Reionization to Exoplanets: Spitzer's Growing Legacy

Young Galaxies as Seen by Spitzer: Cold and Warm

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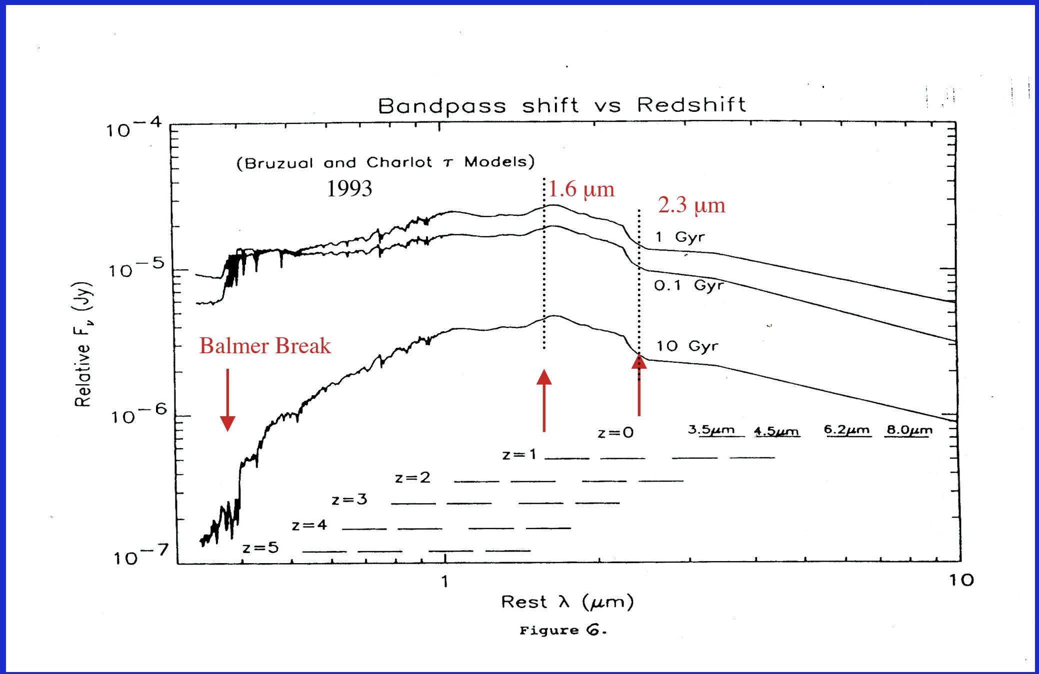
IRAC Observations of the Early Universe

- One of the original scientific objectives of IRAC was to "understand the formation and evolution of normal galaxies to redshifts $z > 3$."
- The IRAC requirement was to determine the SED of a L* galaxy at $z = 3$ (8μm: 6 μJy, 10σ).
- Filters were originally designed to measure photometric redshifts
  - Based on 1.6 μm peak due to H- opacity min in late type stars and the 2.3 μm CO absorption feature.
  - Wright, Eisenhardt, Fazio 1993; Simpson and Eisenhardt (1994)

IMAGING THE REST FRAME VISIBLE LIGHT

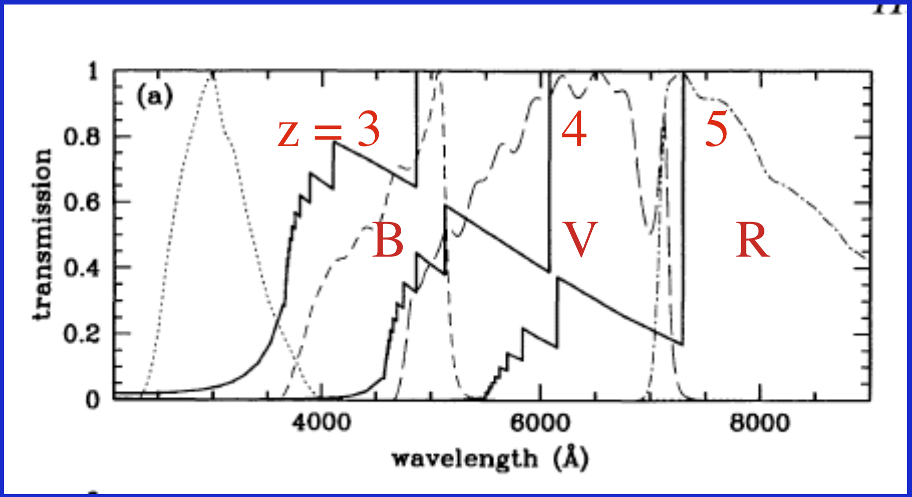


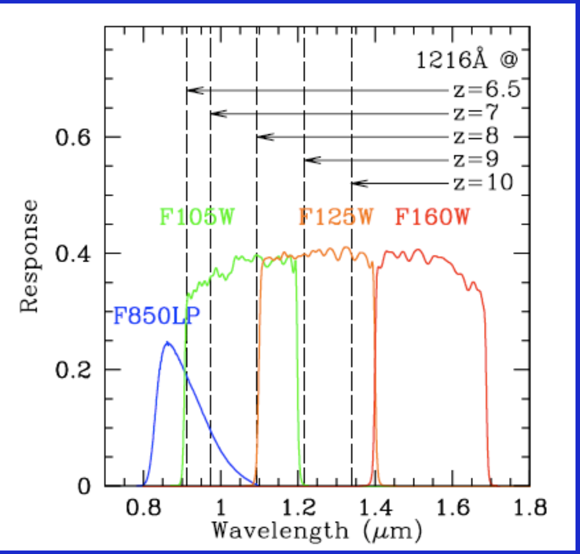
- The 1.6 and 2.3 µm features appear early and are persistent with age.
- For the first time at high z, Spitzer/IRAC offered access to the rest frame visible light of galaxies, longward of the the Balmer break.
- As a result, IRAC photometry at very faint magnitudes is able to constrain the stellar masses and ages of high-redshift galaxies.

FINDING HIGH REDSHIFT GALAXIES

Using the Lyman break (912 A) in the galaxy spectrum (LGBs, "dropouts")

z	dropout
4	B
5	V
6	i
7	z
8	Y
10	J

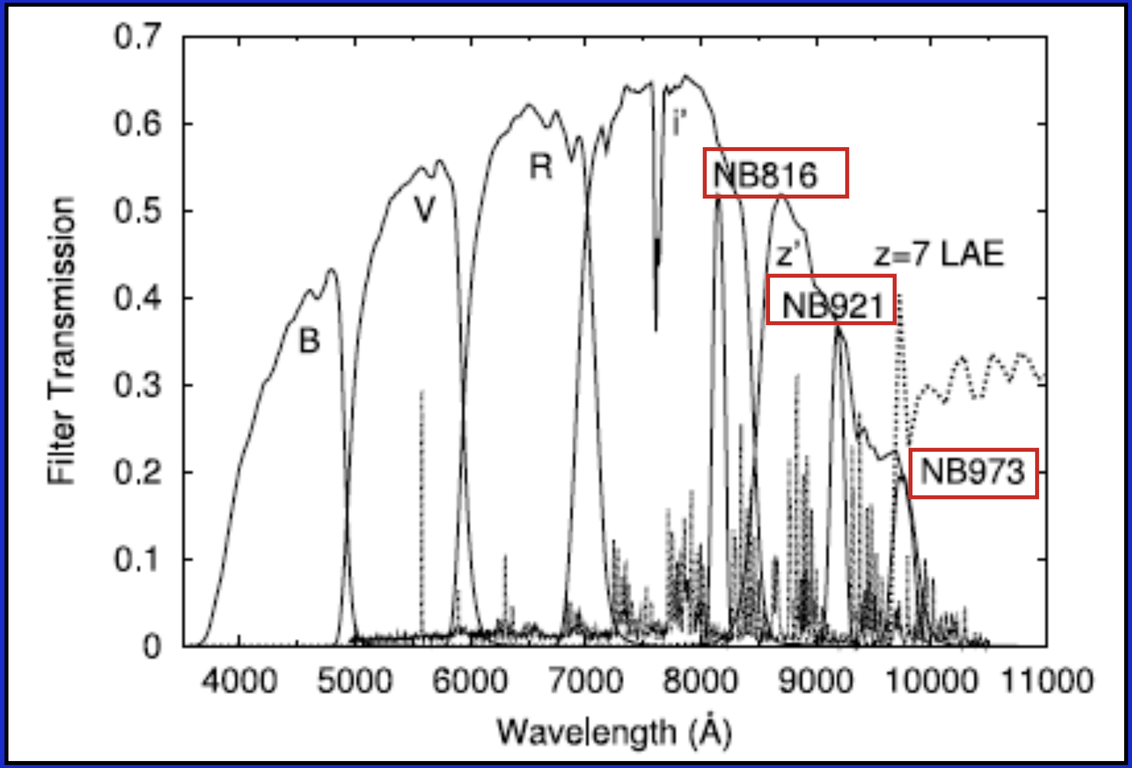




Yan et al. 2009

FINDING HIGH REDSHIFT GALAXIES

Using narrow-band filters to detect the Lyman-alpha emission line (1216 A) from atomic hydrogen in the galaxy spectrum (LAEs).



