Search and confirmation of passive galaxies in the early Universe

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Outline

• Passive galaxies (what are they, why do we care, when did they appear...?)

• Selection techniques
  • A sample of z>3 passive candidates in CANDELS (Merlin+18, +19subm.)

• Confirmation techniques
  • Exploitation of the ALMA archive (Santini+19)

• What can we expect from future big eyes?

• Summary & conclusions
Two populations of galaxies

Schawinski+14
Two populations of galaxies

\[ \log(\text{sSFR/yr}) = -0.7 \log(M/M_\odot) - 5.0 \]

SDSS

\[ 0.07 < z < 0.09 \]
\[ 0.1 < z < 0.2 \]
\[ 0.2 < z < 0.3 \]
\[ 0.3 < z < 0.4 \]
\[ 0.4 < z < 0.55 \]
\[ 0.55 < z < 0.7 \]

AGES

Choi+14
The emergence of the passive population

Local Universe

Bluck+14

Passive galaxies are less abundant at high redshift

High-z Universe

Santini+09

Passive Star-forming

redshift
Passive galaxies at high z: a challenge for theoretical models

Theoretical models struggle to reproduce the observations (Fontana+09, Vogelsberger+14, Feldmann+16, Merlin+19, Cecchi+19, ...)

The abundance of passive galaxies at different epochs is a powerful probe of the delicate interplay among the different physical processes responsible for their rapid assembly and for the abrupt shut-down of their SF activity (e.g. merger-driven starbursts, feedback, ..).

Need for reliable selection criteria!

Fontana, PS, +09
How do we select passive candidates?
Selection techniques: colour-colour diagrams

Observed colours

Star-forming galaxies at $z>1.4$

BzK diagram $z\sim2$

Daddi+04
Selection techniques: **colour-colour diagrams**

**Observed colours**

**BzK diagram**  
$z \sim 2$

**VJL diagram**  
$z \sim 3$

**iHM diagram**  
$z \sim 4$

See also *Labbé+05* (iKM diagram), *Wiklind+08* (JKL diagram, $z>5$), *Mawatari+16* (KLM diagram, $z>5$)
Selection techniques: colour-colour diagrams

Rest-frame colours

UVJ diagram

Quiescent

Star-Forming

(see also Wuyts+07, Williams+09, Patel+11, Straatman+14, Martis16, Fang+18, ....)

Whitaker+11

See also similar diagnostics diagram such as the NUVrJ or NUVrK (Arnouts+13, Ilbert+13, Davidzon+17, …)
Selection techniques: colour-colour diagrams

Straatman+14:

19 UVJ passive galaxies (GOODS-S+COSMOS+UDS)
3.4<z<4.2
logM/M_☉>10.6
15/19 have no FIR detection
Nayyeri+14:

16 post-starburst galaxies (GOODS-S)
Selected from the amplitude of the Balmer break (H-K) (+ (J-H) and (Y-J) + non detections in U and B to reduce contaminants)
3<z<4.5
M~5x10^{10}M_☉

See Wiklind+08, Mawatari+16 for z>5 passive candidates
Selection techniques: SED fitting

(see also Grazian+07, Fontana+09, ...)

Merlin+18, +19subm
Selection techniques: **SED fitting + colour cut**

Deshmukh+18:

Combination of SED fitting (to separate dusty from non-dusty) and colour-cut (to separate blue unobscured from red passive galaxies) $2<z<6$
SED fitting vs colour-colour selection: importance of the SFH

SFH: which is the “best” choice at high z? (Very short timescales, close to formation epoch)

See also Ciesla+16
SED fitting vs colour-colour selection

**Schreiber+18**

The UVJ selection is incomplete

**Deshmukh+18**

('quiescent')

**Merlin+18**

Top-hat models
CANDELS: the deepest multiwavelength data

Deep NIR/MIR photometry is fundamental to sample the 4000Å break in z>3 galaxies

(Official CANDELS catalogs; GOODS-South: Guo+2013, Fontana+2014 K+U bands, + new IRAC data w/ T-PHOT)

Credits: E. Merlin
z>3 passive galaxies in the CANDELS fields

Selection based on SED fitting assuming top-hat SFH with a probabilistic approach

Talk by E. Merlin

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1.73±0.17 \times 10^{-5} \text{ Mpc}^{-3}
z>3 passive galaxies in the CANDELS fields
Selection techniques: issues and uncertainties

**COLOUR-COLOUR DIAGRAMS:**

- Incompleteness and contamination from red dusty galaxies
- May be affected by the lack of one band (used for the selection)

In particular, at high-z:

- Galaxies are redder
- Colour cuts inappropriate to take into account the short timescales available for galaxies to become quiescent

**SED FITTING:**

- Parameter degeneracy
- Rely on few bands
- Sensitive to the details of the adopted library
- Fit with nebular lines sensitive to photo-z uncertainty
How can we confirm the passive nature of these candidates?
Confirmation: spectroscopy

Cimatti+04

4 targets from GOODS/K20 surveys:

18<K<19
1.6<z<1.9
VLT FORS2
3 to 16 hr, tot 34 hr

(see also Kriek+06,+09,+15, Gobat12, Onodera+12, Whitaker+13, Belli+14, van de Sande+16, Hill+16, …)
The most distant spectroscopically confirmed passive galaxy: 
$z=3.713$ (K=22.4, M=$1.7 \times 10^{11} M_\odot$)
Keck MOSFIRE
4 hr H band, 7 hr K band
Median SNR$_K$=6
Confirmation: spectroscopy

Schreiber+18

24 UVJ-selected targets:

21.7<\text{\textit{K}}<24.2

3<\text{\textit{z}}<4

Keck MOSFIRE

1.6 to 7.2 hr in K band

0.7<\text{\textit{SNR}_K}<12

50% have measured redshifts

2 low-z dusty SF-ing
Exclude contamination from dusty galaxies by means of FIR/sub-mm observations.

