# THE NATURE OF FOSSIL GALAXY GROUPS
## ARE THEY REALLY FOSSILS ?

Francesco La Barbera[(1)]; R.R. de Carvalho[(2)]; I.G. de La Rosa[(3)];
R.R. Gal[(4)]; G. Sorrentino[(1)]; J.L. Kohl-Moreira[(5)]

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(1) INAF-OAC, Napoli, Italy; (2) INPE-DAS, Sao Jose dos Campos, Brazil; (3) IAC, Tenerife, Spain; (4) Institute for Astronomy, Honolulu, USA; (5) ON, Rio de Janeiro, Brazil

# LAYOUT

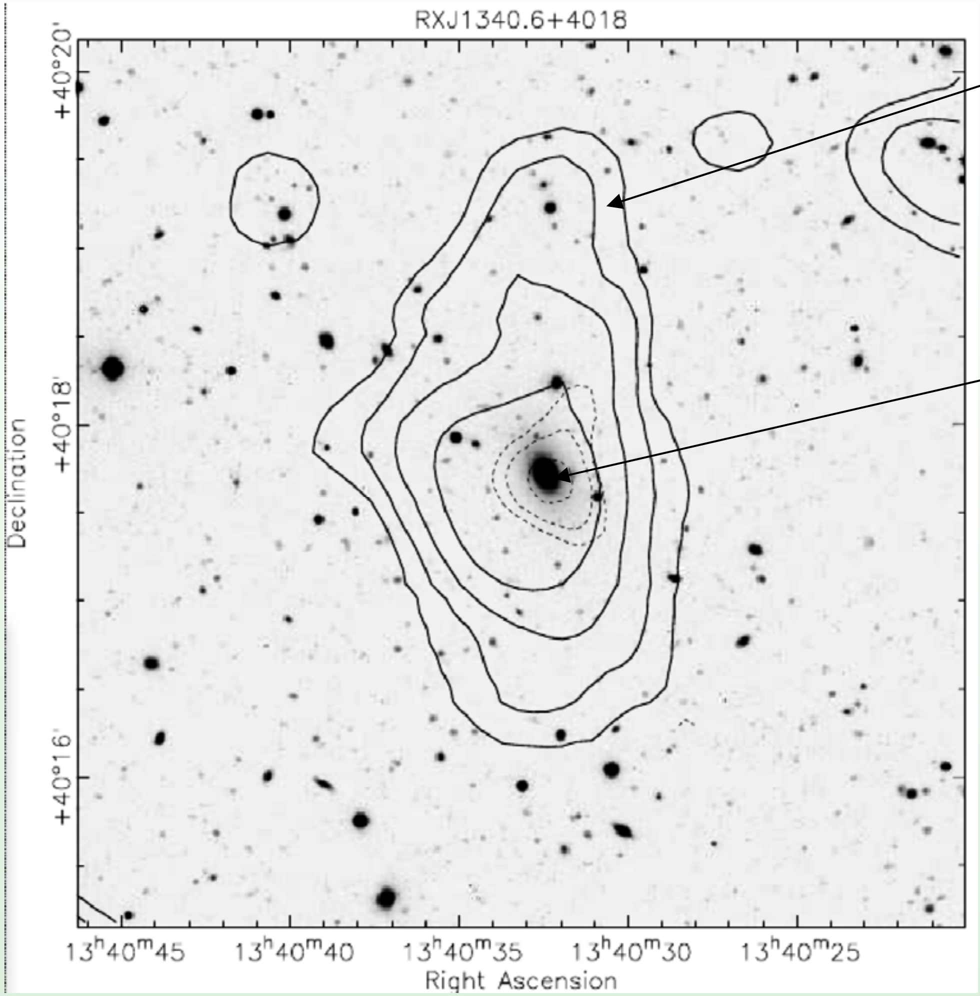
Fossil Groups (FGs): background

FGs and *field* galaxies (FS) from SDSS+RASS

Measuring properties of FGs and FS

FGs vs. FS: comparison

# FOSSIL GROUPS: background




R-band image and overlaid X-Ray contours for the first discovered fossil group RX1340.6+4018 (Ponman et al. 1994, Nat 369), from Jones et al. 2000 (MNRAS 312)

Extended X-ray emission, with $L_X$ typical for a galaxy group/cluster

Bright elliptical galaxy in the center, dominating the optical luminosity with a large magnitude gap $\Delta_{mag}$ between first and second rank galaxies within a given (projected) radius $\rho$

According to the *standard* definition
(Jones et al. 2003, MNRAS 343)

$L_X \geq 10^{42}\ (h_{50})^{-2}$ erg/s

$\Delta_{mag} \geq 2$

$\rho = 0.5 r_{virial}$

# FOSSIL GROUPS: formation scenario

FGs are the final stage of evolution in groups, where $L^*$ galaxies merged to form the bright, central elliptical (Ponman et al. 1994, Nat 369; Jones et al. 2000 MNRAS 312).

$t_{dyn} < t_{Hubble}$ for $M \sim M^*$
$t_{dyn}$ increases for fainter galaxies
$T_{cool,hot\ gas} \sim t_{Hubble}$
(see e.g. Ponman et al. 1994, Nat 369; Ponman & Bertram 1993, Nat 363; Mulchaey & Zabludoff 1999, ApJ 514)

FGs are “failed groups”, i.e. groups originally formed with an atypical galaxy luminosity function, where most of baryons were used up in a single bright galaxy (Mulchaey & Zabludoff 1999, ApJ 514)

FGs are extreme instances of a smooth distribution of galaxy group’s properties, rather than a separate class of systems (Dariush et al.2007, MNRAS 382). The fossilness can be a common phase in the evolution of groups, which is terminated by the infall of fresh galaxies from the group surroundings (von Benda-Beckmann et al. 2008, MNRAS 386).

# Studying FGs

- If the merging scenario holds, FGs might be ideal laboratories to **study the evolution of galaxies and the ICM in isolated, quiescent systems**, in contrast to groups/clusters where several physical mechanisms can play an important role

- The number density of FGs is comparable to that of BCGs and luminous field galaxies, with FGs being a significant fraction of all groups/clusters with the same X-Ray luminosity. This makes **FGs a potentially viable phase to form bright galaxies**

- Explaining the abundance of FGs and their properties can **constrain the cosmological model of structure's formation**

- FGs would be ideal targets for **constraining dark matter density profiles** (by lensing studies)

# FOSSIL GROUPS: (some) previous results

- A dwarf galaxy population is detected around the seed elliptical (**$N_{FG}$=7**; Mulchaey & Zabludoff 1999; ApJ133; Jones et al. 2003, MNRAS 343) However, Vikhlinin et al. 1999 (1999, ApJL 520; **$N_{FG}$=4**) found no fainter galaxy concentrations around OLEGs.

- Seed galaxies have non-boxy isophotes, favoring a formation via gas-rich mergers (**$N_{FG}$=7**; Khosroshahi et al. 2006, MNRAS 372)

- M/L is (i) comparable to that of groups with similar mass (**$N_{FG}$=1**, Mulchaey & Zabludoff 1999; ApJ133; **$N_{FG}$=7**, Khosroshahi et al. 2007, MNRAS 2007); (ii) larger than that of groups/clusters (**$N_{FG}$=4**, Yoshioka et al. 2004, ASR 34; **$N_{FG}$=4**, Vikhlinin et al. 1999, ApJL 520)

- Lack of low velocity (luminosity) satellites (**$N_{FG}$=1**, D'Onghia & Lake 2004, ApJ 612), but this was not confirmed by Zibetti et al. (**$N_{FG}$=6**, 2007, MNRAS 392).

⇕

**Main difficulties are (1) the lack of a large, *well studied* sample of FGs (only ~15 FGs are *well known*, though new SDSS-based samples are becoming available ($N_{FG}$=34; Santos et al. 2007, AJ 134)); and (2) the lack of a consistently defined control sample to establish a benchmark for the properties of FGs.**

# LAYOUT

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FGs vs. FS: comparison

# FG candidates from SDSS
## optical selection

We select a volume-limited sample of galaxies (N=91563) from **SDSS-DR4** as in Miller et al. (2003, ApJ 586), and Sorrentino et al. (2006, A&A 460)

- $\mathbf{M_r<-20}$ (~ separation between *ordinary* and *bright* ellipticals; Graham & Guzmán 2003, AJ 125)

- **Spectroscopy available**
  - **z≤0.095**; where $M_r$ limit equals the apparent magnitude limit of SDSS spectroscopy (r*~17.77)
  - **z≥0.05**; minimizing the aperture bias for nearby large galaxies (Gomez et al.2003, ApJ 584)

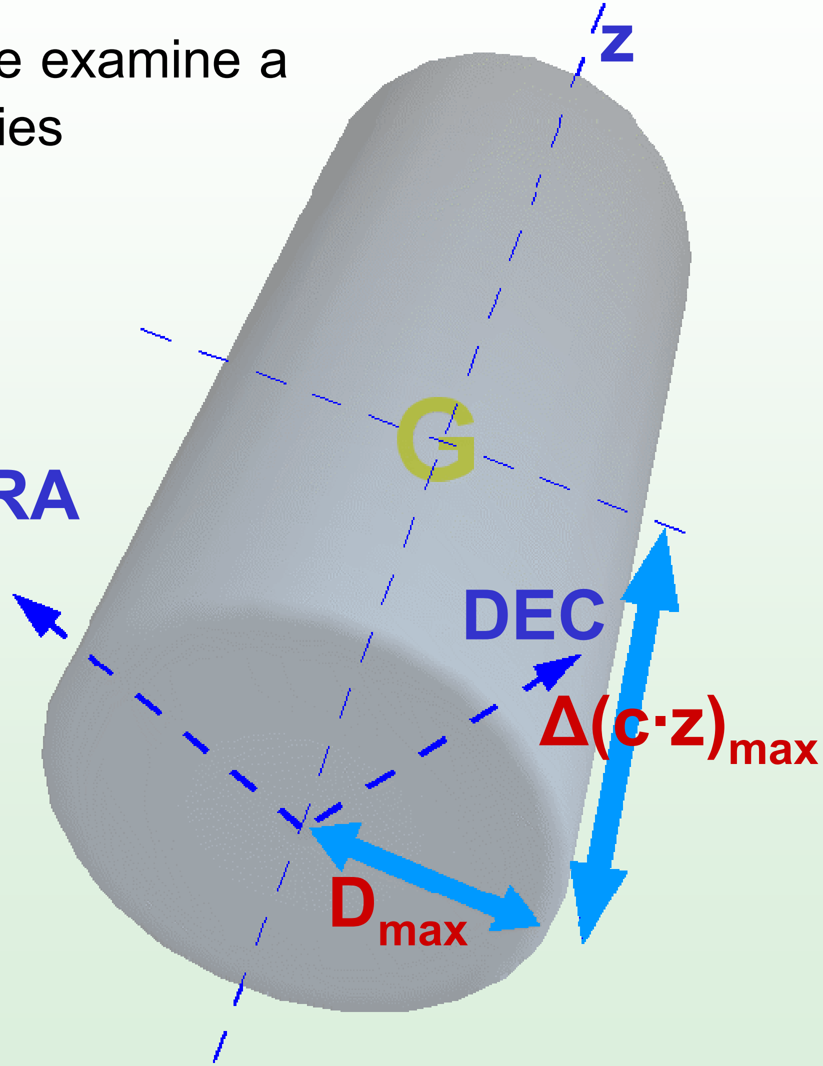
# FG candidates from SDSS

## optical selection criteria

For a given galaxy (G) with redshift $z_G$, we examine a cylinder around it, requiring that ALL galaxies

- within a given redshift interval, $\pm\Delta(c\cdot z)_{max}$, centered on $z_G$
- within a given projected distance on the sky, $D_{max}$, from G

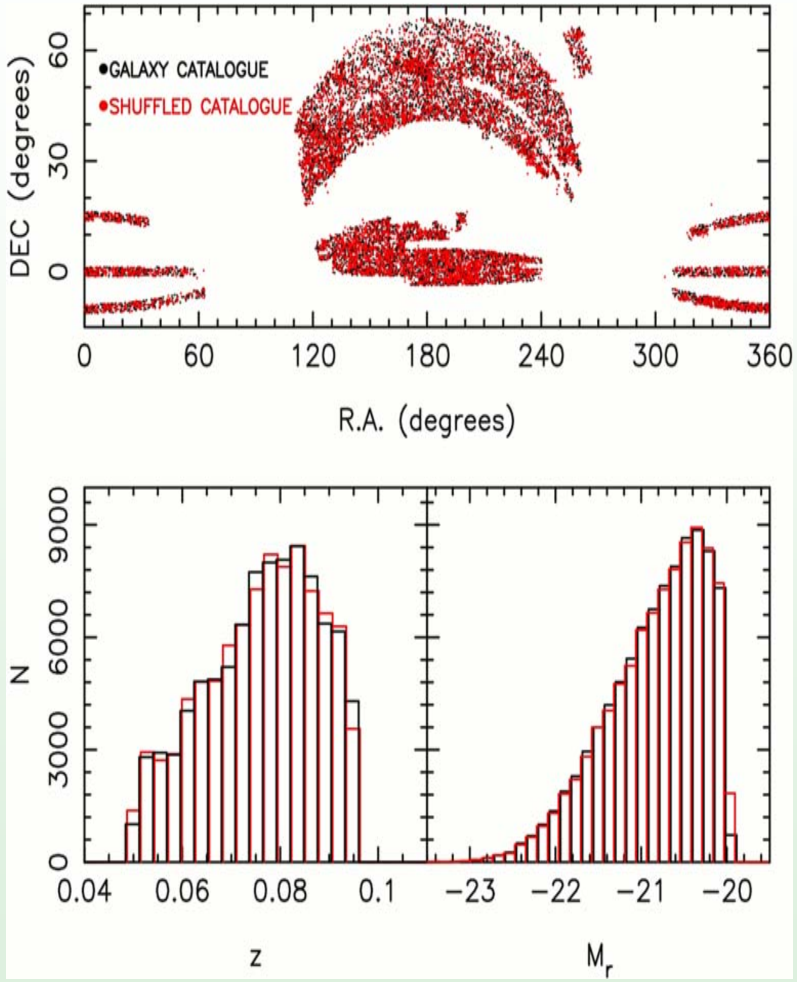
are fainter than G by a magnitude gap larger than $\Delta M_{min}$



# FG candidates from SDSS
## optical selection parameters

We set the values of the three optical selection parameters, **$\Delta(c \cdot z)_{max}$**, **$D_{max}$**, and **$\Delta M_{min}$** as a compromise between the sample size of FG candidates and contamination rates.

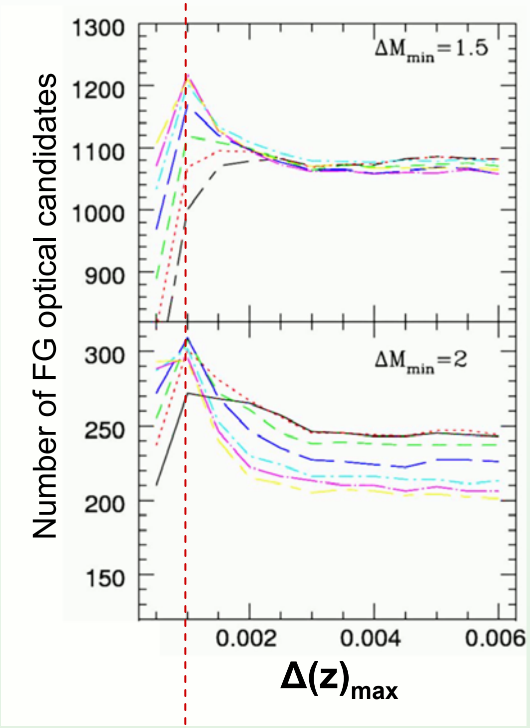
Contamination rates are estimated by shuffling the SDSS-DR4 galaxy catalog and counting the number of FG detections that randomly arise in the shuffled catalog for a given set of **$\Delta(c \cdot z)_{max}$**, **$D_{max}$**, and **$\Delta M_{min}$** values.

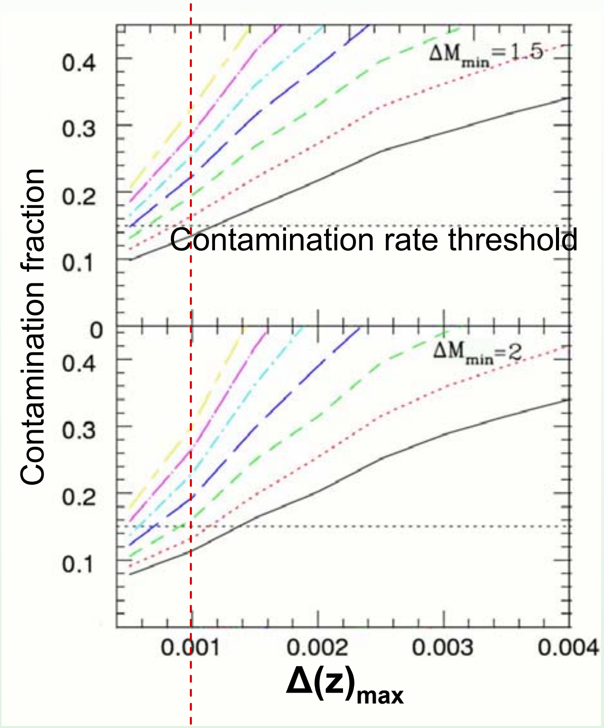


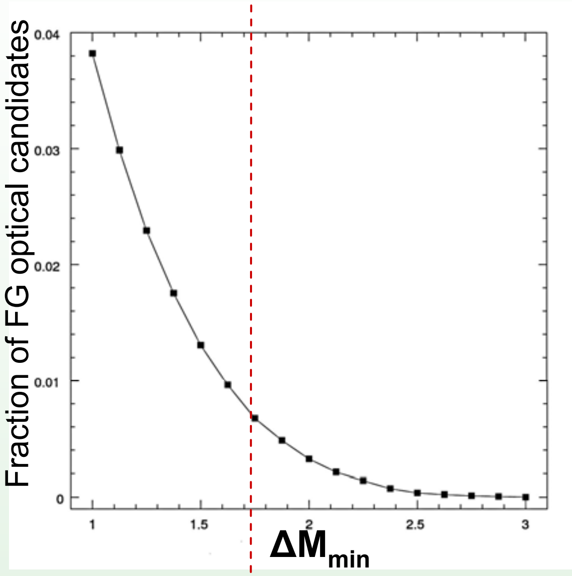

Distribution in RA and DEC (top), redshift (bottom-left) and magnitude (bottom-right) of the SDSS galaxy catalog and one of the shuffled catalogs.

# FG candidates from SDSS

## optical selection parameters



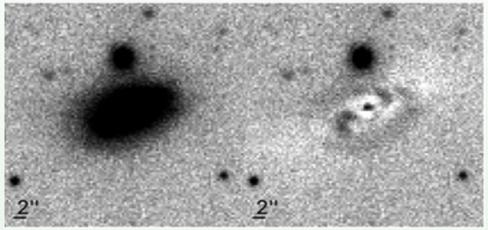

$\Delta(z)_{max}$ =0.001

$D_{max}$=0.35$h_{75}^{-1}$Mpc

$\Delta M_{min}$ =1.75mag

# FG candidates from SDSS
## further optical selections

$\Delta(c\cdot z)_{max}$, $D_{max}$, and $\Delta M_{min}$ → 578 galaxies



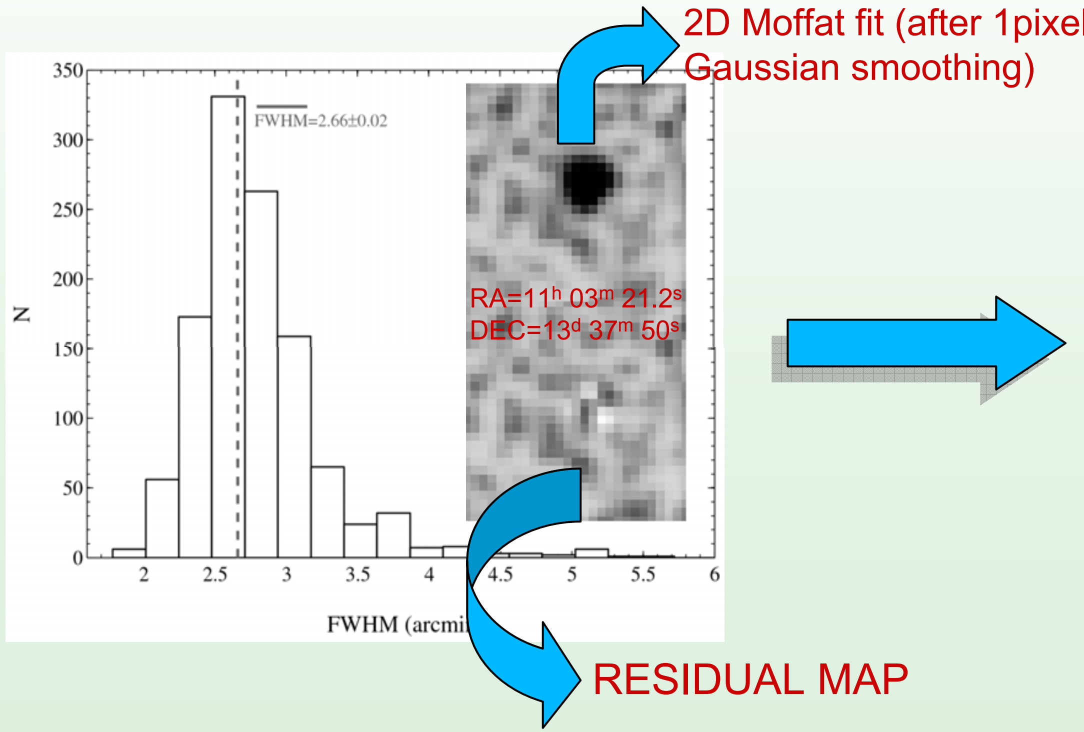

removing spiral galaxies (N=91)
(seed galaxy has to be elliptical)

removing AGN (N=45); as in Sorrentino et al. (2006, A&A 460) by using spectral line-ratio models (Kewley et al. 2001, ApJ 556)

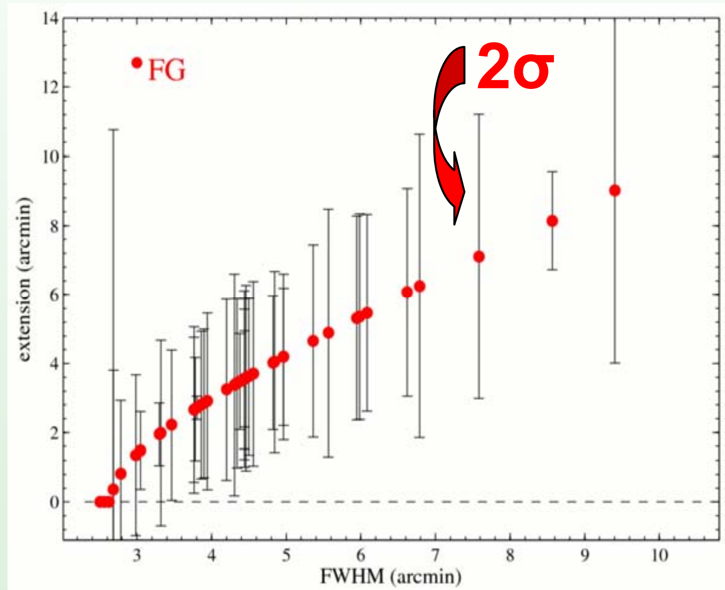
rejecting FGs within 1.5 $h_{75}^{-1}$Mpc from a rich (R>0) Abell cluster
(RASS does not allow us to single out any X-Ray emission)

# FG candidates from SDSS+RASS
## X-Ray selection criteria

For each optical candidate, we measure $L_X$ (0.5-2.0keV) from RASS in apertures of 5, 10, and 20 $r_e$ ($<r_e>$~10''~1kpc). A source has a significant X-Ray detection if it is matched to the optical position (within 1FWHM) and is 3σ above the background in at least one aperture.




