High Redshift Galaxies in CLASH

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Space Telescope Science Institute

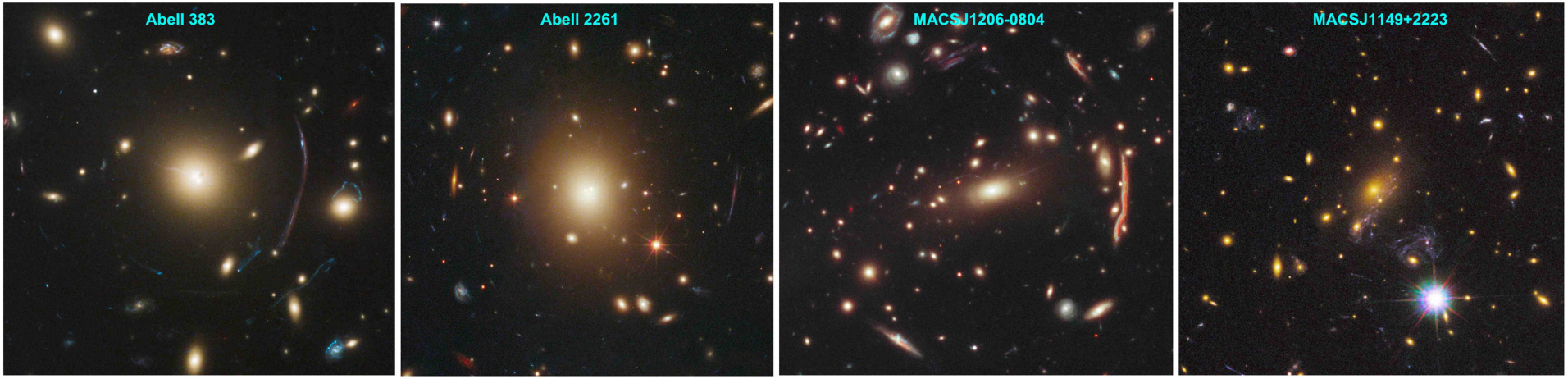
June 2013 – Cosmology in the Era of Extremely Large Telescopes

With special thanks to:
Rychard Bouwens, Larry Bradley, Dan Coe, Claudio Grillo, Polo Infante, Dan Kelson, Anton Koekemoer, Leonidas Moustakas, Piero Rosati, Renske Smit, Wei Zheng, Adi Zitrin & the entire CLASH team

CLASH:

Cluster Lensing And Supernova survey with Hubble

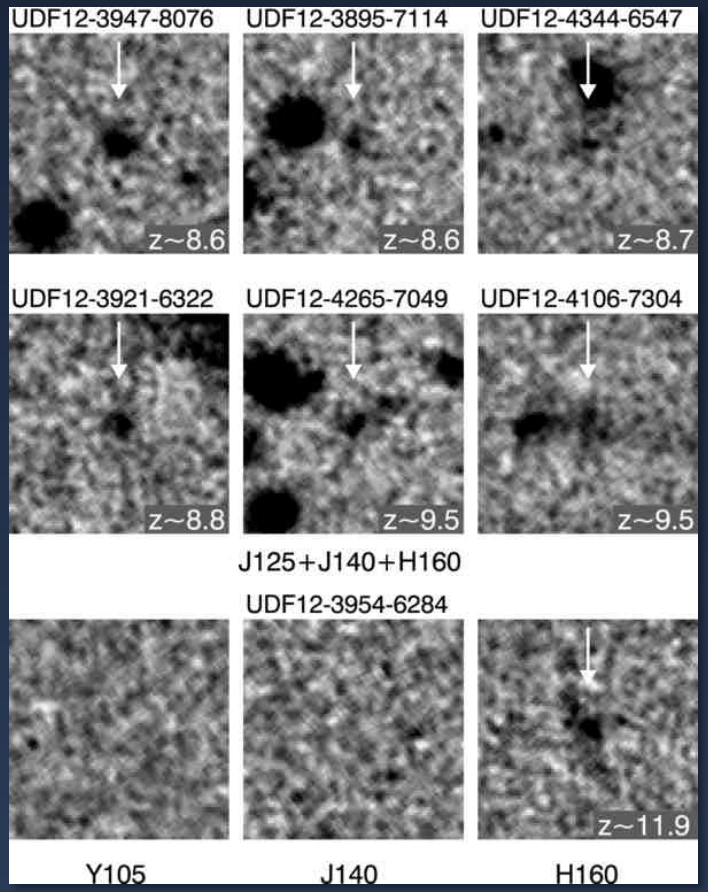
An HST Multi-Cycle Treasury Program designed to place new constraints on the fundamental components of the cosmos: dark matter, dark energy, and baryons.



To accomplish this, we are using galaxy clusters as cosmic lenses to probe dark matter and magnify distant galaxies.

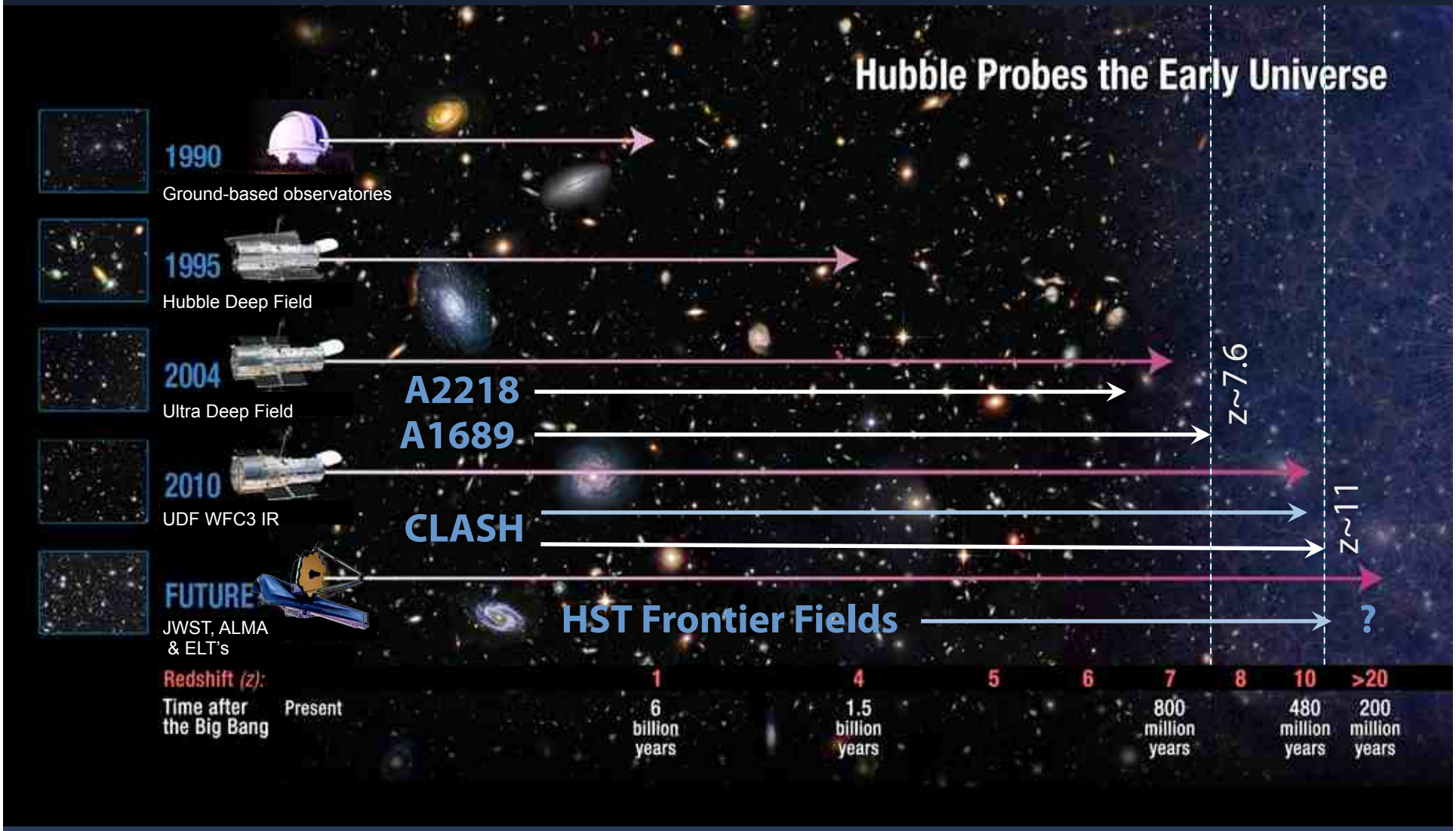
Key Questions in the Era of Extremely Large Telescopes

- When was the epoch of first galaxy formation?
- What are the characteristics (mass, “metal” abundance, star formation rates, global structure) of the most distant galaxies in the universe (t_U < 800 Myr)?
- What was their role in ionizing the intergalactic medium?
- How do galaxies build up and evolve at the earliest times?



z > 8 galaxy candidates from Ellis+ 2013

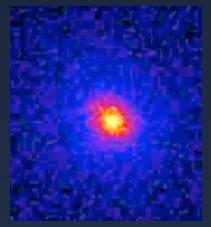
The Impact of Lensing Clusters

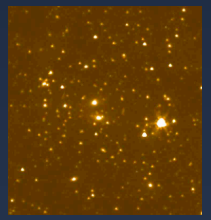
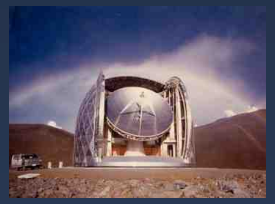
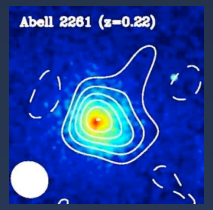


Comprehensive Multi-wavelength Coverage

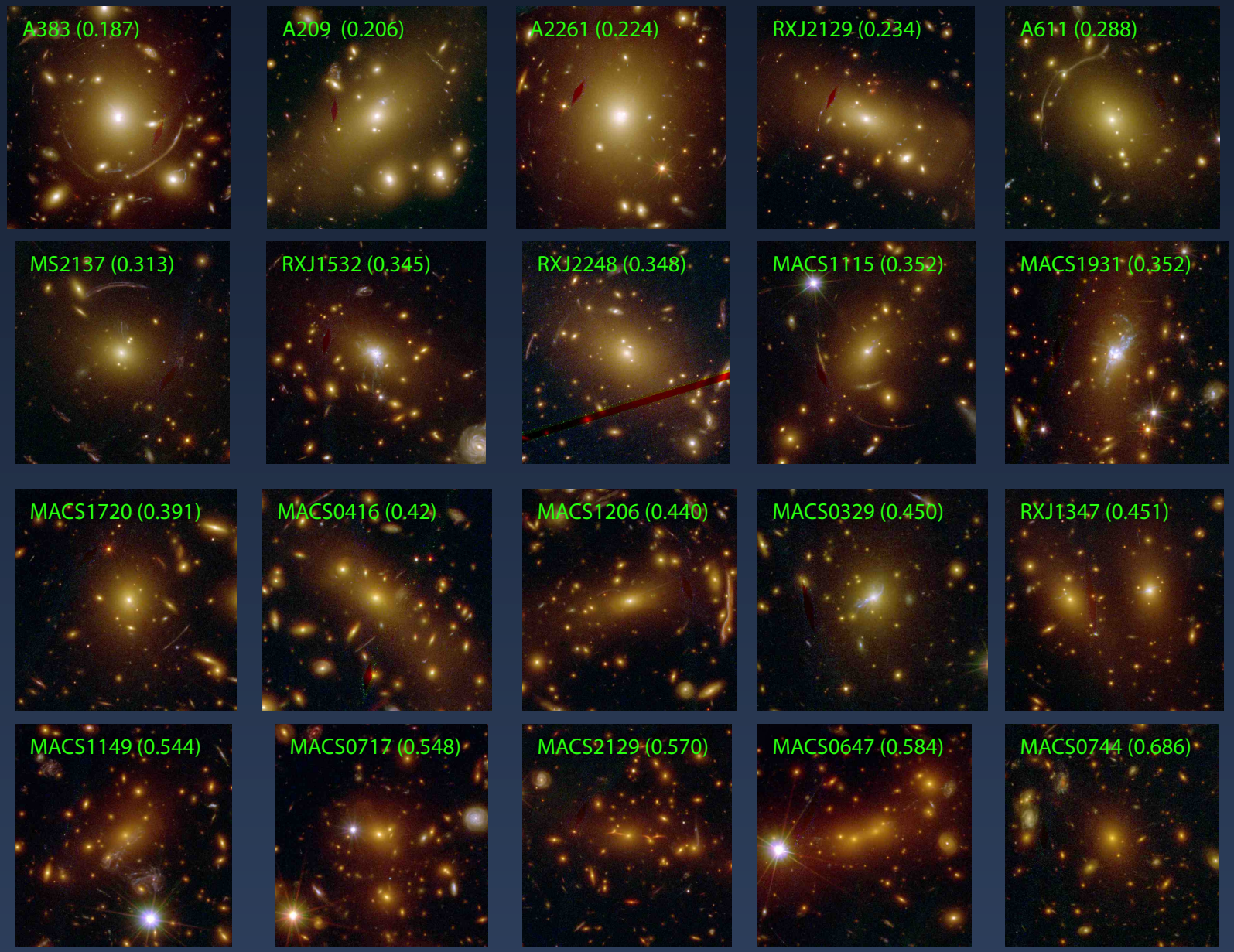
- HST 524 orbits: 25 clusters, each imaged in 16 passbands. (0.23 – 1.6 μm) 20 orbits per cluster (~27 ABmag @ 5σ)
- CLASH observations are 95% done - 23 clusters completed, rest done by July 6.
- Subaru wide-field imaging (0.4 – 0.9 μm)
- Spitzer Space Telescope archival and new cycle 8 data (3.6, 4.5 μm)
- Chandra x-ray Observatory archival data (0.5 – 7 keV)
- SZE observations (Bolocam, Mustang) to augment existing data (sub-mm)
- VLT, LBT, Magellan, MMT, Palomar Spectroscopy



