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Probing Cosmic Dawn : Ages and Star Formation Histories of Candidate $z \geq 9$ Galaxies

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ABSTRACT

We discuss the spectral energy distributions and physical properties of six galaxies whose photometric redshifts suggest they lie beyond a redshift $z \simeq 9$. Each was selected on account of a prominent excess seen in the *Spitzer*/IRAC 4.5μm band which, for a redshift above $z = 9.0$, likely indicates the presence of a rest-frame Balmer break and a stellar component that formed earlier than a redshift $z \simeq 10$. In addition to constraining the earlier star formation activity on the basis of fits using stellar population models with BAGPIPES, we have undertaken the necessary, but challenging, follow-up spectroscopy for each candidate using various combinations of Keck/MOSFIRE, VLT/X-shooter, Gemini/FLAMINGOS2 and ALMA. Based on either Lyman-α or [O III] 88 μm emission, we determine a convincing redshift of z=8.78 for GN-z-10-3 and a likely redshift of z=9.28 for the lensed galaxy MACS0416-JD. For GN-z9-1, we conclude the case remains promising for a source beyond $z \simeq 9$. Together with earlier spectroscopic data for MACS1149-JD1, our analysis of this enlarged sample provides further support for a cosmic star formation history extending beyond redshifts $z \simeq 10$. We use our best-fit stellar population models to reconstruct the past rest-frame UV luminosities of our sources and discuss the implications for tracing earlier progenitors of such systems with the *James Webb* Space Telescope.

Background:

Numerical simulations: Star formation may start from 150 - 250 Myr after Big bang ($z \sim 15 - 20$)

4.5μm detection of Balmer Jump:

z ~ 9 (the universe age: ~ 550 Myr) & The presence of main sequence stars older than 250 Myr

→ galaxy formation originating before a redshift z ~ 14

(Cosmic Dawn: z > 10)

First detection: MACS1149-JD1 at z = 9.11 (Formation: z = 15.4 ± 2.3)

This paper:

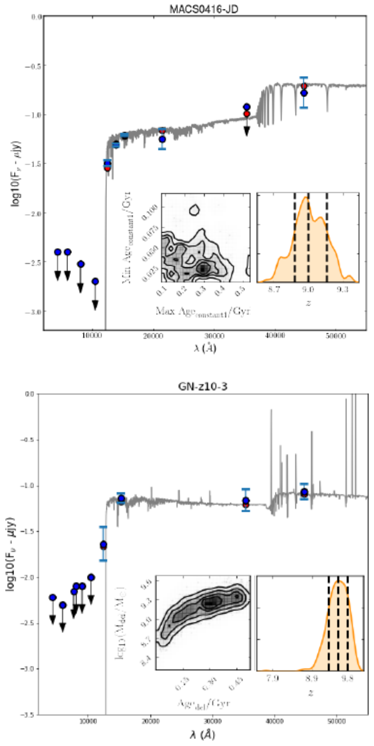
Six promising z ~ 9 candidates (including MACS1149-JD1)

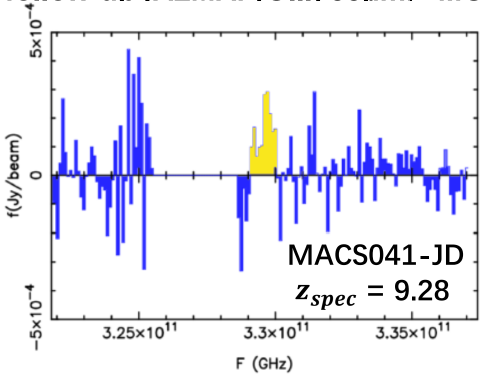
1) 2σ non-detection bluewards & 5σ detection redwards of Lyman break

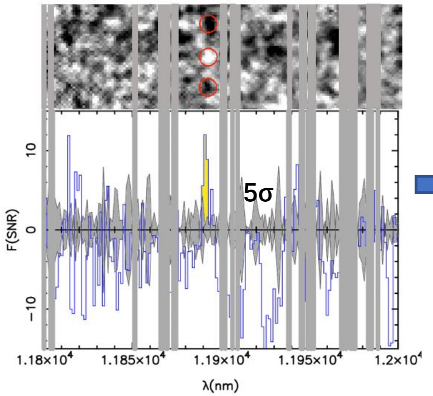
2) [3.6] — [4.5] > 0.5 3) Photo-z permitting z > 9 at 1σ

