Stellar Populations of Massive Quenched Galaxies
0 < z < 2

Nobuo ARIMOTO

Subaru Telescope

M.Onodera (ETZ, Zuerich)
J.Silverman (IPMU-Kavli, Tokyo)
D.Kashino (Nagoya)
J.Zahid (UH)
A.Renzini (Padova)
E.Daddi (CEA, Saclay)
N.Arimoto (Subaru)

Subaru Telescope
MOIRCS/FMOS

Multi-Object Infrared Camera and Spectrograph (MOIRCS) - provides imaging and low-resolution spectroscopy from 0.9-2.5 microns over a 4 arcmin x 7 arcmin field of view.

Fiber Multi Object Spectrograph (FOS) - provides fiber-fed multi-object spectroscopy from 0.9-1.8 microns over a 30 arcmin field of view.
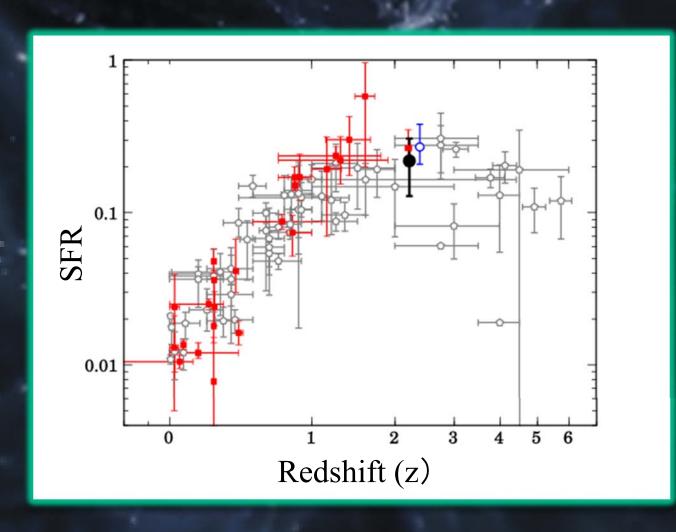
Subaru/FMOS

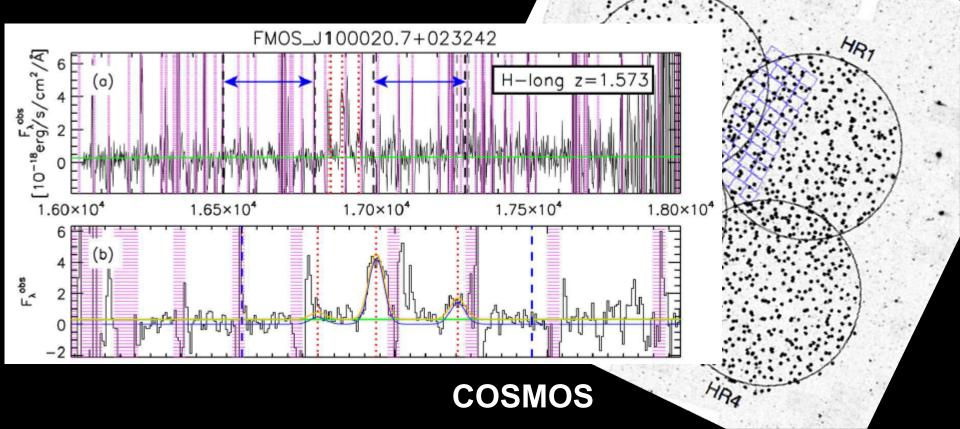|	Low Resolution (LR)	High Resolution (HR)[5]
Spectral coverage	0.9-1.8 μm	0.92-1.12 μm ("J-short") 1.11-1.35 μm ("J-long") 1.40-1.60 μm ("H-short") 1.45-1.67 μm ("H-short prime") 1.60-1.80 μm ("H-long")
Spectral resolution	R=600	R=2200
Dispersion	~5 A/pix	~1 A/pix
Image quality	FWHM = 4-5 pix	
Number of fibers to be extracted as spectra	197(IRS1)[2] 200 (IRS2)	