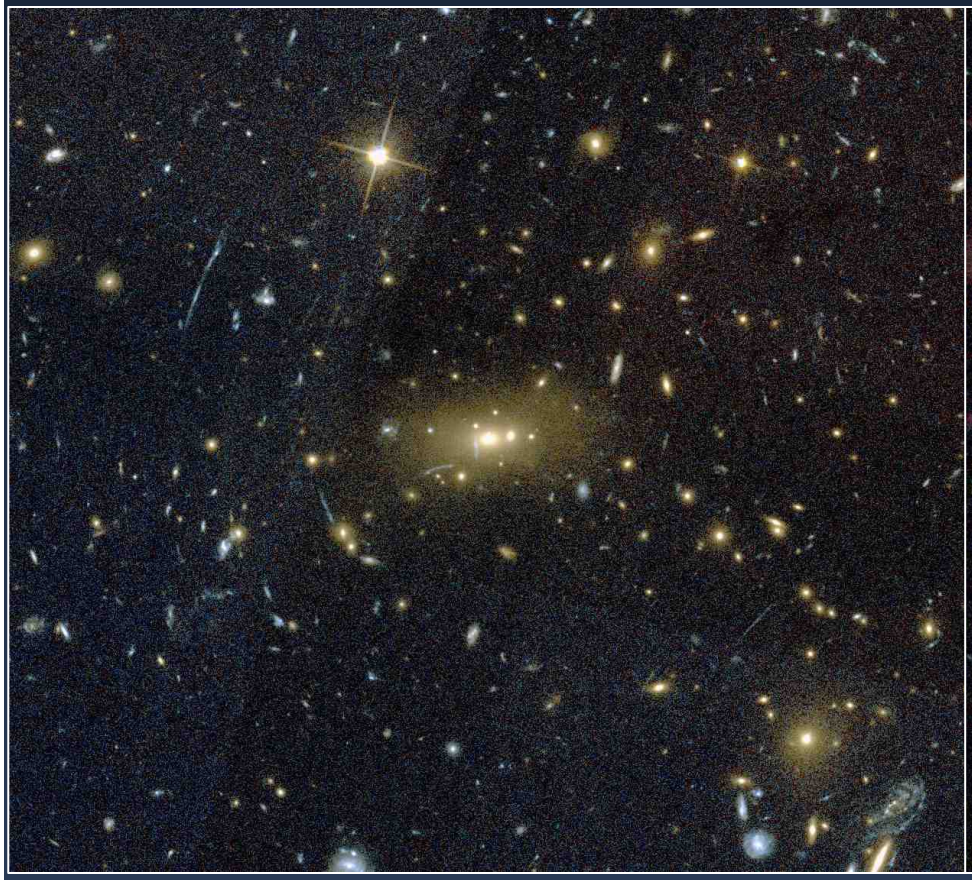

CLASH Gallery: First 20 Clusters



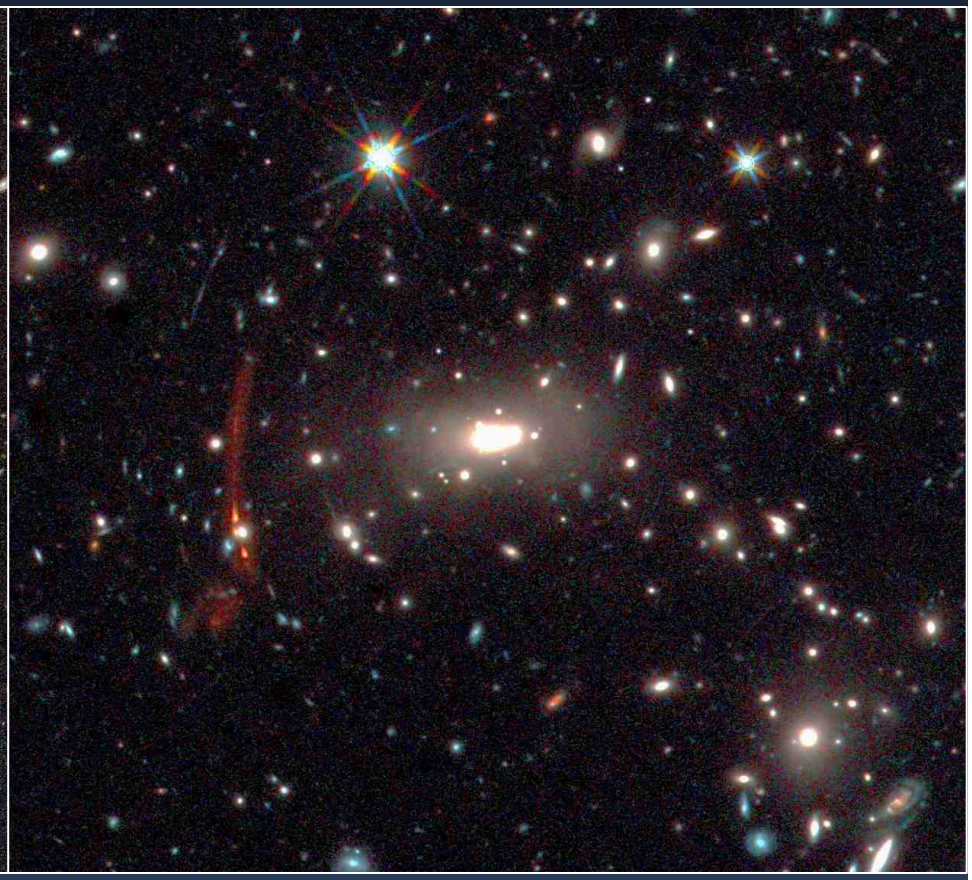
The Power of WFC3-IR Camera

CL J1226+3332 (z=0.89)

Sum of all current ACS data



Sum of all current WFC3-IR data

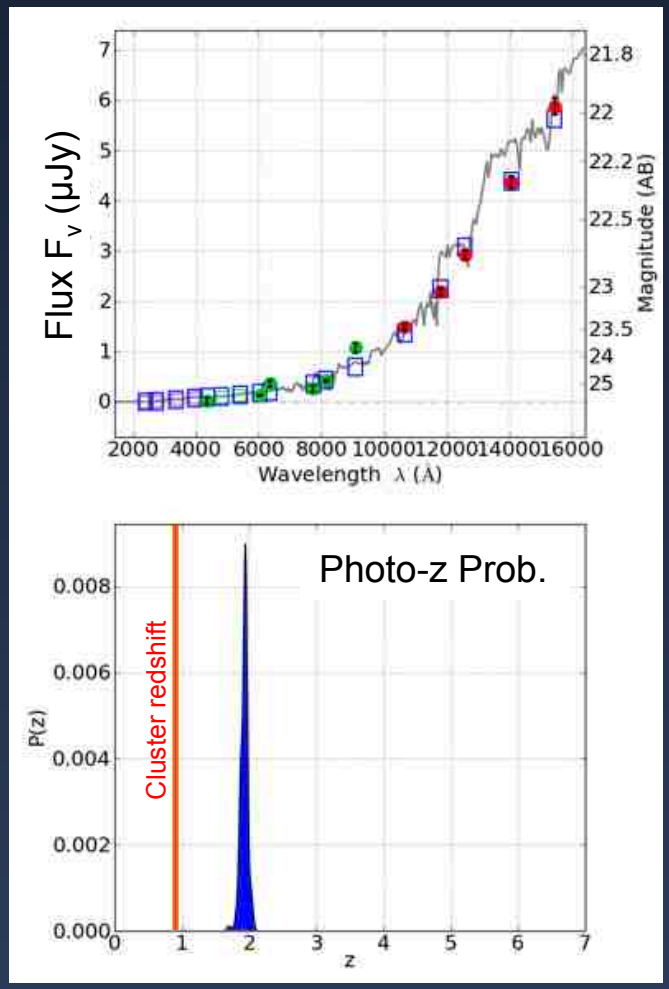


Cluster is x-ray luminous and known to be a good lensing system but no giant arcs.

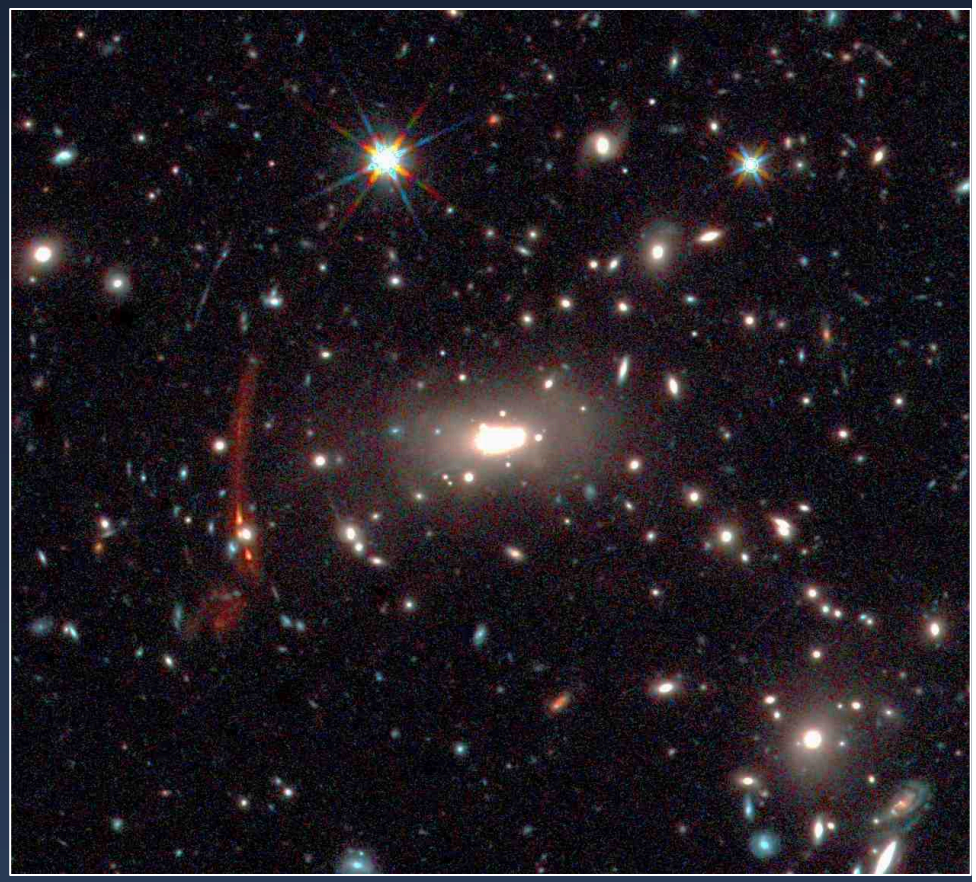
Oh snap! There is a giant arc.
photo-z ~ 1.95

