FRONTIER FIELDS

SPACE TELESCOPE SCIENCE INSTITUTE
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High-Redshift Predictions and Early Results from the Frontier Fields

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MACSJ0416.1-2403
Frontier Fields + SN + CLASH
deep ACS + WFC3/IR imaging

Hubble has observed galaxy evolution

over 13 billion years

Hubble Sequence

Elliptical

Abell S0740
Blakeslee

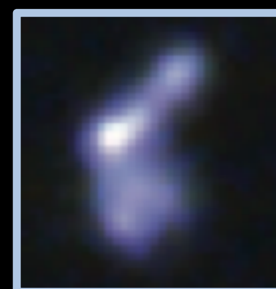
Spiral

M74
Chandar

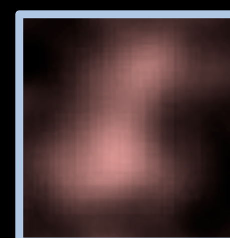
Irregular, Starburst

Antennae
Whitmore

Clump clusters, chains

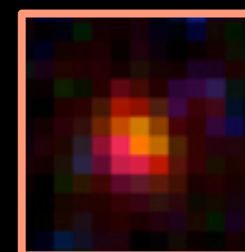


in CANDELS
z = 2.05
Wuyts12
3 Gyr



A1689-zD1
z ~ 7.8
Bradley08
650 Myr

Single clump?
r <~ 100 pc



in CLASH
MACS0647-JD
z ~ 10.8
Coe13
420 Myr

time ←

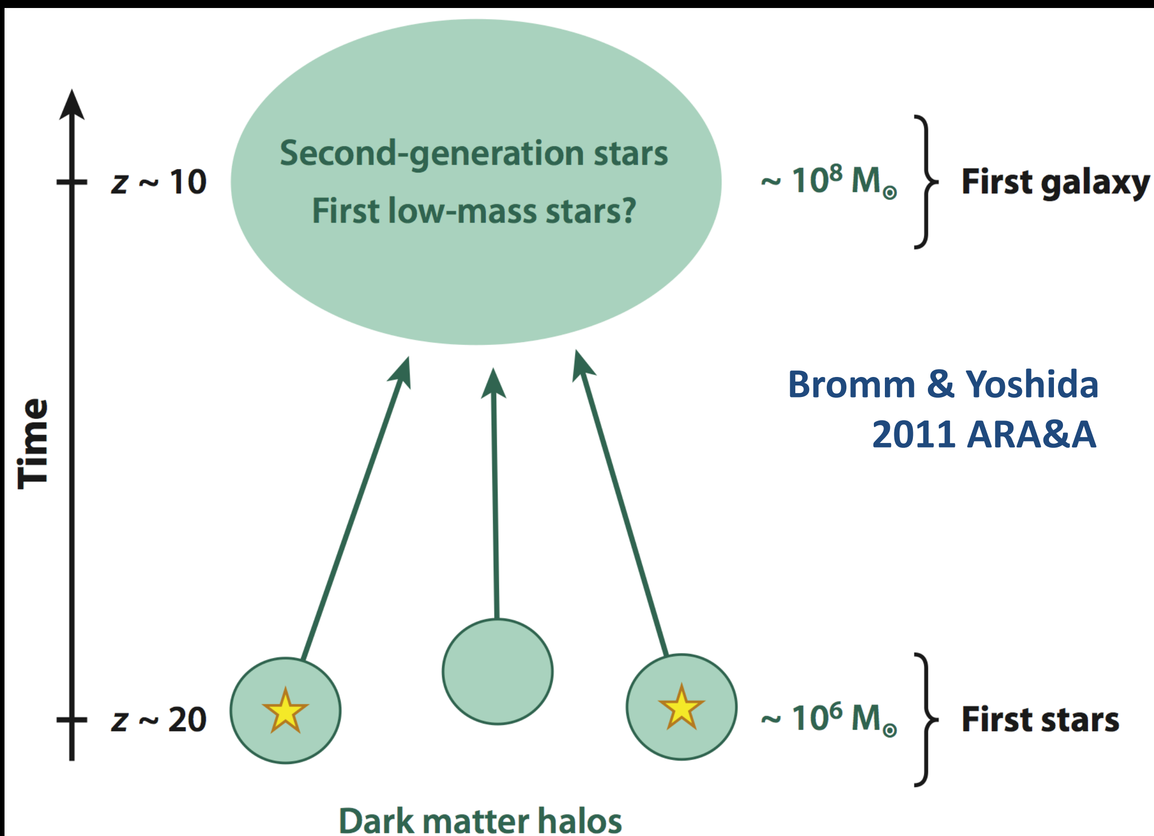
all images from Hubble

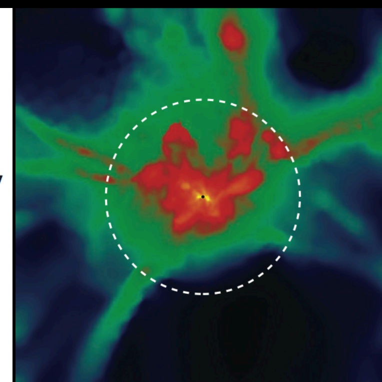
lensed galaxies

Frontier questions about galaxy evolution

- When did the first galaxies form?

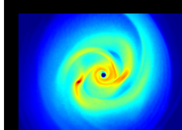
z ~ 10 (465 Myr)
– 30 (100 Myr)





Greif et al. (2010)

Hubble:
z < 13 (325 Myr)

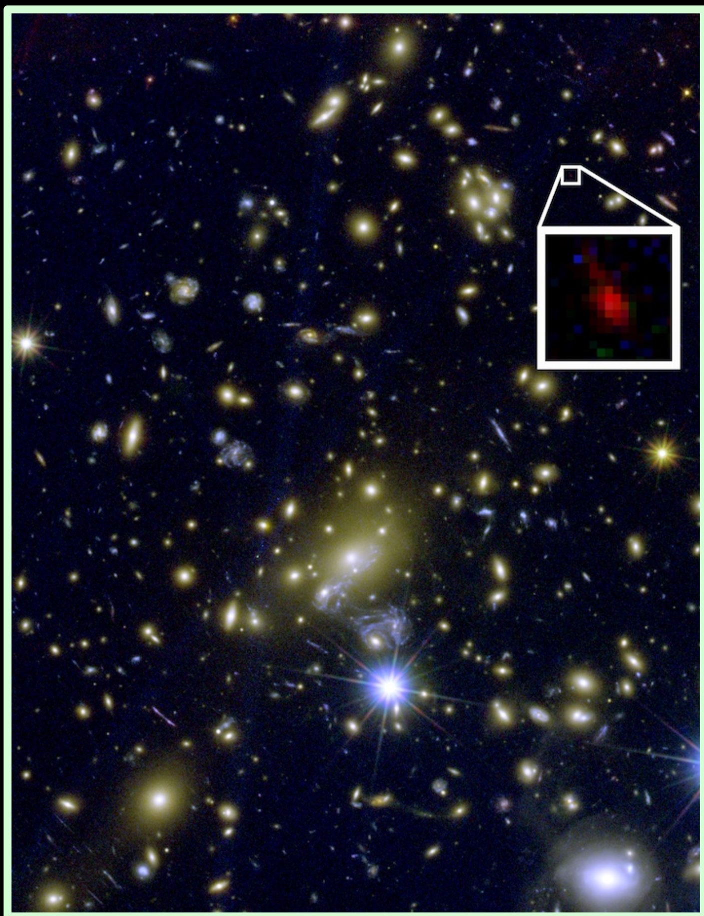


Clark et al. (2011)

Frontier questions about galaxy evolution

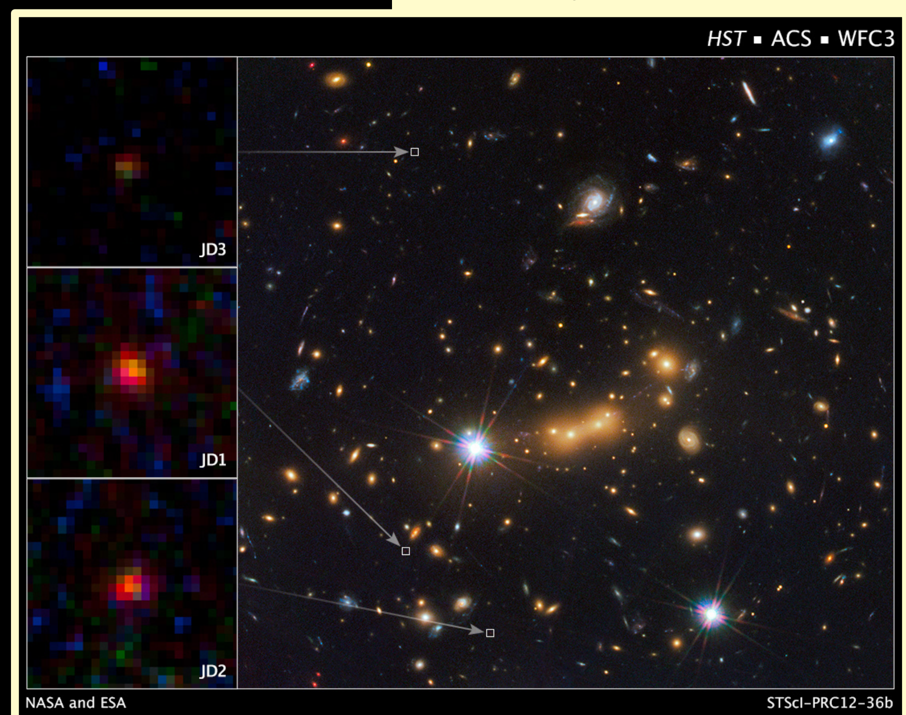
- When did the first galaxies form?
- What were their properties?
- How many were there?
- Did they reionize the universe?