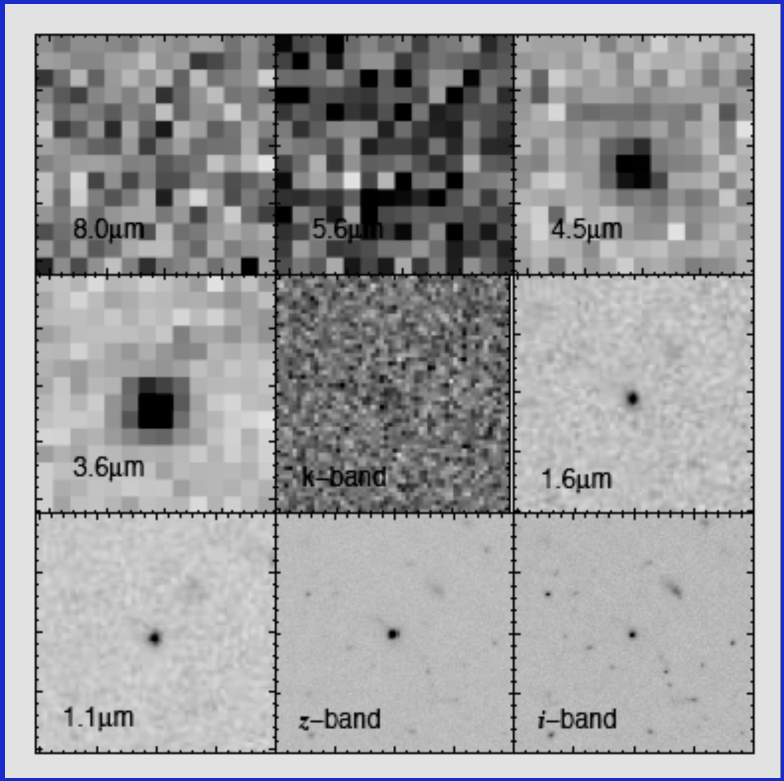
Subaru Suprime-Cam Broadband Filters (Ota et al. 2008)

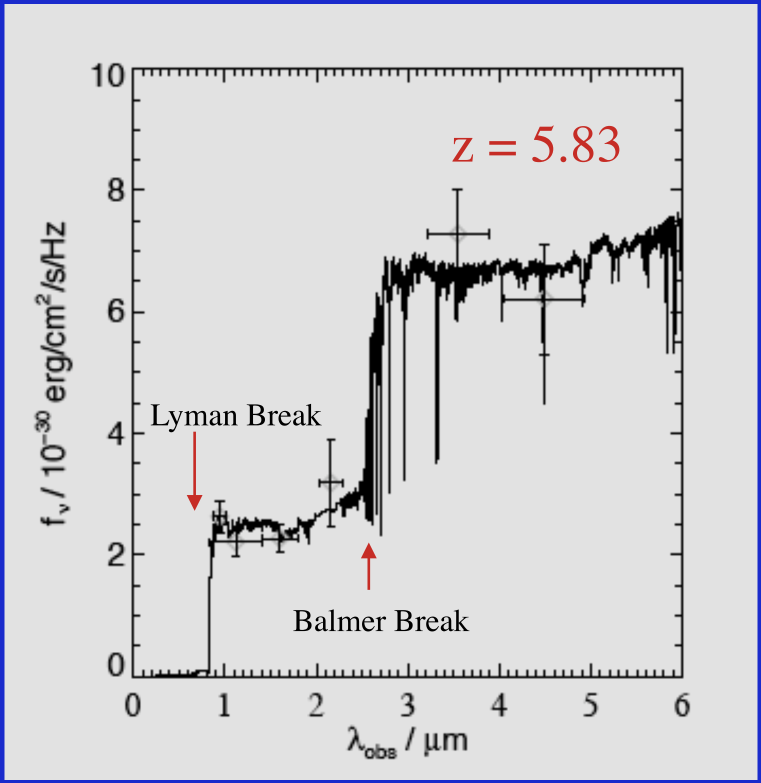
IRAC Observations of Galaxies at z = 5 - 7

The Universe from 1.2 to 0.78 Billion years after the Big Bang

Galaxies at z = 5 - 6 in CDFS

Eyles et al. (2005); HST(ACS); IRAC





Based on I-band dropout technique:

(i - z) > 1.3 mag

with spectroscopic confirmation

SBM03#1 (z = 5.83 galaxy)

M = 2.3 x 10^{10} M(sun)

Stellar age ~ 400 Myr

LGBs in HUDF; z = 5 - 6

Model parameters:

Redshift (z)

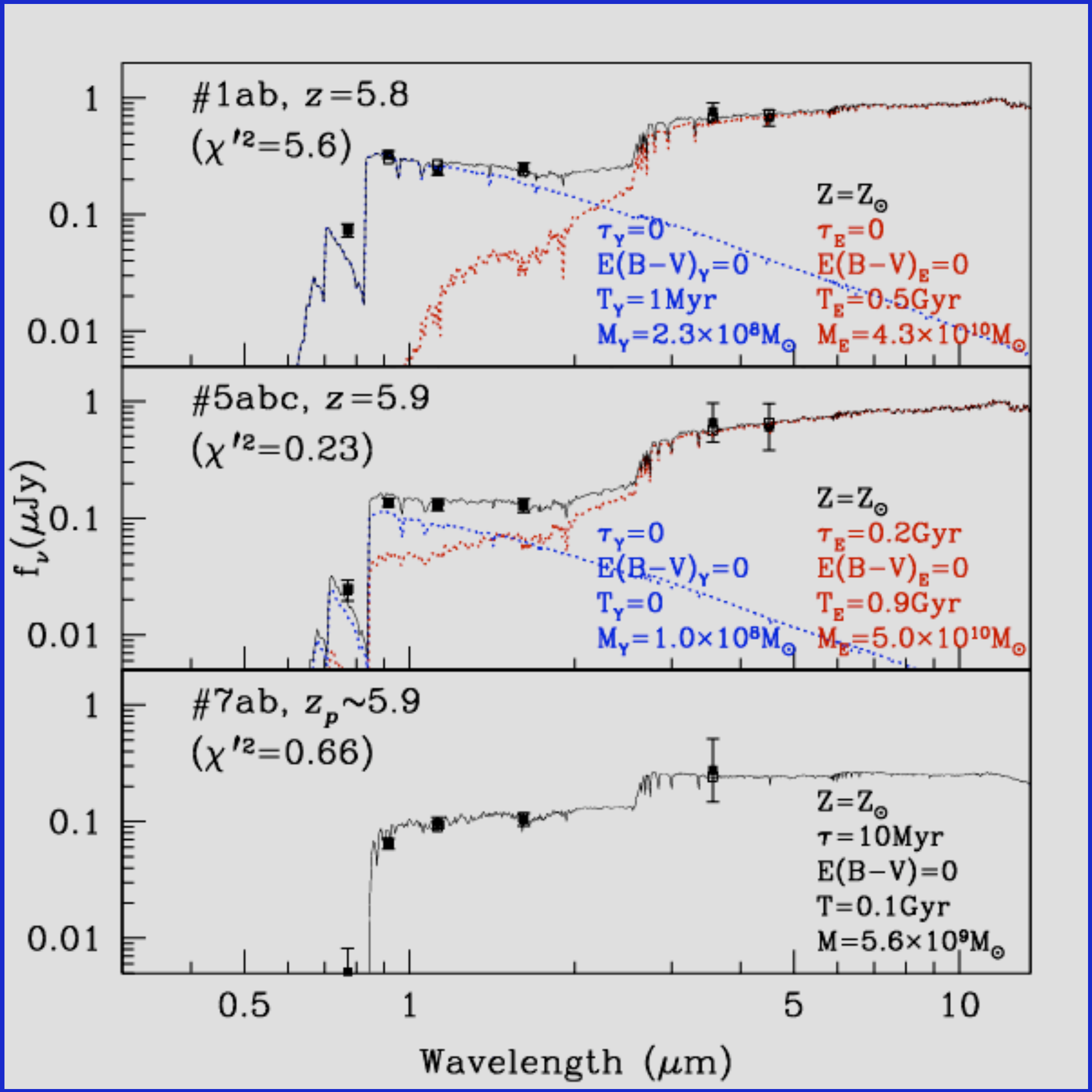
Age (T)

Stellar Mass (M)

Star formation history (τ)

Reddening E (B - V)

Metallicity (Z)



H. Yan et al. (2005)

IRAC Observations of Lyα Emission Galaxies at z = 5.7

K. Lai, J. Huang, G. Fazio, L. Cowie, E. Hu, Y. Kakazu

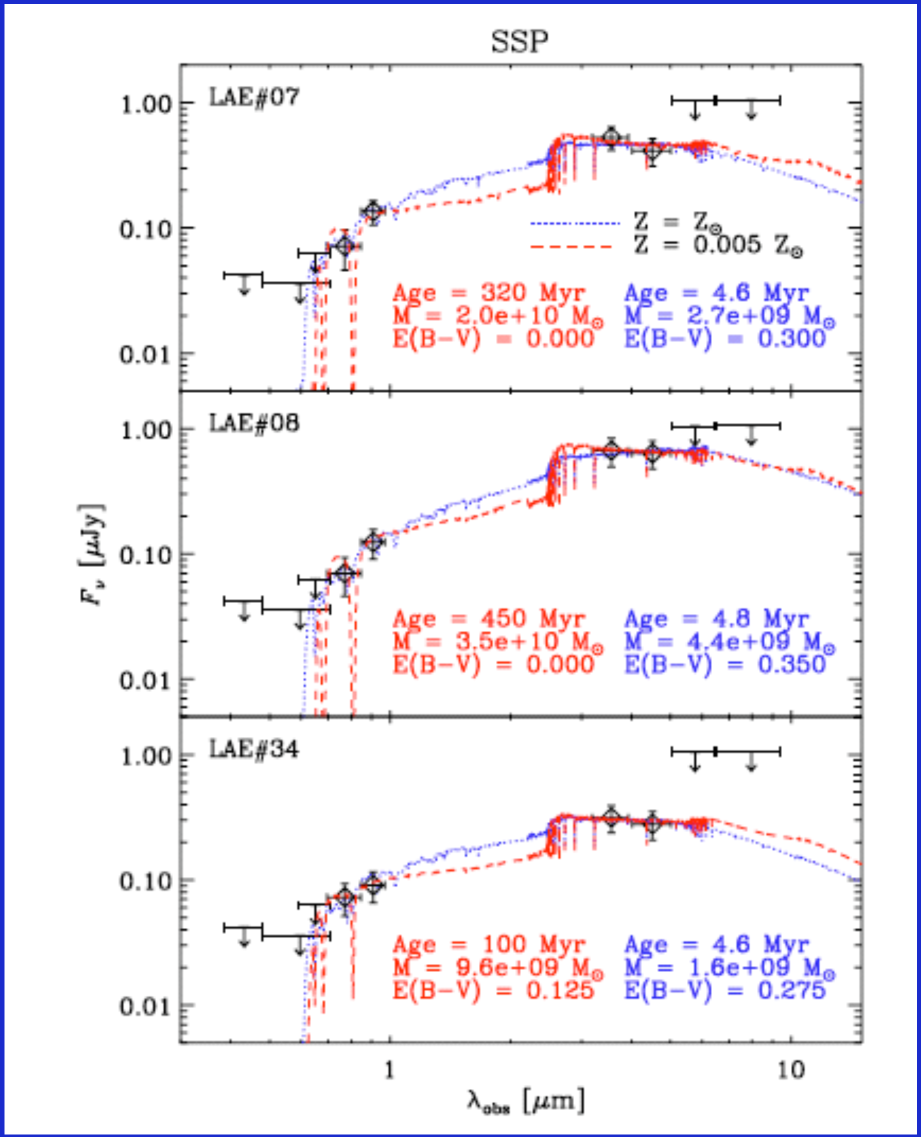
Best fit simple stellar population (SSP) models used (burst+constant star formation)

Blue-dotted (red-dashed) line is for a model with Z = Zsun (0.005 Zsun)

Appear to be dusty young starbursts, with ages ~ 5 Myr, M ~ 10^9 Msun, and reddening E(B-V) = 0.35

Alternate view: dust free, ages ~ 100 Myr and masses ~ 10^{10}.

Very little constraints on metallicity; near-IR observations could resolve this problem



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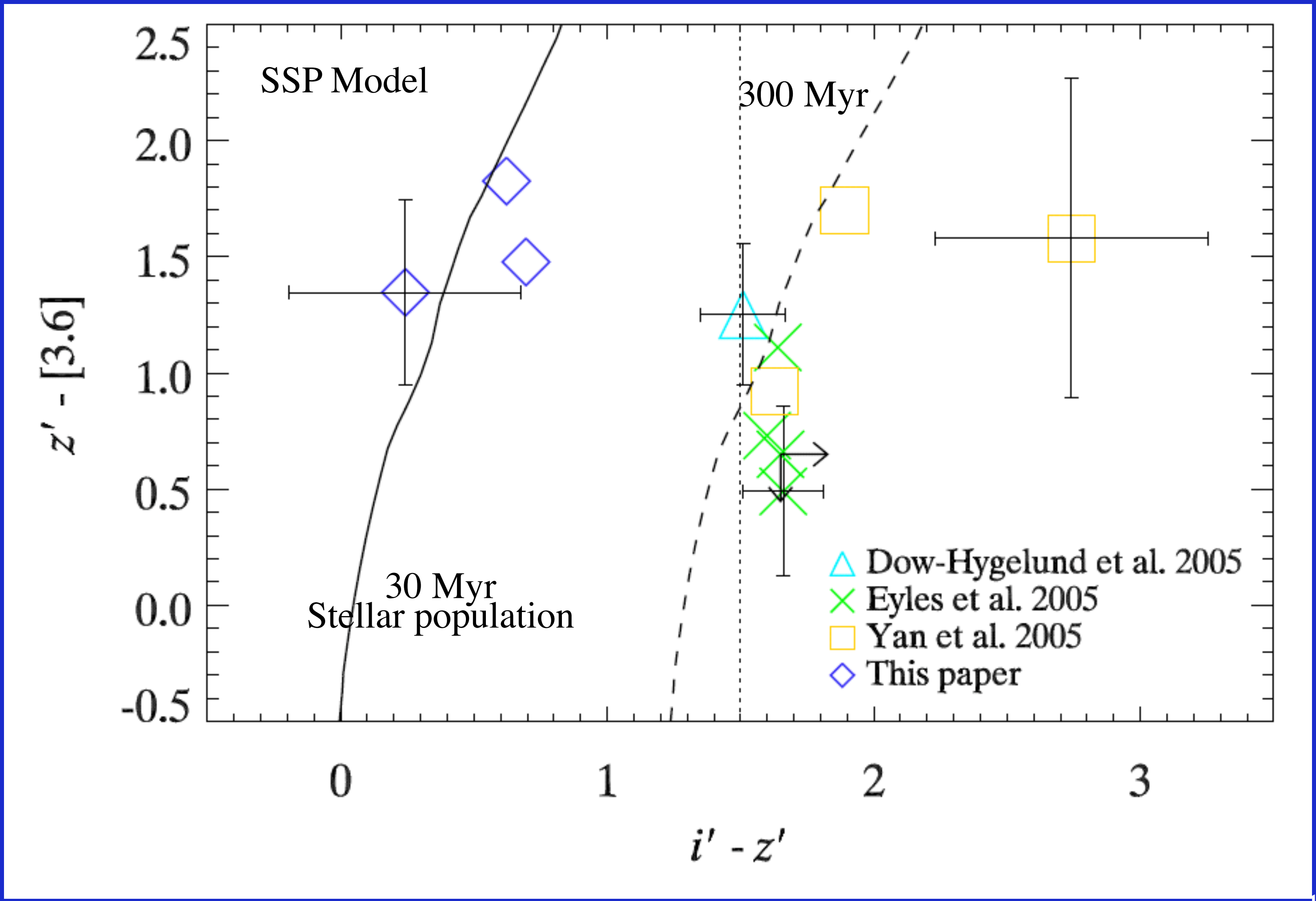


Galaxies at z = 5 - 6

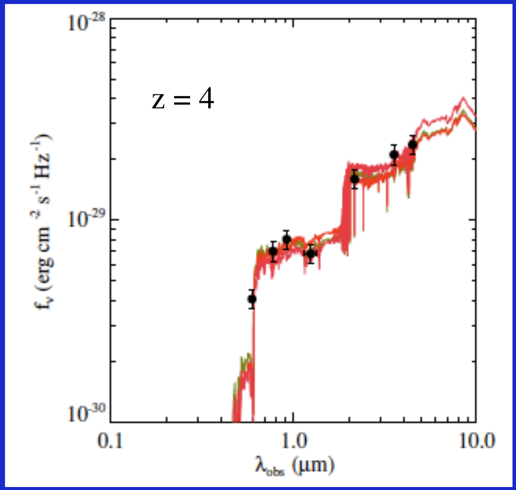
Eyles et al. (2005; 2007); Yan et al. (2005; 2006); Dow-Hygelund et al. (2005)
Stark et al. (2007)

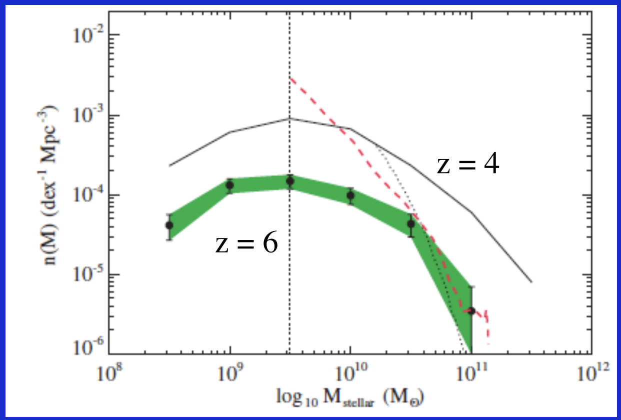
- Galaxies as massive as ~ 10^{10} M(sun) already existed when the Universe was less than a billion years old.
  - Consistent with solar abundance and no reddening.
- Photometry shows pronounced Balmer break that results from the dominant presence of stars with ages of a few hundred Myr.
  - strongly indicates that the Universe was already forming massive galaxies at ages less than 800 million years ($z > 7$-10).
- Spitzer allows the first constraints to be placed on the star formation rate density integrated over the first 800 Myr of the Universe.
- A subset of this population exists that is younger and considerably less massive.

Evolution of Lyman Break Galaxies Between z = 4 - 6

Stark et al. (2009); GOODS fields; HST(ACS); Spitzer(IRAC; MIPS)

- No strong evolution of stellar masses and stellar ages of galaxies of fixed UV luminosisty from z = 6 - 4
- Consistent with drop in UV LF between z = 4 - 6
- Star formation episodic (~ 500 Myr)
- Stellar mass function of UV luminous sources grows significantly from z = 6 - 4
- Significant fraction of quiescent massive galaxies (DRGs) at z ~ 2-3 were assembled at earlier times.





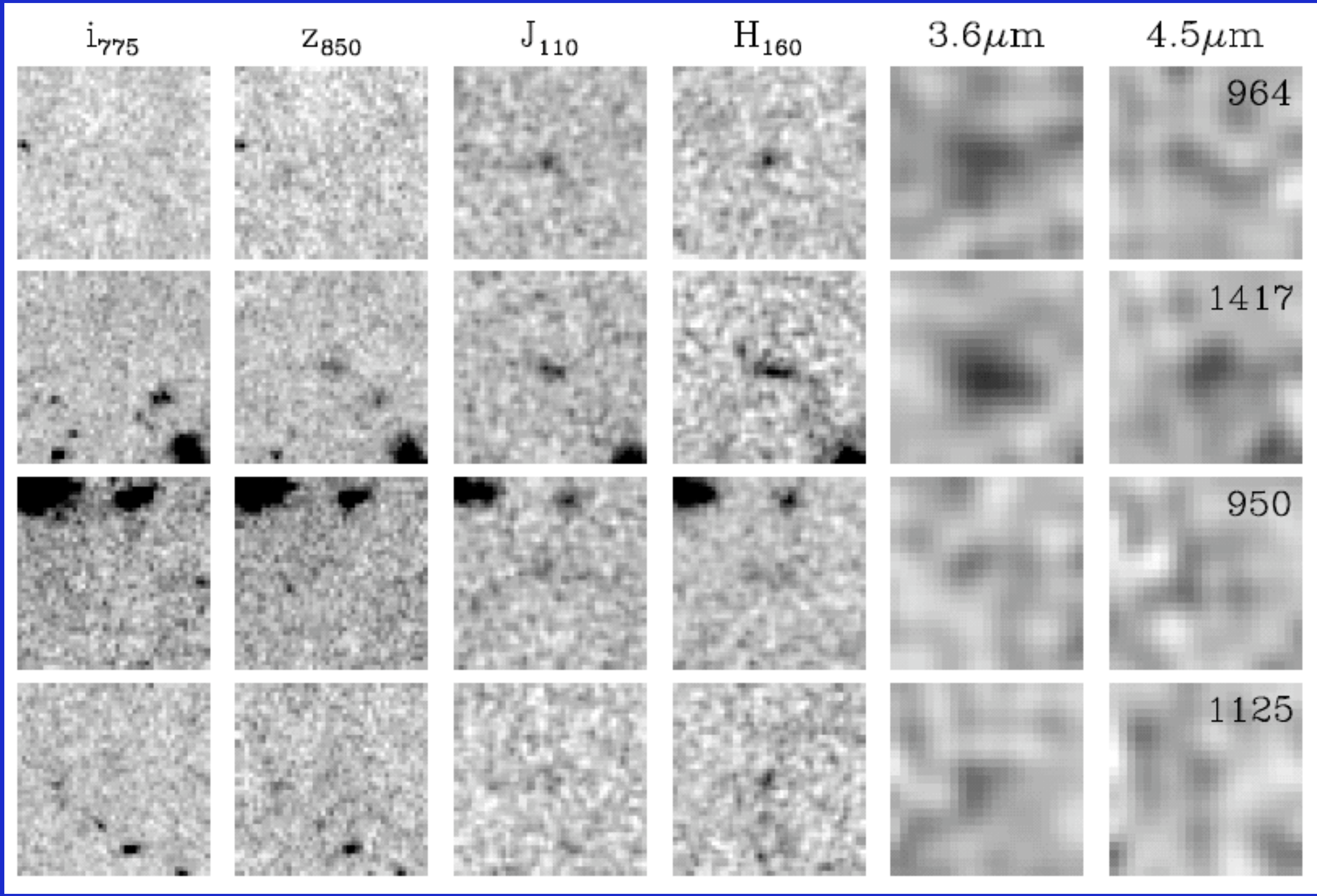
Observations of Galaxies at z ~ 7

The Universe was ~ 800 Million
Years Old

HST/SPITZER IMAGES OF GALAXIES AT Z ~ 7

Labbe et al. (2006); HUDF; HST(ACS, NICMOS): IRAC; VLT; Magellan

z - band dropouts



SPECTRAL ENERGY DISTIBUTION OF IRAC DETECTED Z ~ 7 GALAXIES

Labbe et al. (2006)

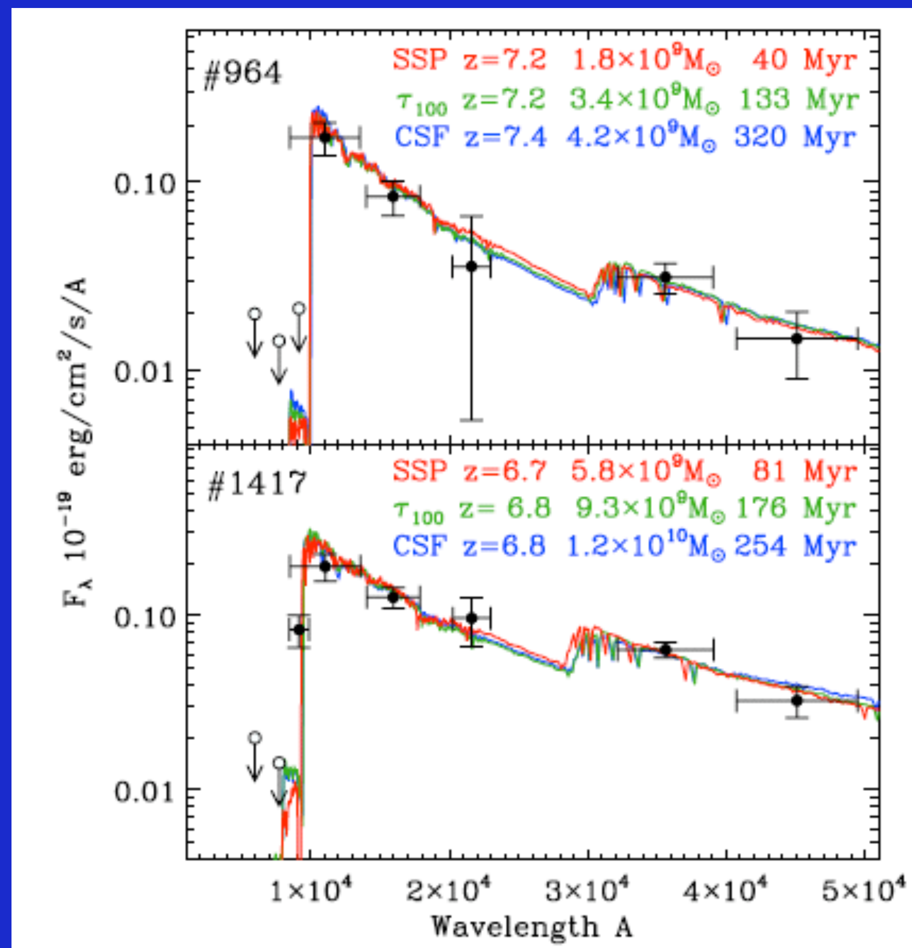
Spitzer/IRAC confirmed the reality of these galaxies (Universe ~ 750 Myr old).

IRAC observations constrain the mass and ages of these galaxies

- **mass: 1 - 10 x 10^9 M(sun)**
- **stellar ages: 50 - 200 Myr**

Galaxies must have formed during the era of reionization.

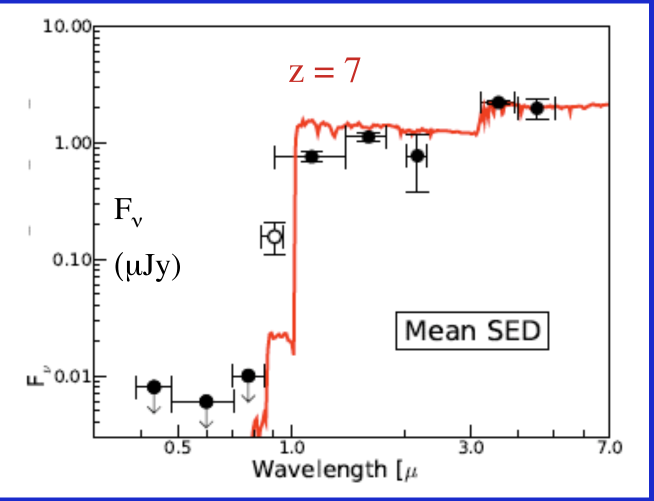
However, not sufficient to reionize the Universe.

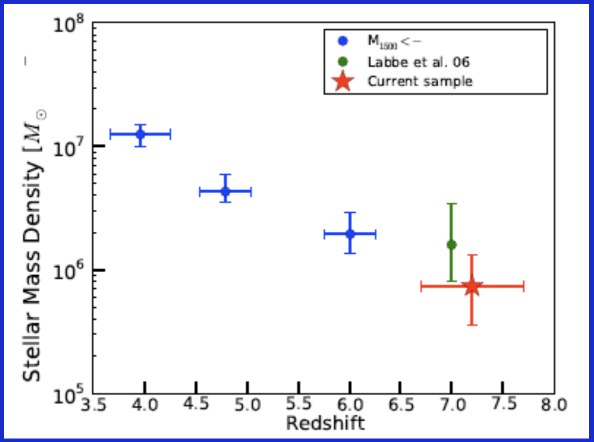


Stellar Mass Density and Specific Star formation Rates at z = 7

Gonzalez et al. (2009); HST (ACS, NICMOS); Spitzer/IRAC

- Robust sample of 11 z = 7 galaxies (z-dropouts) detected by IRAC
- GOODS field; 80 arcmin^2
- Stellar masses: 0.1-13 x 10^9 Msun
- Ages: 20 - 400 Myr
- Most of stars formed at z >8
- Little or no dust extinction (same as z = 4 - 6)
- SFR ~ 10 Msun/yr
- Stellar mass density as a function of z

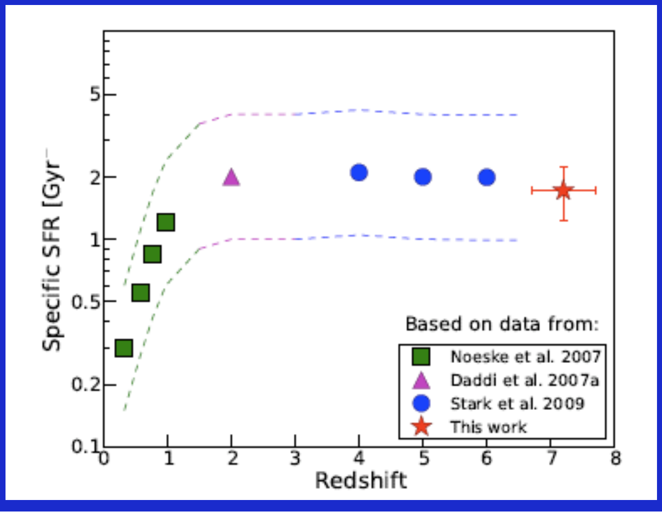


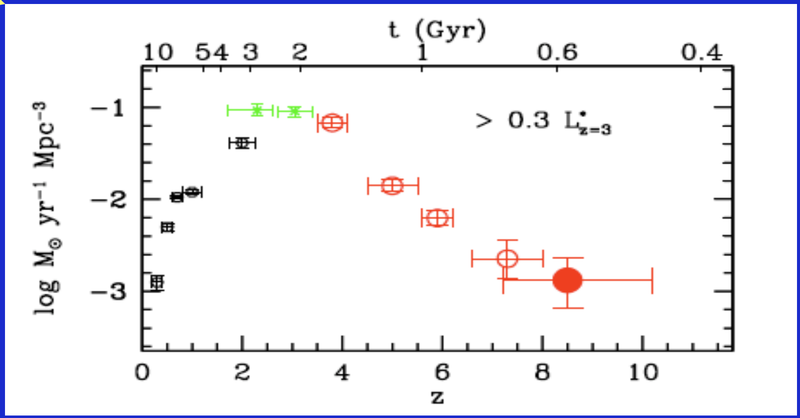


Stellar Mass Density and Specific Star formation Rates at z = 7

Gonzalez et al. (2009)

- Specific SFR constant at high z as a function of redshift
- Star formation rate density can be inferred at z = 8
- SFR density far below critical level ionize universe at z~8
- Substantial amount of star formation not observed





IRAC OBSERVATIONS OF SUB-L* z ~ 7 and 8 GALAXIES

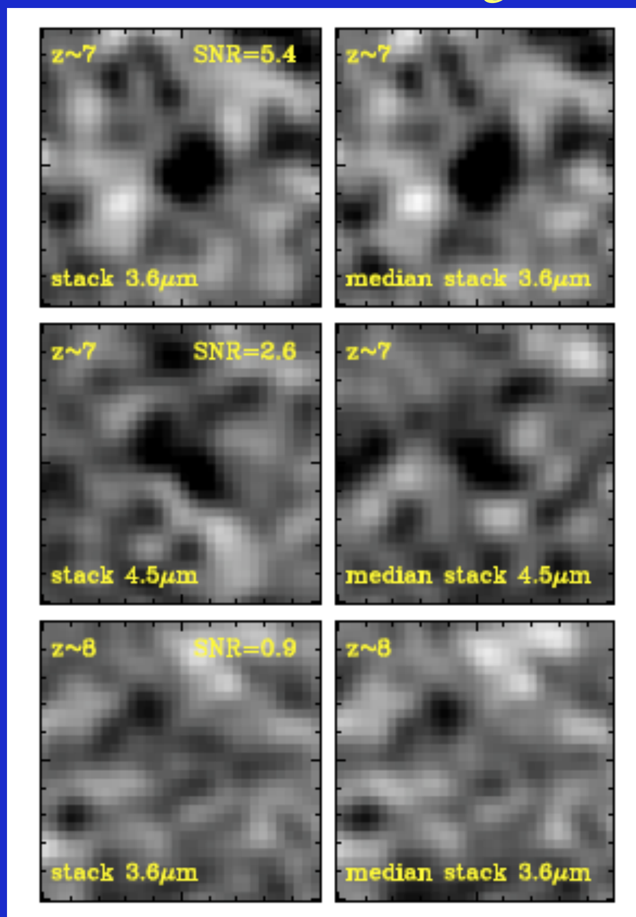
Labbe et al. (2009); Oesch et al. (2009); Bouwens et al. (2009); Bunker et al. (2009); McLure et al. (2009); Wilkins et al. (2009);HST(ACS;WFC3); IRAC; VLT; Magellan; z and Y dropouts