The Power of WFC3-IR Camera

CL J1226+3332 (z=0.89)

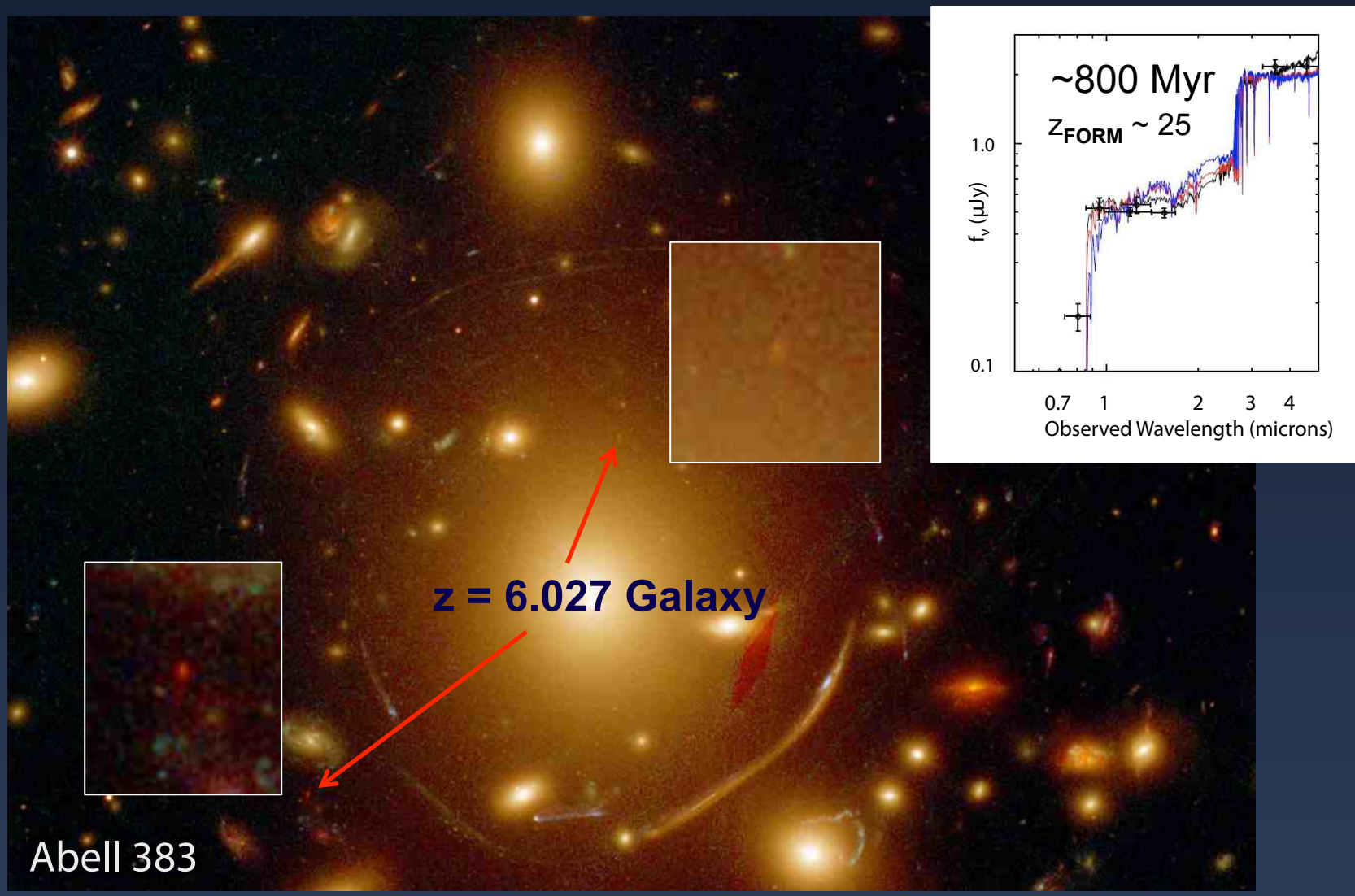


Sum of all current WFC3-IR data



Oh snap! There is a giant arc.
photo-z ~ 1.95

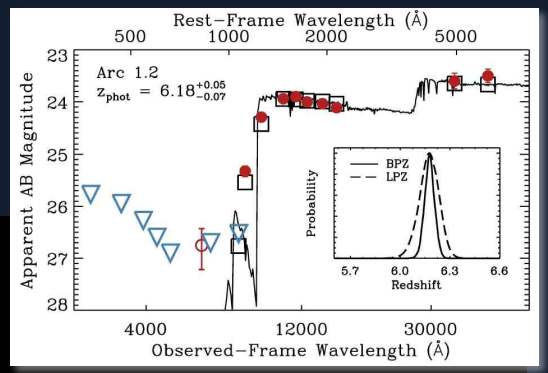
Richard et al. 2011: z = 6 lensed Galaxy in A383



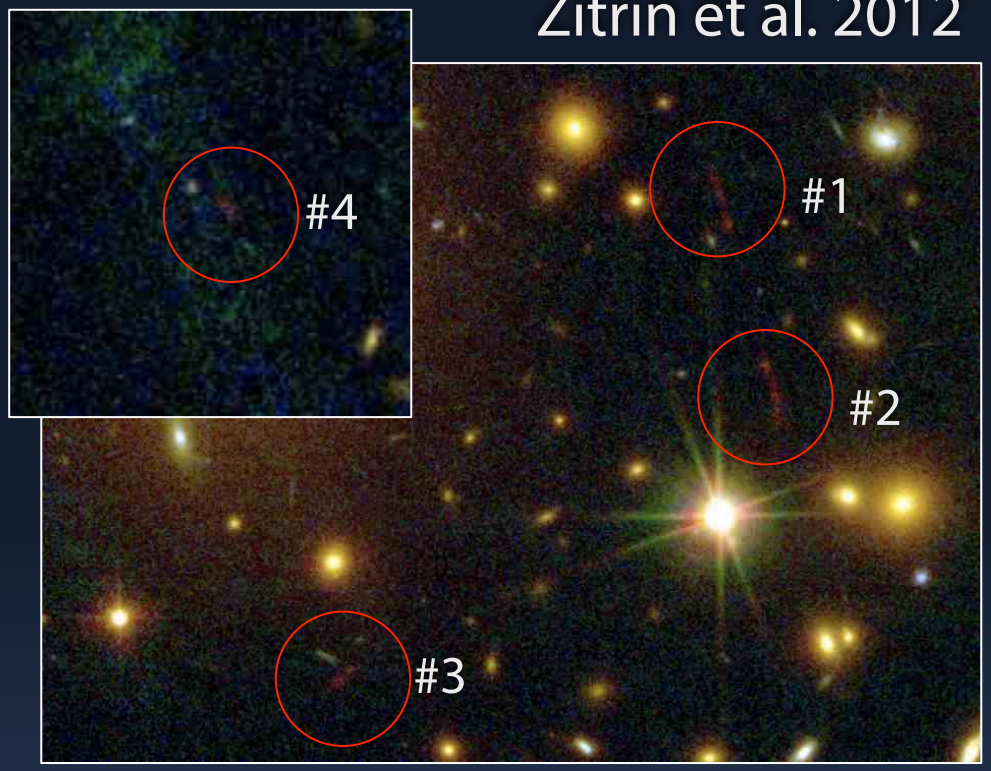
11.4 x magnification

MACS J0329-02: Quadruply-lensed Galaxy at z_{ph}= 6.15

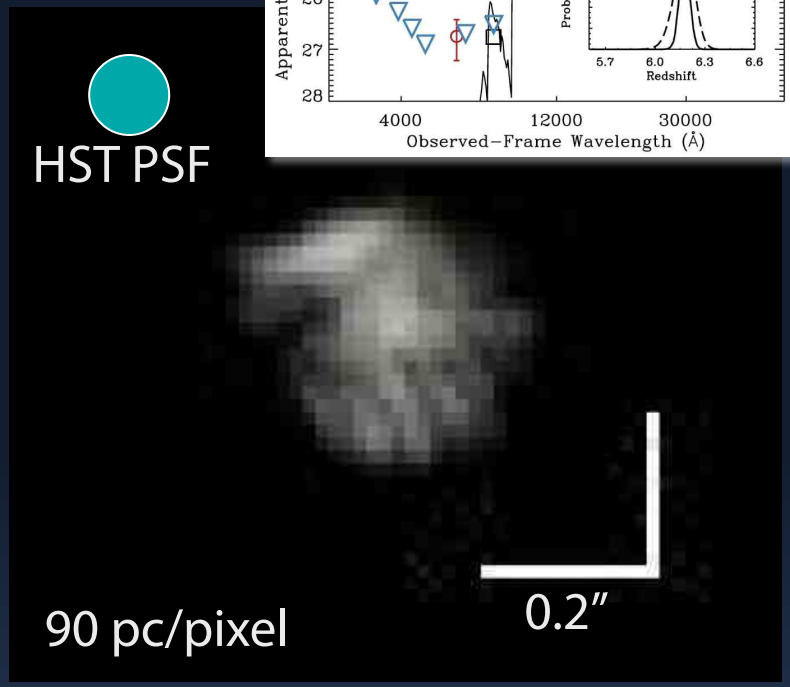
Age <400 Myr $z_F < 9.8$



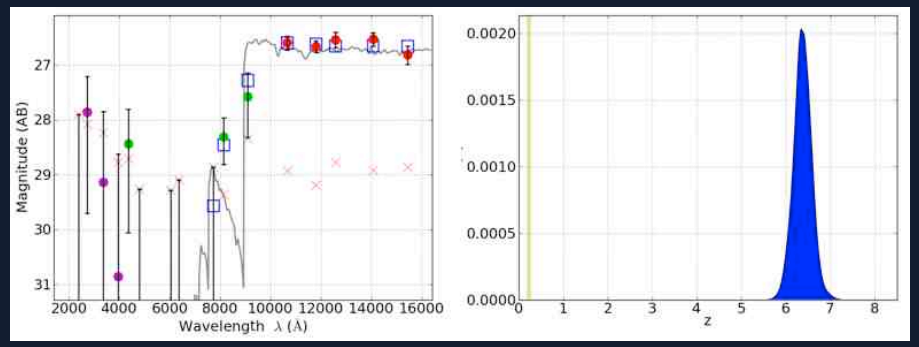
Zitrin et al. 2012

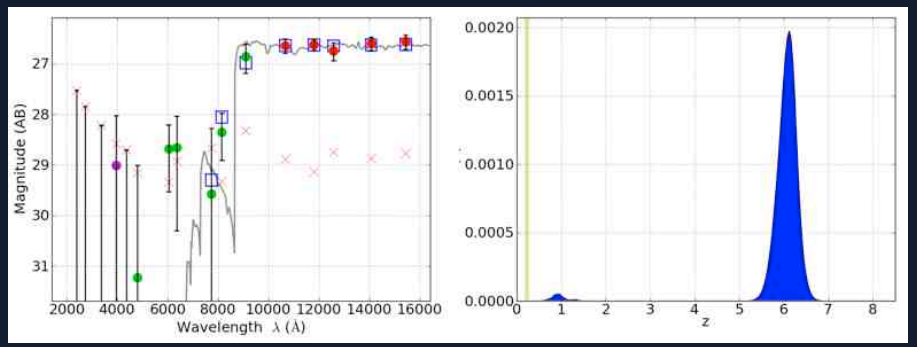


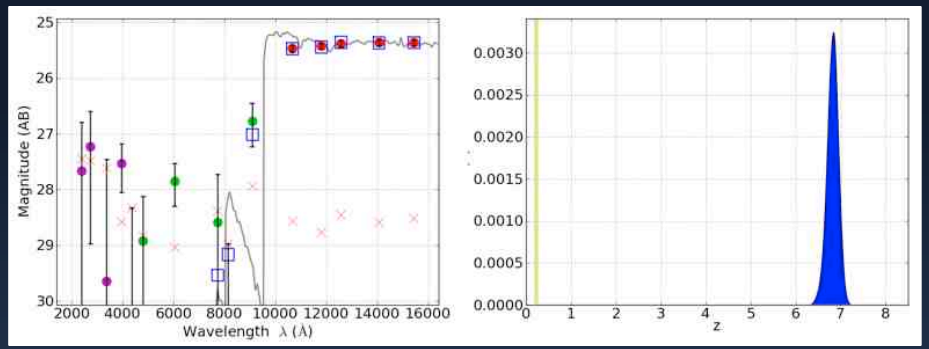
Magnifications: #1 = 11.6, #2 = 17.6, #3 = 3.9, #4 = 3.7