CLAS aled two robust candidates in the first 500 Myr



MACS1149-JD
z ~ 9.6 (490 Myr)
Wei Zheng et al. (2012)
Nature 489, 406

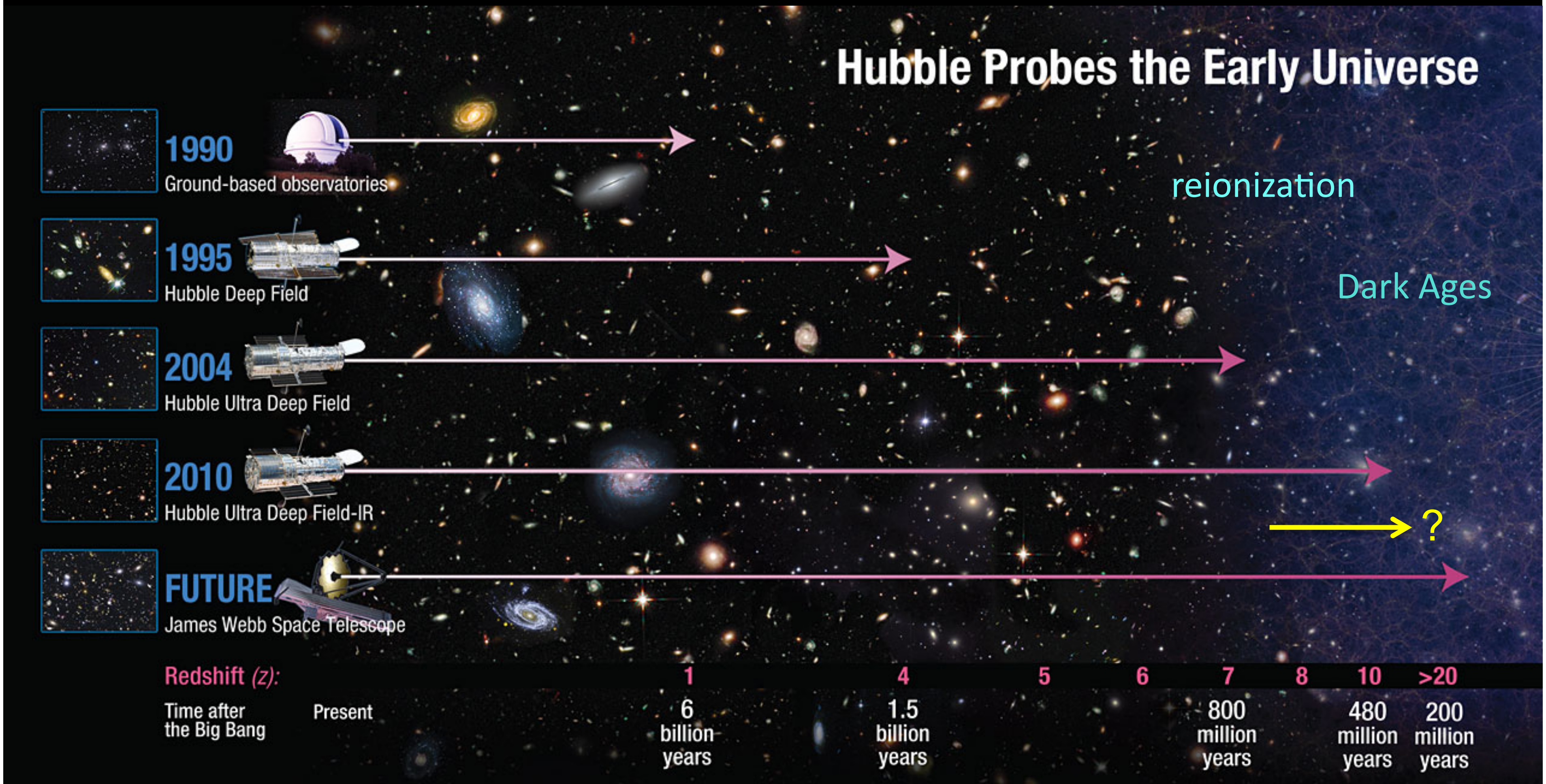
MACS0647-JD
z ~ 10.8 (420 Myr)
Dan Coe et al. (2013)
ApJ 762, 32



in 2 / 5 “high-magnification” CLASH clusters

How can we improve on the Hubble deep fields before the launch of JWST?

-Matt Mountain
STScI director



Coe & Zheng led white paper recommending deep WFC3/IR imaging of strong lensing galaxy clusters

A Preview of JWST: Measuring Cosmic Evolution from z ~ 8 to z ~ 11 with Gravitational Lenses

Mapping structure formation in the first 1 billion years of cosmic history is required for a comprehensive understanding of star and galaxy formation. Unlensed sources in this epoch are extremely faint (>28 mag) and are a challenge to observe even with the largest telescopes today. While JWST will reveal this epoch in detail, we can get a jump-start by combining HST's resolution with the gravitational lensing amplification of massive clusters. Current field searches to date have yielded a single z ~ 10 candidate, suggesting dramatic evolution in the < 200 Myr between z ~ 10 and 8, including an order of magnitude buildup in star formation rate density (SFRD). Searches behind lensing clusters with the CLASH program have yielded two z ~ 9 – 11 candidates to date, more consistent with an evolving luminosity function (dM*/dz ~ 0.3) as extrapolated from lower redshifts (z ~ 4 – 8) and lensed through our models. However, these results remain uncertain due to small number statistics. A 250-orbit HST survey of 6-10 galaxy clusters, each to a depth of 25-40 orbits (primarily with WFC3/IR), would distinguish between these two scenarios with >99% confidence. New tests confirm that lens magnification uncertainties are not a primary source of uncertainty. These data will robustly constrain the z ~ 10 SFRD and galaxy formation models, providing one of the keys to understanding the source and epoch of reionization.

The buildup of stars from z ~ 10 – 8: CLASH observations to date have yielded one lensed candidate each at z ~ 9.6 (Zheng12) and 10.7 (Coe12), both with AB mag ~ 26. This is consistent with (slightly below) expectations of ~4 such galaxies based on the observed z ~ 8 luminosity function (Bradley12) extrapolated to higher redshifts assuming dM*/dz ~ 0.3 (as observed between z ~ 4 – 8) and magnified through our lens models (cropped to the WFC3/IR FOVs and with foreground galaxies masked out). In the field, the single z ~ 10 candidate detected to date (Bouwens11) suggests a lower number count density by a factor of ~six (Oesch12). The implication from this latter work is that SFRD increased by an order of magnitude over the ~200 Myr between z ~ 10 and 8, a greater increase than observed over the following ~800 Myr to z ~ 4 (Fig. 1). At least one galaxy formation model predicts such a dramatic buildup (Trenti10). However strong observational conclusions are not yet possible given the small number counts.

Ten galaxies at z ~ 9 – 11: Based on extrapolations of an evolving luminosity function and the observed lensed number counts in CLASH, we expect observations one magnitude (6 times) deeper to reveal ~10 galaxies at z ~ 9 – 11 (Fig. 2). This is conservative with respect to the extrapolation from z ~ 4 – 8 (which suggests ~20) but optimistic based on the single field z ~ 10 candidate (which suggests only ~3). The primary goal of these observations is to determine to high confidence (Fig. 3) which of these scenarios is true, placing robust constraints on SFRD at z ~ 10 for the first time and providing an important new test for galaxy formation models.

