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A massive quiescent galaxy confirmed in a protocluster at z = 3.09

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ABSTRACT

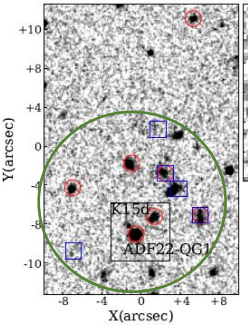
We report a massive quiescent galaxy at $z_{spec} = 3.0922^{+0.008}_{-0.004}$ spectroscopically confirmed at a protocluster in the SSA22 field by detecting the Balmer and Ca II absorption features with multi-object spectrometer for infrared exploration (MOSFIRE) on the Keck I telescope. This is the most distant quiescent galaxy confirmed in a protocluster to date. We fit the optical to mid-infrared photometry and spectrum simultaneously with spectral energy distribution (SED) models of parametric and nonparametric star formation histories (SFH). Both models fit the observed SED well and confirm that this object is a massive quiescent galaxy with the stellar mass of $\log(M_\star/M_\odot) = 11.26^{+0.03}_{-0.04}$ and $11.54^{+0.03}_{-0.00}$, and star formation rate of $SFR/M_\odot\ yr^{-1} < 0.3$ and $= 0.01^{+0.03}_{-0.01}$ for parametric and nonparametric models, respectively. The SFH from the former modeling is described as an instantaneous starburst while that of the latter modeling is longer-lived but both models agree with a sudden quenching of the star formation at ~ 0.6 Gyr ago. This massive quiescent galaxy is confirmed in an extremely dense group of galaxies predicted as a progenitor of a brightest cluster galaxy formed via multiple mergers in cosmological numerical simulations. We newly find three plausible [O III]λ5007 emitters at $3.0791 \leq z_{spec} \leq 3.0833$ happened to be detected around the target. Two of them just between the target and its nearest massive galaxy are possible evidence of their interactions. They suggest the future strong size and stellar mass evolution of this massive quiescent galaxy via mergers.

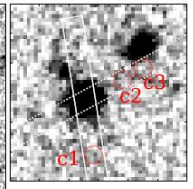
Background:

Massive quiescent galaxies have been confirmed up to **z ~ 4** by spectroscopy.
Star formation accompanied with centrally concentrated intense starburst.
Environmental dependence is still **unknown**:
Previously found in general fields or their environments are poorly explored.

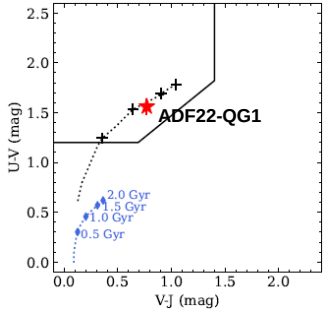
This paper:

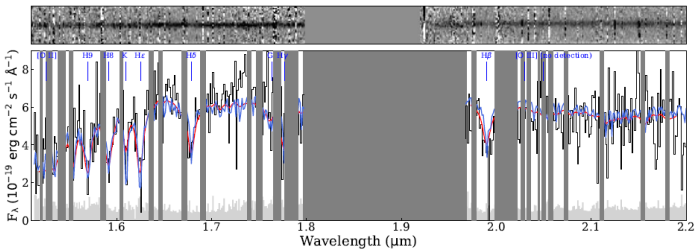
A massive quiescent galaxy at the ADF22 field of the SSA22 protocluster





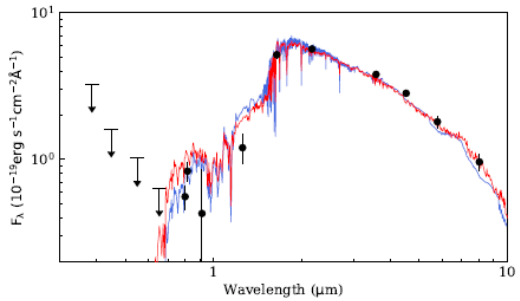
MOIRCS Ks
(0.4", 5σ mag: 25.34AB)
Red circles: [O III]
Blue squares: CO(3-2)

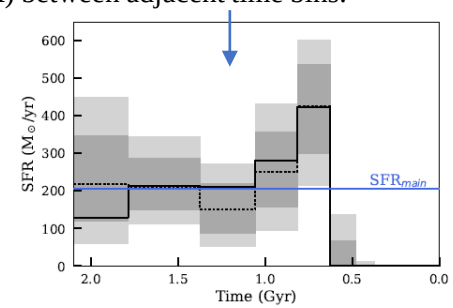




$Z_{spec} = 3.0922$, the most distant QG in proto-cluster so far.

SED fitting: ($u^*BVRi'z'JHK_s, 3.6, 4.5, 5.8$ & 8.0 μm-band + 1d spectrum)
Parametric model (FAST++): red curve, exponential / delayed / composite
Non-Parametric model (PROSPECTOR): blue curve
A continuity SFH prior which fits for Δlog(SFR) between adjacent time bins.