IRAC Stacked Images

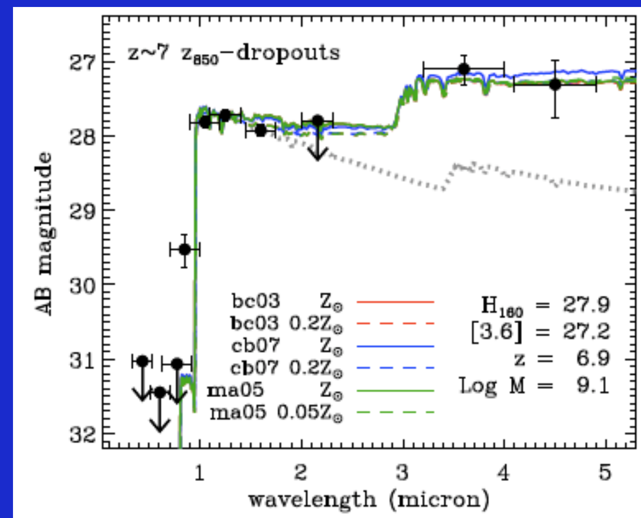
z = 7
3.6 μm

z = 7
4.5 μm

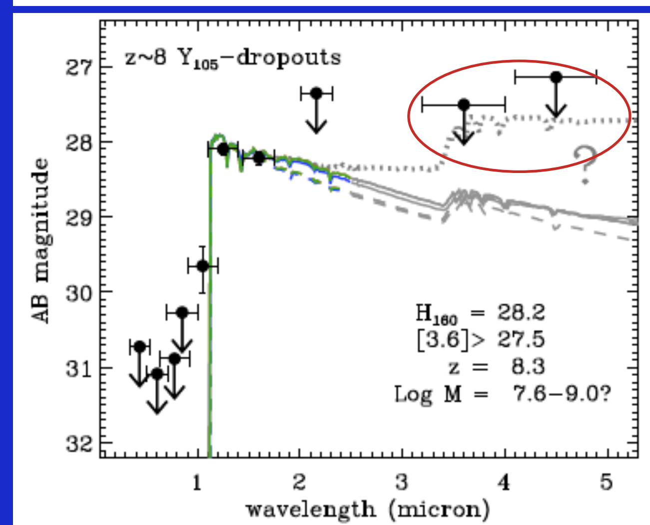
z = 8
3.6 μm



z = 7



z = 8

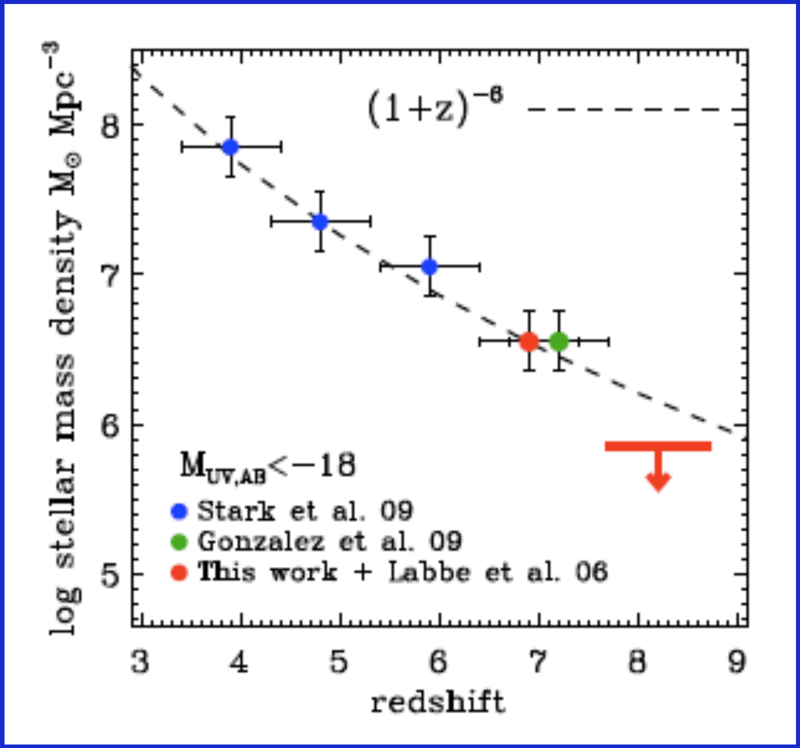


IRAC OBSERVATIONS OF SUB-L* z ~ 7 and 8 GALAXIES IN HUDF

Labbe et al. 2009

- Important insights into the earliest phases of galaxy evolution.
- Relatively high stellar ages
  - ~ 300 Myr and M/L_v ~0.2
- Specific star formation rate does not depend on stellar mass
- Highlights a significant contribution of low luminosity galaxies to the z ~7 stellar mass density.
- Stellar mass could provide a substantial contribution to ionize universe

Stellar Mass Density vs z



THE SEARCH FOR LENSED GALAXIES AT Z ~ 7

z~7 galaxy in A2218

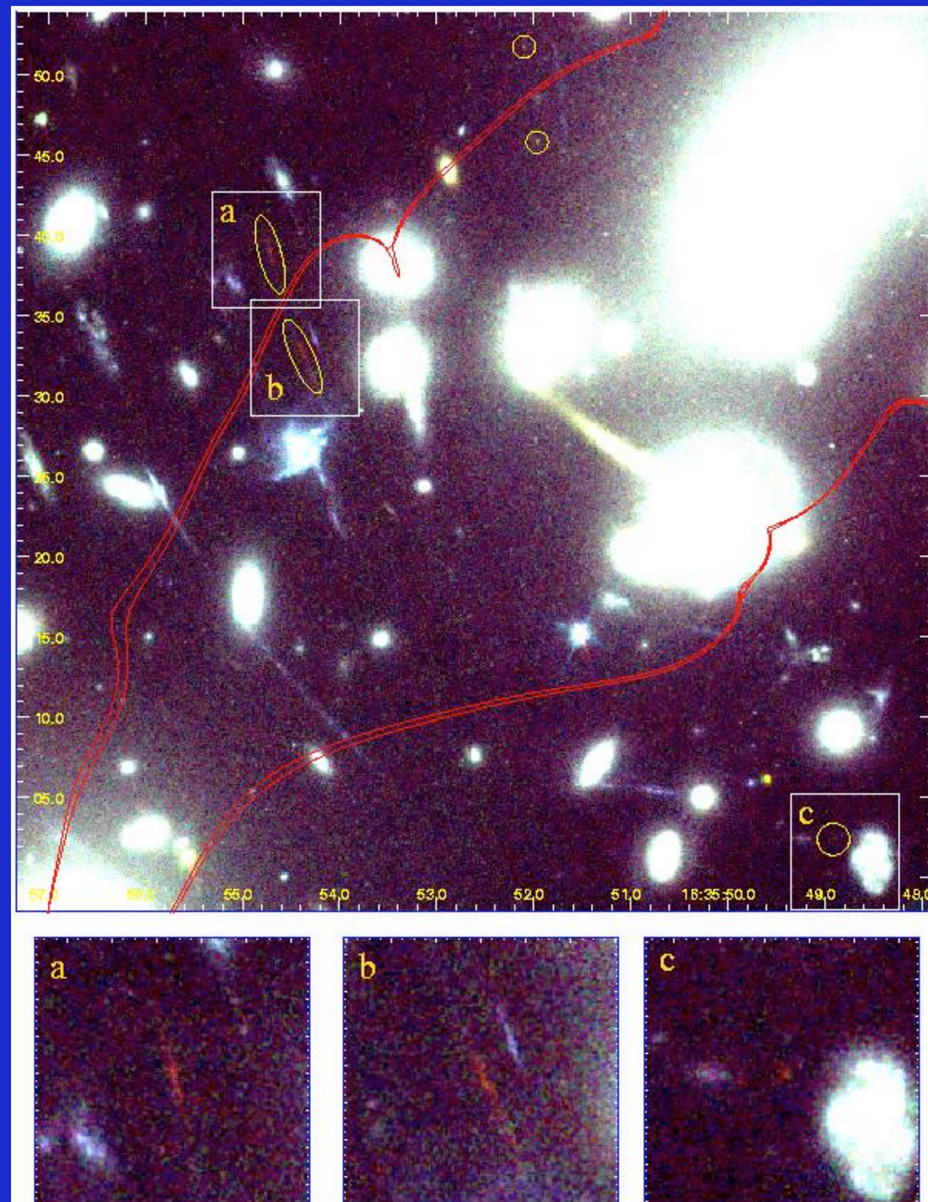
- Discovered by Kneib et al. (2004) in HST images.

- Triply lensed (component a, b, and c)

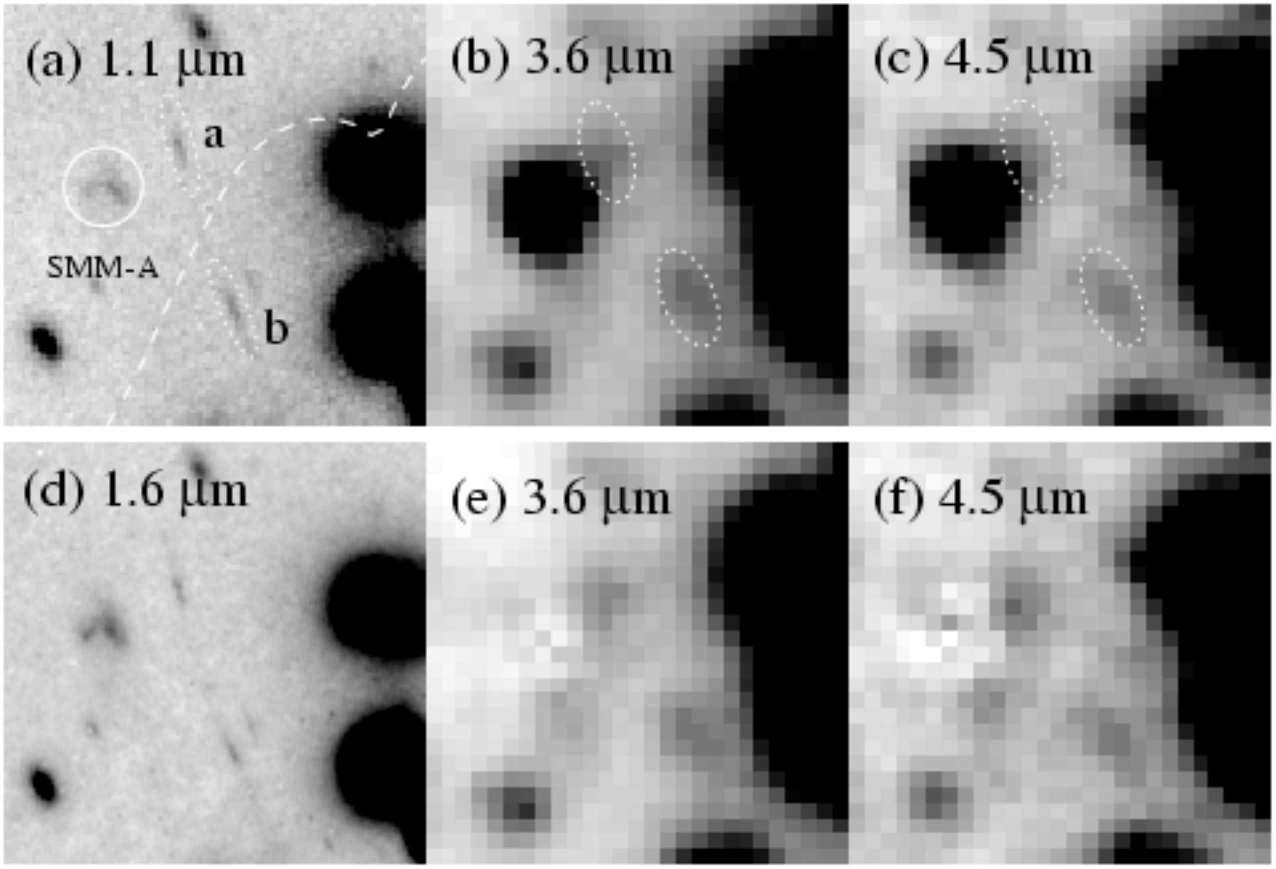
- Components a & b magnified by a factor of 25