Subaru/FMOS

| Detector system		
	IRS1	IRS2
Detector array	HAWAII-2 (Sci #55)	HAWAII-2 (Sci #90)
Array format	2048 x 2048	
Pixel size	18 μm	
Readout elesctronics	TUFPAC+Messia V	SDSU IR Gen III
Readout time (= Minimum exposure time)	~17 sec	~6 sec
Gain	~2.0 e-/ADU	~3.8 e-/ADU
Dark current	< 0.1 e-/sec/pix	< 0.1 e-/sec/pix
Total background[3]	~0.2 e-/sec/pix	~0.2 e-/sec/pix
Readout noise[4]	~30 e-/pix rms	~15 e-/pix rms
Linearity	<1% up to 40,000 ADU	~1% up to 20,000 ADU

Cosmic Star Formation History
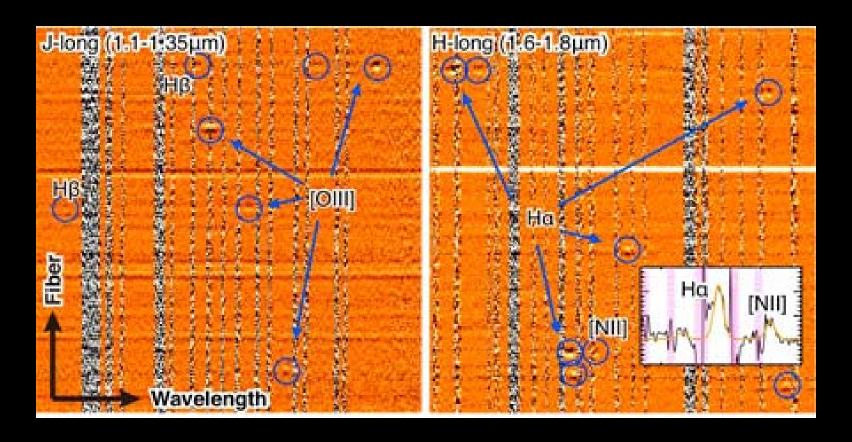
Survey of Star-Forming Galaxies

Silverman et al. (2014) arXiv1409.044
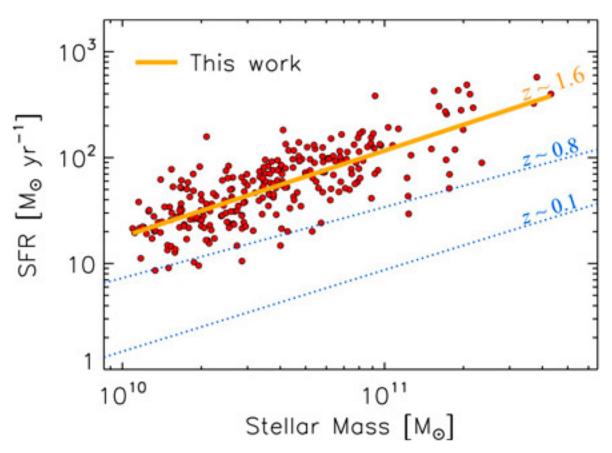Zahid et al. (2014) ApJ 792, 75
Kashino et al. (2014) ApJL 777, 8

COSMOS

FMOS Spectra in J/H-Band

FMOS spectra in the J-band (left panel) and H-band (right panel), each of which filters light so that only specific wavelengths can pass through. The horizontal axis refers to the wavelength direction while the vertical axis indicates individual spectra observed through each fiber.
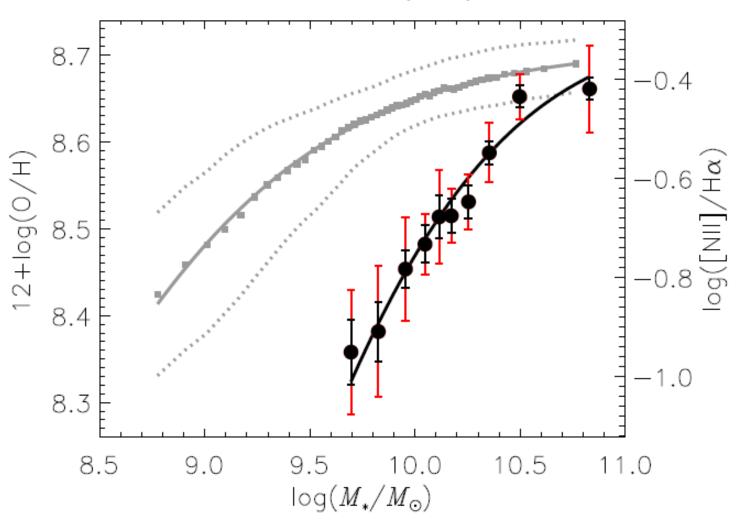
Marching to the Beat
Kashino et al. (2013)

