An Extremely Massive Quiescent Galaxy at $z = 3.493$: Evidence of Insufficiently Rapid Quenching Mechanisms in Theoretical Models*

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ABSTRACT

We present spectra of the most massive quiescent galaxy yet discovered at $z > 3$, spectroscopically confirmed via the detection of Balmer absorption features in the $H-$ and $K-$bands of Keck/MOSFIRE. The spectra confirm a galaxy with no significant ongoing star formation, consistent with the lack of rest-frame UV flux and overall photometric spectral energy distribution. With a stellar mass of $3.1^{+0.1}_{-0.2} \times 10^{11}$ $M_\odot$ at $z = 3.493$, this galaxy is nearly three times more massive than the highest redshift spectroscopically confirmed absorption-line identified galaxy known. The star-formation history of this quiescent galaxy implies that it formed $>$ 1000 $M_\odot$/yr for almost 0.5 Gyr beginning at $z \sim 7.2$, strongly suggestive that it is the descendant of massive dusty star-forming galaxies at $5 < z < 7$ recently observed with ALMA. While galaxies with similarly extreme stellar masses are reproduced in some simulations at early times, such a lack of ongoing star formation is not seen there. This suggests the need for a more rapid quenching process than is currently prescribed, challenging our current understanding of how ultra-massive galaxies form and evolve in the early Universe.

arXiv.1910.10158

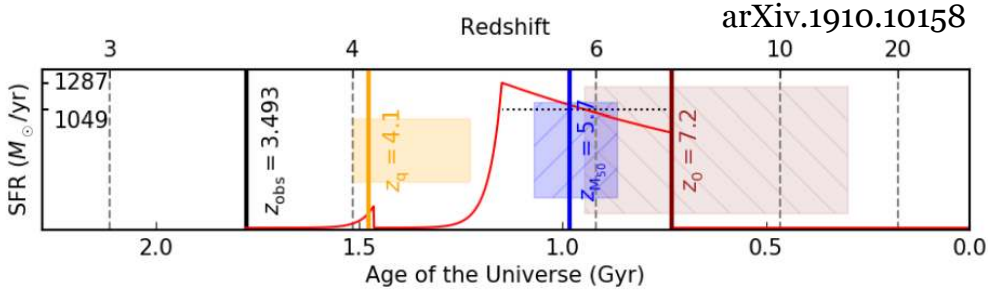

Figure 3. Best fit star-formation history for XMM-2599. The red curve indicates the SFR over cosmic time, with the maximum SFR and a characteristic average SFR shown in solar masses per year on the y-axis. The black line indicates the spectroscopic redshift and the maroon line is the time that the galaxy began forming stars. The orange line is the time at which SFR drops below 10% of the previous average SFR while the blue line denotes the time at which half of the final stellar mass has been formed. Shaded regions correspond to 1σ confidence intervals.

Fig3. Best-fit SFH↑
z ~ 7.2で星形成を開始、0.5Gyrの間1000Msun/yrで成長、その後τで減衰。

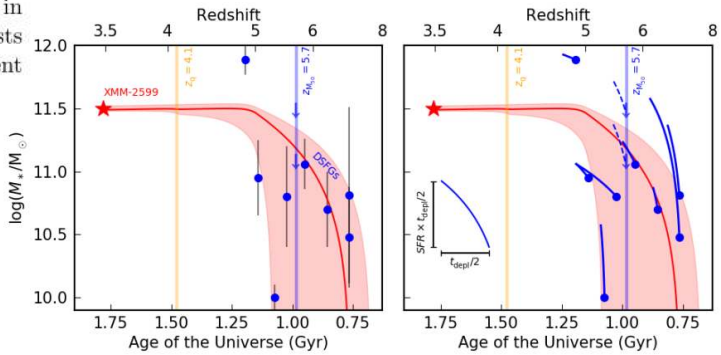

Figure 4. High-redshift DSFGs as potential progenitors of XMM-2599. We show the stellar mass evolution for XMM-2599 in red as calculated from our best-fit SFH, with a shaded 68% confidence interval. **Left:** Several high-redshift DSFGs are shown in blue with errors on masses (Capak et al. 2011; Riechers et al. 2013; Cooray et al. 2014; Ma et al. 2015; Riechers et al. 2017; Strandet et al. 2017; Marrone et al. 2018; Williams et al. 2019; Jin et al. 2019). Reported upper limits are plotted as arrows. **Right:** Blue segments show the evolution of the DSFGs assuming the published star formation rate held constant over half the gas depletion timescale (*i.e.*, half of the available gas is turned into stars). When no gas depletion timescale or gas mass is reported, we set $t_{depl} = 0.1$ Gyr, a value typical of the population. The overlap of these tracks with the mass evolution of XMM-2599 suggests that they are potential high-redshift progenitor systems.