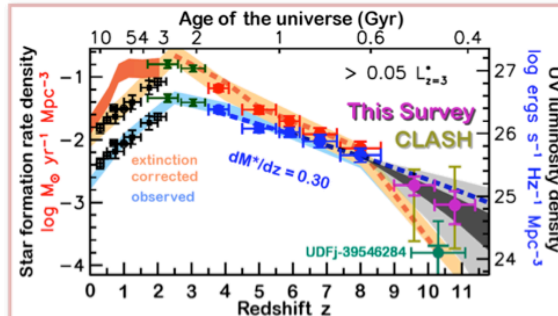
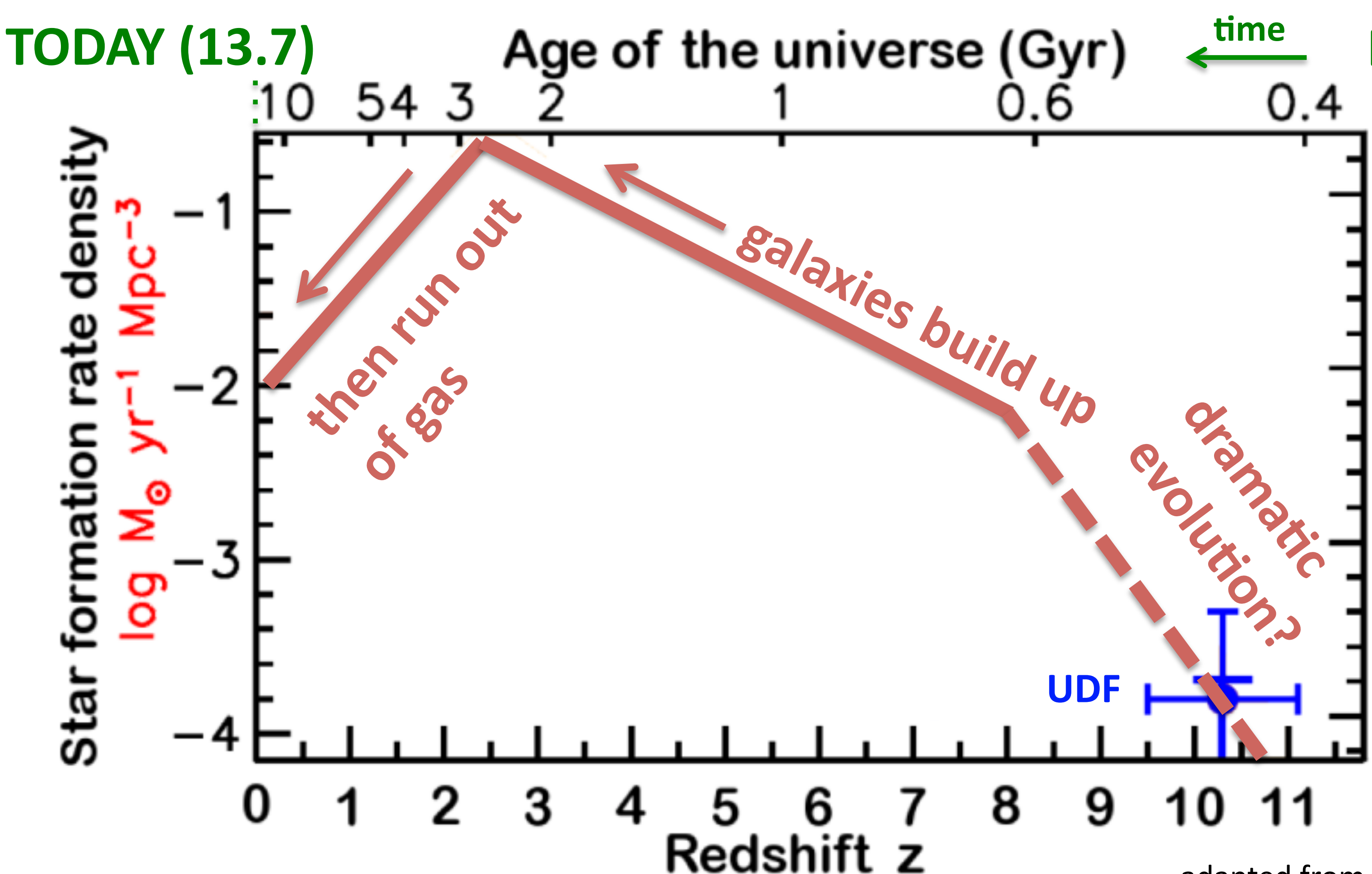


Fig. 1 – This survey will provide the first robust constraints on the z ~ 10 SFRD (magenta and dark gray), significantly reducing the current uncertainties from CLASH (yellow and light gray) and the field (green). SFRD constraints from lower redshifts with and without correction for dust extinction are from works as compiled by Bouwens12.

submitted to the
HDFI science working group
chaired by James Bullock

Dramatic build up at z > 9 (first 500 Myr)?

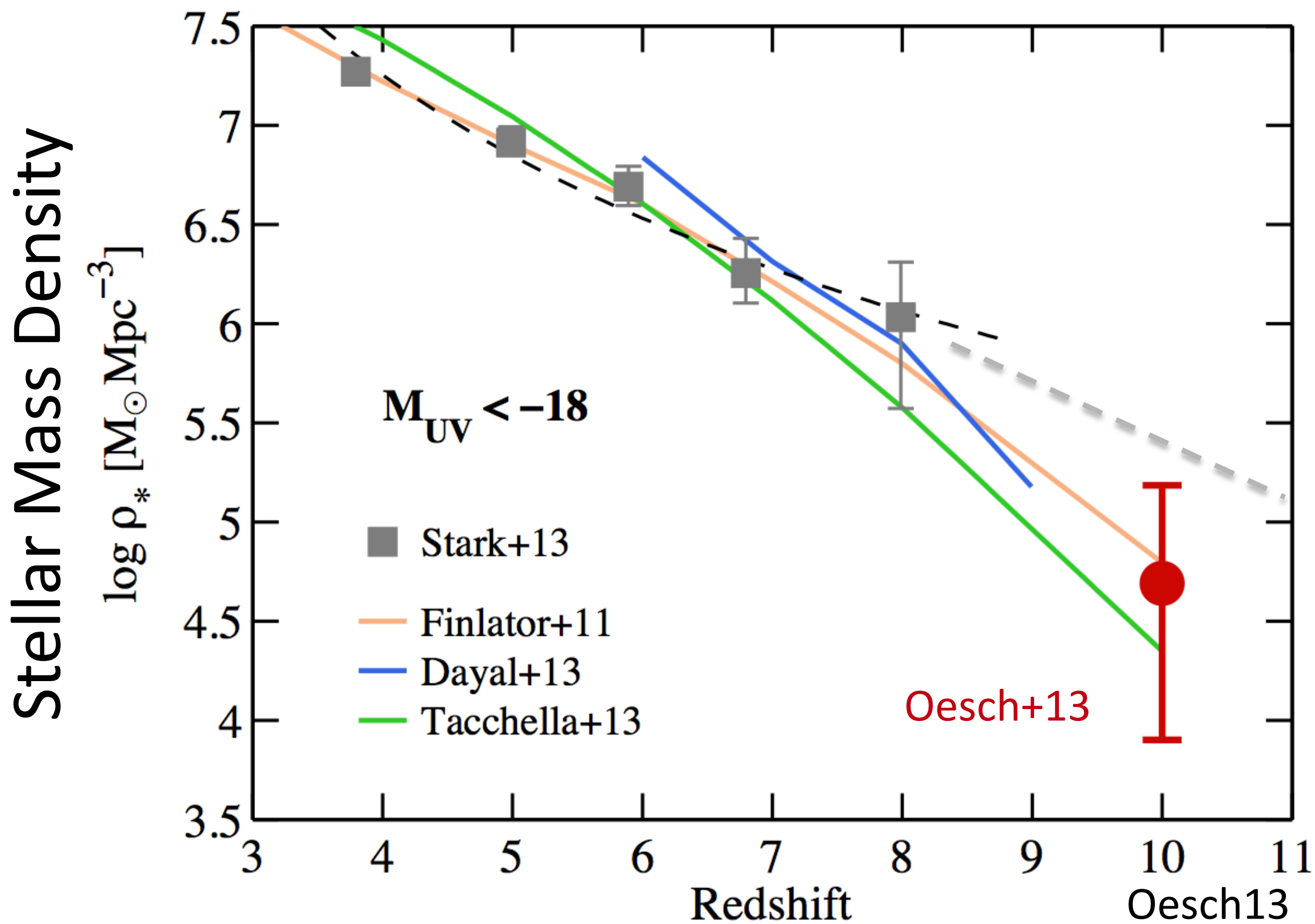


Implications for reionization / first galaxies?