Target	RA	DEC	z_{phot}	M_{uv}	$M_\star$ [$\times10^9 M_\odot$]	Age (Myr)	f_M (z>10) [%]
MACS0416-JD[a]	04:16:11.52	-24:04:54.0	$9.25^{+0.08}_{-0.09}$	-20.83±0.22	$1.50^{+0.84}_{-0.61}$	360^{+108}_{-157}	$74.1^{+8.1}_{-25.6}$
MACS1149-JD1[b]	11:49:33.59	22:24:45.76	$9.44^{+0.02}_{-0.03}$	-19.17±0.04	$0.44^{+0.05}_{-0.04}$	484^{+17}_{-36}	$86.5^{+2.0}_{-4.3}$
			9.11	-19.12±0.04	$0.66^{+0.09}_{-0.04}$	512^{+10}_{-12}	$93.3^{+4.2}_{-5.1}$
GN-z10-3[c]	12:36:04.09	+62:14:29.6	$9.57^{+0.23}_{-0.27}$	-20.72± 0.12	$1.57^{+0.81}_{-0.63}$	265^{+153}_{-145}	$38.0^{+23.1}_{-38.0}$
GN-z9-1[d]	12:36:52.25	+62:18:42.4	$9.22^{+0.32}_{-0.33}$	-20.81± 0.18	$2.18^{+1.24}_{-0.85}$	323^{+137}_{-168}	$65.1^{+18.7}_{-32.2}$
GS-z9-1[d]	03:32:32.05	-27:50:41.7	$9.26^{+0.41}_{-0.42}$	-20.38±0.20	$2.47^{+1.62}_{-1.03}$	326^{+128}_{-176}	$70.6^{+12.5}_{-25.4}$
UVISTA-1212[e]	10:02:31.81	02:31:17.10	$8.88^{+0.27}_{-0.46}$	-22.93±0.20	$9.7^{+5.10}_{-4.72}$	280^{+172}_{-174}	$32.4^{+47.2}_{-32.4}$

SED fitting + Spectroscopic follow-up (ALMA: [OIII] 88μm, MOSFIRE: Lyman-α):



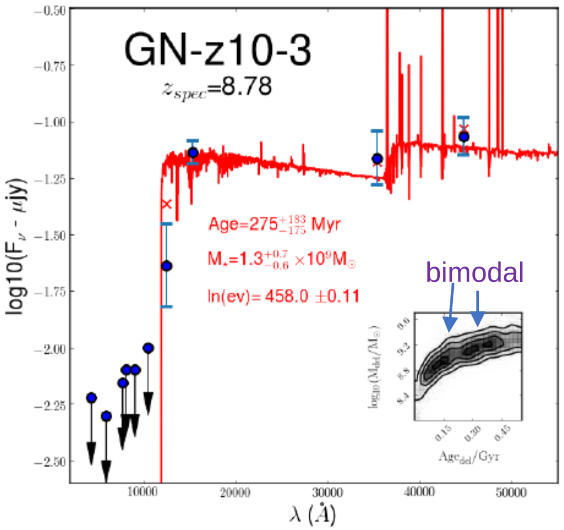




Updated SED fitting result

Target	z_{spec}	$M_\star$ [$\times10^9 M_\odot$]	Age (Myr)	f_M (z>10) [%]
MACS0416-JD	9.28	$1.37^{+0.75}_{-0.55}$	351^{+115}_{-153}	$71.8^{+10.4}_{-20.3}$
MACS1149-JD1	9.11	$0.66^{+0.09}_{-0.04}$	512^{+10}_{-12}	$93.3^{+4.2}_{-5.1}$
GN-z10-3	8.78	$1.27^{+0.70}_{-0.61}$	275^{+184}_{-175}	$39.1^{+24.6}_{-38.9}$

significant contribution to the IRAC excess from rest-frame optical emission lines

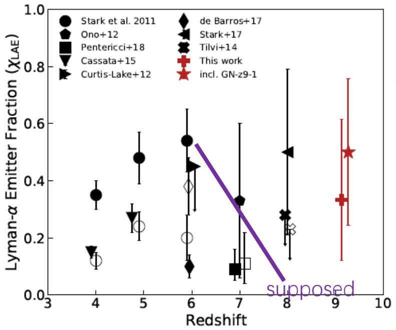


The z~9 Lyman-α fraction:

2 (3) of all 6 samples shows Lyman-α emission

(large fraction, be opposed to reionization theory)

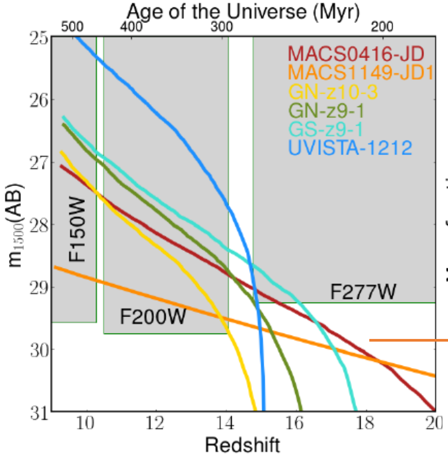
Transmission through both the galaxy and the IGM



Selection bias of most-luminous object. Create and located in large ionized bubbles

Star formation history at z > 10 (include future prospect):

JWST observation (rest 1500Å):



Redshift evolution of UV luminosity density: