The gas-galaxy-halo connection

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The galaxy diversity
The galaxy zoology: the Hubble sequence

How did galaxies form and evolve from the initial baryon density field to the galaxy diversity as seen today?

Elliptical galaxies
or early-type galaxies
or “red” galaxies

Spiral (disk) galaxies
or late-type galaxies
or “blue” galaxies

dwarf, irregular,
+ peculiar galaxies and
active galactic nuclei

rare objects but carry
some precious information
about galaxy evolution

How did galaxies form and evolve from the initial baryon density field to the galaxy diversity as seen today?
The galaxy statistics (e.g. the stellar mass function)

- all galaxies. redshift evolution
- sf galaxies. Dominate at faint luminosity/low z
- passive galaxies. Dominate at bright luminosity

Ilbert et al. (2013)
What is the interplay between physical processes?

ΛCDM cosmology

No cooling, no star

Star formation stops

Star formation goes on

Galaxy evolution: depends on halo mass, environment and redshift

Hubble sequence observed today

Mo et al. (2011)

SDSS, Blanton & Hogg
Star formation (in)efficiency in dark matter haloes

Stellar mass function depends on halo mass (environment)

Star formation efficiency depends on halo mass (environment)

(Local Universe)

Moster et al. (2010)
Lin et al. (2014)
At $z=0$, from low- to high-mass haloes

Observations in the local Universe (mostly: SDSS)
Where do we stand at z=1?

Ideally one wants to probe both the low- and high-mass regime.

\[ \frac{M_{\text{star}}}{M_h} \]

low mass galaxies = requires deep data

COSMOS/UDS at z=1

CFHTLS/KIDS/DES at z=1

Clusters = requires volume
NUV < 24.5, ugriz < 25, K < 22, ~ 0.1 Gpc$^3$ in 0.5 < z < 1.0
Where do we stand at $z=1$?

$rac{M_{\text{star}}}{M_h}$

Unique depth/volume combination at $z=1$!

- CFHTLS/VIPERS-NIR at $z=1$

- $M^*$ gals $\sim 10^{10} \, M_\odot$

- Clusters $\sim$ a few $5 \times 10^{14} \, M_\odot$
Stellar to halo mass relationship

\[ \Omega_b/\Omega_m = 0.171 \]

\[ M_*/M_h \]

- This study (total)
- This study (satellites)
- This study (centrals)
- Leauthaud et al. (2012), z\sim0.9
- Behroozi et al. (2013), z\sim1.0
- George et al. (2011), z\sim0.8
- Hilton et al. (2013), z\sim0.5
- van der Burg et al. (2014), z\sim1.0
- Balogh et al. (2014), z\sim0.9

JC et al. (2015)
Comparison with simulations

Deficit of star formation in medium mass \((10^{10})\) satellites
The *gas*-galaxy-halo connection

- gas “temperature cycle” and AGN feedback are the drivers of star formation
- $f_{\text{gas}}$ is a **key observable** to understand galaxy evolution
- galaxy group regime is the **new frontier** for X-ray probes
- we measured stacked X-ray, lensing and star fraction profiles for groups up to $z=1$ in CFHTLenS/XXL field
- we obtained **constraints on baryon fraction** down to $10^{12} \ M_{\text{sun}}$ halos up to $z=1$
I. The gas-halo connection as a tracer of feedback

- AGN feedback
  - expulses the gas to outer regions (>r500)
  - flattens out profile (decreases Lx)
  - gas fraction is a sensitive probe of AGN feedback strength

Le Brun et al. (2014)

Hydro simulations measured fractions (z=0)

“halo-mass desert”
I. The gas-halo connection as a tracer of feedback

- several models: self-regulated jets, QSO thermal blast
- low-mass regime is most sensitive to feedback modes

Gaspari et al. (2014)
II. The gas-halo connection as a tool for cosmology

• Mgas as primary proxy for halo mass?

• XXL clusters reveal tighter for Mgas-Tx

Lieu et al. (2016)  
Eckert, Ettori, JC et al. (2016)
Probing the gas in groups is very challenging

- X-ray brightness is proportional to gas density
- hot gas in groups is thousand times dimmer than in massive clusters
- star binaries become as bright as hot gas at low-mass
- is AGN contamination an issue?
- so far hot gas profiles were only measured at low-z or for a handful of very deep observations
Probing the gas in groups is very challenging

- but we can “stack” X-ray photons from optically detected BCGs

- requirements:
  - contiguous X-ray survey
  - a sample of central galaxies (although a gas-profile parametric model including satellites is feasible)

- main drawback of stacking analysis is that we can’t easily measure the scatter -> need to assume one

- biased results if scatter is off
Stacking $L_x$ in the local Universe

- Anderson et al. (2014) stacked X-ray luminosities of local BCGs
- followed-up with lensing masses by Wang et al. (2015)
- impressive detection of hot gas signal down to group-scale systems
- but large PSF, no density profile -> no gas mass
- restricted to the local Universe
Stacking $L_X$ at higher redshift

- Leauthaud et al. (2010) stacked X-ray detected groups in deep XMM/Chandra data
- measurements up to $z=1$
- group/cluster regime at mid-$z$, massive cluster regime at high-$z$, no gas masses

Leauthaud et al. (2010)
The XXL survey

- **X-ray survey** over 50 deg$^2$ (2 fields) with XMM-Newton
- contiguous 10 ks observations (largest program ever allocated with XMM)
- resolution four times better than ROSAT

