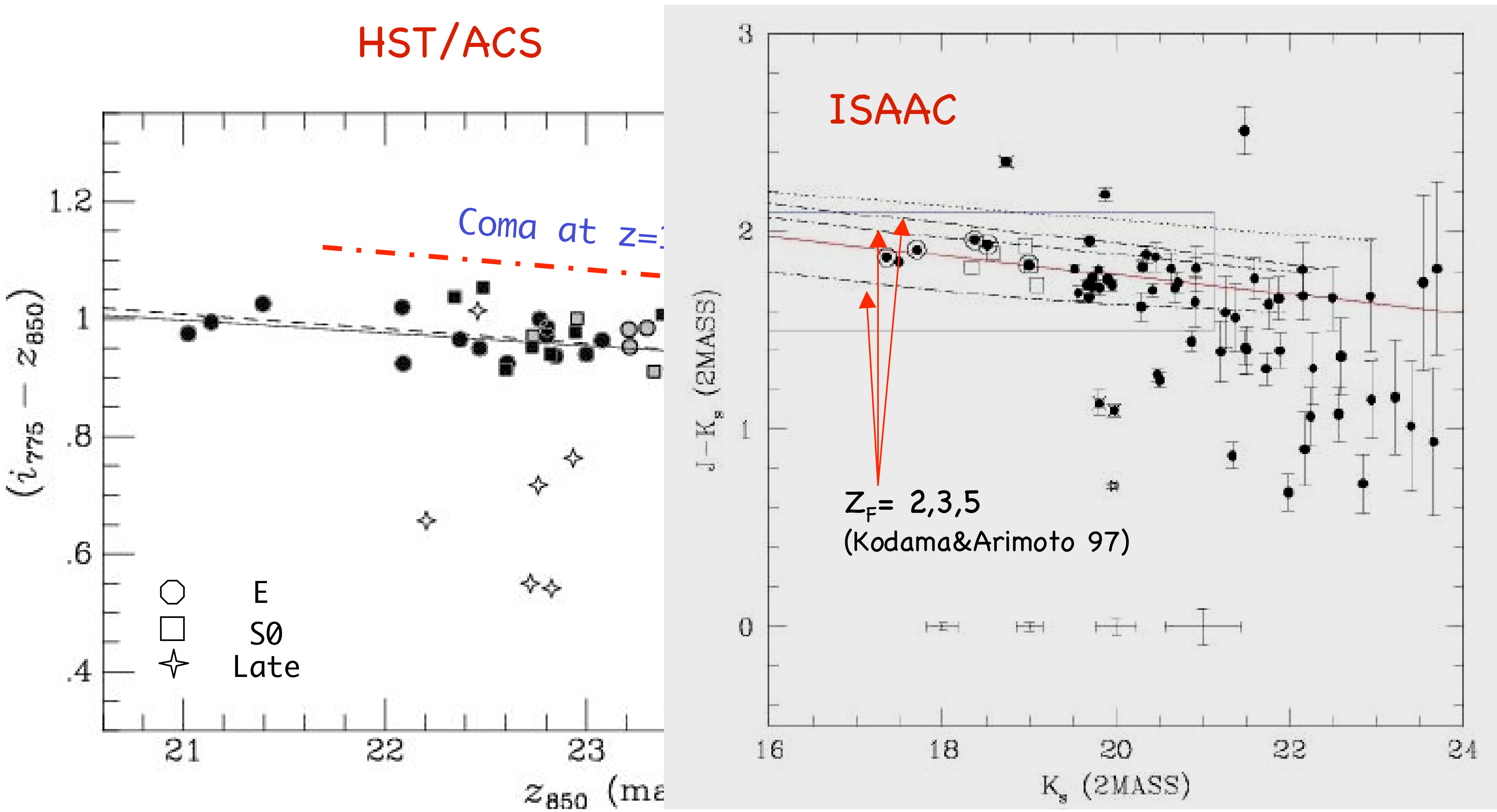
σ_V=750±70 km/s



RDCS1252-2927 (z=1.24)
i-z Color
SDSS i mag (F775W)
20 < i < 26
(i-z)

RDCS1252 (z = 1.24) C-M Relation with HST/ACS and VLT/ISAAC

(Blakeslee et al. 03; Lidman et al. 03; Rosati et al . 04)

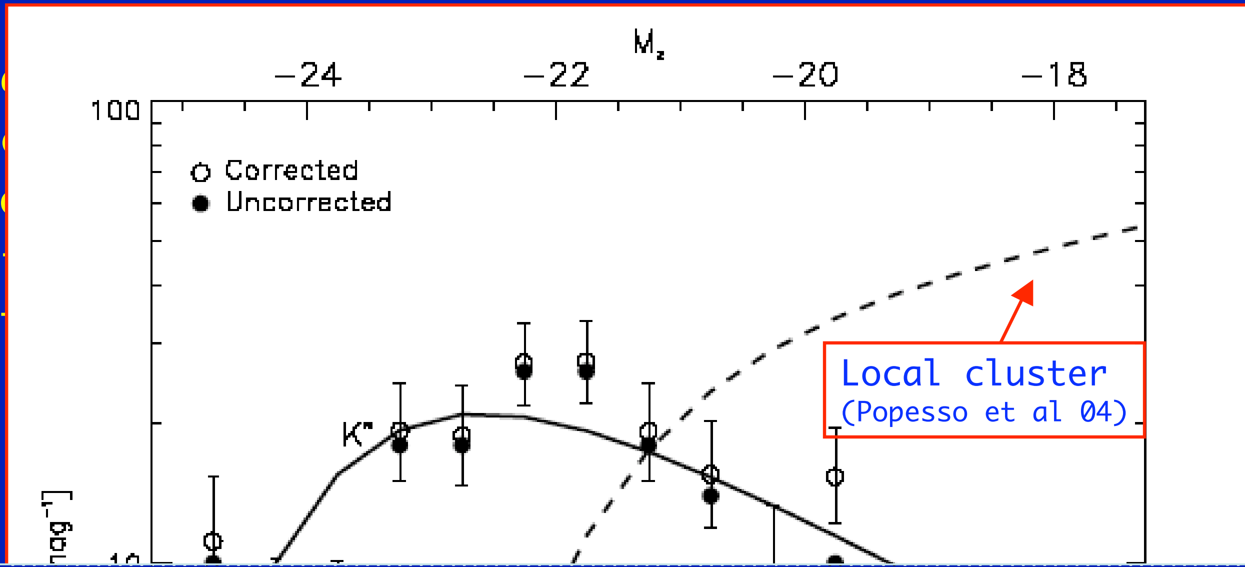


The scatter and slope of the red sequence is very similar to low-z clusters, basically frozen over 