←Fig4. Mass assembly history
1000Msun/yrの成長段階がdusty SFGと類似。
→ Dusty SFRの祖先か？

シミュレーションで再現できないMassive Quiescent銀河@z~3.5の発見

- Keck/MOSFIREでz~3.5のmassive quiescent銀河を分光同定。
  - On-source積分時間：2.2+2.4hrs@H, 2.4hrs@K-band
- SED fitting w/ FAST++ → simulationでは予測（再現）できないSFH
- 急峻なSF quenchingの物理 (AGN shock/feedback等) が欠いている？

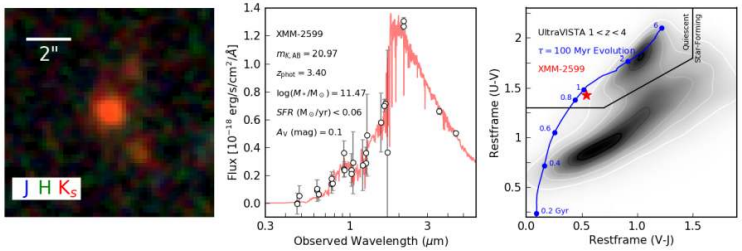

Figure 1. Photometric properties of XMM-2599. **Left:** Near-infrared imaging of XMM-2599. **Middle:** Photometric spectral energy distribution of XMM-2599. Data are shown in white with gray 1σ errorbars, while the best fit template to the photometry alone is shown in red. Listed properties are also derived from the photometry alone. **Right:** XMM-2599 on the restframe *UVJ* diagram. A mass-complete sample of galaxies at $1 < z < 4$ from UltraVISTA are shown in gray for comparison. The evolution of a population with an exponentially-declining star-formation history parameterized by $\tau = 100$ Myr is shown in blue, with several ages labeled in Gyr.

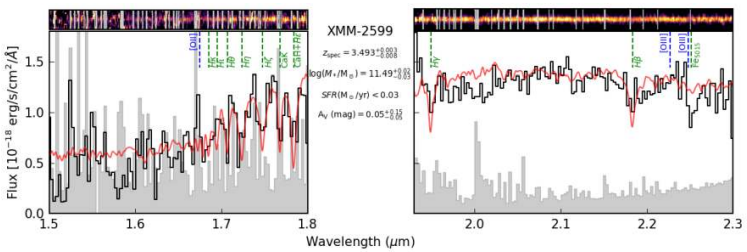

Figure 2. Near-infrared H and K band spectra for XMM-2599 and best-fit model. **Top:** The telluric corrected 2D spectra, smoothed for visual clarity. Strong sky lines are masked with gray lines. **Bottom:** The 1D extracted spectra, shown in bins 30 Å wide, are black, while the 1σ noise (including telluric correction) is gray. The best fit template to the combined photometry and spectroscopy is plotted in red. The location of absorption features are indicated in green, and the wavelengths corresponding to nebular emission from oxygen are blue.

Fig5. シミュレーションと比較→

星形成フェーズ(z~6-5) は再現出来ているが、その後の急なquenching (z~4-3) が合わない。

- 単独の銀河でない可能性
  - Close pair, dry merger? なさそう (Fig1)
  - そうだとしてもまだmassive (1e11.2)
- 測光へのコンタミ
  - そうだとしてもまだmassive (1e11.4)
- Dusty SBの可能性
  - UVJ 2色図：post-SB位置→dust減光弱
  - Dust減光では吸収線は作れない。

激しい星形成直後に急にquenchさせる物理過程が必要。

- AGN起因のshock・feedbackによるガス加熱等。

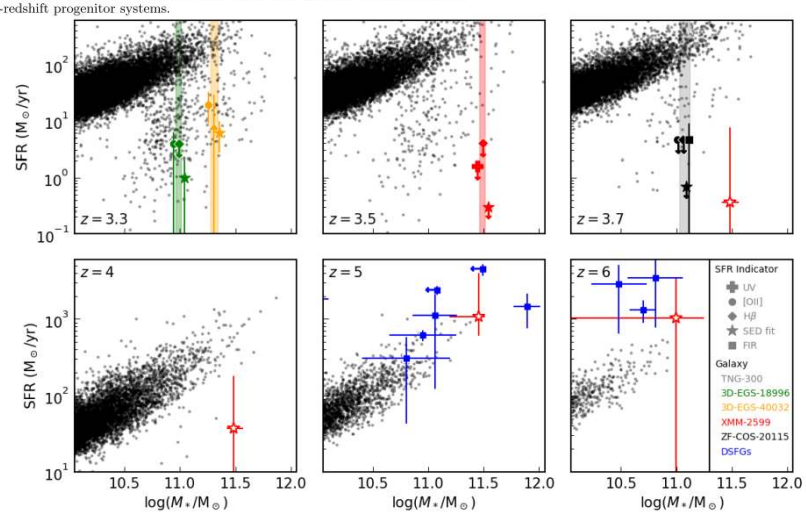

Figure 5. Comparison to the Illustris TNG-300 simulation on the SFR-M_* plane. We show the spectroscopically confirmed absorption-line identified UMGs at $z_{spec} > 3$ (green, orange, red, and black), simulated galaxies from six snapshots in Illustris TNG-300 (gray), and the DSFGs from Figure 4 (blue). Several probes of star formation are shown differentiated by marker style, many as 1σ upper limits. These are offset along the abscissa for visual clarity, while the best-fit stellar mass is shown as a column, with the width indicating the 68% statistical error. Using the best-fit SFH from Figure 3, we plot the position of XMM-2599 at previous epochs as well (open red stars). Note that the range of the ordinate axis differs in the two rows.