- Lens model suggests z~7

- Continuum break at ~ 1 μm consistent with z~7



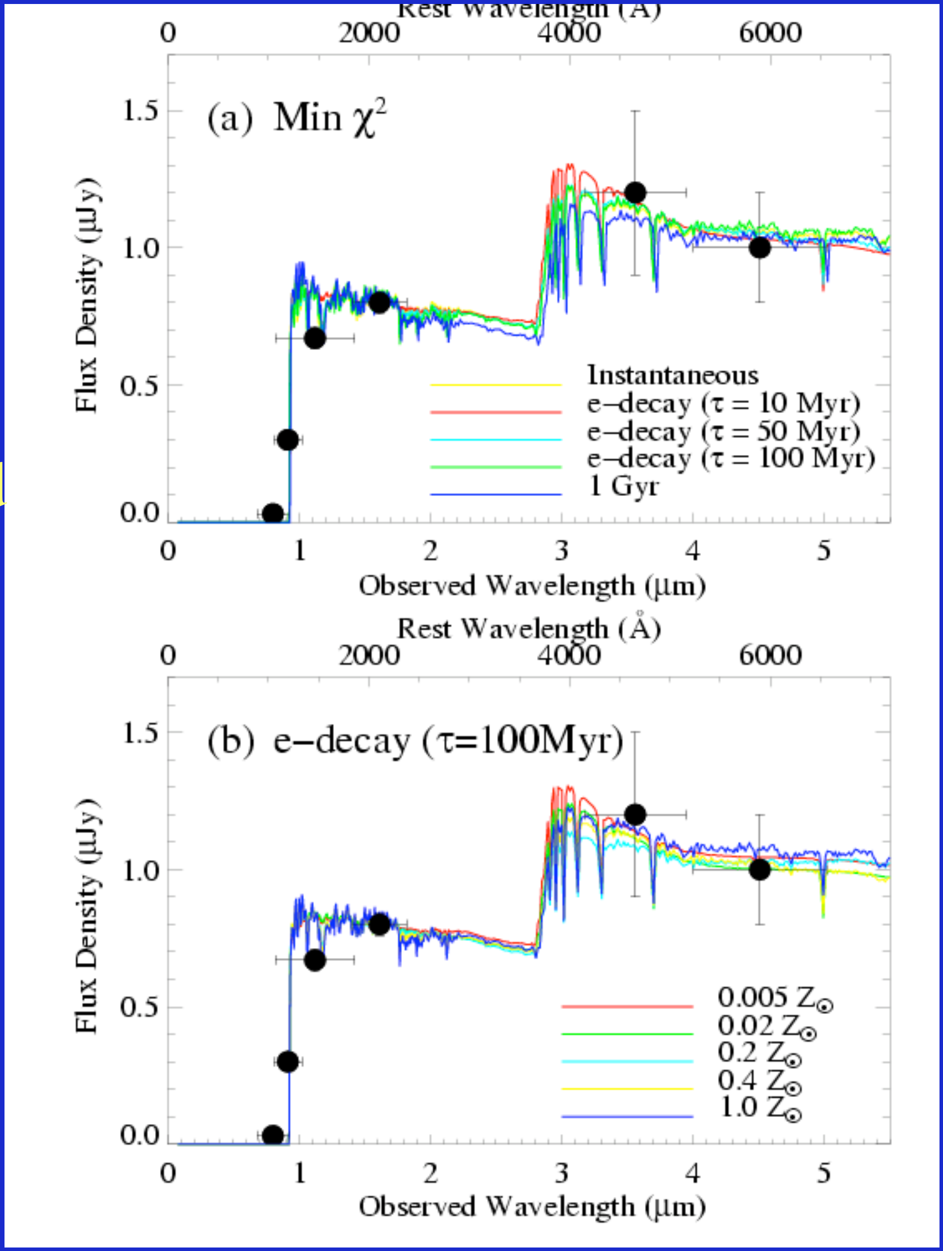
Spitzer/HST Images of z~7 galaxy



Egami et al. 2004

SED model fitting

- Bruzual-Charlot model
- Redshift: 6.6-6.8
- Significant Balmer Break
  → Age > 50 Myr, quite possibly a few/several hundred Myr
- Steeply rising UV continuum toward 1216A
  → low extinction and/or low metallicity (degenerate)
- Stellar mass: ~ 10^9 $M_\odot$ → 1/10 of z = 3-4 LBG stellar mass
- SFR: ~ 0.1-5 $M_\odot yr^{-1}$

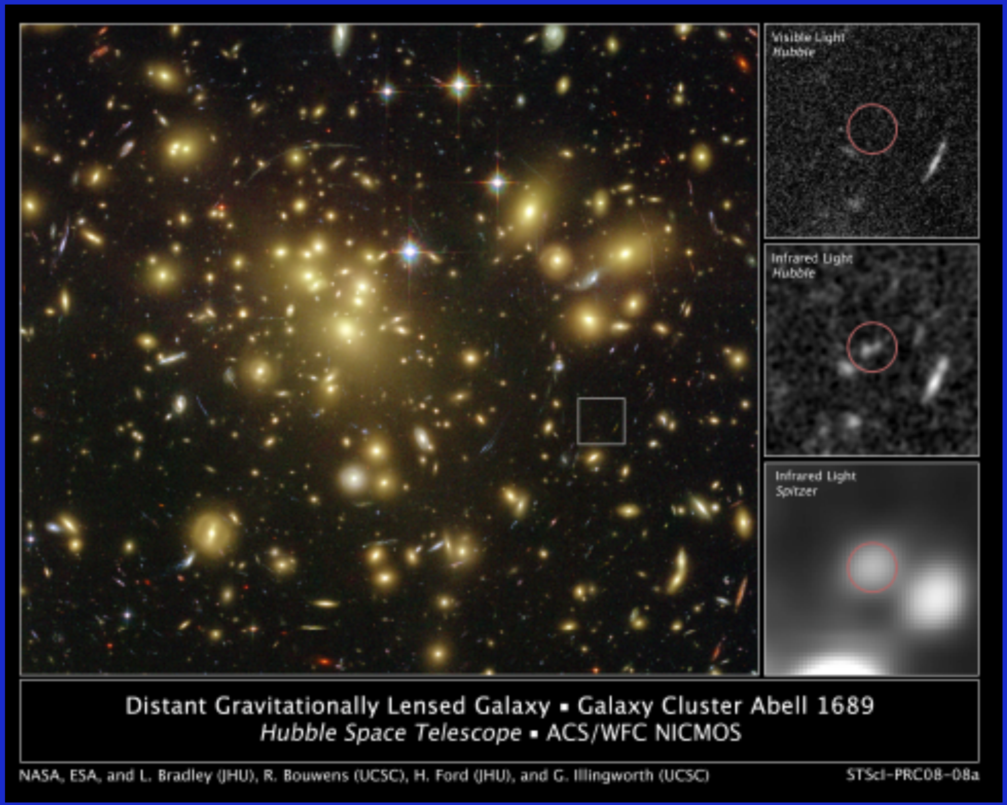


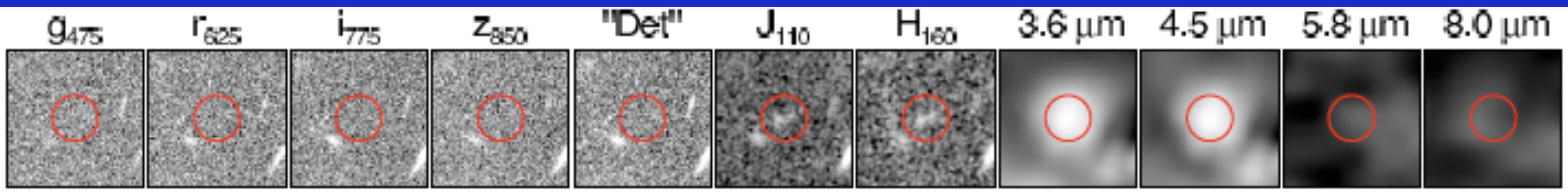
Egami et al. 2004

Lensed Galaxy at z ~ 7.6 in Abell 1689

Bradley et al. (2008); HST(ACS; NICMOS); IRAC

- Massive galaxy cluster Abell 1689 (z = 0.18)
- Cluster magnification: ~ 9.3 at z = 7.6
- Star formation is occurring in compact knots of ~ 300 pc
- Brightest observed, highly reliable z>7 galaxy candidate found to date