*Confirmation: look at the sub-mm!*

Schreiber+18

Star-forming, dusty galaxy

Passive, dust-free galaxy

ALMA
41 $z>3$ passive candidates in CANDELS (Merlin+19subm.) observed by ALMA in Band 6 or Band 7.

All data are imaged to $\geq 0.6$ arcsec resolution.

Only 1 source is detected at $4\sigma$ (few marginal detections at $<3\sigma$, consistent with a normal distribution of the SNR for undetected sources).

For the remaining sources, no detection even in the stacks.

ALMA flux measurements converted into (constraints on the) SFR.

Santini+19, Santini+in prep.
Validation of robust individual candidates

Compare ALMA predictions to the SF-ing solutions of the opt fit (free redshift)

SF-ing solutions require very high SFR, conflicting with ALMA predictions → the source is confirmed as passive

The SF-ing optical solutions are consistent with ALMA at 3σ (and 1σ) → the source is not confirmed as passive (but not rejected either)

Santini+19, Santini+in prep.
Validation of robust individual candidates

RESULTS:

25 out of 41 candidates (61%) are robustly ($\geq 3\sigma$) confirmed

→ the SFing solutions of the optical fits are rejected by ALMA observations

The remaining sources are inconclusive (available ALMA data is not deep enough)

Santini+19, Santini+in prep.
Validation of the whole population in a statistical sense

- 29 sources (71%) are individually confirmed at $1\sigma$
- The stacks are on average consistent with being passive

Santini+19, Santini+in prep.
Validation of the whole population in a statistical sense

- 29 sources (71%) are individually confirmed at $1\sigma$
- The stacks are on average consistent with being passive
- Comparison with the location of the MS:
  - 23 (56%) candidates located at least $1\sigma$ below the MS
  - 10 (24%) candidates located at least $3\sigma$ below the MS

Santini+19, Santini+in prep.
How are they going to improve the selection?

How much faster would the spectroscopical confirmation of the candidates be?
Passive candidate confirmation with (Extremely) Big Eyes

Source: JWST Pocket Guide

\[
\text{SNR}=5 \quad \sim \quad \text{~1 hr}
\]

\[
\text{~} 10 \text{ hr}
\]

\[
\text{~} 34 \text{ hr}
\]

\[
\text{JWST NIRSPEC}
\]

\[
\text{253M MOS}
\]

\[
R \sim 1000
\]

\[
0.1 \text{ arcsec/px}
\]

(sensitivity for point sources, scaled assuming an average size of 0.22 arcsec)

\[
\text{SNR}=5
\]

\[
x_{10-15} \text{ faster than MOSFIRE}
\]
Kendrew+16

Used the simulation pipeline HSIM (Zieleniewski+15) to predict spectra for passive galaxies of various redshifts, masses and light profiles observed in 10 hr with HARMONI on the E-ELT.
Passive candidate confirmation with Extremely Big Eyes

Source: Kendrew+16

- Resolve morphology
- Rotation curves
- Metallicity gradients
- Stellar populations

ELT-IFU HARMONI
R=3100
λ=0.7–2.45 μm
30x60 mas spaxels (sensitivity for point sources, scaled assuming an average size of 0.22 arcsec)

SNR=5

~ 145 hr
~ 43 hr
~ 10 hr
~ 4.9 hr

faintest
median
Passive candidate confirmation with Extremely Big Eyes

Source: MOSAIC white paper

ELT-MOS MOSAIC
R~5000
λ<1.8 µm
(sensitivity for point sources, scaled assuming an average size of 0.22 arcsec)

SNR=5

BUT does not extend beyond 1.8 µm
Summary & conclusions

- High-z passive galaxies are challenging, but crucial to better understand the various physical processes responsible for galaxy assembly and evolution.

- Need accurate selection techniques + confirmation of individual candidates

- Several results confirm the existence of passive galaxies in the early Universe (z>3)

- 102 candidates at z>3 selected in CANDELS by ad-hoc SED fitting technique (Merlin+18, +19subm.)

- ALMA data lends decisive evidence to the quiescent nature of our candidates (Santini+19, Santini+in prep.):
  - 61% individually and robustly confirmed adopting conservative assumptions
  - Available observations are not deep enough to individually confirm the remaining candidates with high confidence
  - The stacking analysis and the lack of reliable detections corroborates the passive nature of the remaining candidates, at least in a statistical sense

- Future big eyes will provide a great contribution to the study of early passive galaxies and allow a much more robust classification and analysis

Thanks