Star formation rates show a clear increase with mass, reaching over 500 M⊙ per. As the age of the Universe increases, star formation decreases uniformly across the population.

Mass - Metallicity Relation
SF Galaxies (z~1.6)
Zhaid et al. (2014)

Subaru/PFS	Blue	Red		NIR
		Low Res	Mid Res	
Collimator F/#	2.5			
Camera F/#	1.1			
# of science fibers	597 or 600			
Operating temperature	3 +/- 0.5 degC			
Input fiber core diameter	129um			
Wavelength coverage	380-650nm	630-970nm	710-885nm	940-1260nm
Resolving power	~2300	~3000	~5000	~4300
Detector — Type	CCD (Hamamatsu, with a new blue coating)	CCD (Hamamatsu, with the same coating as HSC)		H4RG (Teledyne, 1.7um cutoff)
Detector — Format	(4K x 2K) x 2	(4K x 2K) x 2		4K x 4K
Detector — Pixel size	15um			
Detector — Readout noise	~4 e-/pix			4 e-/pix
Detector — Dark	~0.4 e-/pix/hour			0.01 e-/pix/s
Thermal background	None			0.006 e-/pix/s

Subaru/PFS

Hα+[NII]
(λ6562.8, z<0.9)
[OIII] (λ5007, z<1.5)
Hβ (λ4861.3, z<1.6)

Subaru/PFS
Stellar Population Study

D4000 (λ4000, z<2.15)
Hδ (λ4102, z<2.07)
CN1, CN2 (λ4178, z<2.02)
Ca 4227 (z<1.98)
Hγ(λ4341, z<1.90))
Fe 4383 (z<1.87)
Fe 4531 (z<1.78)
C2 4668 (z<1.70)
Mg1 (λ5134, z<1.45)
Mg2 (λ5196, z<1.42)
Mgb (λ5192, z<1.42)
Fe 5270 (z<1.39)
Fe 5335 (z<1.36)
Fe 5406 (z<1.33)
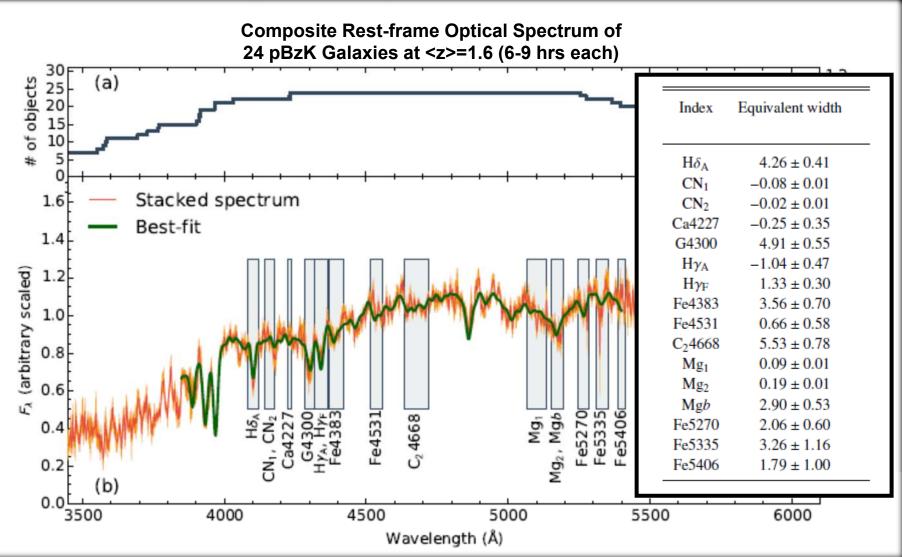
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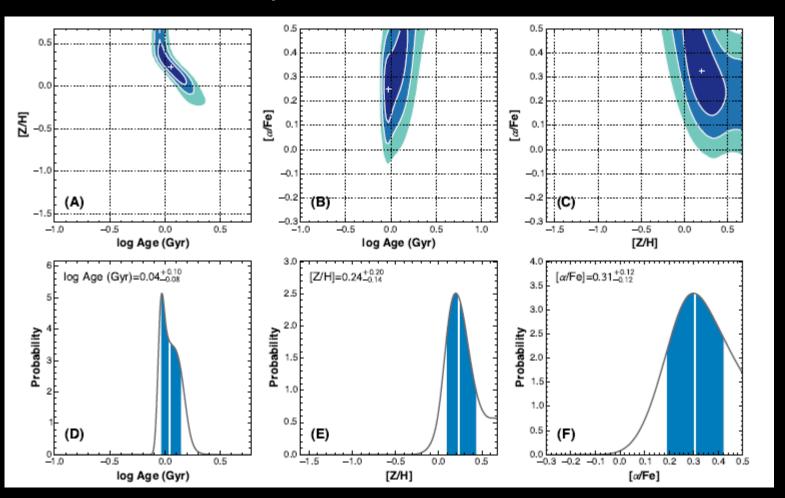## Rapid evolutionary transition revealed in massive quenched galaxies (Onodera et al. 2015)