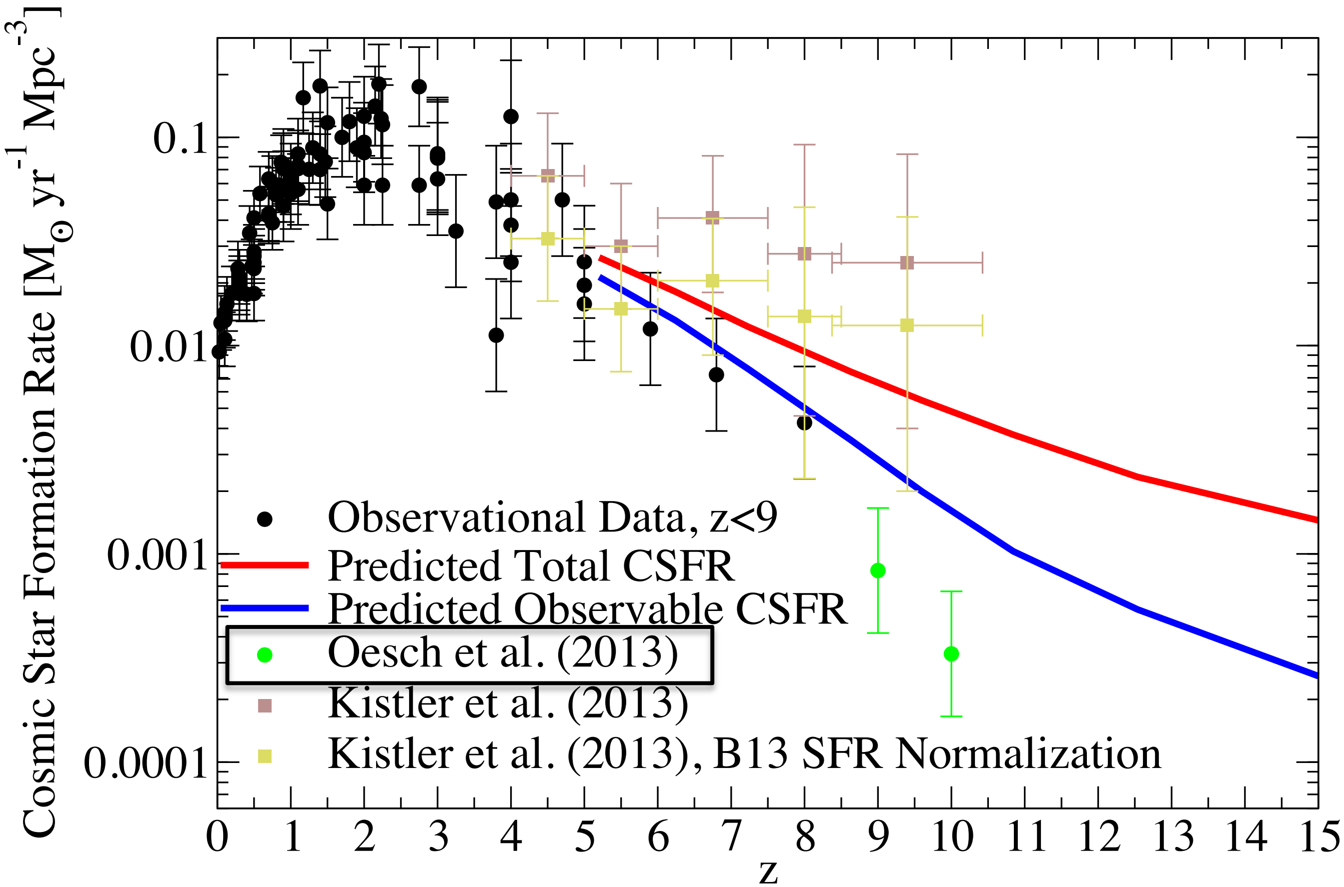
Only one z~10 candidate found where nine were expected (Bouwens11, Oesch13)

adapted from Bouwens12
see also Oesch12,13

Multiple models predict z > 9 drop off in star formation rate and mass densities

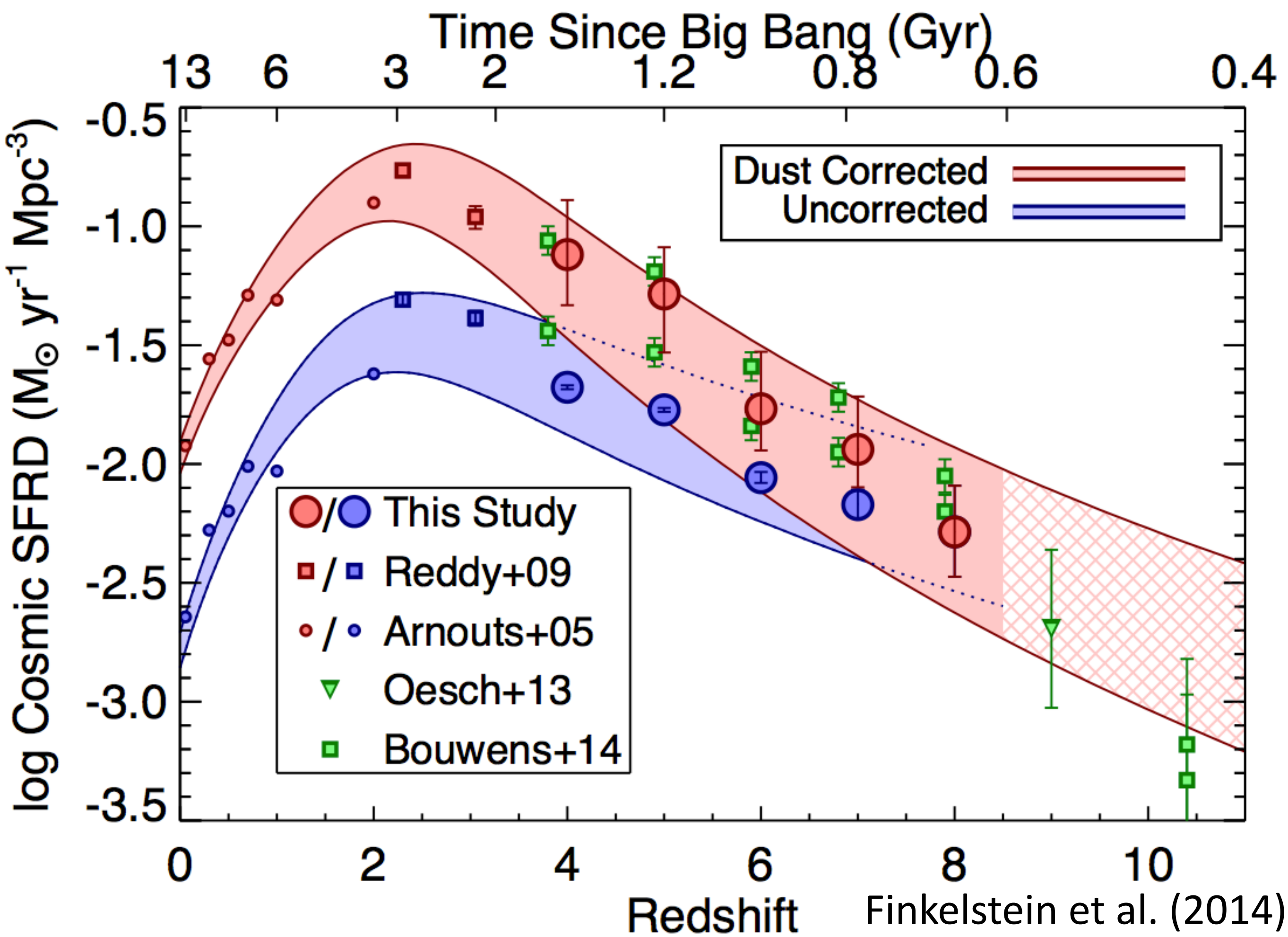


But at least one model predicts smoother z > 9 evolution



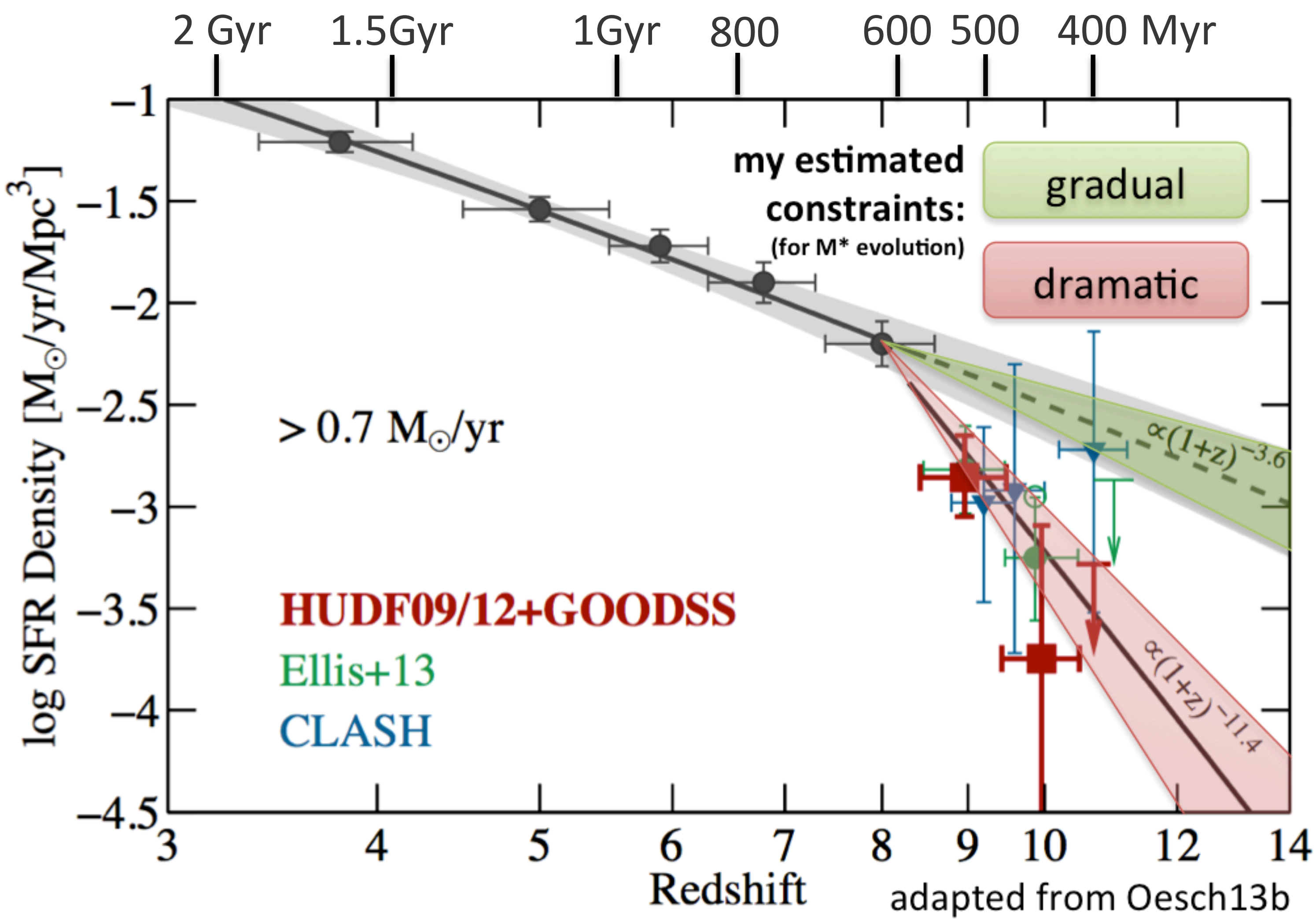
Behroozi & Silk (2014)