FWHM of RASS PSF from 1232 point sources in the RASS BSC (Voges et al. 1999, A&A 349)



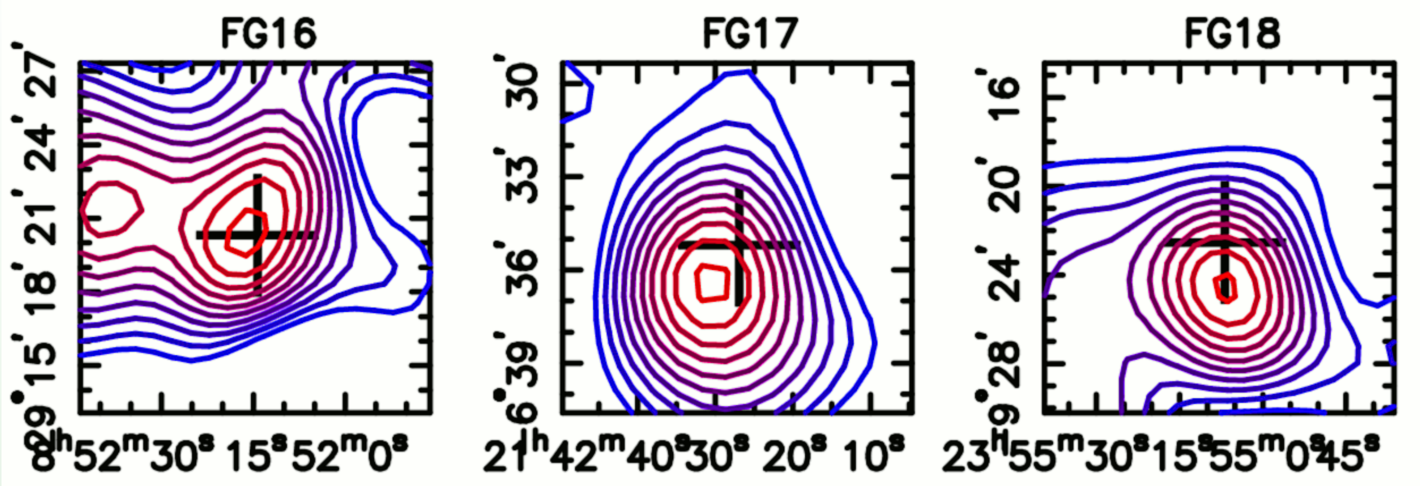

The extension is measured by subtracting in quadrature the PSF FWHM from the FWHM of FGs.

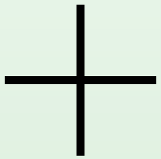
# FG candidates from SDSS+RASS

## X-Ray selection

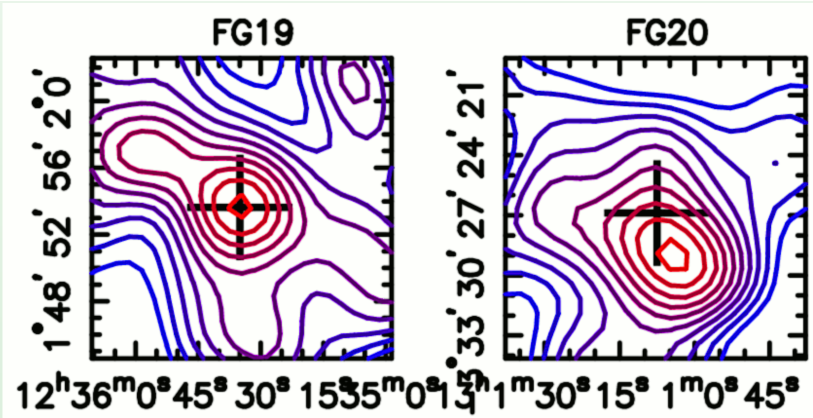
**THESE SELECTIONS LEAD TO A SAMPLE OF 25 FG CANDIDATES**

(after accounting for SDSS spectroscopic incompleteness due to fiber placement)



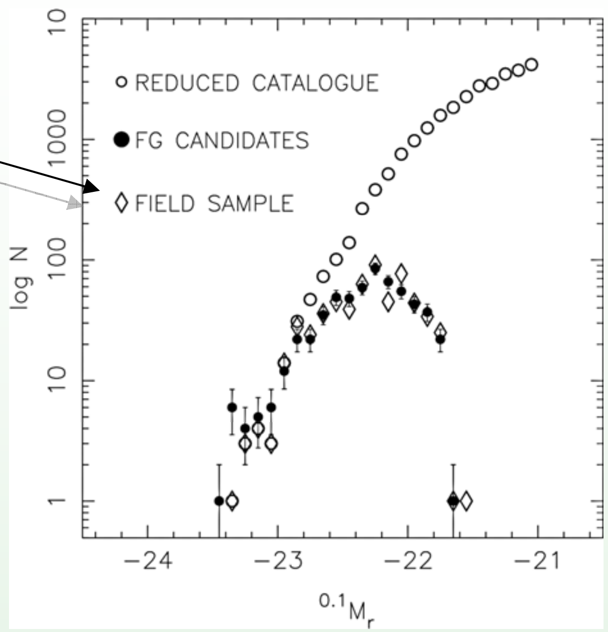
**OPTICAL POSITION**




X-Ray contours from RASS for 5 out 25 FGs. Crosses mark the position of the optical sources. A 2 pixel Gaussian smoothing has been applied.

# CONTROL SAMPLE from SDSS+RASS

We select 578 galaxies from the SDSS catalog after removing FGs (**NO** cylinder selection)




removing spiral galaxies and AGN

only X-ray significant detections with projected distance from a rich (R>0) Abell cluster larger than 1.5Mpc → **N=22**