65% of look-back times !

K-band Luminosity Function of cluster galaxies at z=1.24

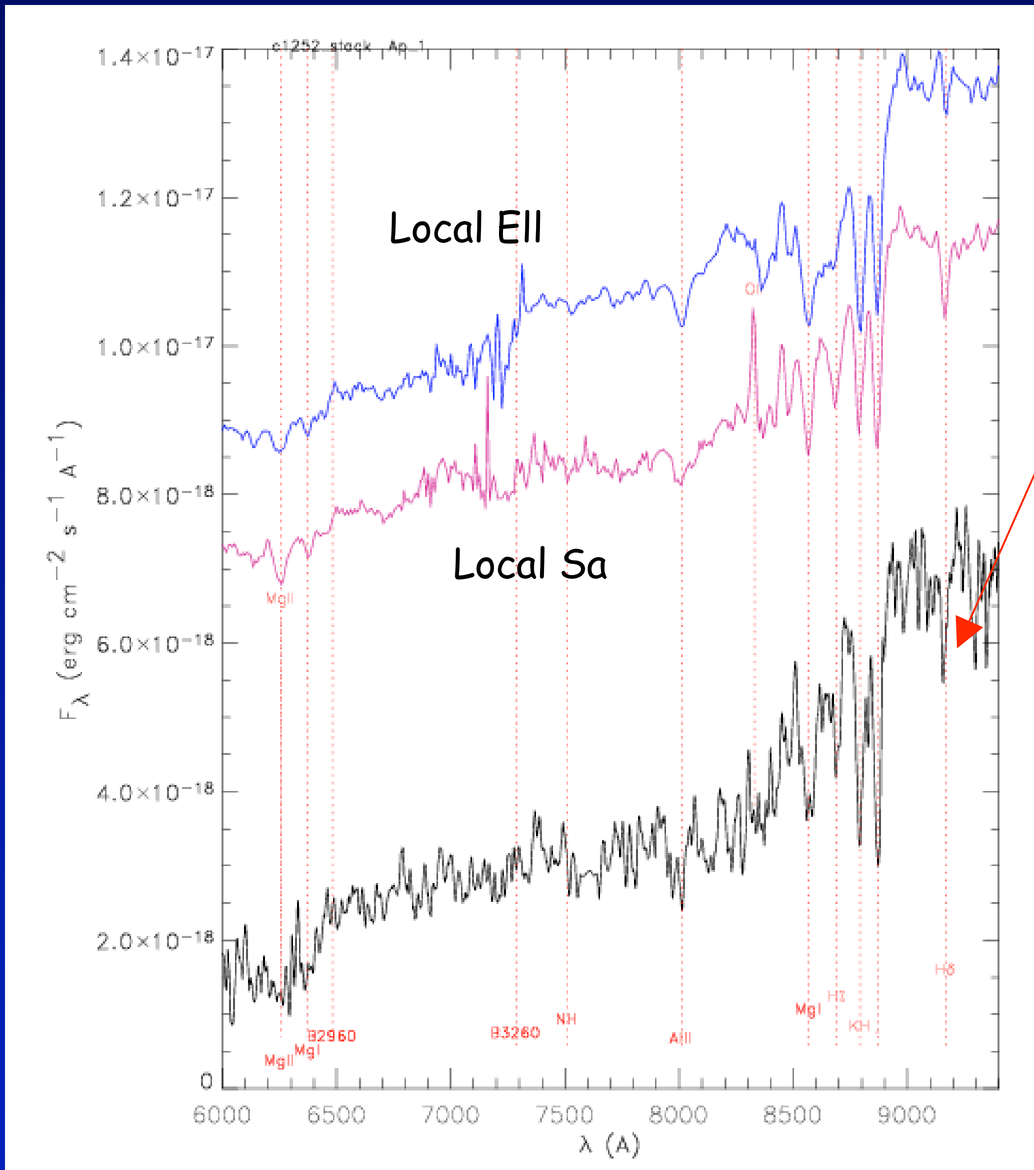
(Toft et al. 04)