De-lensed view (source plane)

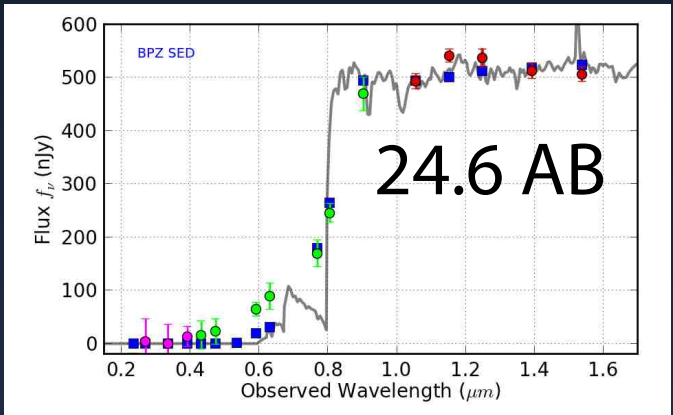


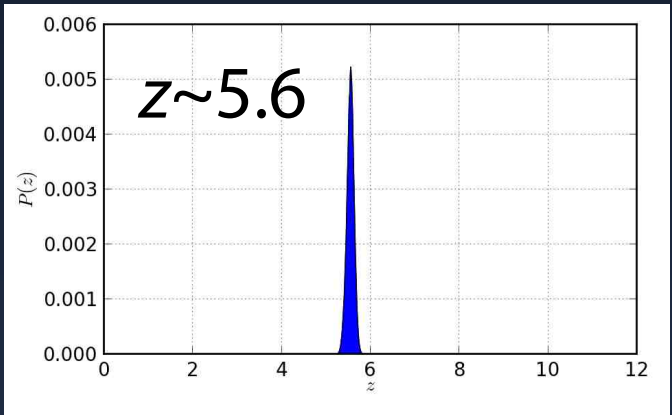


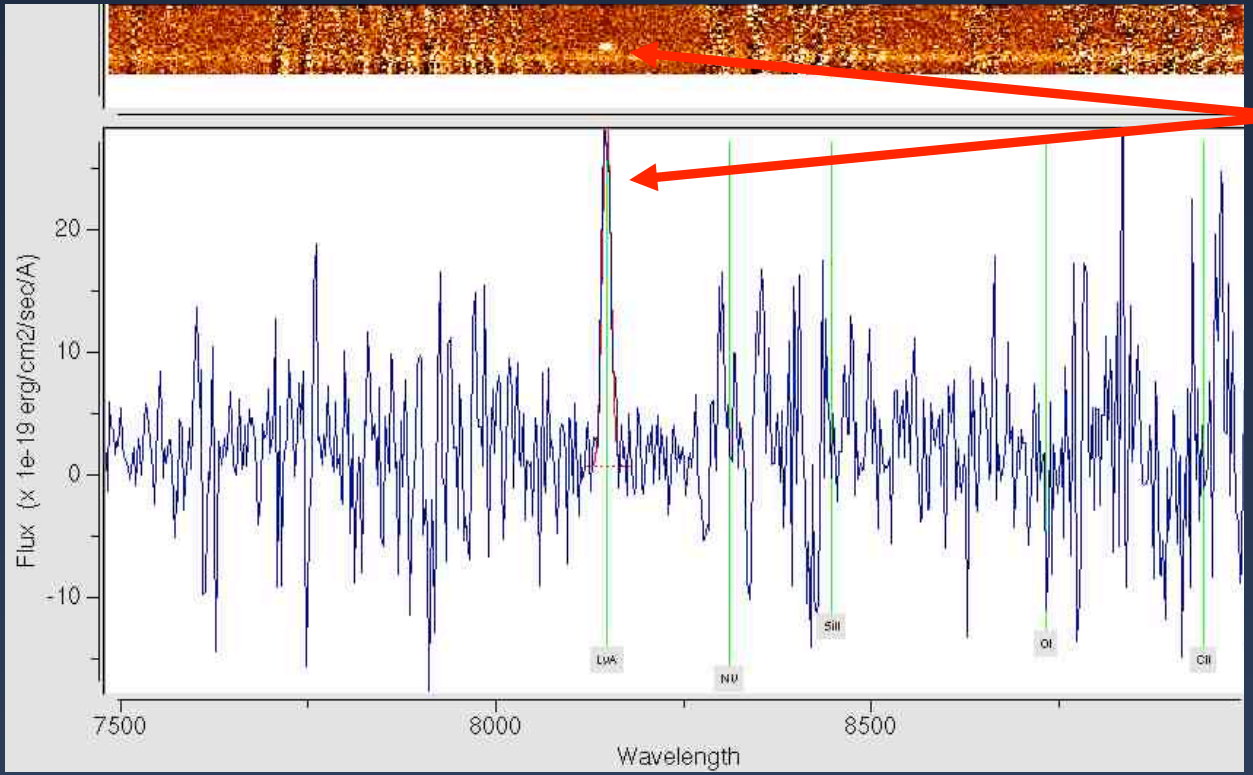


Some Examples of CLASH *z* > 6 Candidates

CLASH: Sample High-z Candidate





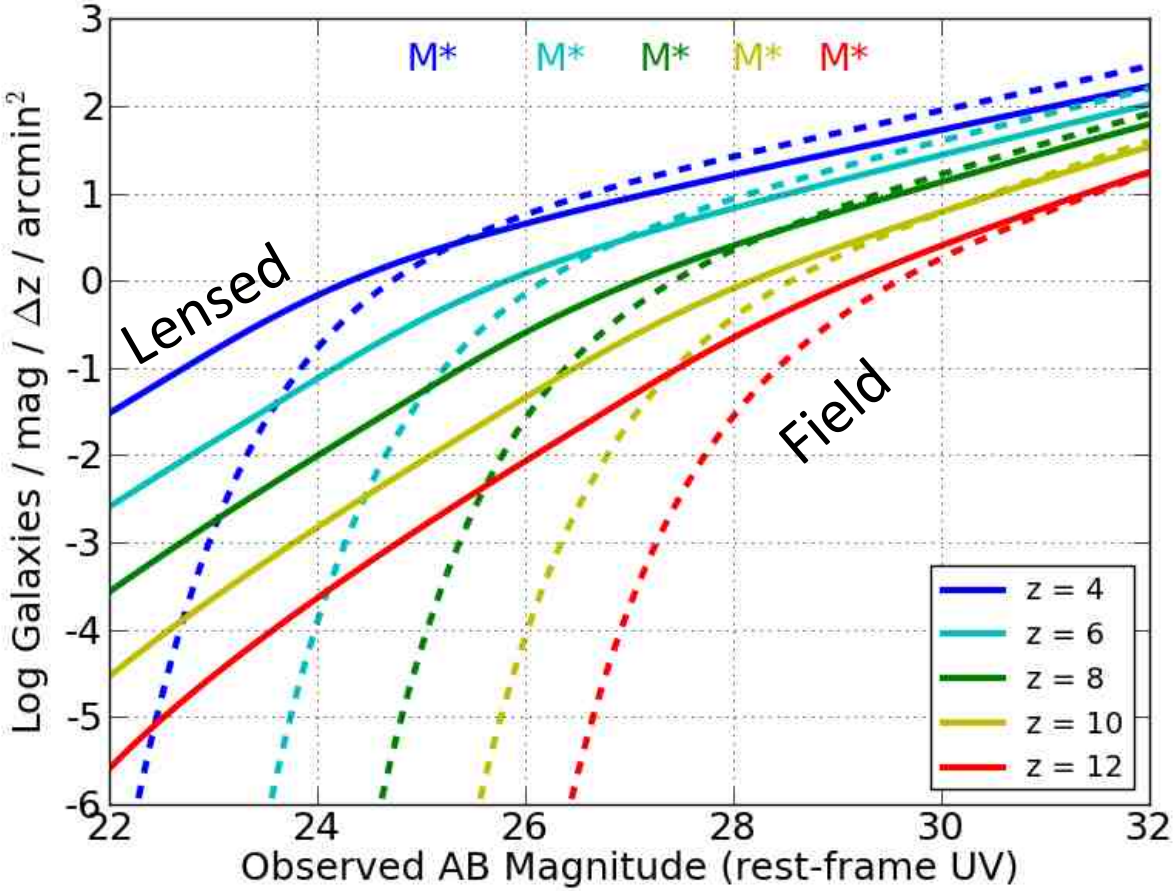


Lyman-α
@8151 Å

$z = 5.703$

VLT – VIMOS
(1 hour exp)
P. Rosati et al.

Lensing wins at brighter magnitudes / higher redshifts



Bouwens12a luminosity function evolving all 3 parameters

CLASH: Magnified High-*z* Galaxies

CLASH finds a large number of high-redshift galaxies

- Steep LFs largely mitigate the decreased intrinsic source-plane area
- Higher spectral and spatial resolution than typical LBG surveys
- Detection of sources fainter than possible in most high-*z* surveys

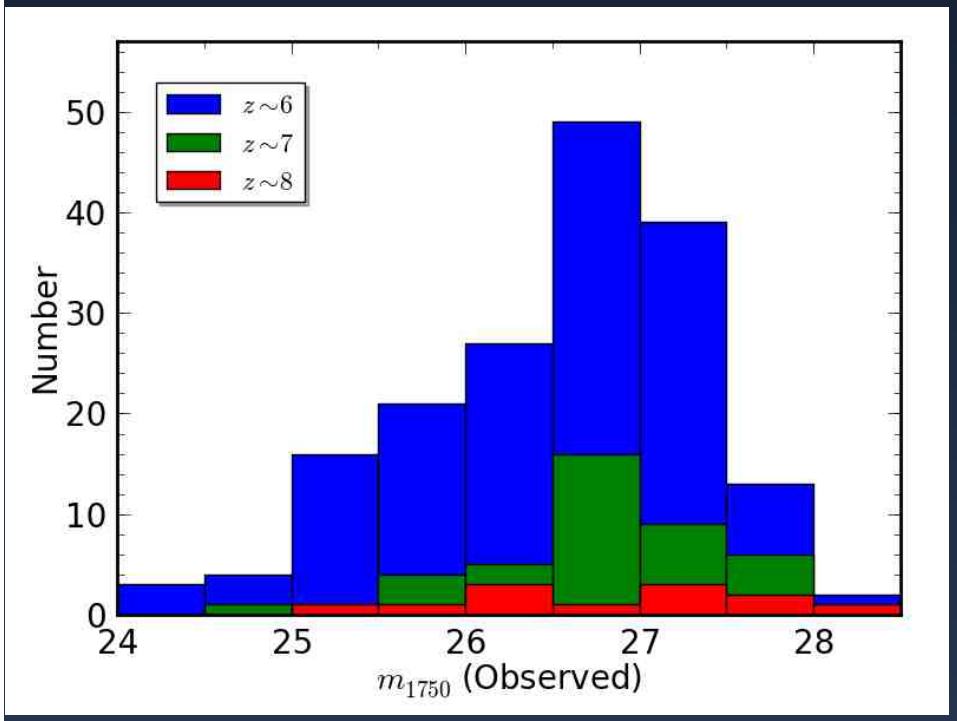
	$z \sim 6$	$z \sim 7$	$z \sim 8$	$z \sim 9$	$z \sim 10$	$z \sim 11$	Total
16 clusters	192	43	12	2	1	1	251
Survey extrapolation	~300	~67	~19	~3	~2	~2	393