Composite Rest-frame Optical Spectrum of
24 pBzK Galaxies at $<z>=1.6$ (6-9 hrs each)

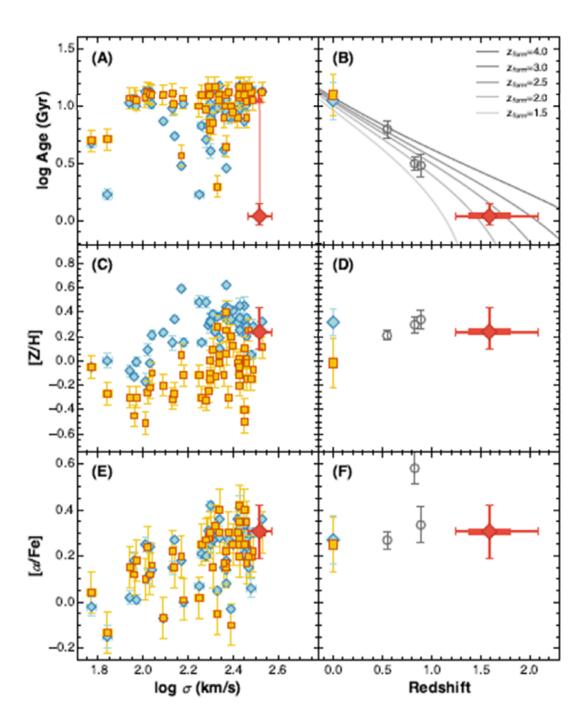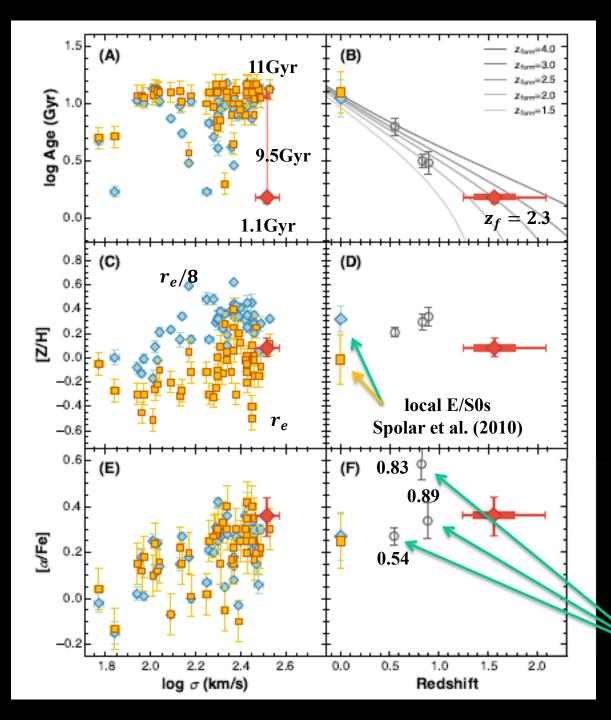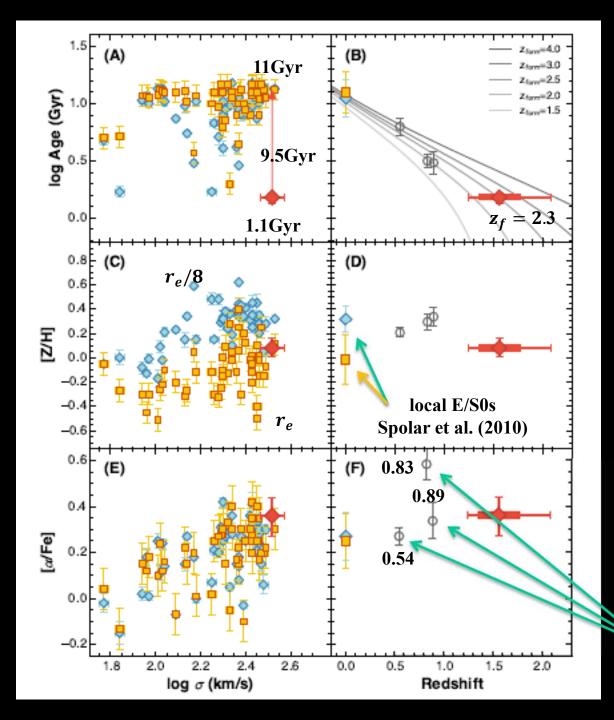| Index	Equivalent width
$H\delta_A$	4.26 ± 0.41
CN_1	-0.08 ± 0.01
CN_2	-0.02 ± 0.01
$Ca4227$	-0.25 ± 0.35
$G4300$	4.91 ± 0.55
$H\gamma_A$	-1.04 ± 0.47
$H\gamma_F$	1.33 ± 0.30
$Fe4383$	3.56 ± 0.70
$Fe4531$	0.66 ± 0.58
C_24668	5.53 ± 0.78
Mg_1	0.09 ± 0.01
Mg_2	0.19 ± 0.01
Mgb	2.90 ± 0.53
$Fe5270$	2.06 ± 0.60
$Fe5335$	3.26 ± 1.16
$Fe5406$	1.79 ± 1.00