- The K-b… …alaxies
- At these… …pe of the formati… …history)
- Depth o… …elow L* (accura… …nd α)



- Compared to local clusters in the same rest-frame band (z):
  - Shape of the bright end of the LF does not evolve significantly
  - L* brightens by $\Delta M_z* = 1.4 \pm 0.5$
- Massive elliptical, dominating the bright end of the LF, were already in place at z=1.24
- These observations are a challenge for hierarchical models which predict α to steepen and K* to dim as massive gals break-up in their progenitors.
- Very similar findings in the field! (Pozzetti+ 03, from K20 survey)

Stacked spectrum of 10 brightest members at <z> = 1.237 (Rosati 03)

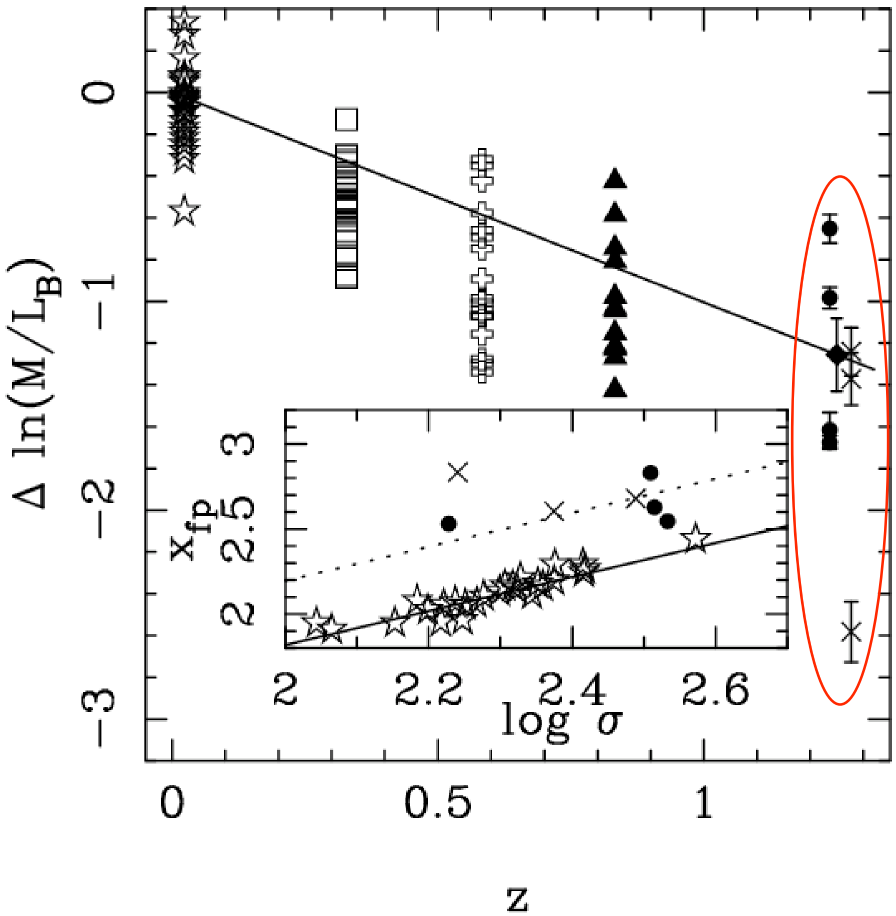


> Significant H_δ abs line
> Signatures of other balmer lines

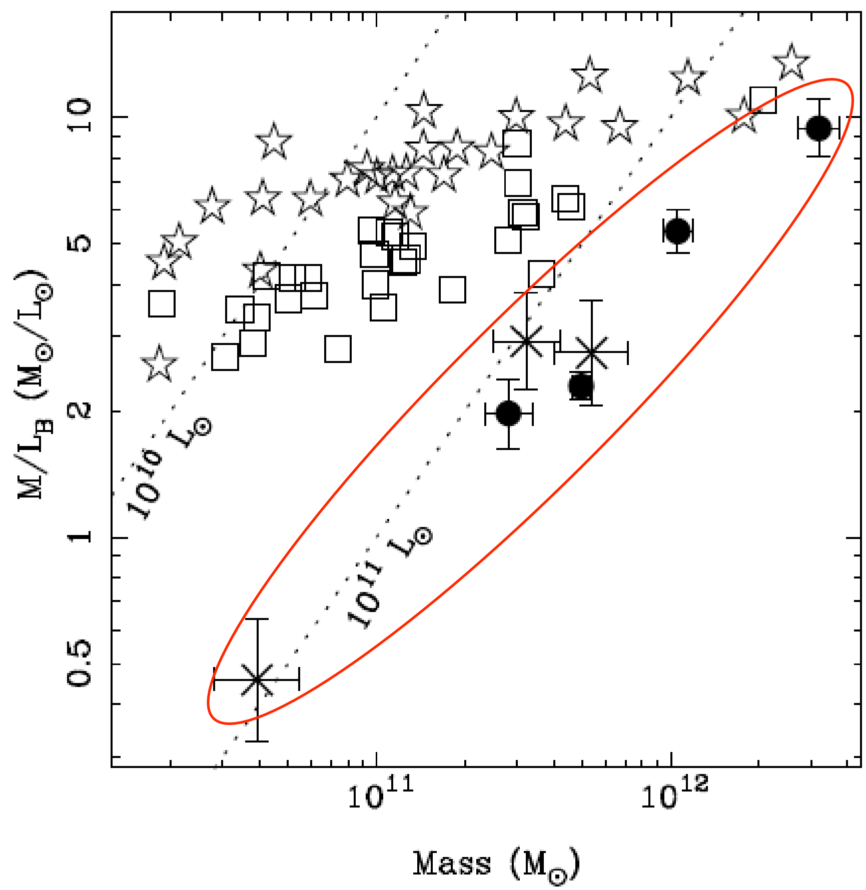
- Most luminous Early-types harbour relatively young (post starburst) stellar pops !

- Formation redshift z_F <~ 3
- Last SF @ z=1.4-1.8
- Complex SF history needed…

The Fundamental Plane of cluster galaxies at z=1.25 (Holden et al. 2004)