Pacaud et al. (2016)
The XXL survey

ROSAT all sky survey

XXL

XMM pointing
A unique combination of data

- near-IR from WIRCam follow-up
- 20-40% complete spectroscopy for bright galaxies (VIPERS/SDSS)
- lensing data from CFHTLenS
- secure BCG sample

Figure 1. Footprints of the different datasets used in this work. Our selection is based on WIRCam data shown in red and covering approximately 25 deg$^2$ (23.1 deg$^2$ after masking). The CFHTLS MegaCam pointings are shown in grey, the GALEX DIS observations as large blue circles (in purple if overlapped with WIRCam), the spectroscopic surveys VIPERS/VVDS in light green and PRIMUS in dark green. The SDSS/BOSS coverage is almost complete. The data outside the WIRCam footprint are not used, and shown here only for reference.

Simulating the CFHTLS-Wide data depth, we have checked that this incompleteness is caused by red galaxies above $z=1$ and does not affect our sample selected in the range $0.5 < z < 1$.

The $K_s$ MAG_AUTO estimates are then simply matched to their optical counterparts based on position.

In addition to this dataset, we also use the CFHTLS-D1 WIRDS data (Bielby et al. 2012), a deep patch of 0.49 deg$^2$ observed with WIRCam $J$, $H$- and $K_s$-bands and centered on $02^h 26^m 59^s$, $-04^\circ 30' 00''$. All the bands reach 50% completeness at AB magnitude 24.5.

The WIRCam observations are shown in Fig. 1 as the red regions. After rejecting areas with poor WIRCam photometry and those with CFHTLenS mask flag larger than 2, the corresponding effective area used in this work spans over 23.1 deg$^2$, divided into 15 and 8.1 deg$^2$ in the VIPERS-W1 and VIPERS-W4 fields, respectively.

### 2.3 The UV-GALEX observations

When available, we make use of the UV deep imaging photometry from the GALEX satellite (Martin et al. 2005; Morrissey et al. 2005). We only consider the observations from the Deep Imaging Survey (DIS), which are shown in Fig. 1 as blue circles ($\sim 1.1$ deg$^2$). All the GALEX pointings were observed with the NUV channel with exposure times $T_{\text{exp}} \geq 30$ ksec. FUV observations are available for 10 pointings in the central part of W1.

Due to the large PSF (FWHM $\sim 5''$), source confusion becomes a major issue in the deep survey. To extract the UV photometry we use a dedicated photometric code, EMphot (Conseil et al. 2011) which will be described in a separate paper (Vibert et al. in prep.). In brief, EMphot uses $U$-band (here the CFHTLS $u$-band) detected objects as a prior on position and flux. The uncertainties on the flux account for the residual in the [simulated − observed] image. The images reach a depth of $\text{m}_{\text{NUV}} \sim 24.5$ at $\sim 5\sigma$. As for the WIRCAM data, the GALEX sources are matched to the optical counterparts based on position.

The NUV observations cover only part of the WIRCam area with $\sim 10.8$ and 1.9 deg$^2$ in VIPERS-W1 and VIPERS-W4, respectively. The UV photometry slightly improves the precision of photometric redshifts and the stellar mass estimates in the GALEX area. However, by comparing our measurements inside and outside the GALEX area, we have checked that the addition of UV photometry does not make a significant change for the galaxies of interest in this study.
A large volume up to $z=1$

- surface of a few 10’s of deg$^2$
- but equivalent to large volume at $z > 0.2$
Stacking X-ray photons

- we selected a sample of ~20,000 central galaxies from spectroscopy and deep optical/near-IR data

- binned in 3 redshift bins \((0.2 < z < 1.0)\) and 6 stellar mass bins \((10.5 < \log M_{\text{star}} < 12.0)\)

- low-mass bins contains ~3,000 gals -> 30 Ms (!) of X-ray observations per bin (1 year of XMM data)

- point sources detected in soft and hard bands masked

(from M. Ramos)
Where do we stand in the $L_x$/redshift plane?

- X-ray detected halos & wide area surveys
- XXL
- Leauthaud et al. (2010) deep X-ray observations
- Stacked X-ray observations
- X-ray binary stars limit
Stacked X-ray profiles (0.2 < z < 0.35)

Preliminary results
Stacked X-ray profiles (0.2 < z < 0.35)

Preliminary results
Galaxy-galaxy lensing profiles ($0.2 < z < 0.35$)

Preliminary results
X-ray luminosity versus halo mass

Preliminary results
Gas fraction (z~0.29)

Preliminary results
Extreme AGN feedback is ruled out

Preliminary results
Gas fraction at high-z

Preliminary results
Gas fraction at high-z

- gas fraction evolution?

- Vikhlinin et al. (2009), Lin et al. (2012)

- increased gas fraction between $z \sim 0.1$ and 0.6

- evolution due background critical density evolution (hence $M_{500}$)?
Measurement systematics?

Preliminary results
AGN contamination?

Preliminary results
The baryon fraction

Preliminary results
Conclusions

• measured the halo-galaxy connection up to z=1 in the CFHTLS

• measured X-ray and lensing profiles up to z=1 in galaxy groups

• rules out extreme AGN feedback

• self-regulated feedback seems to be favoured (TBC)

• baryon fraction increasing with redshift?

• very low-mass regime still exploratory, systematics not under full control

• -> needs better photo-z’s and lensing large area (Subaru HSC)

• -> and deeper X-ray observations (Athena, STAR-X?)