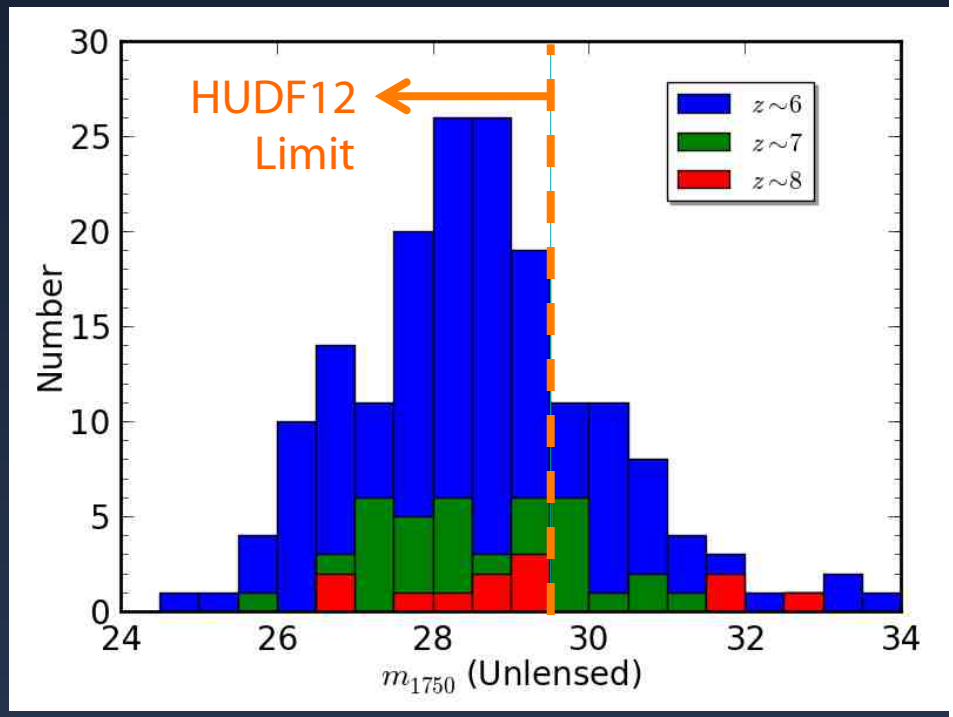
Largest sample of lensed star-forming galaxies at z >~ 5.5 to date

7 multiply-imaged systems at *z* >~ 5.5

Bradley et al. (2013a)

CLASH: Magnified High-z Galaxies





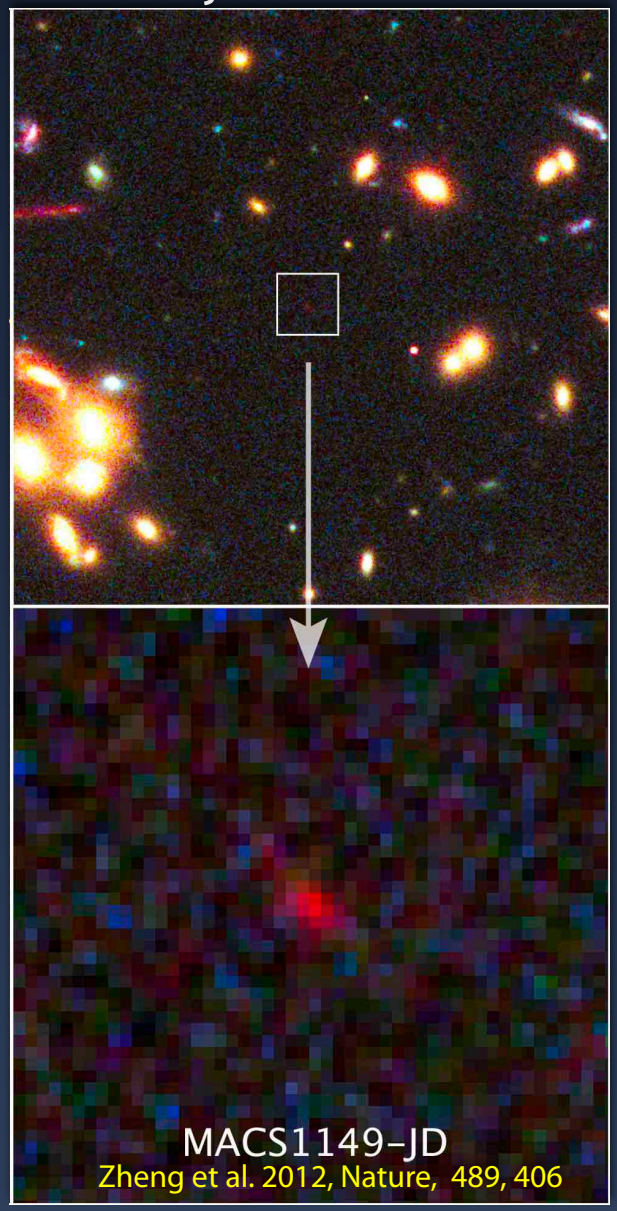
Median magnifications: μ ~ 4.7, 4.7, 4.9 for *z* ~ 6, 7, 8 samples

Instrinsic (unlensed) magnitudes nearly reach 34 mag

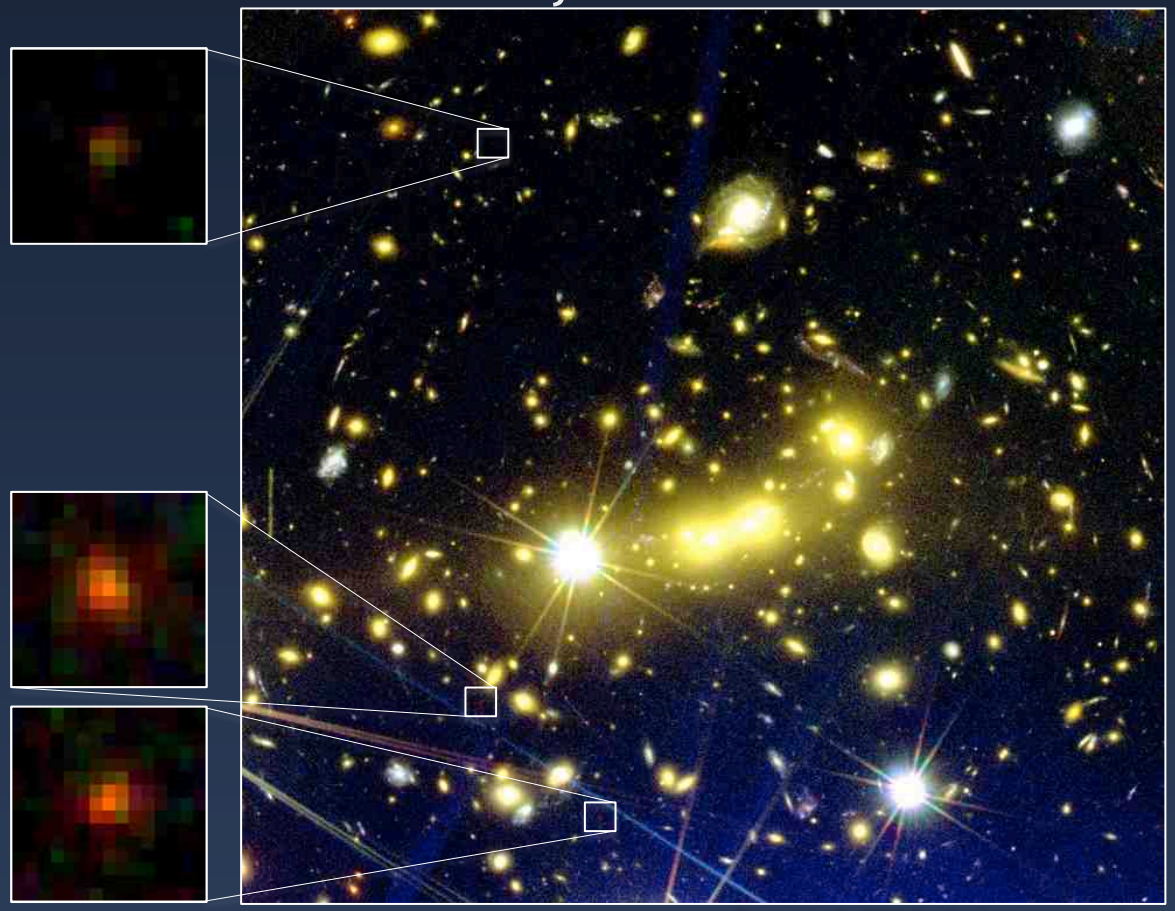
Caveat: largest magnifications have large uncertainties!

Two z > 9 Lensed Galaxies

z = 9.6 object in MACSJ1149+2223



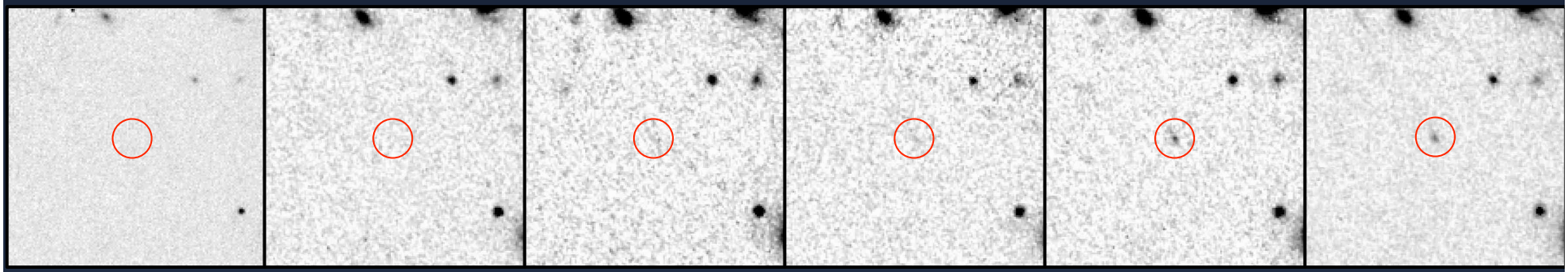
z = 10.8 object in MACSJ0647+7015



Coe et al. 2012, ApJ, accepted

z > 9 Lensed Galaxy Candidates

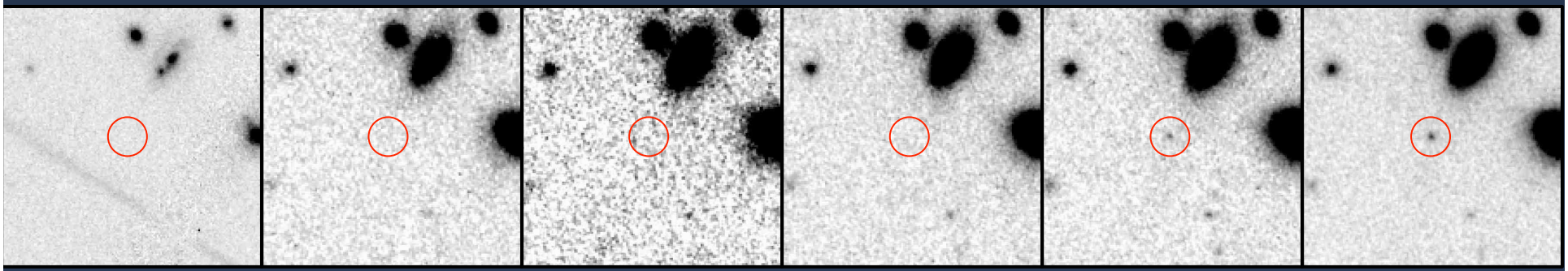
MACS1149-JD1 (z = 9.6)



Sum of 8 ACS filters	NIR F105W	NIR F110W	NIR F125W	NIR F140W	NIR F160W
<1 sigma	<1 sigma	3.6 sigma	4.9 sigma	13 sigma	16 sigma

Neither object's position and flux varies significantly over course of 2 – 3 months

MACS0647-JD1 (z = 10.8)