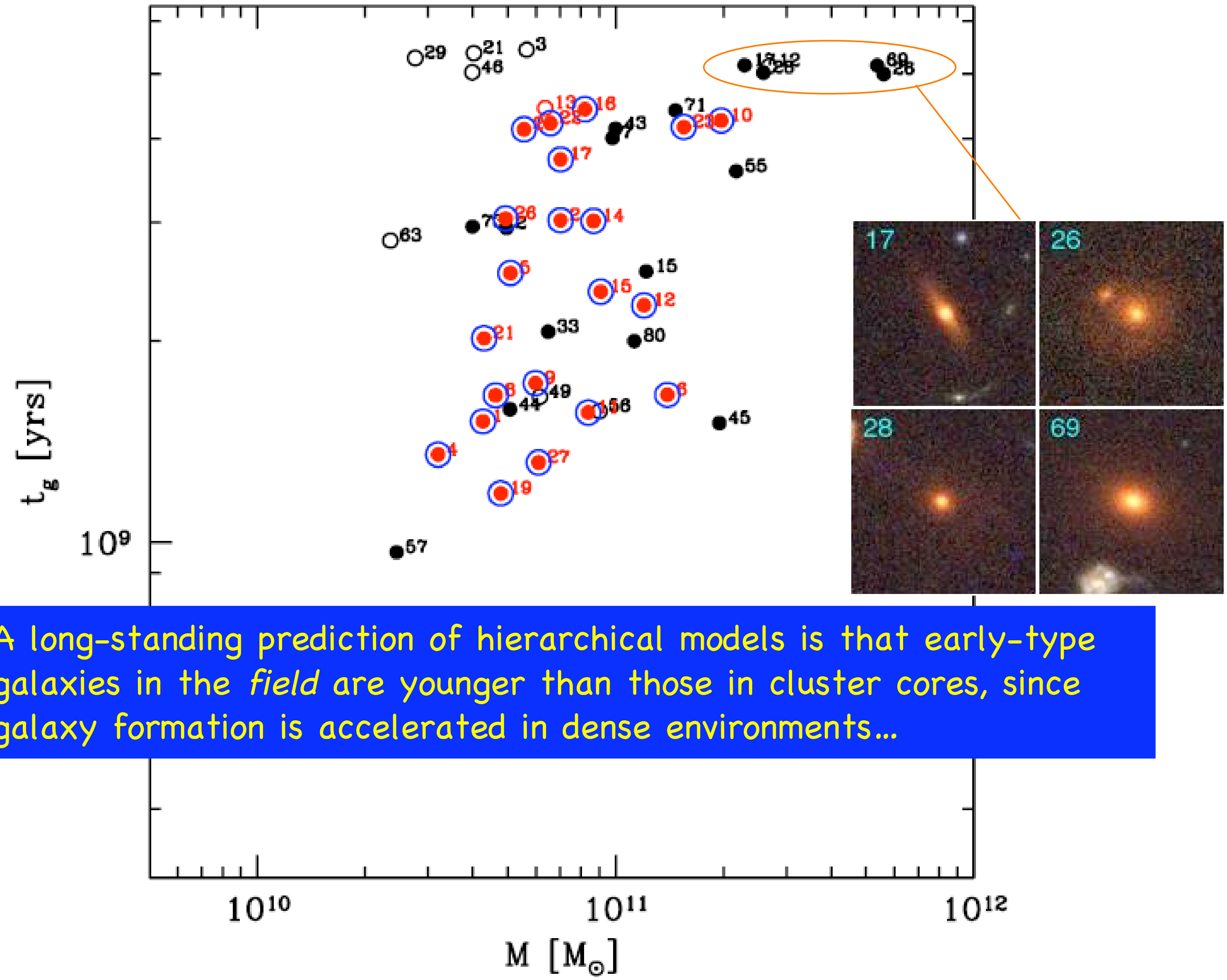
$$\log r_e = \alpha \log \sigma + \beta \log < I_e > + \gamma$$



M/L ∝ (1.0 ± 0.2) z = f(τ, IMF, Z)

⇒ $z_f = 2.2^{+0.8}_{-0.4}$
or t=2.8 Gyrs before observation

Stellar Masses and Ages from SED fitting of spectrophotometry of cluster galaxies at z=1.24: *cluster* vs *field* (with S.Berta)



A long-standing prediction of hierarchical models is that early-type galaxies in the *field* are younger than those in cluster cores, since galaxy formation is accelerated in dense environments...

Difficulties in the standard models

- The conversion of baryons into stars is a complex, poorly understood process. SAMs use phenomenologically-motivated but simplistic rules for SF

- The standard model + SAMs fail to predict the **stellar mass assembly** and the **star formation history** as inferred from observations, latest SAMs fix this…

- Over last 5 years it has become apparent that galaxy formation is **not** bottom-up as expected
  "The DM hierarchy must be inverted for baryons" (J.Silk, 2000)
  "Down-sizing effect" (today popular word)
  - massive galaxies are red, old and metal rich
  - dwarfs are blue, young and metal-poor