X-ray extension > 0 (at 2σ level) → **N=17**
**against N=25 FGs**

# LAYOUT

Fossil Groups (FGs): background

FGs and *field* galaxies (FS) from SDSS+RASS

Measuring properties of FGs and FS

FGs vs. FS: comparison

# Measuring FG and FS properties

***Global* properties**

**X-Ray luminosity**

**density excess**

**spatial density**

***Galaxy* properties**

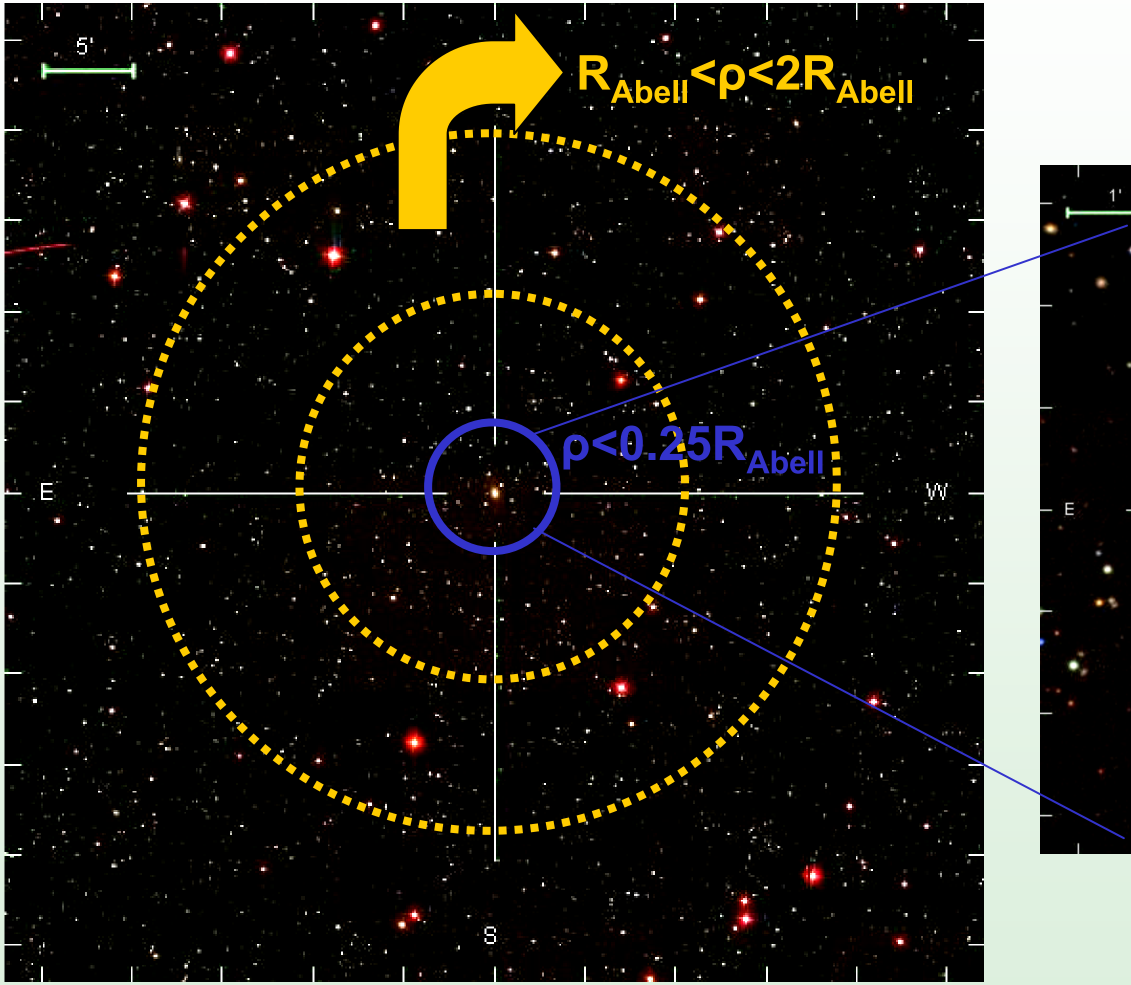
**distance to the red sequence**

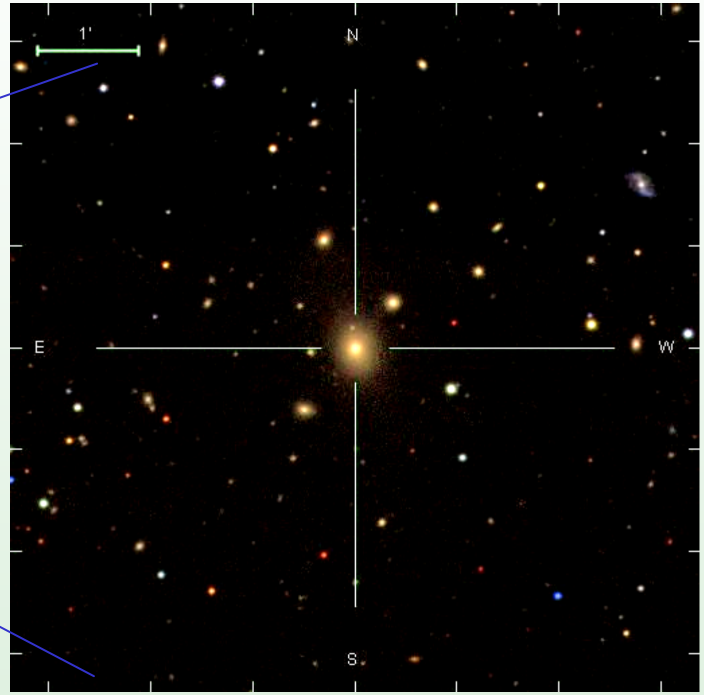
**structural parameters**:
effective radius, Sersic index,
boxy/disky A4 parameter, internal color gradients

**velocity dispersion**

**stellar population parameters**:
(age,metallicity, α-enhancement)

# DENSITY EXCESS

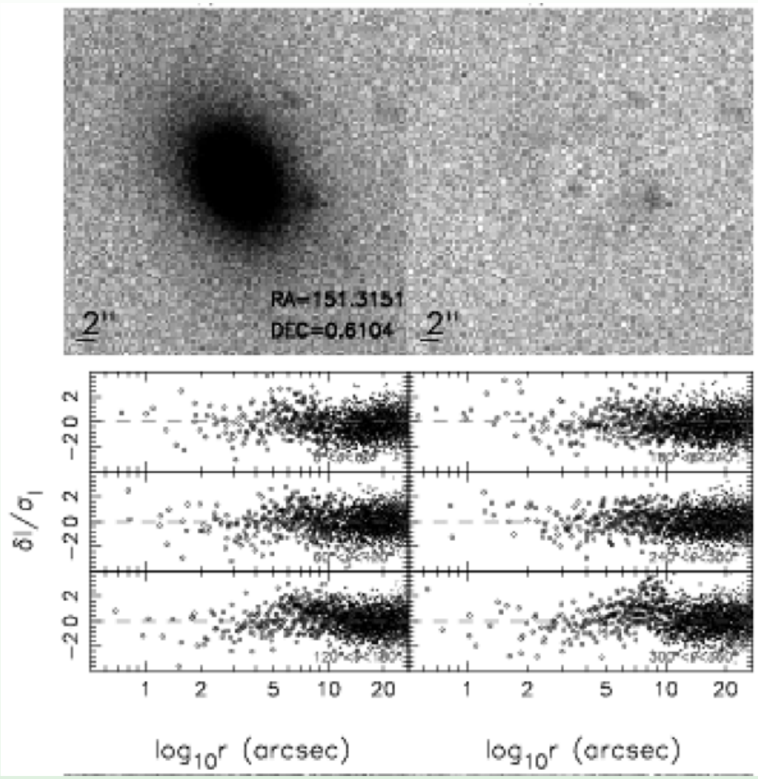


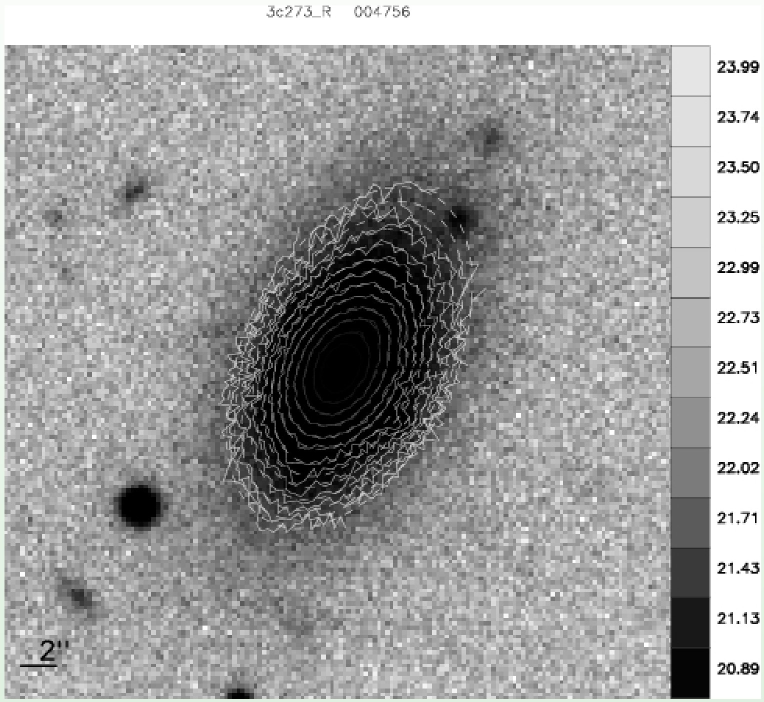




SDSS color snapshots for FG#1. The density excess is measured by subtracting the density of background/foreground galaxies in the outer ring from the density **inside the circle** around the seed galaxy.

# STRUCTURAL PARAMETERS

$I(x,y)=I_0 \cdot Exp[-b_n(r/re)^{1/n}]$ ⟺ $I_{obs}(x,y)=I \circ PSF(x,y)$

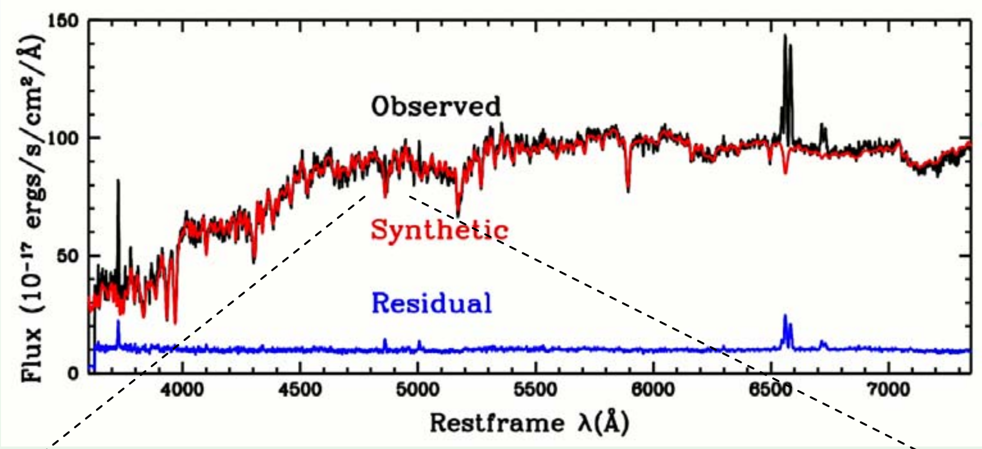


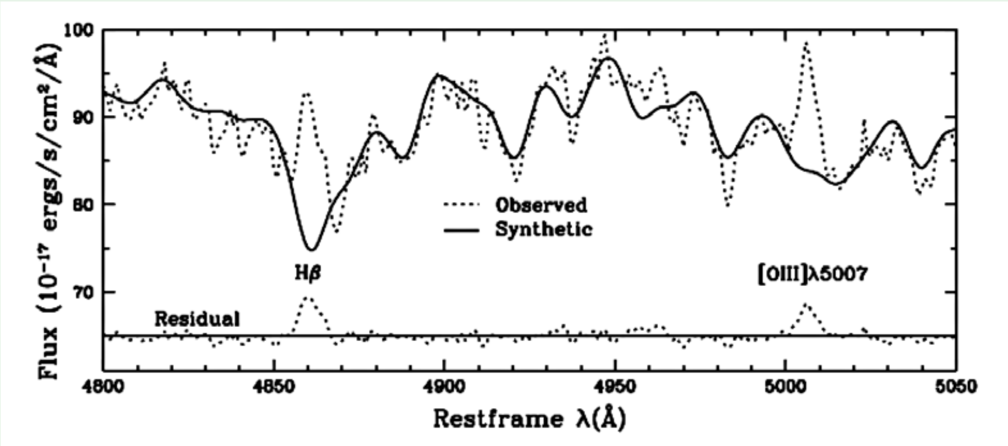




Structural parameters are measured by running 2DPHOT (La Barbera et al. 2008, PASP 120) on SDSS g- and r-band images. Galaxies are fitted by seeing-convolved Sersic models (left), and isophotes are analyzed (right) according to a sin/cos expansion (Bender et al. 1989, A&A 217). Internal color gradients are estimated by the slope of the radial color profile inside galaxies