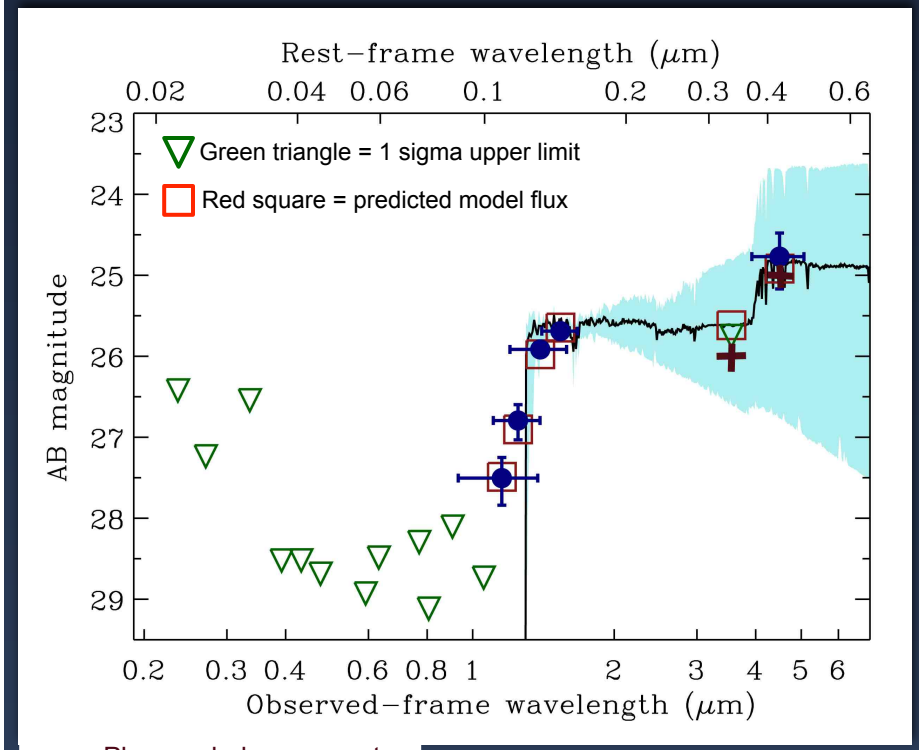


Sum of 8 ACS filters	NIR F105W	NIR F110W	NIR F125W	NIR F140W	NIR F160W
<1 sigma	<1 sigma	<1 sigma*	<1 sigma	6 sigma	12.4 sigma

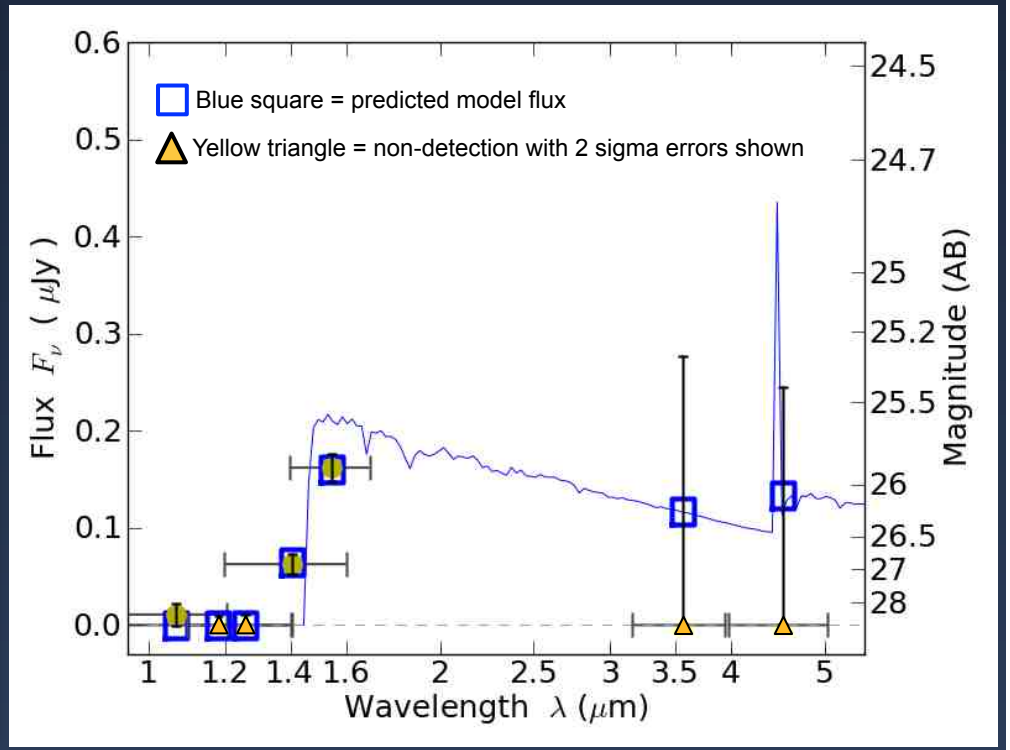
Spectral Energy Distributions

MACS1149-JD: z = 9.6 +/- 0.2
Stellar mass: ~1.5 x 10^8 Msol
SFR: ~1.2 Msol/yr
Age: < 200 Myr (95% CL), z_{Form} < 14.2
$r_{1/2}$: ~0.14 kpc (de-lensed)

MACS0647-JD: z = 10.8 +/- 0.5
Stellar mass: 10^8 - 10^9 Msol
SFR: ~4 Msol/yr (Salpeter IMF)
Age: < 400 Myr (95% CL)
$r_{1/2}$: < 0.10 kpc (de-lensed)

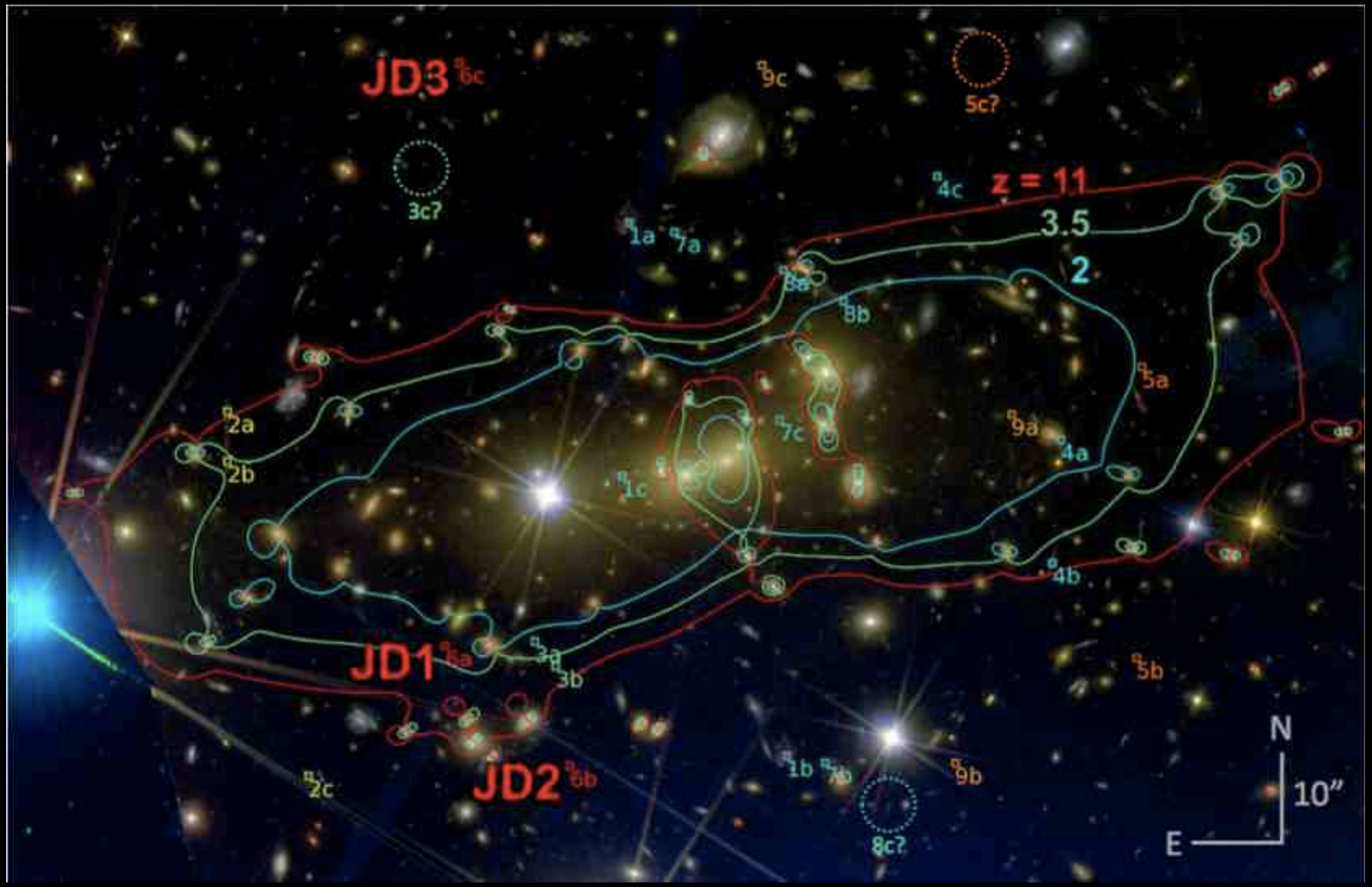


Plus symbols represent new, deeper IRAC data

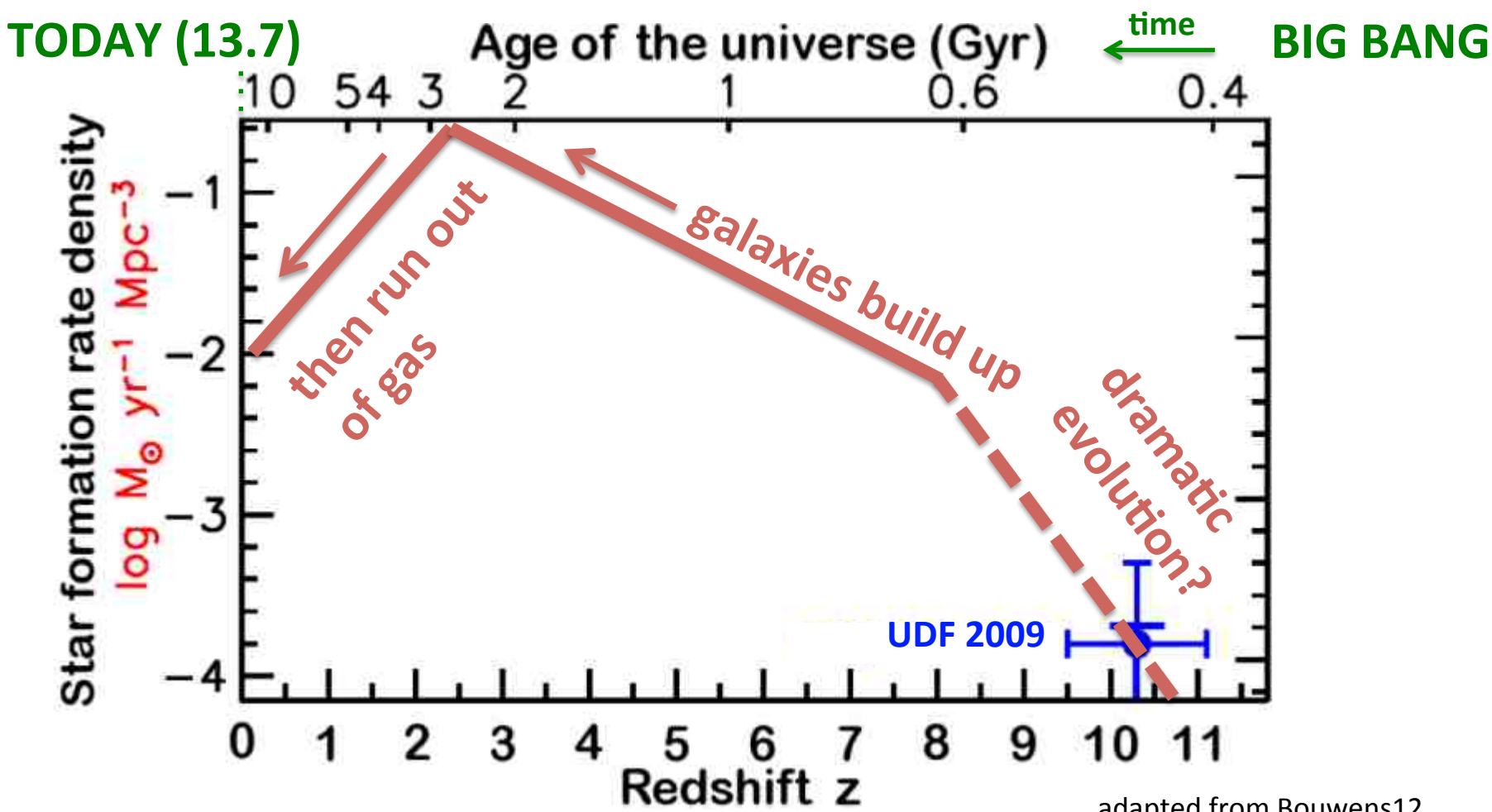


In both cases, best fit SED is a starburst galaxy

Observed positions and fluxes are consistent with our lens models. Models are based on 20 strongly lensed images of 8 other galaxies.



Previous searches for galaxies in the first 500 Myr came up short.
Only one candidate was found where six were expected.
This suggested a dramatic buildup in galaxy numbers.