Summary: Cluster Formation & Evolution

- Cluster formation was already in an advance state by z=1.2
  - Cluster space density evolve only at the high end of the mass function
  - Scaling relations and ICM metallicity do not evolve significantly -> energy injection, metal production pushed at high-z (z>~3)

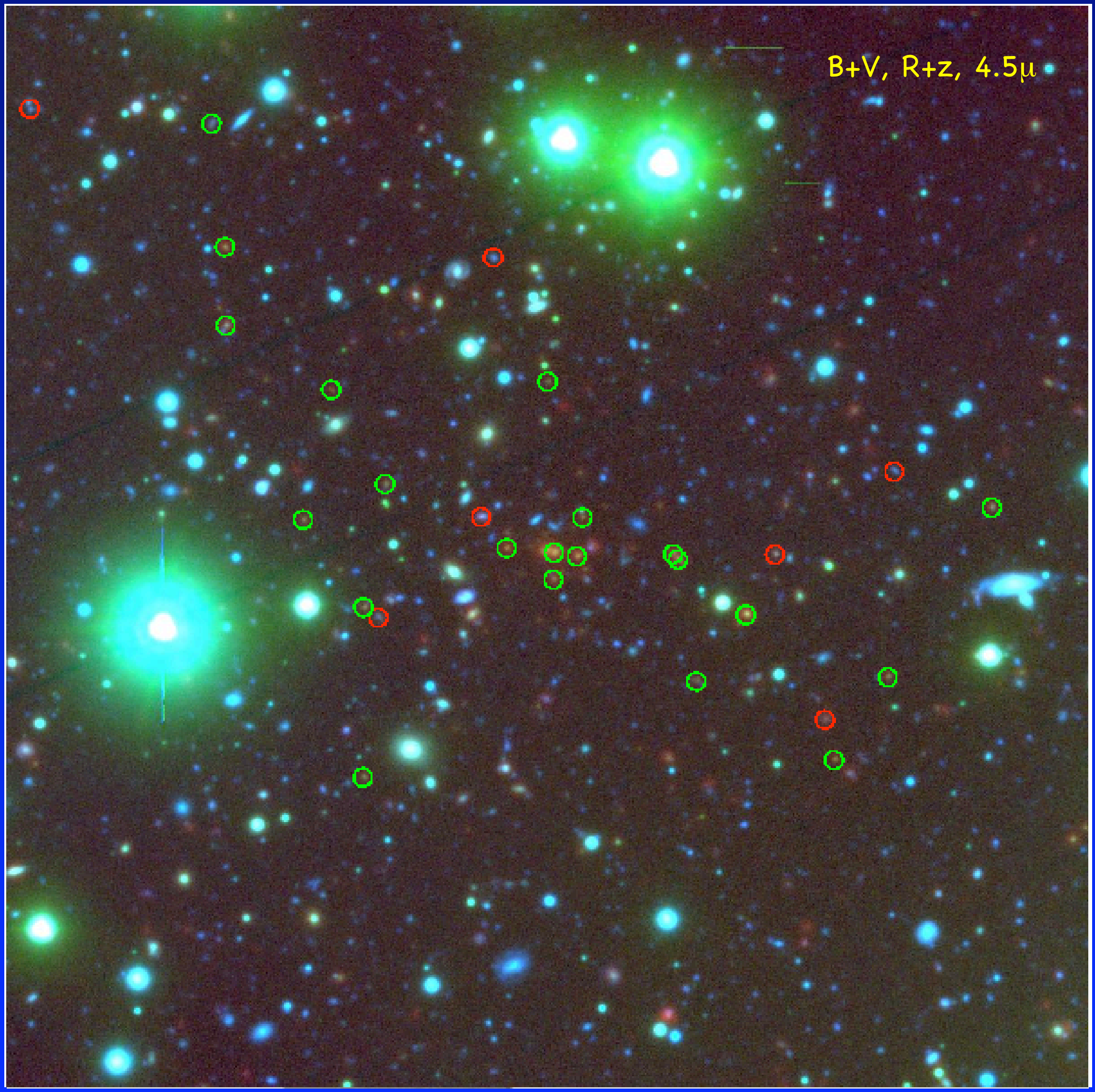
- Mode and Formation of cluster early types ?
  - Massive early types already in place at z=1.2, form a tight red sequence which evolved very little down to the present
  - The bulk of their stars formed at z=2-3 but there are signatures of recent continued SF even at the high mass end.
  - Shape K-band LF of cluster galaxies has not evolved significantly out to z=1.2 (i.e. over 10 Gyr) → push merging events at higher z
  - In general, observations are difficult to reconcile with hierarchical models (similarly to studies in the field, e.g K20 study)