Subaru Telescope

Rapid evolutionary transition revealed in massive quenched galaxies (Onodera et al. 2015)

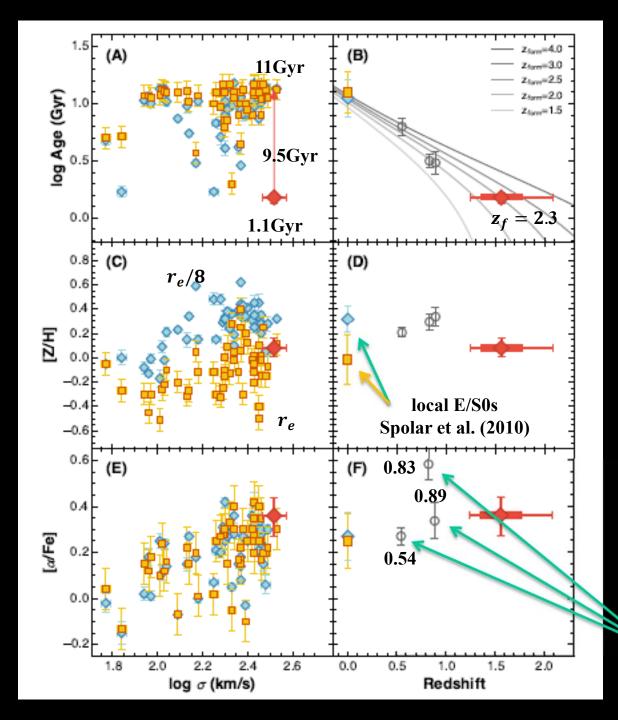**Composite Rest-frame Optical Spectrum of
24 pBzK Galaxies at <z>=1.6**