And at least one recent analysis finds a smoother z > 9 evolution



Finkelstein et al. (2014)

The Frontier Fields should confirm or rule out dramatic z > 9 evolution with high confidence



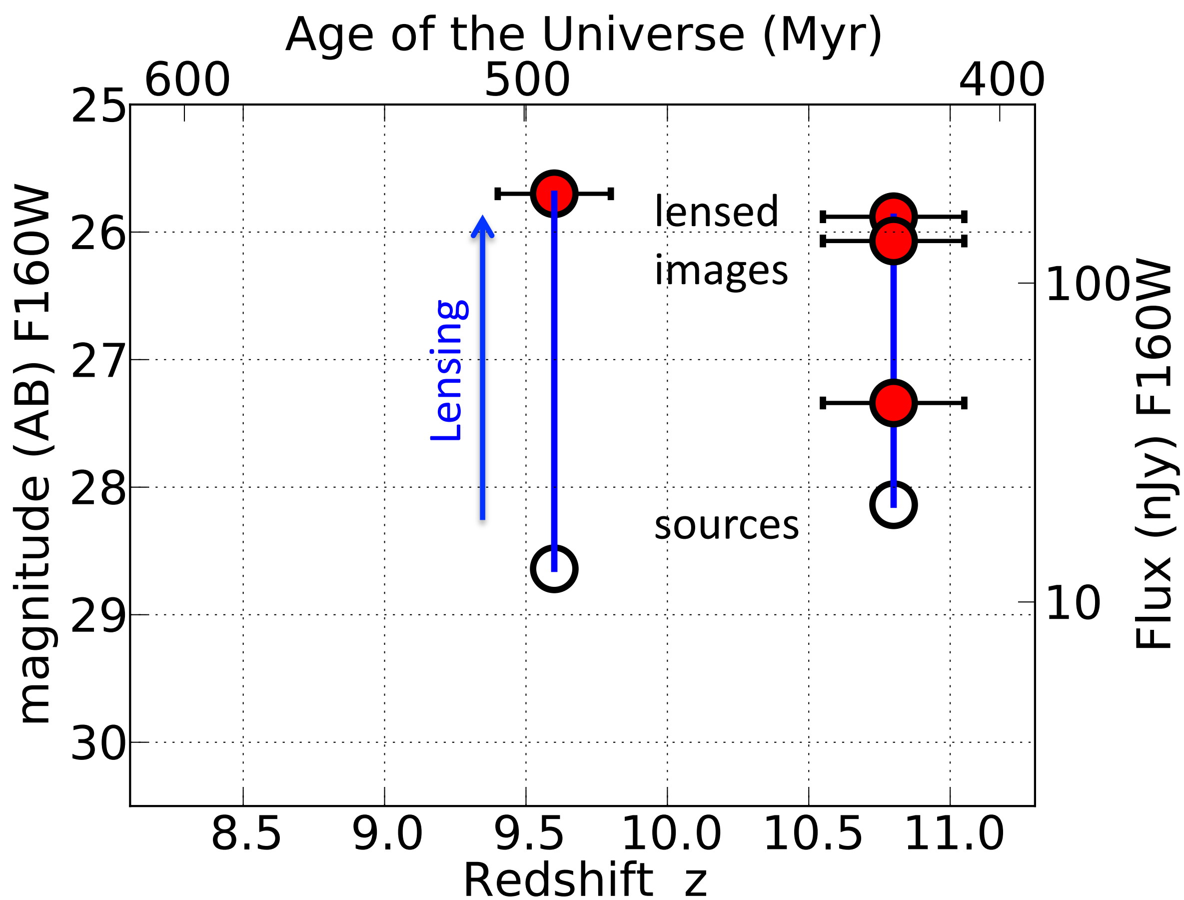
Full FF:
6 lensed +
6 blank
fields:

~70 z > 9 galaxies

(F160W < 28.7)

~13 z > 9 galaxies

Only a handful of z > 9 candidates have been discovered to date

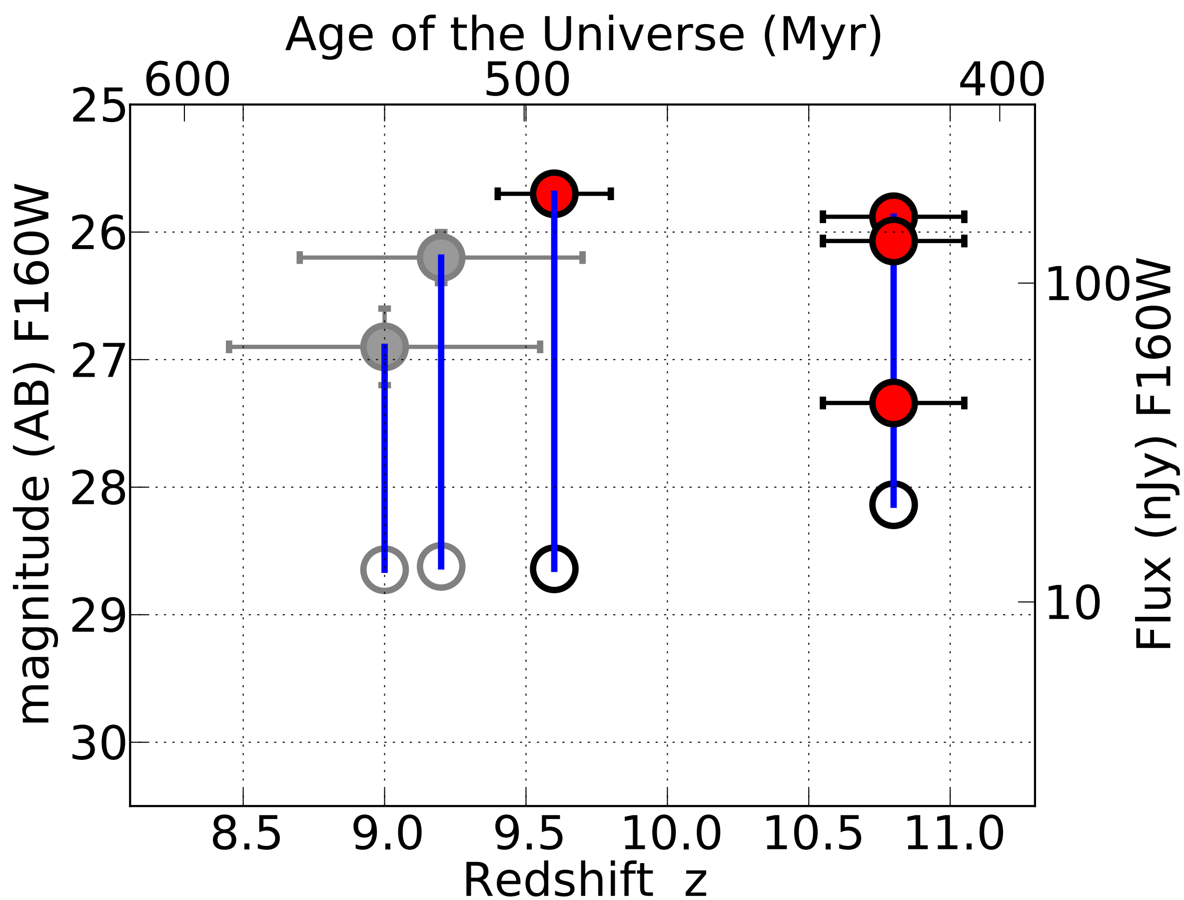


Lensed

magnifications

(Zheng12, Coe13)