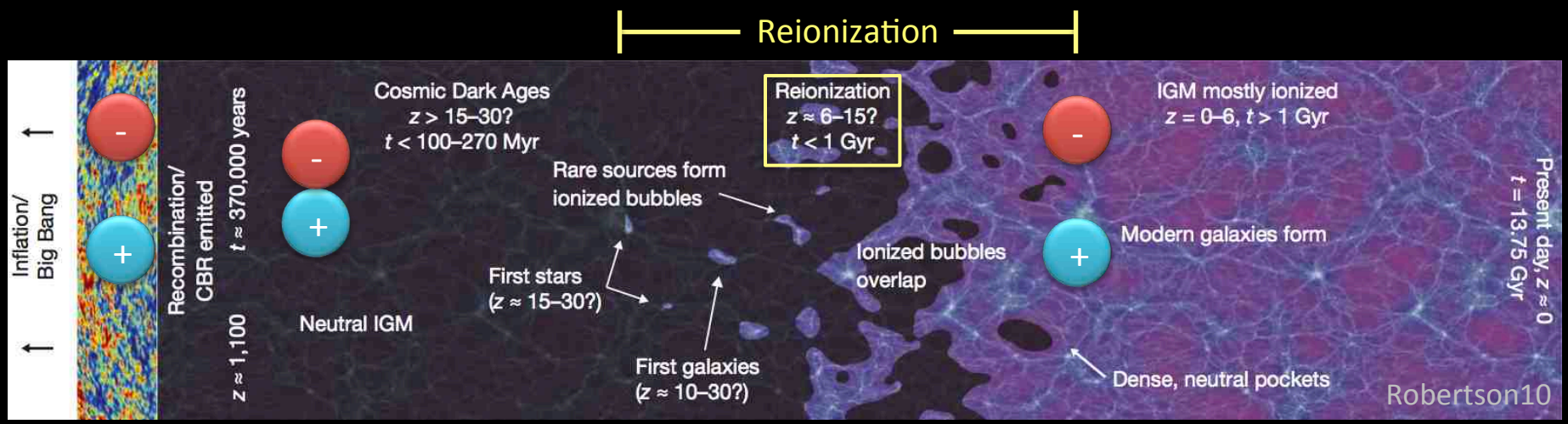


adapted from Bouwens12
see also Oesch12,13

Such dramatic evolution has implications

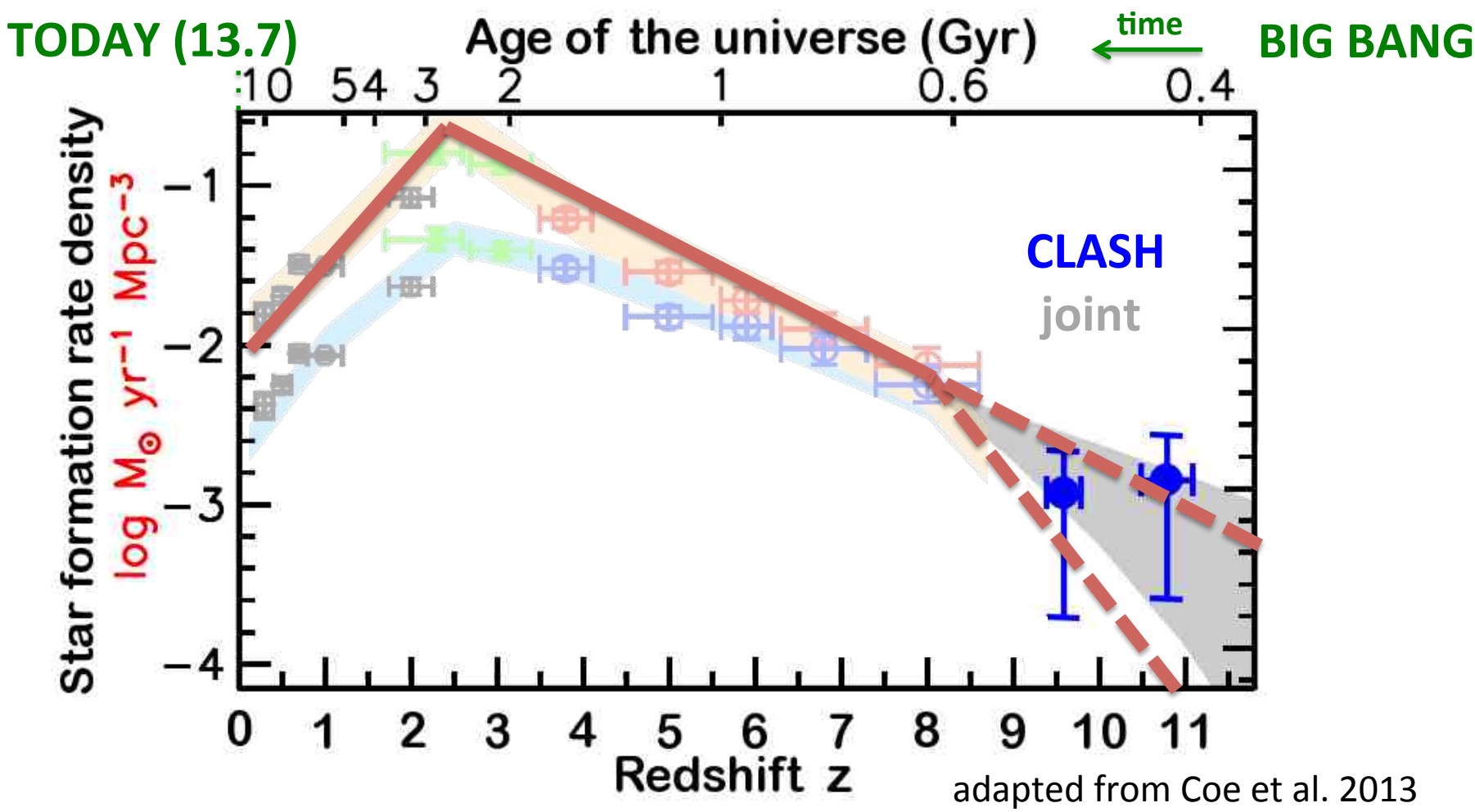
(e.g., Trenti+2010, Jaacks+2011, Alvarez+2012, Bouwens+2012, Dunlop+2012/13, Robertson+2013)

- low mass (<10^9) galaxies must be a dominant source of the ionizing radiation at z > 8
- sources of cosmic re-ionizing radiation at z>8 may have low clumping factors
- sources may have harder UV energy output (higher beta) and/or higher escape fractions
- Not enough faint galaxies to reionize the z>8 universe? Other more exotic ionizing energy mechanisms may need to be invoked.



CLASH discoveries are consistent with expectations

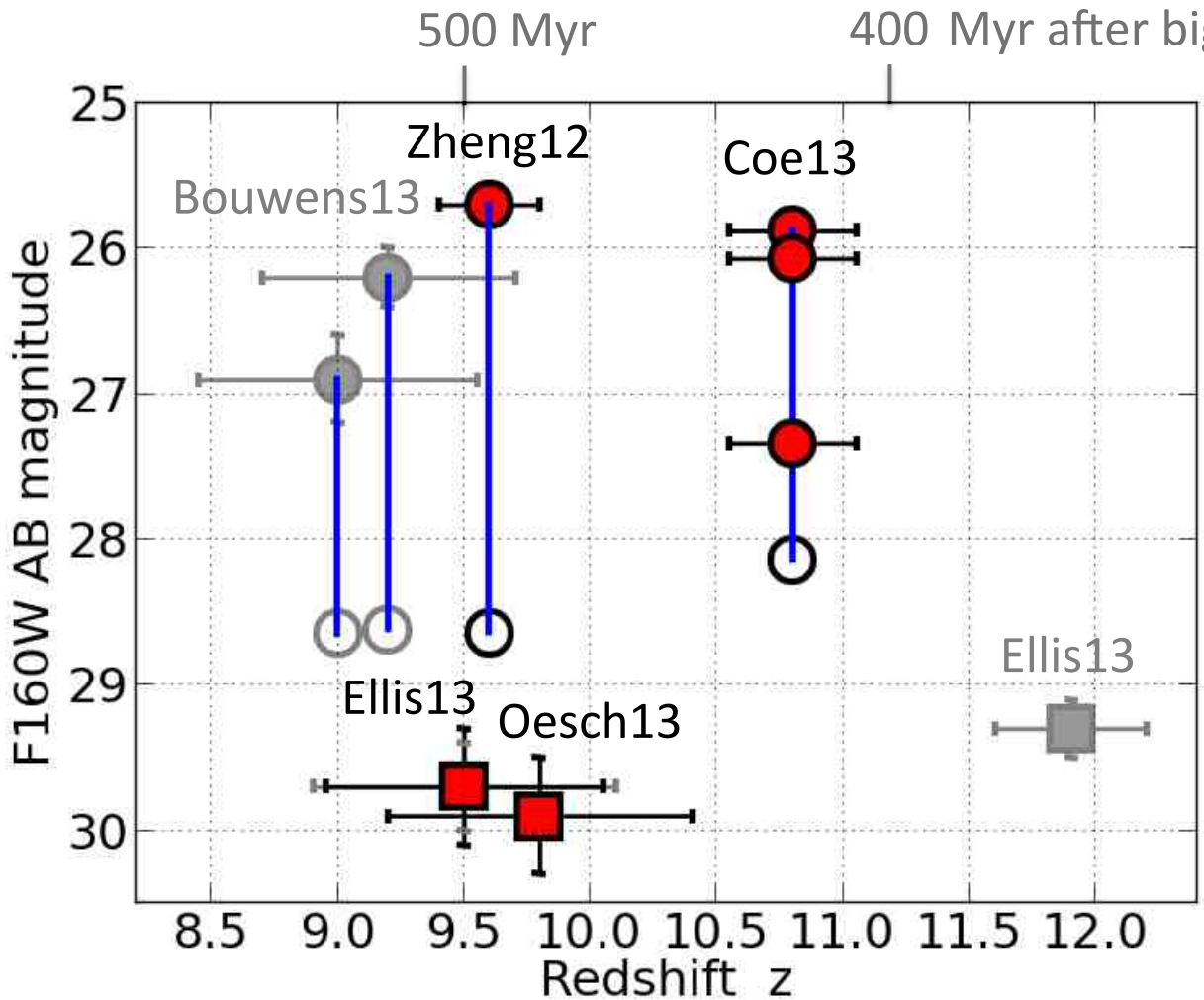
but errors cannot rule out dramatic evolution seen in UDF



adapted from Coe et al. 2013

CLASH and UDF12 yield 4–8 candidates at z > 9 where previously only one was known

Highest spectroscopic redshift: z = 7.215 (Shibuya12)