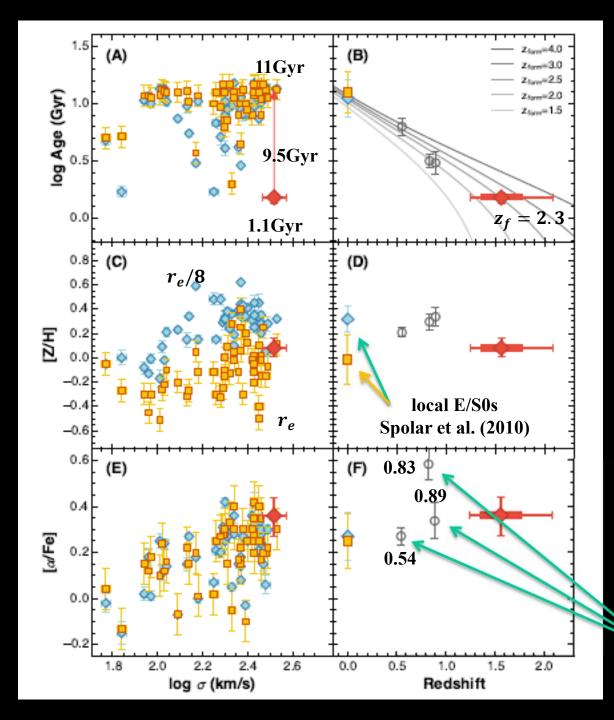(A) 11Gyr 9.5Gyr 1.1Gyr

(B) $z_{form}=4.0$ $z_{form}=3.0$ $z_{form}=2.5$ $z_{form}=2.0$ $z_{form}=1.5$ $z_f = 2.3$

(C) $r_e/8$ r_e

(D) local E/S0s Spolar et al. (2010)

(E)

(F) 0.83 0.89 0.54

Clusters of Galaxies (Jørgensen & Chiboucas 2013)

(A) log Age (Gyr) vs log σ (km/s)
11Gyr
9.5Gyr
1.1Gyr

(B) $z_{form}=4.0$, $z_{form}=3.0$, $z_{form}=2.5$, $z_{form}=2.0$, $z_{form}=1.5$
$z_f = 2.3$

(C) [Z/H]
$r_e/8$
r_e

(D)
local E/S0s
Spolar et al. (2010)

(E) [α/Fe]

(F)
0.83
0.89
0.54

log σ (km/s)   Redshift

The same ages as local quenched galaxies.

Clusters of Galaxies
(Jongensen & Chiboucas 2013)
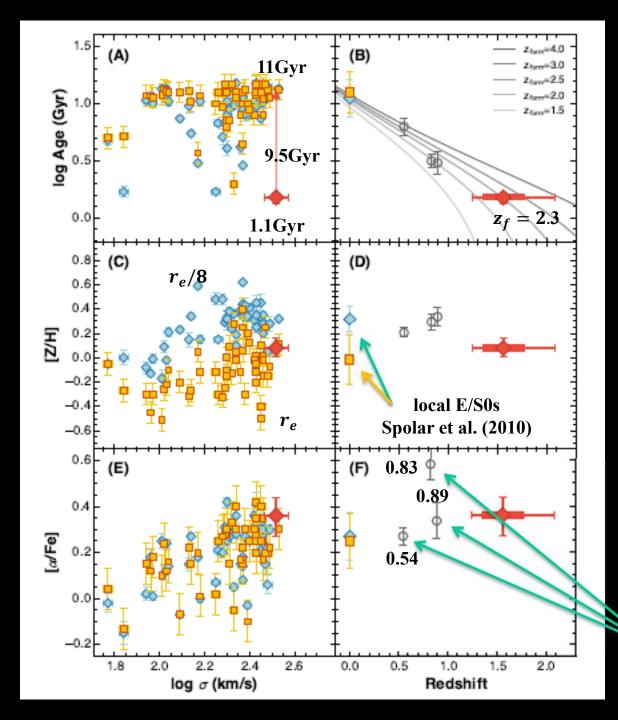
The formation redshift would be $2.0 < z_f < 2.5$ for the bulk of stars.