Only a handful of z > 9 candidates have been discovered to date



Lensed

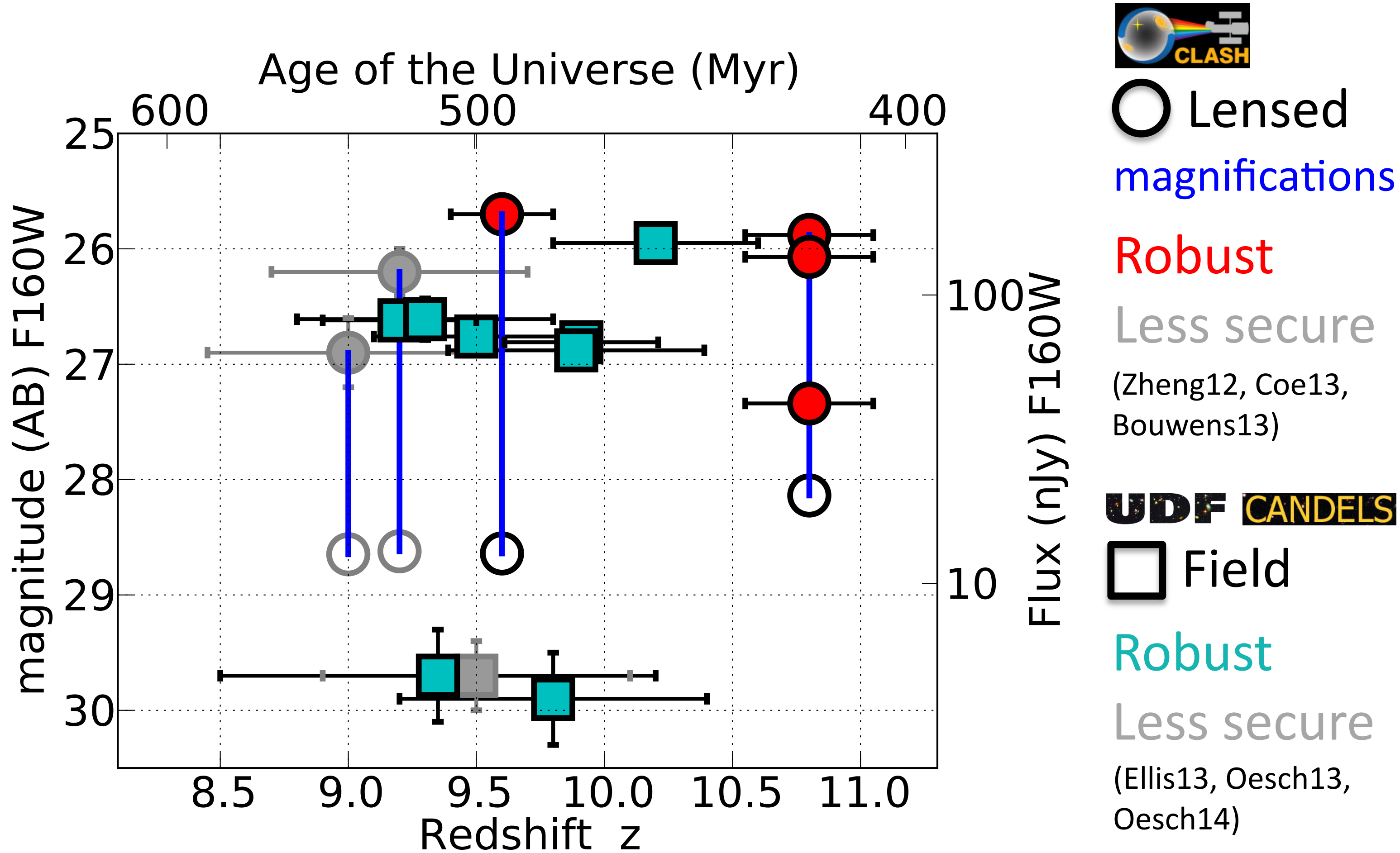
magnifications

Robust

Less secure

(Zheng12, Coe13, Bouwens13)

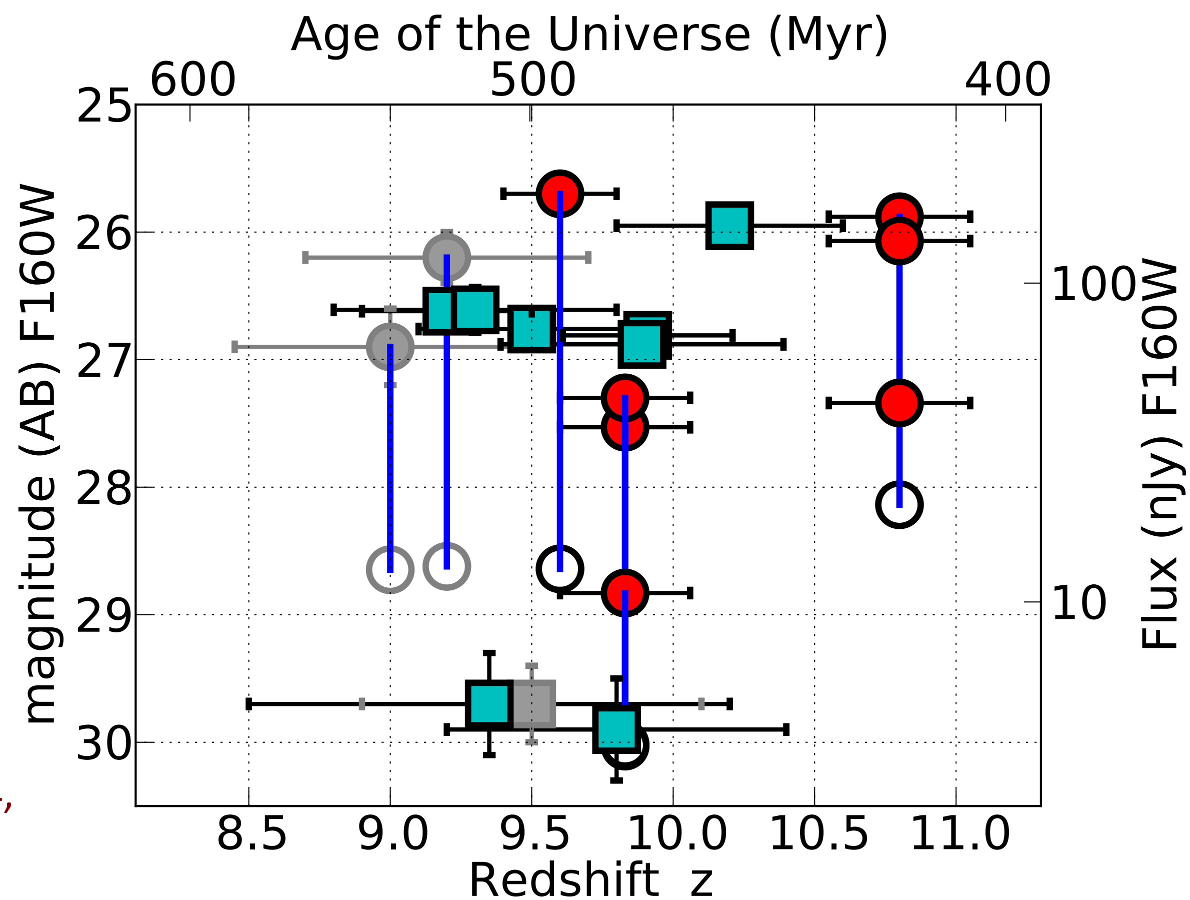
Only a handful of z > 9 candidates have been discovered to date



Only a handful of z > 9 candidates have been discovered to date

~14 z > 9 candidates

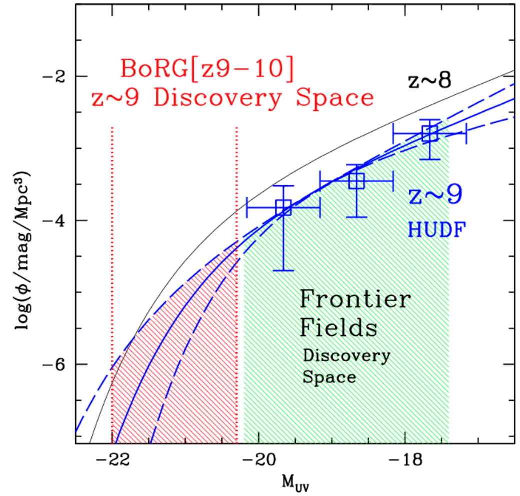
~200 z ~ 8 candidates
(e.g., Bouwens14, Finkelstein14)