Future Prospects

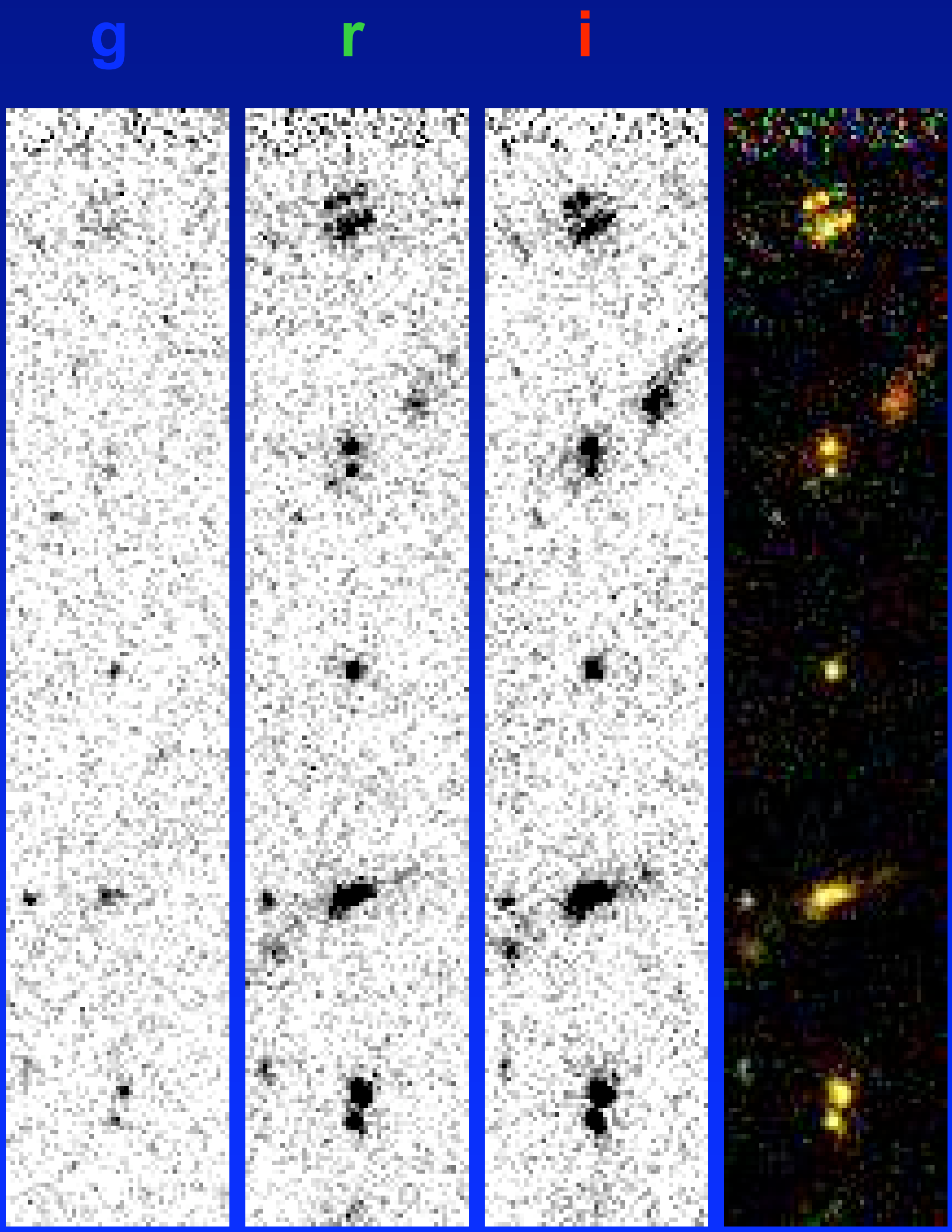
- Upcoming Spitzer IR observations (rest frame K) will probe stellar mass assembly at large look-back times.
- Push the search for clusters at z>1.5-2: large area Spitzer surveys, SZ surveys + large FoV X-ray satellites.
- Link to z=2-4 proto-clusters around RGs (Miley et al.) ?
- From phenomenology to fundamental theory of gal formation ?? the wealth of information coming from new ground-based and space facilities will hopefully drive the development of physical models for the evolution of baryons.