Clusters of Galaxies (Jongensen & Chiboucas 2013)

The same metallicity as local quenched galaxies.

Little or no evolution of metallicity over the past 10 Gyr.

Clusters of Galaxies (Jongensen & Chiboucas 2013)

The same [α/Fe] ratio as the local E/S0s.

Little or no evolution of the [α/Fe]-σ relation over the past 10 Gyr.

Clusters of Galaxies
(Jongensen & Chiboucas 2013)

Conclusions

We conclude that the stellar population content, i.e., their age, metallicity and α-element enhancement of our <z>=1.6 galaxies, qualify them as possible progenitors of similarly massive quenched galaxies at z=0, upon their passive evolution.
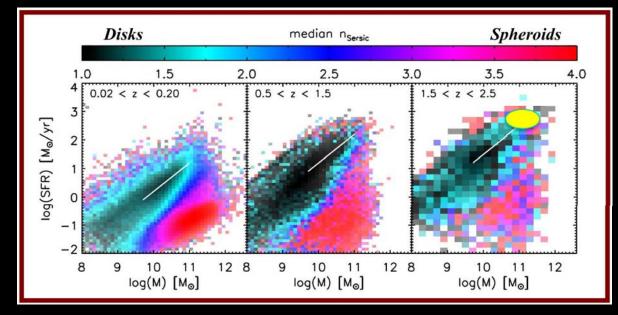
Star Formation History of Quenched Galaxies @ <z>=1.6

① The average age ~1.0 Gyr of our quenched galaxies is essentially a measure of the time elapsed since their star formation was quenched.

② Indeed, if the SFR was rapidly increasing prior of quenching, the corresponding formation redshift $z_f = 2.3$ must be close to the quenching epoch, as most of the stars formed in a short time just prior to quenching.

③ An α-element enhancement relative to the solar abundance ratios is the natural outcome of such a short time period of star formation (no signature of SNeIa).

Star Formation History of Quenched Galaxies @ <z>=1.6

④　To build a stellar mass of $2.3 \times 10^{11} M_{\odot}$ by z=2.3, the SFR of ~400$M_{\odot}$/yr just prior to quenching would be required.

⑤　This matches very well the measured SFR of main sequence star-forming galaxies of similar stellar mass at z>2.

Wuyts et al. (2011)

Precursors
Star-Forming Main Sequence Galaxies @ z>2

High galacto-centric distance

Bulge?

The inner quenched spheroidal components argue for an inside-out quenching process, as expected for either AGN feedback or gravitational quenching.

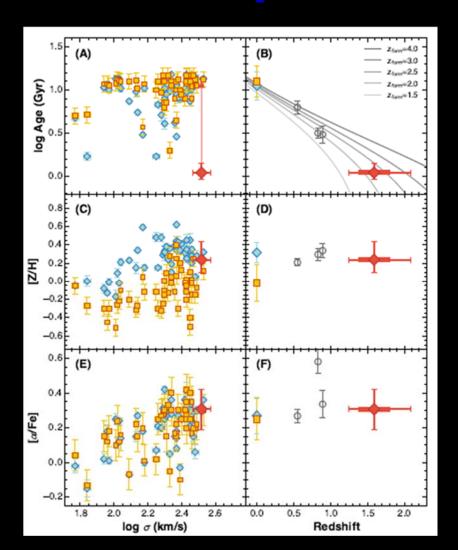These galaxies show strong nuclear outflows ~1600km/s, which are most likely driven by AGN feedback.

Foster-Schreiber et al. (2009), Genzel et al. (2014b)

Summary

The known properties of massive z~2.5 main sequence galaxies qualify them as likely precursors of our quenched galaxy at <z> = 1.6 and rapid, internal processes such as AGN feedback and gravitational quenching seem the likely mechanisms responsible for quenching star formation.

Subaru/PFS Strategy
Stellar Populations across Cosmic Time

**Stellar Population Parameters
(age, [Z/H], [α/Fe], σ)
at different redshifts**

**Stellar Population Parameters
Along the RED Sequence
(dependence on mass)**

**Stellar Population Parameters
of ○□△○s**