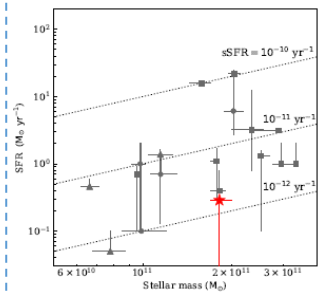


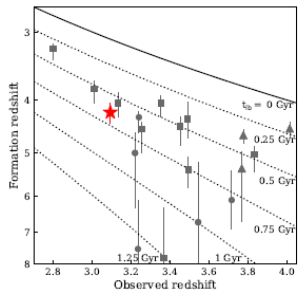
Properties	ADF22-QG1
z_{spec}	$3.0922^{+0.0008}_{-0.0004}$
r_{eff}/kpc[a]	1.01 ± 0.04
$\log(M_{\star,FAST++}/M_\odot)$	$11.26^{+0.03}_{-0.04}$
$\log(M_{\star,continuity}/M_\odot)$	$11.54^{+0.03}_{-0.00}$
$SFR_{FAST++}/M_\odot\ yr^{-1}$	< 0.3
$SFR_{continuity}/M_\odot\ yr^{-1}$	$0.01^{+0.03}_{-0.01}$
$SFR_{[O\ II]}/M_\odot\ yr^{-1}$	$2 - 14$
$SFR_{IR}/M_\odot\ yr^{-1}$	$< 9 - 21$
$sSFR_{FAST++}/yr^{-1}$	$< 1.8 \times 10^{-12}$
$sSFR_{continuity}/yr^{-1}$	$0.7^{+10.3}_{-0.7} \times 10^{-14}$
$sSFR_{[O\ II]}/yr^{-1}$[b]	$1 - 8 \times 10^{-11}$
$sSFR_{IR}/yr^{-1}$[b]	$< 5 - 12 \times 10^{-11}$
$A_{V,FAST++}$/mag	$0.5^{+0.1}_{-0.1}$
$\hat{\tau}_{2,continuity}$	$0.13^{+0.02}_{-0.02}$
$\log(t_{50,FAST++}/yr)$	$8.79^{+0.05}_{-0.05}$
$\log(t_{50,continuity}/yr)$	$9.08^{+0.08}_{-0.02}$
$\log(\langle SFR\rangle_{main,FAST++}/M_\odot\ yr^{-1})$	$4.06^{+0.45}_{-1.23}$
$\log(\langle SFR\rangle_{main,continuity}/M_\odot\ yr^{-1})$	$2.31^{+0.06}_{-0.04}$
$\log(t_{q,FAST++}/yr)$	$8.78^{+0.04}_{-0.20}$
$\log(t_{q,continuity}/yr)$	$8.80 - 8.91$
$\log(\tau_{decl,FAST++}/yr)$	$7.0^{+2.5}_{-0.0}$

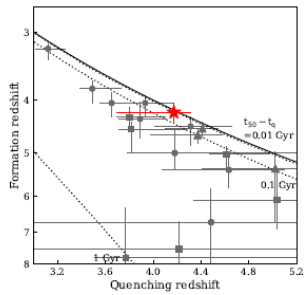
Result:

1. low sSFR for both cases
2. [O II] emission line:
   $F[O\ II] = 5.7 \times 10^{-18}\ erg\ s^{-1}cm^{-2}$
   $SFR_{[O\ II]} = 2 - 7\ M_\odot \gg SFR_{SED}$
   [O II] emission lines are frequently seen in QGs at high z and $SFR_{[O\ II]}$ are tend to be higher than those from SED modeling (weak AGN or LINERs ?)
3. SFH from Prospector is flatter than that from FAST++ and does not take an extreme value. But both case have very similar quenched time ~0.6 Gyrs ago. (Sudden quenching)
4. No significant environmental dependence from this sample (rapid formation from FAST++)

Compare with high-z quenched galaxies (FAST++):



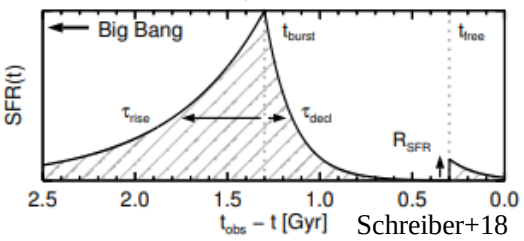




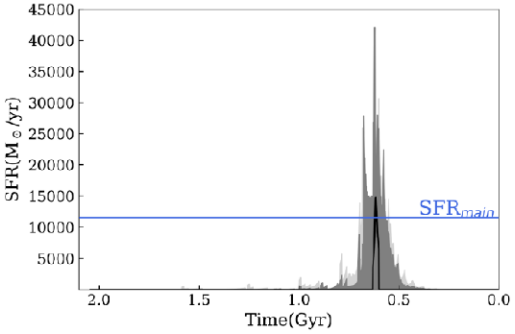
$$SFR_{base}(t) \propto \begin{cases} e^{(t_{burst}-t)/\tau_{rise}} & \text{for } t > t_{burst} \\ e^{(t_{burst}-t)/\tau_{decl}} & \text{for } t \leq t_{burst} \end{cases} \quad (1)$$

and

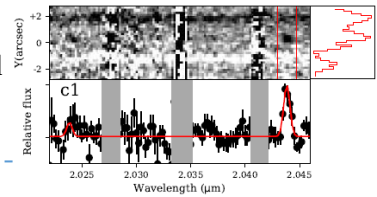
$$SFR(t) = SFR_{base}(t) \times \begin{cases} 1 & \text{for } t > t_{free} \\ R_{SFR} & \text{for } t \leq t_{free} \end{cases} \quad (2)$$



Schreiber+18



5. Three [OIII] emitters detected (too faint in Ks image)



Discussion:

1. SFH: FAST++ result seems unrealistic (brightest SMG ~ $5000 M_\odot/yr$, over the Eddington limit)
   SFH from Prospector is more realistic (similar to those of SMGs, progenitors?)
2. Size and mass evolution
   Progenitor of Brightest Cluster Galaxies
   Needs a strong size evolution (mergers)
   ADF22-QG1 is in a dense group of galaxies. [O III] emitters is possible evidence of interaction with K15d