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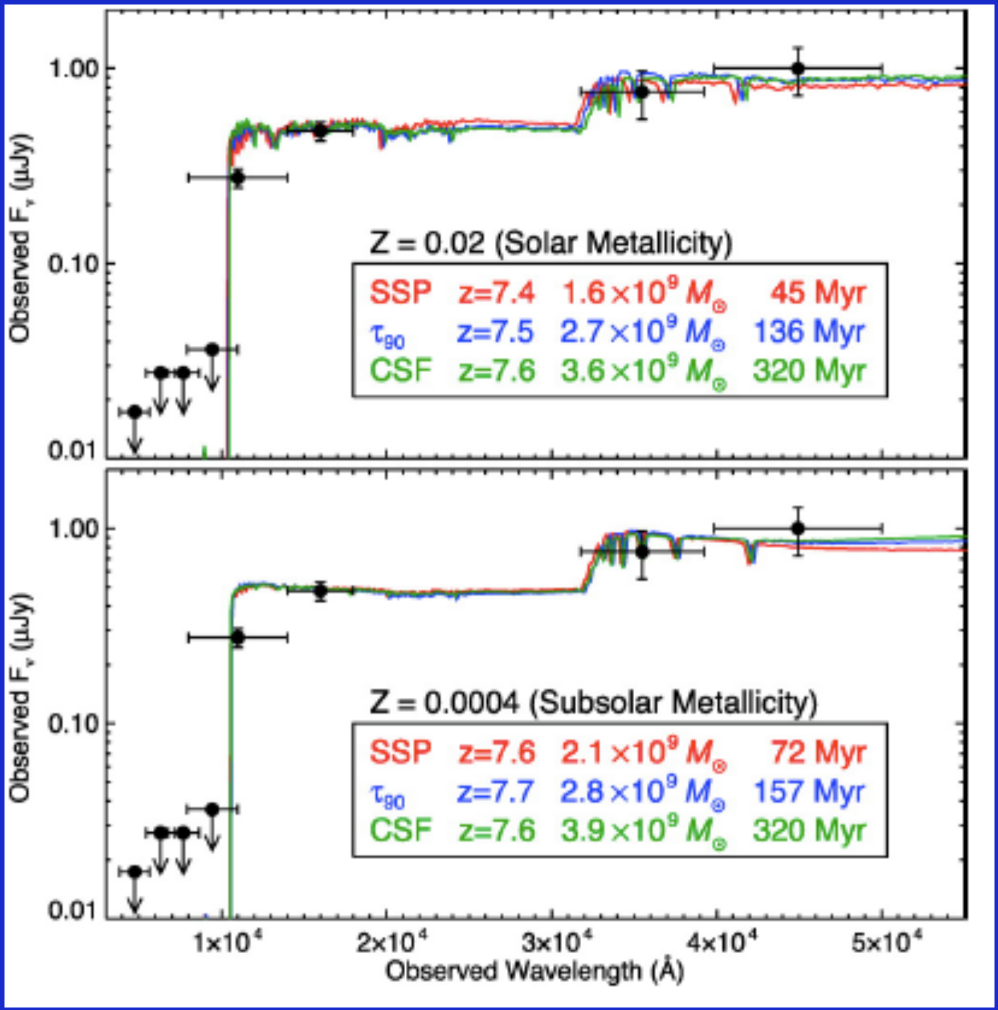
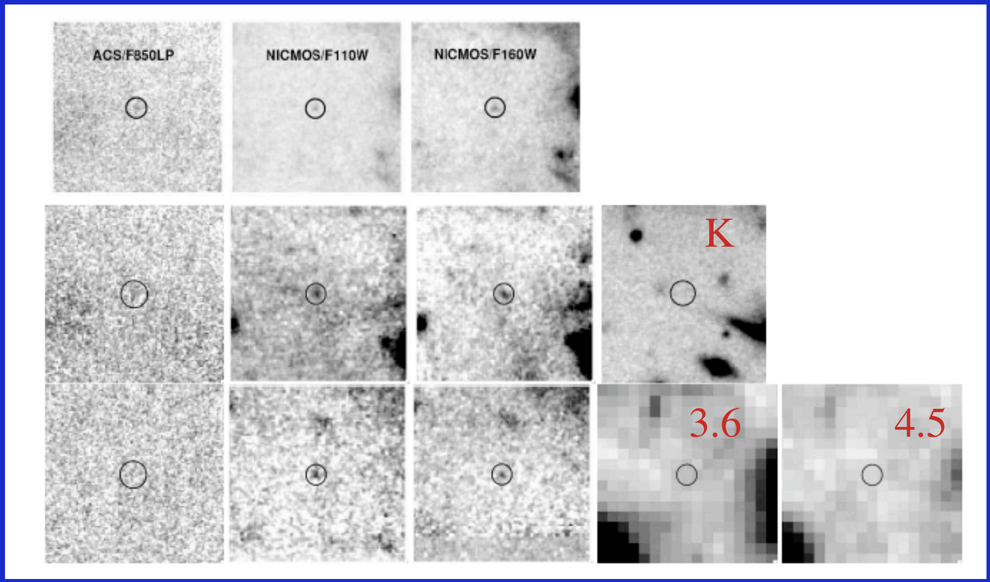


Search for Lensed Galaxies z > 7

Richard et al. 2009



Stacked images of z-band dropouts

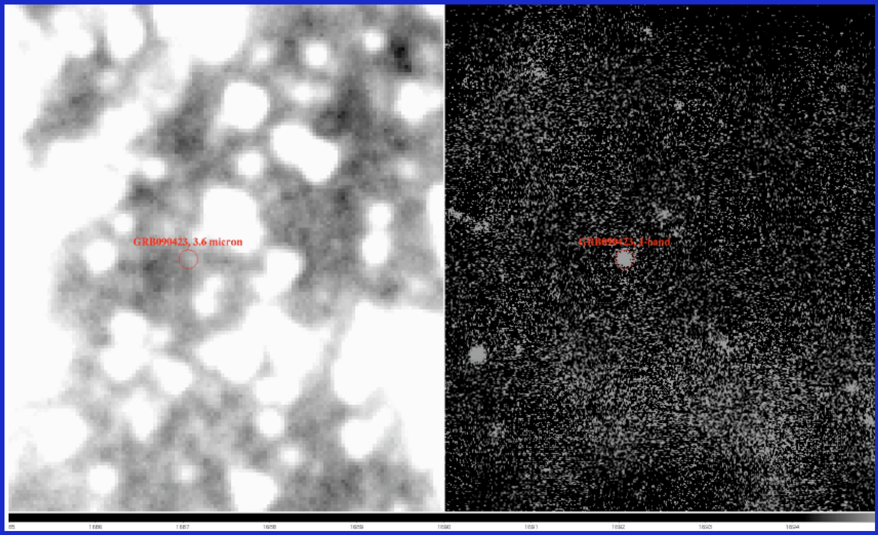
- Object: constrain abundance of low luminosity star-forming galaxies at $z = 7 - 10$
- Observed 6 foreground clusters
- 12 candidates (10 z-band and 2 J-band dropouts); 5 possible $z > 7$
- No Lyα emission lines detected
- Stacked images suggest very young population, little reddening; high z

Spitzer/IRAC Observations of the GRB at z ~ 8.3

R. Chary et al. (2009); GCN Circular 9582

- One of first results during Warm Mission IWIC (DDT; June 2009).
- Detection of afterglow at 3.6 μm (72 hrs; 27.2 AB mag; 47 nJy; 3 σ); approximate predicted flux.
- Detected 46 days after the burst (5 days in rest frame).
- Second epoch of observations planned for Feb 2010 to detect the underlying host galaxy

3.6 μm　　J-Band



Red circles: 1 arcsec diameter

Spitzer Warm Mission
SEDS: Spitzer Extended Deep Survey

- PI: Giovanni Fazio (SAO)
  - 47 Co-I's from 23 institutions
- Primary Scientific Objective
  - Galaxy formation in the early Universe
  - Obtain first complete census of the assembly of stellar mass as a function of cosmic time back to the era of reionization
  - Series of secondary objectives
- Unbiased survey 12 hrs/pointing at 3.6 and 4.5 microns ([3.6] = 26 AB, 5 σ) in five well-studied fields (0.9 sq deg)
  - 10 times area of deep GOODS survey
- Total Time: 2108 hrs over 1.5 years
- No proprietary time on data

Spitzer Warm Mission
The IRAC Lensing Survey:
Achieving JWST depth with Spitzer

- PI: Eiichi Egami (University of Arizona)
  - 12 Co-Investigators from 10 institutions
- Primary Scientific Objectives:
  - Characterize z>6 galaxies (expect ~50 z~7-8 galaxy detections)
  - Support future Herschel and ALMA surveys
  - Search for z>6 supernovae
- IRAC imaging survey of 47 massive lensing clusters (5 hrs/band, 2 bands) for which accurate mass models exist from HST, Keck and VLT data exists; achieve depths of ~ 10 nJy through amplification.
- First time such a large, statistical sample of clusters will be systematically employed to probe the high-z Universe.
- Hours approved: 526.4
- The resultant data set will be a great Spitzer legacy, particularly for JWST science.

Summary

- Detecting the most distance galaxies known in the Universe, back to the era of reionization (z~7) has been one of most remarkable achievements of Spitzer Space Telescope (85-cm mirror).

- When combined with deep, broadband multi-wavelength data, Spitzer observations can be fit to stellar population synthesis models to determine the spectral energy distribution of these galaxies and to constrain their stellar masses and ages and their star formation histories.

- These results showed that:
  - Massive galaxies (~ 10^{10} Msun) with stellar ages (~200-300 Myr) existed in early Universe
  - The stars in these galaxies formed several hundred years earlier (z~8-11)
  - There exists a substantial contribution of low luminosity galaxies at z=7 that could provide a significant fraction of the energy to ionize the Universe.

- Spitzer Warm Mission will provide a unique opportunity to obtain the first complete census of the assembly of stellar mass as a function of cosmic time back into the era of reionization, yielding unique information on galaxy formation in the early Universe.

- Spitzer will leave a very important legacy for JWST