Robust

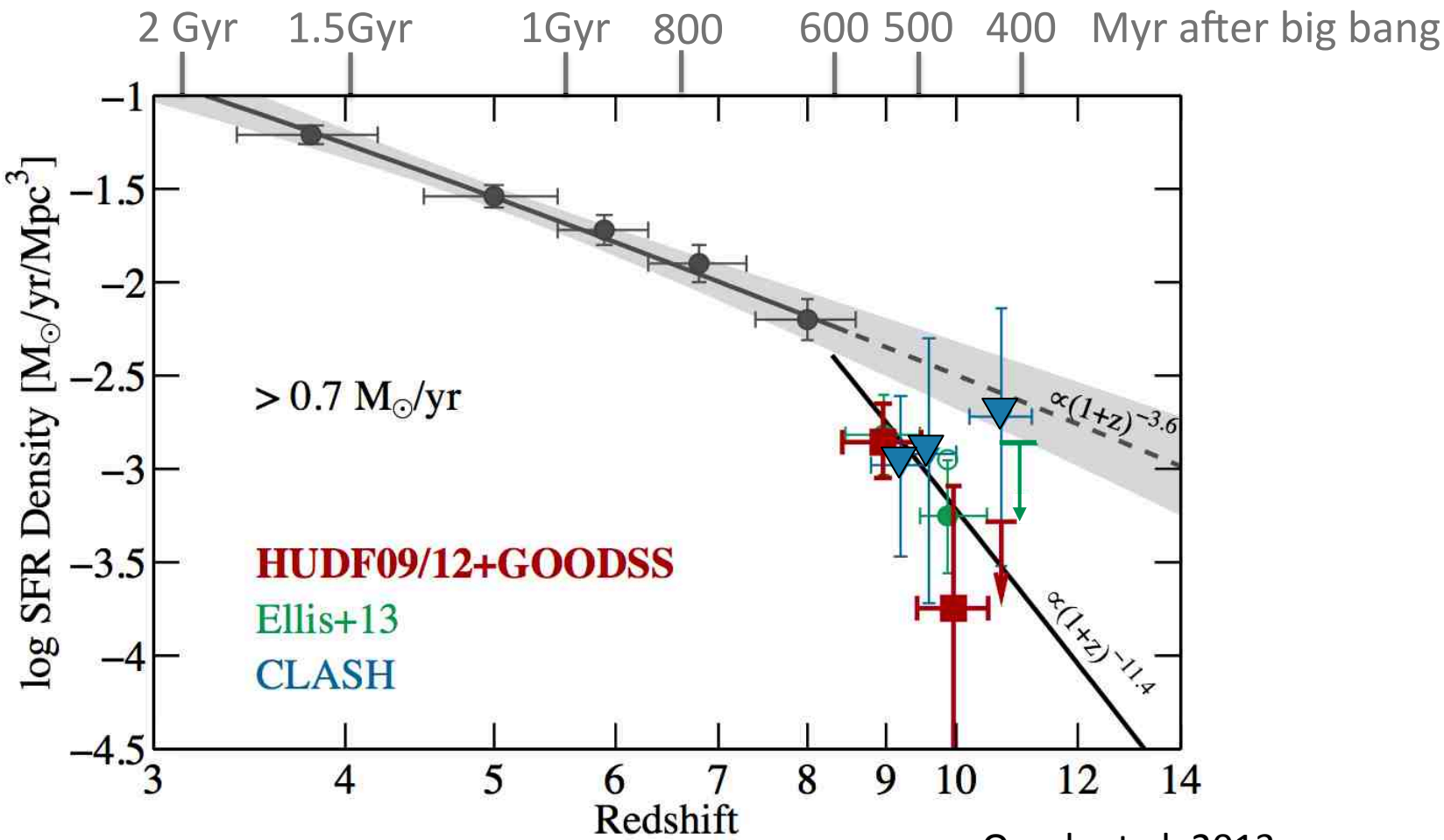
Less secure

CLASH

Lensing magnifications

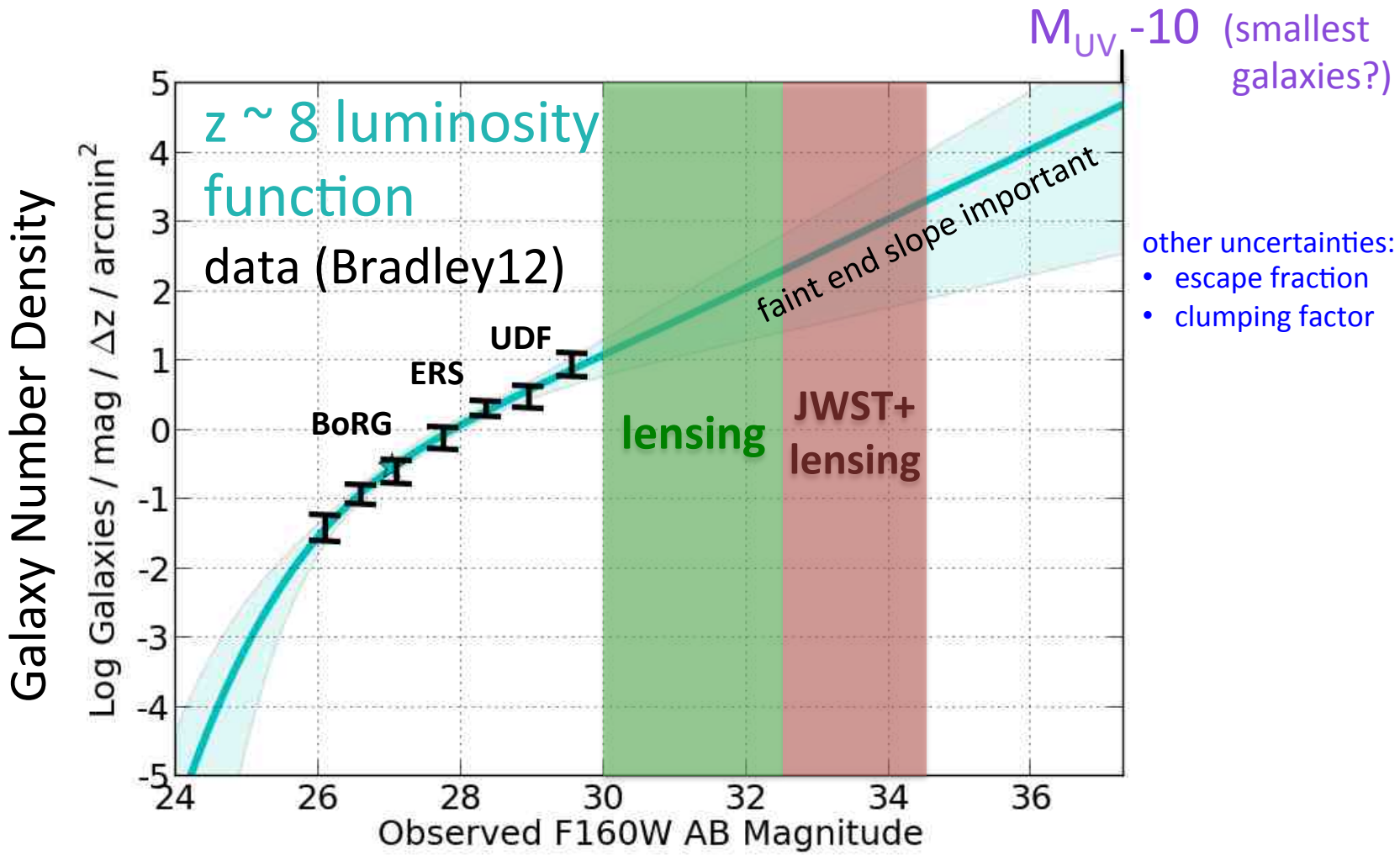
UDF12

CLASH and UDF12 provide our first constraints on z > 9 galaxy evolution. Additional observations are required.



Oesch et al. 2013

Deeper and wider NIR lensing surveys required

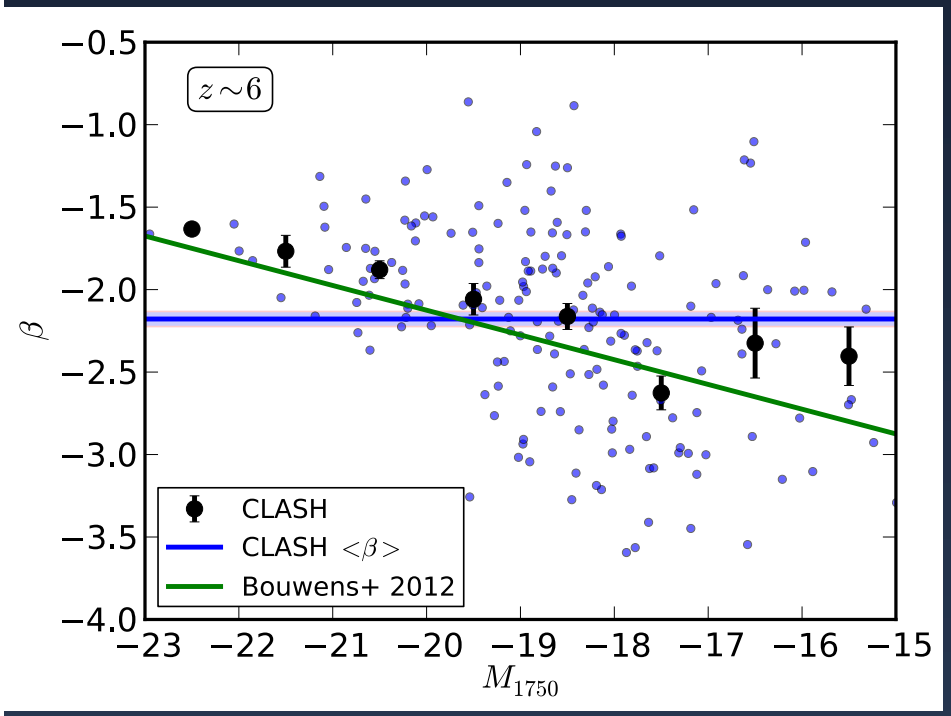


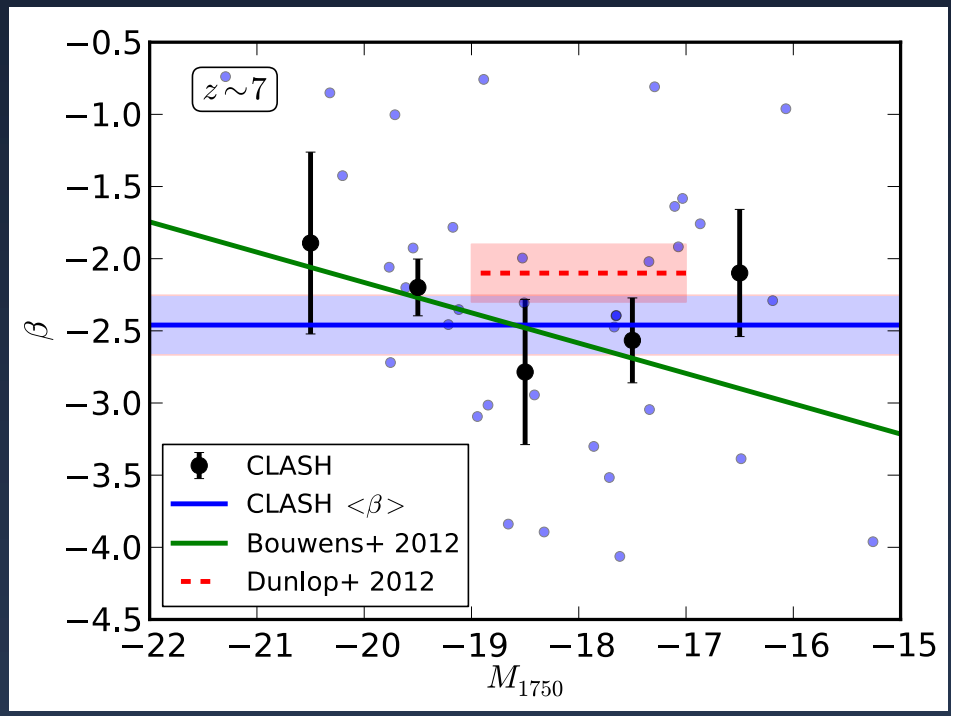
other uncertainties:
- escape fraction
- clumping factor

Rest-Frame UV-Continuum Slopes (β)

β is the power-law slope of the UV continuum: $f_\lambda \sim \lambda^\beta$

CLASH: IR spectral coverage gives better measures at $z \sim 6$-8





Find βs that are bluer than typical local starbursts (β < -2.0)

$z \sim 6$: <β> = -2.18 ± 0.05 ➔ β becomes bluer at fainter intrinsic magnitudes

$z \sim 7$: <β> = -2.45 ± 0.21
$z \sim 8$: <β> = -2.36 ± 0.30
} Consistent with little or no dust

Bradley et al. (2013b)

Summary: CLASH High-z Galaxies

- CLASH identifies 251 high-redshift ($z \geq 5.5$) galaxies (in 16 clusters). Expect ~400 in full survey (25 clusters).
  - Similar observed surface densities as legacy field surveys down to H_{160} ~ 27.5 AB (5σ limit).
- CLASH has at least two robust $z > 9$ lensed galaxy candidates with 8x – 15x magnification that yield H-mag 25.7 – 25.9.
- CLASH + IR-UDF provide the first results on the star formation rate density at $z > 8$ (albeit with large uncertainties).
  - Searches for $z > 8$ galaxies may suggest dramatic evolution in SFRD
  - The Frontier Fields program should provide much better constraints.
- Lensing provides most detailed look at structure of $z > 6$ galaxies. Often reach 100 – 200 pc resolution at these redshifts – *equiv. to resolution of diffraction limited 10-m to 20-m telescope.*
- Find β's that are bluer than typical local starbursts: $\langle\beta\rangle$ = -2.18, -2.45, -2.36 for z~6, 7, 8, respectively.

HST + ELTs + JWST + ALMA + space NIR sky surveys have and/or will transform our understanding of the early universe.