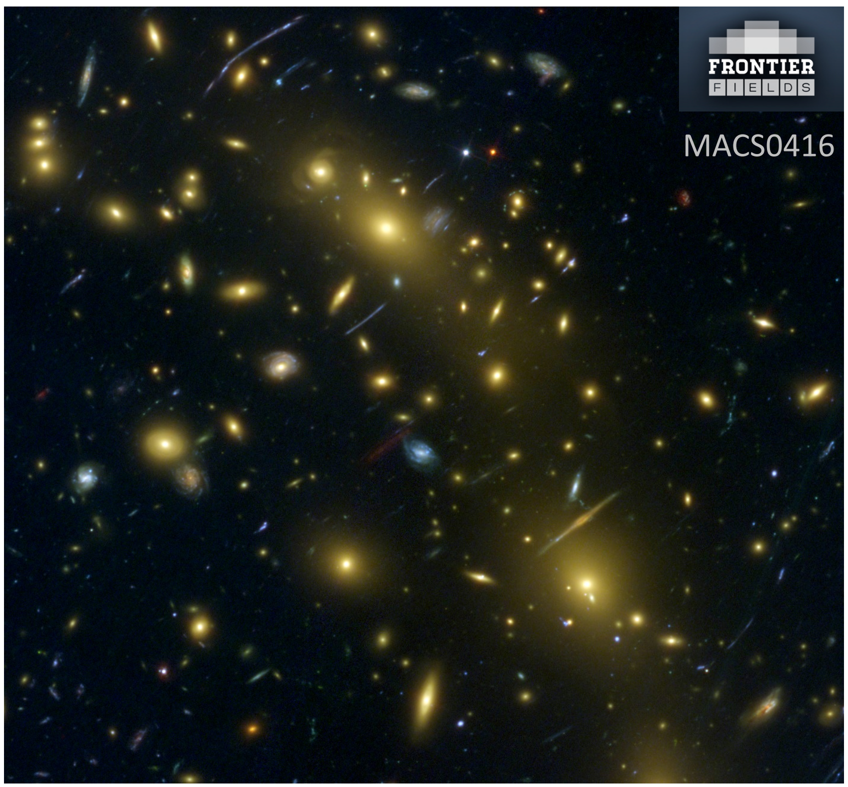


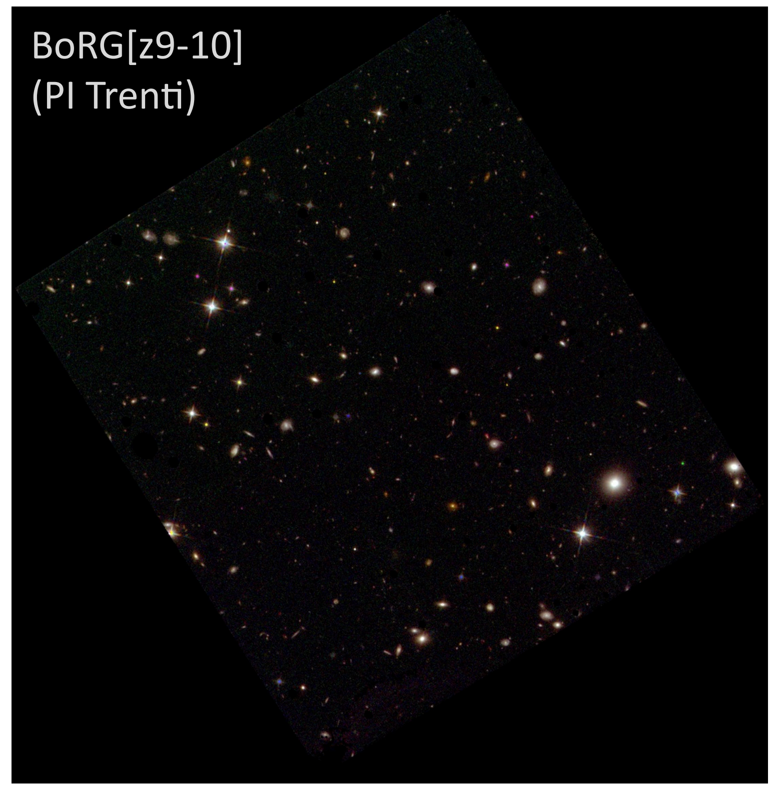
Lensed
magnifications
Robust
Less secure
(Zheng12, Coe13, Bouwens13, Zitrin14)

UDF CANDELS
Field
Robust
Less secure
(Ellis13, Oesch13, Oesch14)

The Frontier Fields and BoRG[z9-10] may make z ~ 9 the new z ~ 8 with ~100 candidates

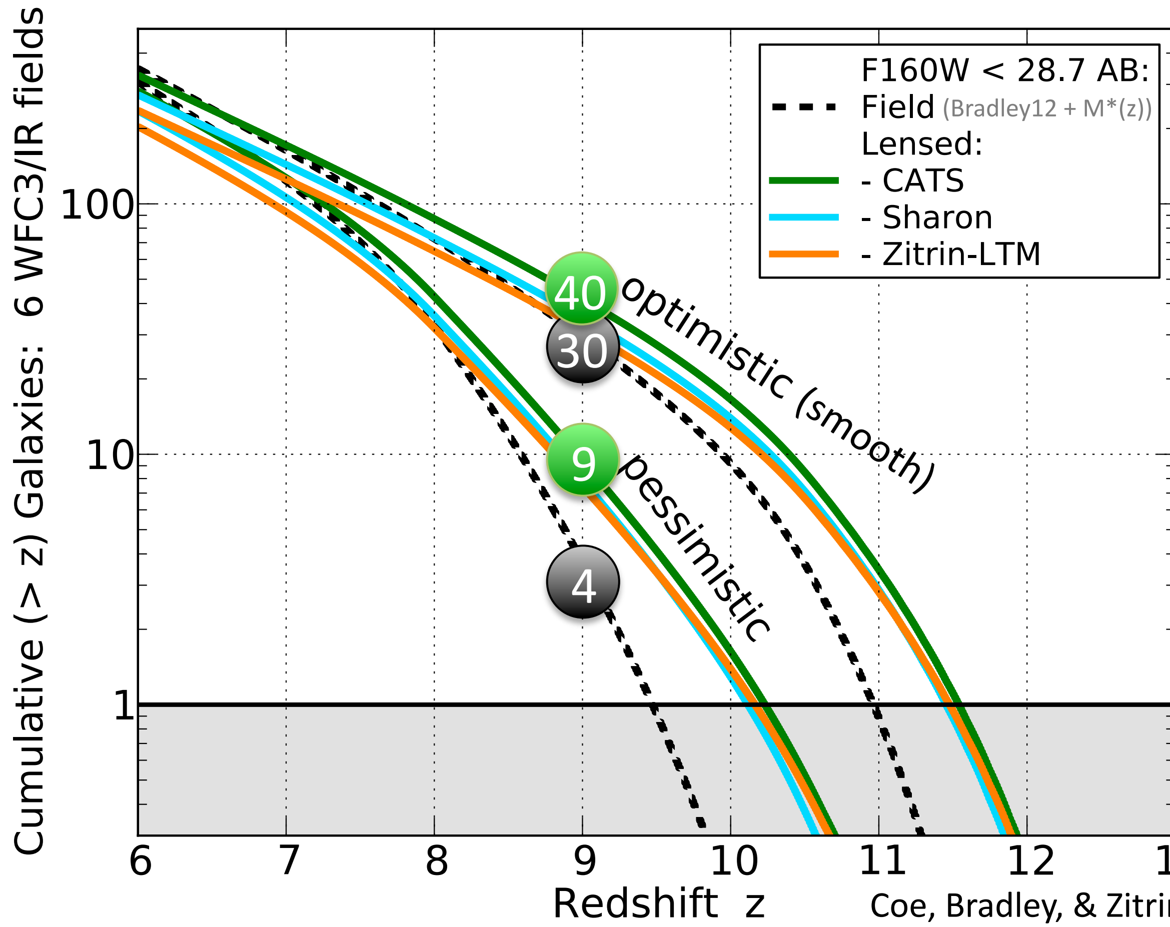






We predict up to ~70 z > 9 galaxies in the Frontier Fields (6 per field)

not accounting for incompleteness



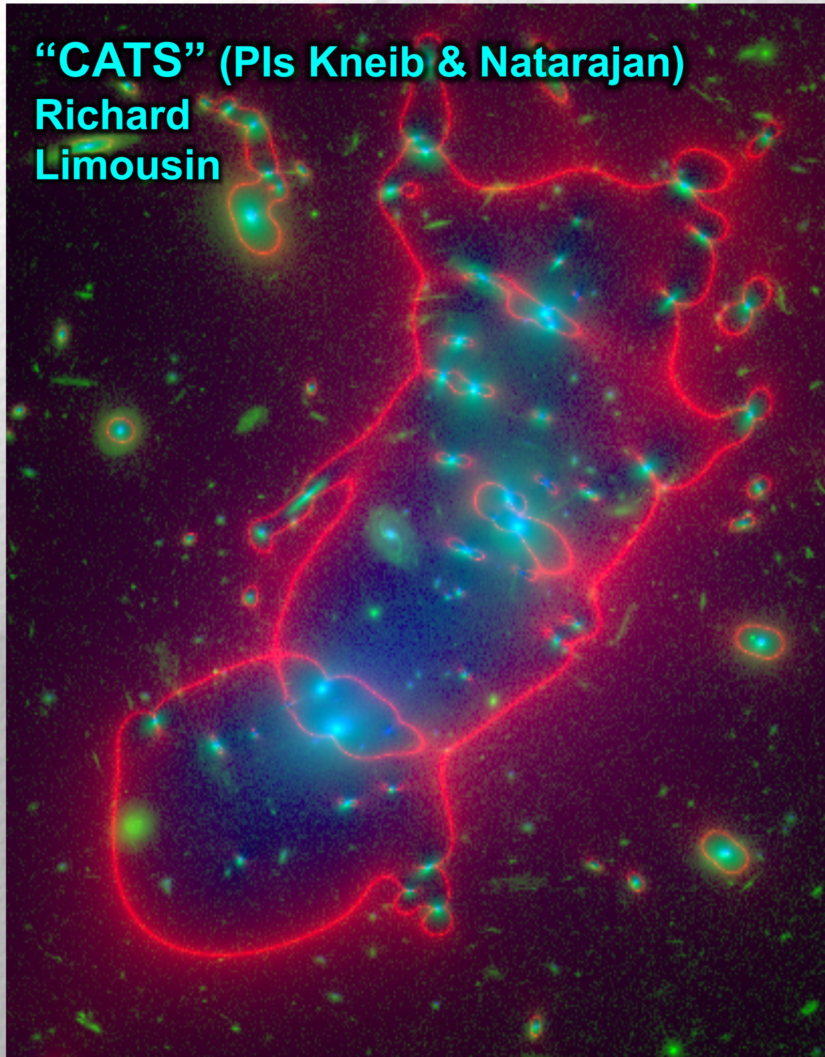
Coe, Bradley, & Zitrin (2014)