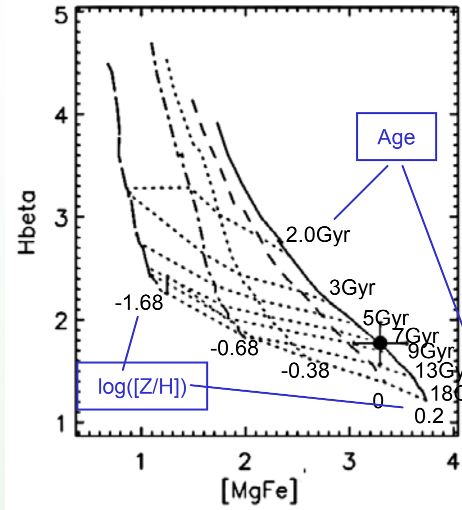
# SPECTROSCOPIC PARAMETERS

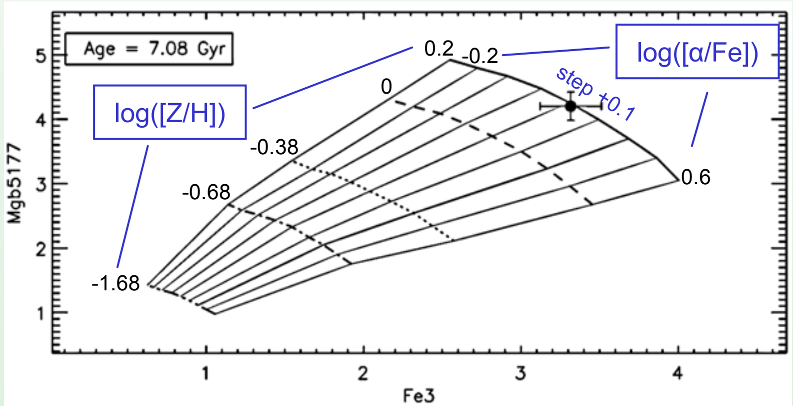
SDSS spectra are fitted (using STARLIGHT; Cid Fernandes et sl. 2005, MNRAS 358), with a set of SSP SEDs, broadened to match the galaxy's $\sigma_0$.




Residual spectrum revealing the $H_\beta$ nebular emission.




Age is measured from the [MgFe]' vs. $H_\beta$ grid. [Z/H] and [α/Fe] are inferred from the $Fe_3$ vs. Mgb grid. Grid are specifically constructed for each galaxy, degrading the models to match instrumental resolution and $\sigma_0$.

# LAYOUT

Fossil Groups (FGs): background

FGs and *field* galaxies (FS) from SDSS+RASS

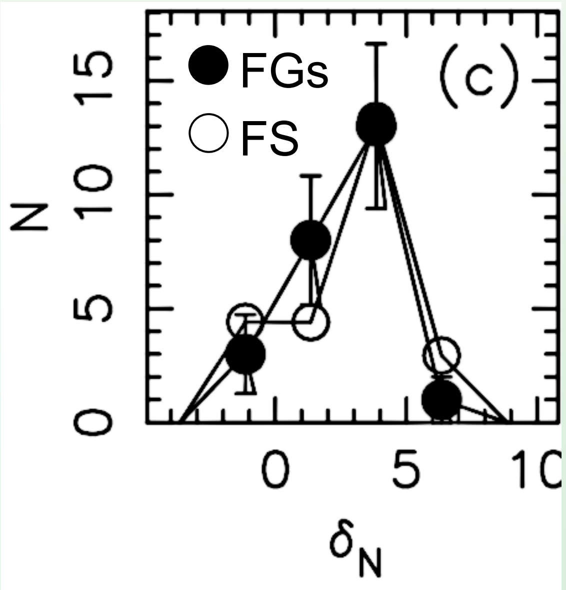
Measuring properties of FGs and FS

**FGs vs. FS: comparison**

# COMPARISON OF *GLOBAL* PROPERTIES

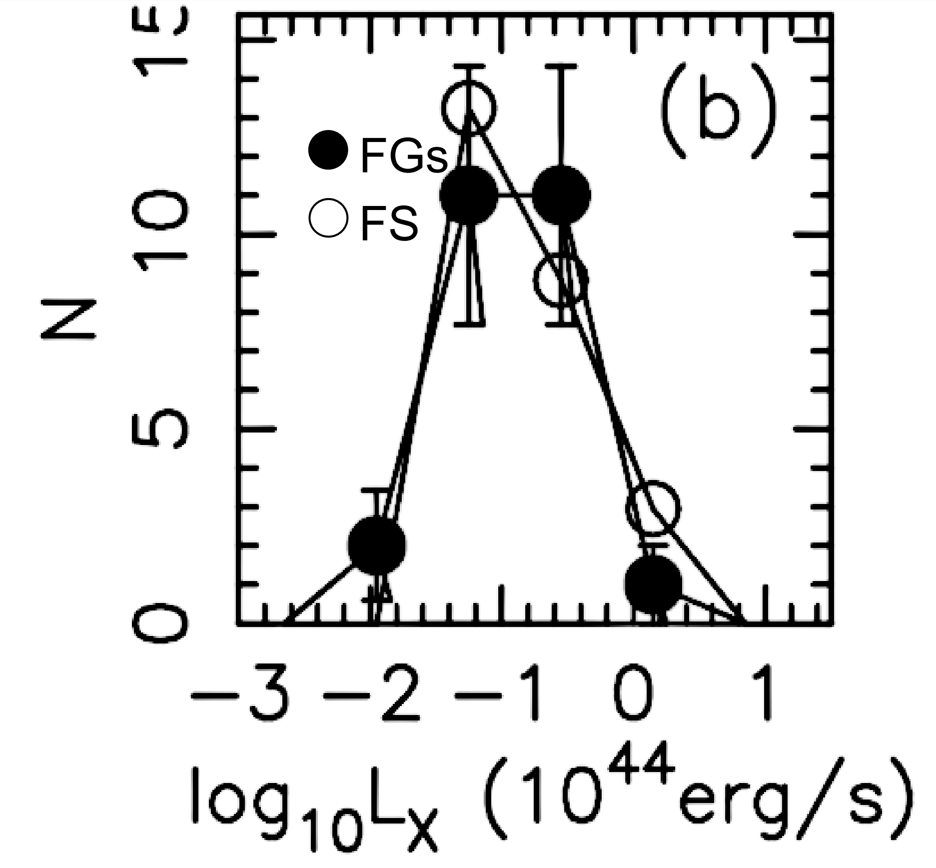
We estimate the space density of FGs (h=0.75) using $1/V_{max}$ statistics (Avni & Bahcall 1980, ApJ 235)

| | OUR ($Mpc^{-3}$) | PREVIOUS STUDIES ($Mpc^{-3}$) | |
|---|---|---|---|
| $L_X > 0.44 \cdot 10^{42}$ erg $s^{-1}$ | $3.4 \cdot 10^{-6}$ | $1.5 \cdot 10^{-6}$ | Vikhlinin et al. 1999 |
| | | $6.7 \cdot 10^{-6}$ | Romer et al. 2000 |
| | | $6.75 \cdot 10^{-7}$ | Jones et al. 2003 |
| | | $5.4 \cdot 10^{-6}$ | Dariush et al. 2007 (simulations) |




$\delta_N > 0$ → existence of a faint galaxy population around BOTH FGs and FS. The mean value of $\delta_N$ is 2.5±0.4 for FGs and 2.5±0.5 for field galaxies.

# COMPARISON OF *GLOBAL* PROPERTIES

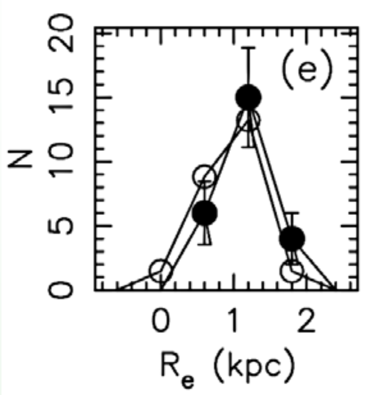


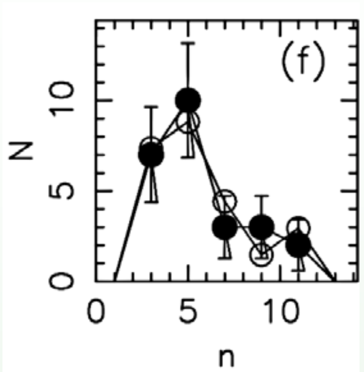

X-Ray luminosities of FGs and FS are very consistent. The mean log($L_X$) values amount to -0.9±0.092 and -0.84±0.15 for FGs and field galaxies, respectively.

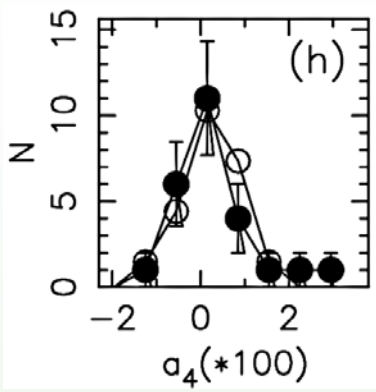
Since FGs and FS have similar optical luminosities (by construction), we do not find that fossils have enhanced $L_X$ ( in contrast to Khosroshahi et al. 2007 and Jones et al. 2003)

**IS $L_x$ for FGs HIGH BUT NOT EXCEPTIONAL WITH RESPECT TO BRIGHT ELLIPTICALS IN GROUPS** (as found for the M/L from Khosroshahi et al. 2007) ?

# *GALAXY* PROPERTIES: PHOTOMETRY

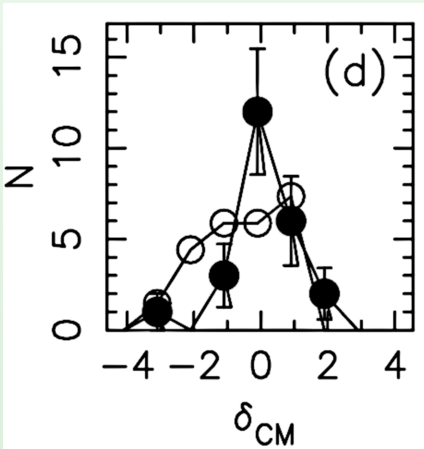


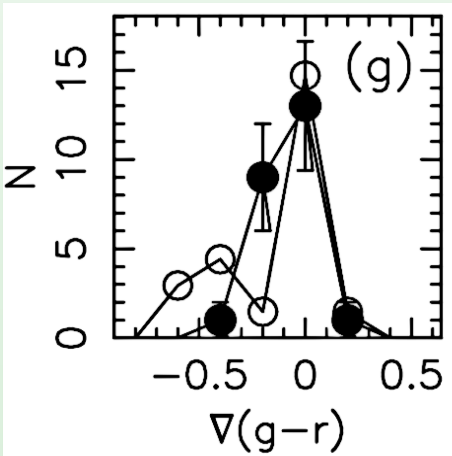




FG and FS seed galaxies have very similar structural properties.

Seed galaxies have **both disky and boxy isophotes** (in contrast with Khosroshahi et al. 2007 and in agreement with simulation results of Díaz-Giménez et al. 2008, A&A 490)

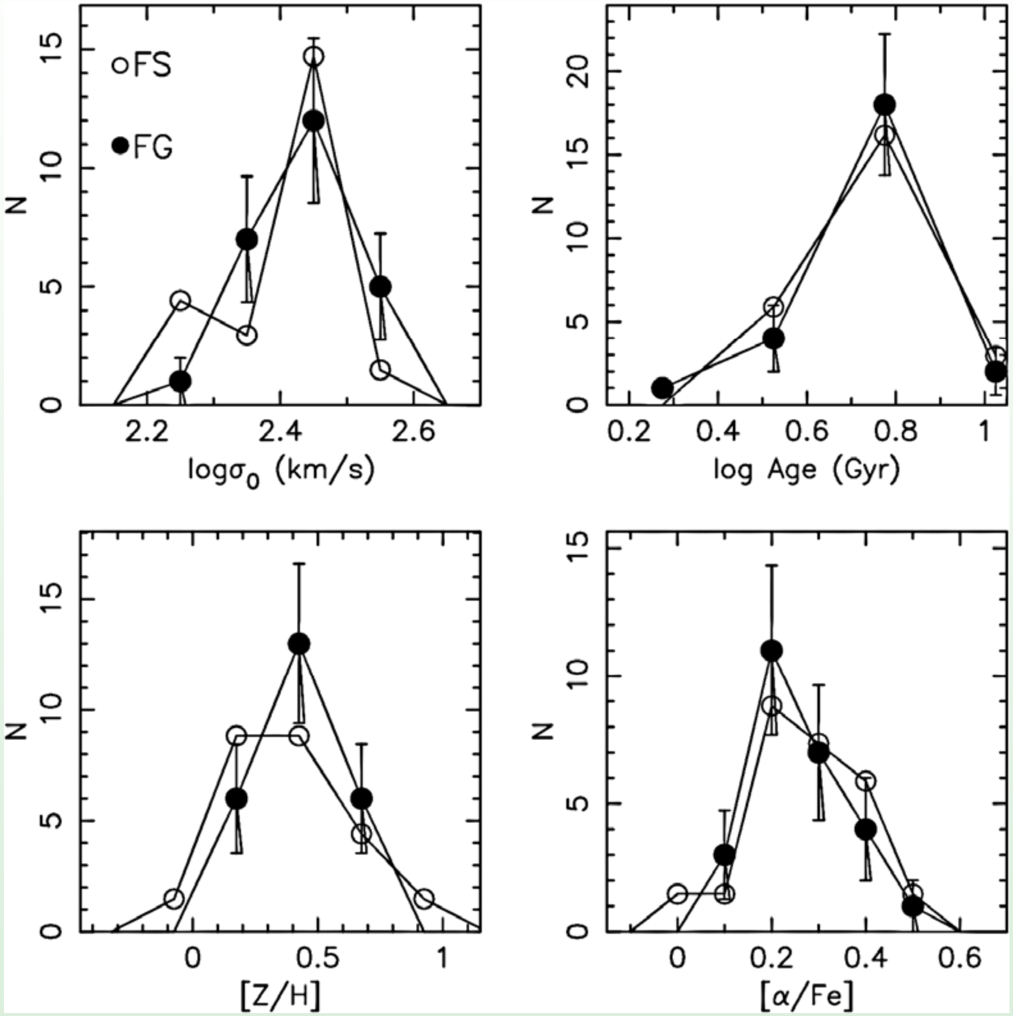



Distance to the red sequence and color gradient distributions have consistent peak values, though FGs seem to have narrower distributions.

The KS tests indicate no significant difference.

# *GALAXY* PROPERTIES: SPECTROSCOPY

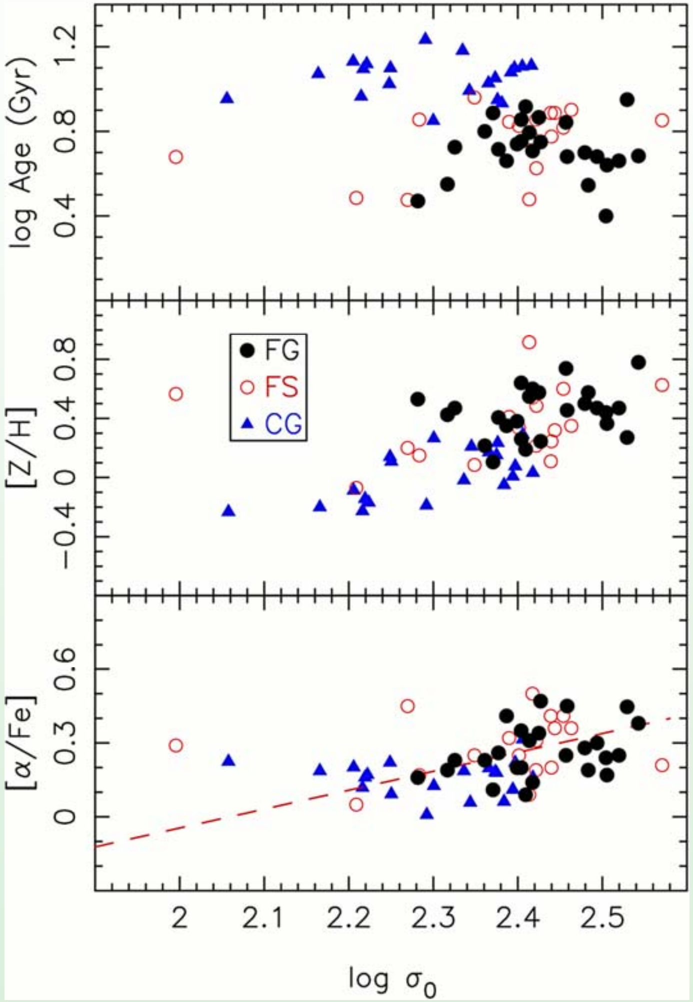



FG and FS seed galaxies have fully consistent distributions of

- $\sigma_0$ (galaxy mass)
- luminosity weighted Age
- metal content [Z/H]
- abundance ratio [α/Fe]

**very similar star formation history**

# CGs → FGs ???




Twenty early-type galaxies (ETGs) in HCGs from de La Rosa et al. (2007, AJ 133), re-analyzed as FGs

ETGs in HCGs have higher Age and lower [Z/H] than *field* (Proctor et al. 2005, MNRAS 349; Mendes de Oliveira et al. 2005, A&A 285) **AND** FG galaxies

ETGs in HCGs have lower [α/Fe] than both *field* **AND** FG ellipticals

**CGs → FGs ??? NO**

**Dry mergers do NOT increase [α/Fe].**

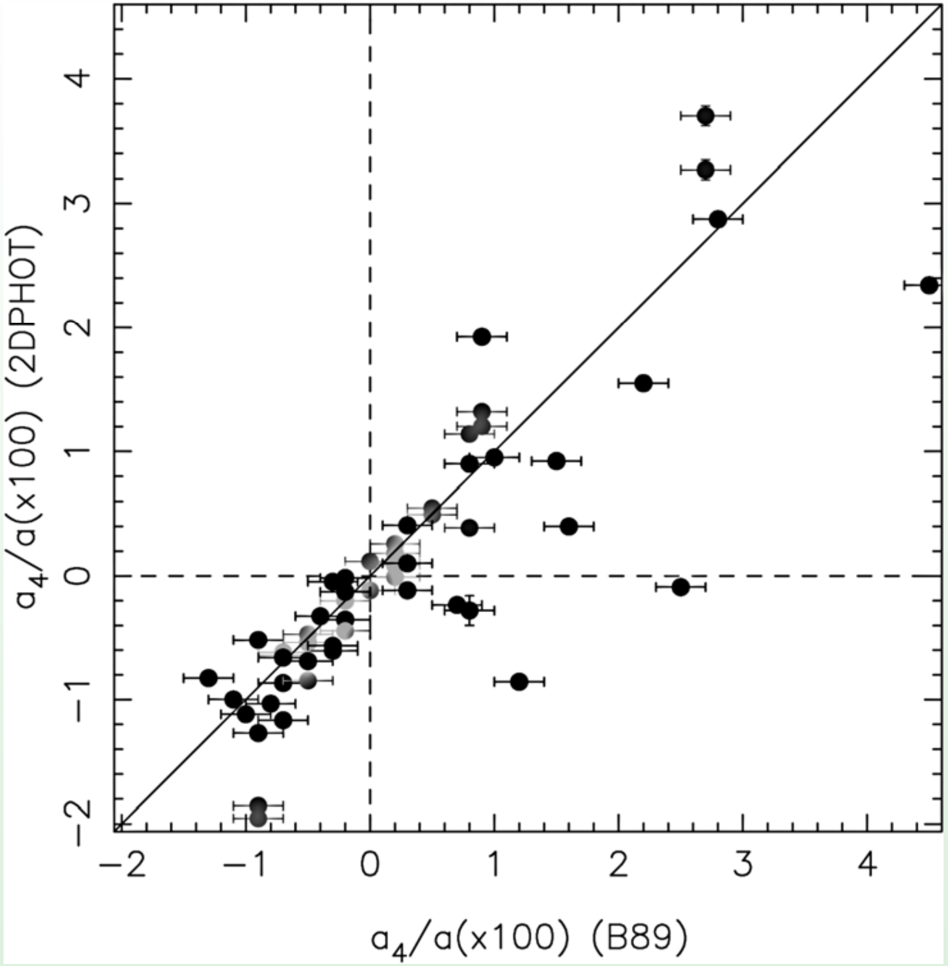
**Wet mergers not dominant ($\nabla_{g-r}$ and $A_4$)**

**UNLESS CGs at z>0 are different than the nearby ones** (de Carvalho et al. 2005, AJ 130; Mendes de Oliveira & Carrasco 2007, ApJL 670 )

# Conclusions

- We have defined a new sample of 25 Fossil Groups with SDSS+RASS data, and a control sample of 17 “field” galaxies (FS), selected in the *same* way as FGs.
- **Both FGs and FS exhibit a positive density excess**, indicating the presence of fainter galaxies around them.
- **FGs and FS are fully consistent as far as global properties** (density excess, X-Ray luminosity) **AND galaxy properties** (structural parameters and stellar populations) are concerned.
- We find that **seed galaxies in FGs have both disky and boxy isophotes**, questioning the idea that they mainly form by gas-rich mergers and supporting the idea that also more massive BCG ellipticals might form through a fossil phase.
- Ellipticals in CGs have higher ages, lower metallicities, and lower abundance ratios than those in FGs and the *field*, inconsistent with the idea that (most of) FGs form from CGs.
- Approved XMM proposal (Prp: 060539; PI M. Paolillo) to investigate the nature of the X-Ray emission around FGs.

# STRUCTURAL PARAMETERS



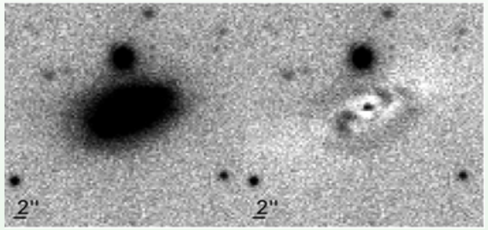

Comparison of 2DPHOT (La Barbera et al. 2008, PASP 120) a4 estimates (from SDSS r-band images) with those reported by Bender et al. 1989 A&A 217. Grey symbols show the results of repeated measurements of $a_4$ from multiple SDSS images of the same galaxies.

# FG candidates from SDSS

## further details on optical+X-Ray selection

$\Delta(c \cdot z)_{max}$, $D_{max}$, and $\Delta M_{min}$ → 578 galaxies

↓




removing spiral galaxies (N=91)
(seed galaxy has to be elliptical)

↓

removing AGN (N=45); as in Sorrentino et al. (2006, A&A 460) by using spectral line-ratio models (Kewley et al. 2001, ApJ 556)

↓

retaining only the 102 FG candidates with X-Ray significant detection (>3σ in at least one aperture)

# FG candidates from SDSS
## further details on optical+X-Ray selection

74 (out of 102) significant detections are retained after removing those sources close to rich clusters

↓

We match the optical and X-Ray sources by considering a matching distance lower than the FWHM of the X-Ray source. 43 (out of 74) survive this criterium

↓

Only (N=35) sources with extent larger than 0 at 2σ are retained. The error on the extent parameter is obtained from the error on the FWHM value. This last uncertainty is estimated by a bootstrap procedure. RASS images are 1pixel smoothed, and fitted with a Moffat distribution (after running S-Extractor with a detection threshold of 2σ over an area of 5 pixels and masking out all the sources but the one closest to the optical position). A noise image is created by bootstrapping pixel values in the residual image. The Moffat fit is added to the noise frame and the fit is repeated.

# FG candidates from SDSS
## further details on optical+X-Ray selection

We check if there are possible gap contaminants (i.e.g galaxies inside the selection cylinder with $\Delta M<1.75$) with spectroscopy in either SDSS-DR6 or NED. This leads us to invalidate 9 out of 35 FGs. Moreover, we find one candidate to have three contaminants in the gap with concordant photometric redshifts. This was excluded from the final list, leading to N=25 FGs.

The same analysis leads to remove 4 (out of 8) FG candidates with unresolved X-Ray emission

As a further check for the significant detection of the X-Ray source, we checked That 20 (out of 25) FGs have X-Ray significant emission in both the large ($20r_e$) and the smaller 5 or 10 $r_e$ apertures.