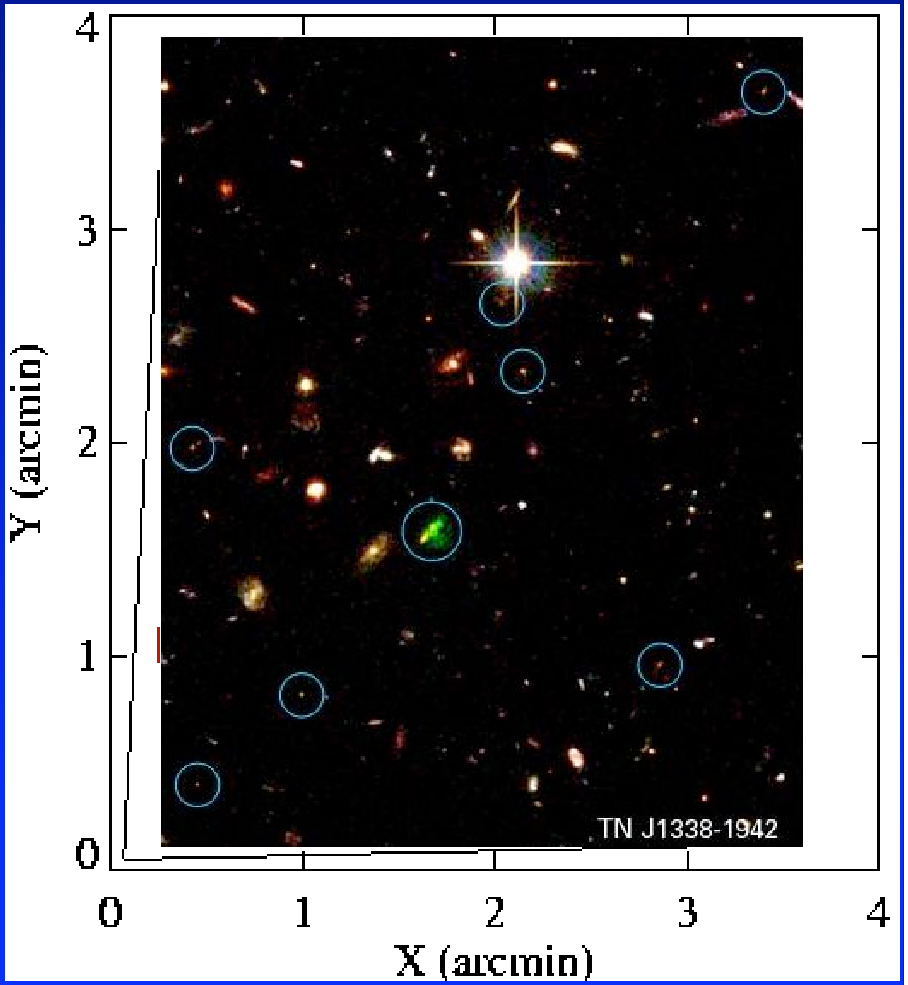

The End
Abell 1689 (z=0.18)
(ACS b r I z)

Sneak preview to Spitzer/IRAC data on RDCS1252...



TN J1338-1942: a protocluster at z = 4.1





Ly-α emitters and Ly-break galaxies

Crucial role of scaling relations in X-ray clusters

- Cluster scaling relations (L_X-T, M-T, S-T, etc.) and their evolution with z ⇒ diagnostics of the coupling between galaxy formation and ICM physical properties
- Without galaxy formation, pure gravitational processes (adiabatic compression and accretion shocks during collapse) ⇒ self-similar clusters (Kaiser 96)

Hydrostatic equilibrium: ⇒ $T(M,z) \propto M^{2/3}(1+z)$

Bremsstrahlung emission: ⇒ $L_X \propto M\rho T^{1/2}$

$$\Rightarrow L_X \propto M^{4/3}(1+z)^{7/2} \propto T^2(1+z)^{3/2}$$

$$\Rightarrow S\ (\text{entropy}) \propto (T/\rho^{2/3}) \propto T\ (1+z)^{-2}$$

} Self-similar relations

...but clusters do not follow these scaling relations! Self-similarity must be broken by non-gravitational processes of entropy generation: pre-heating from feedback processes from SN, AGN activity and radiative cooling (both in low massive systems)

The Chandra view of high-z clusters

(a lot of complexity revealed)

$Sqrt(I_x) \propto \rho_{gas}$