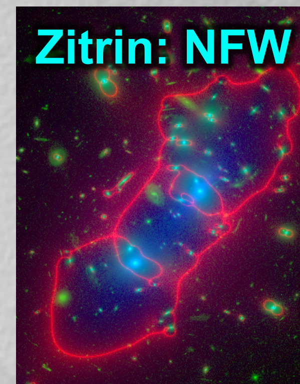
Lens model uncertainties propagate to some, but not all, observables

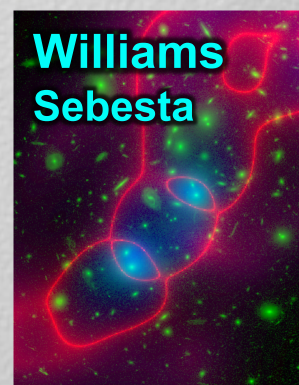
Full uncertainties	**Reduced uncertainties**	**No added uncertainties**
Luminosity: - Mass - Star formation rate Size (radius)	(integrated quantities) Number counts: - Luminosity function - Star formation rate cosmic density	Colors: - Redshift - Age (Balmer break) - Metallicity - Equivalent Width (EW) - UV slope β Specific star formation rate (SFR / stellar mass)

Did galaxies reionize the early universe?

Pre-FF submitted lens models of Abell 2744







Abell 2744
red = magnification for a lensed galaxy at z = 9
green = HST
blue = mass

available via MAST: http://archive.stsci.edu/prepds/frontier/lensmodels/

3 new lens models submitted based in part on Frontier Fields HST imaging

* = Based in part on FF imaging	Abell 2744	MACS J0416.1-2403	MACS J0717.5+3745	MACS J1149.5+2223	Abell S1063	Abell 370
CATS						
CATS v2		*				
Sharon						
Sharon v2						
Zitrin-NFW						
Zitrin-LTM						
Zitrin-LTM-Gauss						
GLAFIC	*					
Williams						
Williams v2		*				
Bradac						
Merten						

available via MAST: http://archive.stsci.edu/prepds/frontier/lensmodels/

Interactive model magnification web tool

Hubble Frontier Fields lens model magnification estimates

archive.stsci.edu/prepds/frontier/lensmodels/webtool/magnif.html

Hubble Frontier Fields lens model magnification estimates

Calculated at any redshift from the mass and shear maps submitted by each team (see lensing primer).
(**Not** extrapolated from the magnification maps pre-calculated at z = 1, 2, 4, 9.)
Lens model main page

Single lensed galaxy:
RA: 4:16:05.555
Dec: -24:03:53.0
z = 9
observed radius (arcseconds): 0

List of lensed galaxies: RA, Dec, z, (optional) radius

```
0:14:23.219 -30:23:44.07 10.8
4h16m12.356s -24h04m35.01s 7.8
(109.36925, 37.772828) 5.3
11 49 36.888 22 24 18.93 3.2
342.2026 -44.536809 2.1
2:39:51 -1:34:09 0.9
3.47968, -30.37596 9.6
```

Save results with run number and optional passcode:

Models: (README) — 68.3 % confidence, calculated from a range of models provided by each group
show all results from each range of models, yielding likelihood distributions

- CATS — with uncertainties
- Sharon — with uncertainties
- Zitrin-NFW — with uncertainties
- Zitrin-LTM — with uncertainties
- Zitrin-LTM-Gauss — with uncertainties
- Williams — with uncertainties
- Bradac — with uncertainties
- Merten — with uncertainties

All None — All None

Uncertainty calculations add a few seconds response time per lensed galaxy per group.

Retrieve magnification estimates

This web-based lens model tool is not supported or maintained by MAST. If you have any questions about its use, or about the accuracy of its results, please email Dan Coe at DCoe@STScI.edu.

Input

RA, Dec, redshift of lensed galaxies

Hubble Frontier Fields lens model magnification estimates

Lensing cluster: MACSJ0416.1-2403 (z = 0.396)

Lensed source (z = 9.0):
RA, Dec = (04:16:05.555, -24:03:53.00) = (64.02315, -24.06472)
observed radius = 0.0 arcseconds

CATS	1.83 best;	$1.84^{+0.09}_{-0.10}$	[1.74, 1.93]	median and 68.3% confidence range
Sharon	3.05 best;	$2.99^{+0.22}_{-0.20}$	[2.79, 3.21]	median and 68.3% confidence range
Zitrin-NFW	1.45 best;	$1.47^{+0.04}_{-0.03}$	[1.44, 1.51]	median and 68.3% confidence range
Zitrin-LTM	1.88 best;	$1.62^{+0.21}_{-0.11}$	[1.51, 1.83]	median and 68.3% confidence range
Zitrin-LTM-Gauss	1.48 best;	$1.44^{+0.39}_{-0.42}$	[1.03, 1.83]	median and 68.3% confidence range
Williams	1.22 best;	$1.21^{+0.03}_{-0.04}$	[1.18, 1.25]	median and 68.3% confidence range
Bradac	2.36 best;	$2.11^{+0.07}_{-0.04}$	[2.07, 2.18]	median and 68.3% confidence range
Merten	4.45 best;	$10.24^{+1.85}_{-0.87}$	[9.37, 12.09]	median and 68.3% confidence range

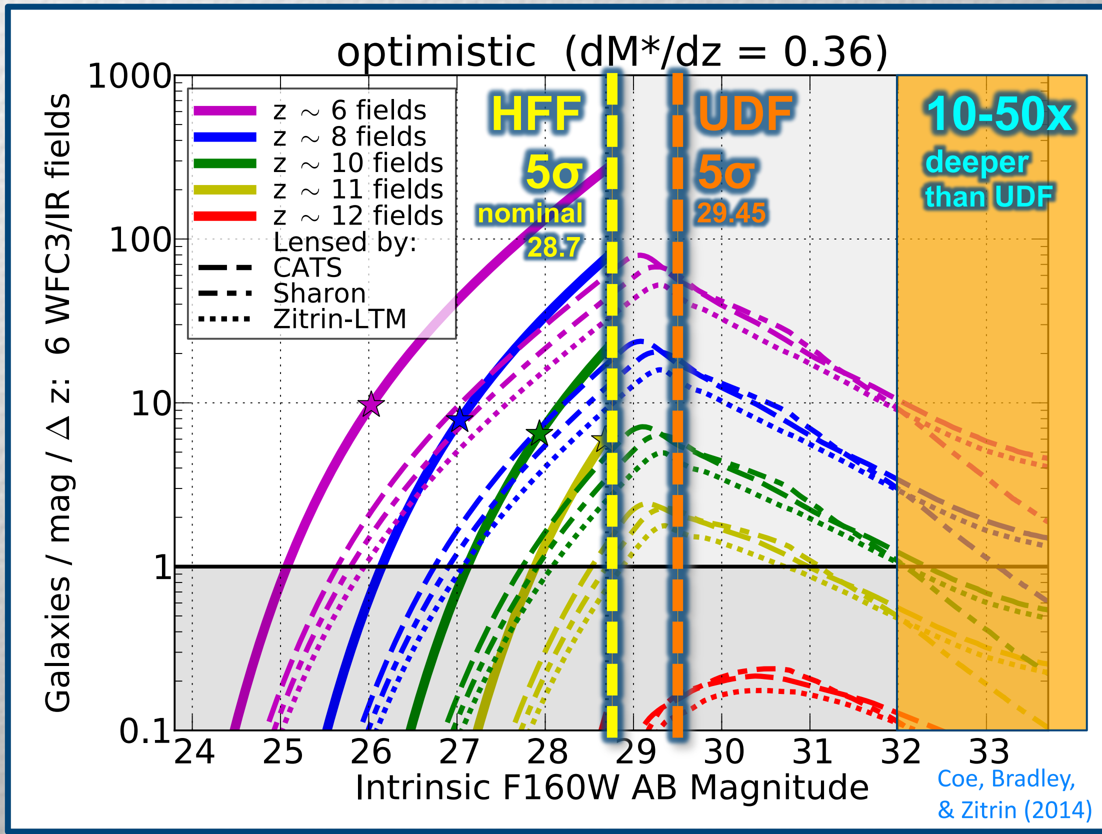
Back to input page

This web-based lens model tool is not supported or maintained by MAST. If you have any questions about its use, or about the accuracy of its results, please email Dan Coe at DCoe@STScI.edu.

Output

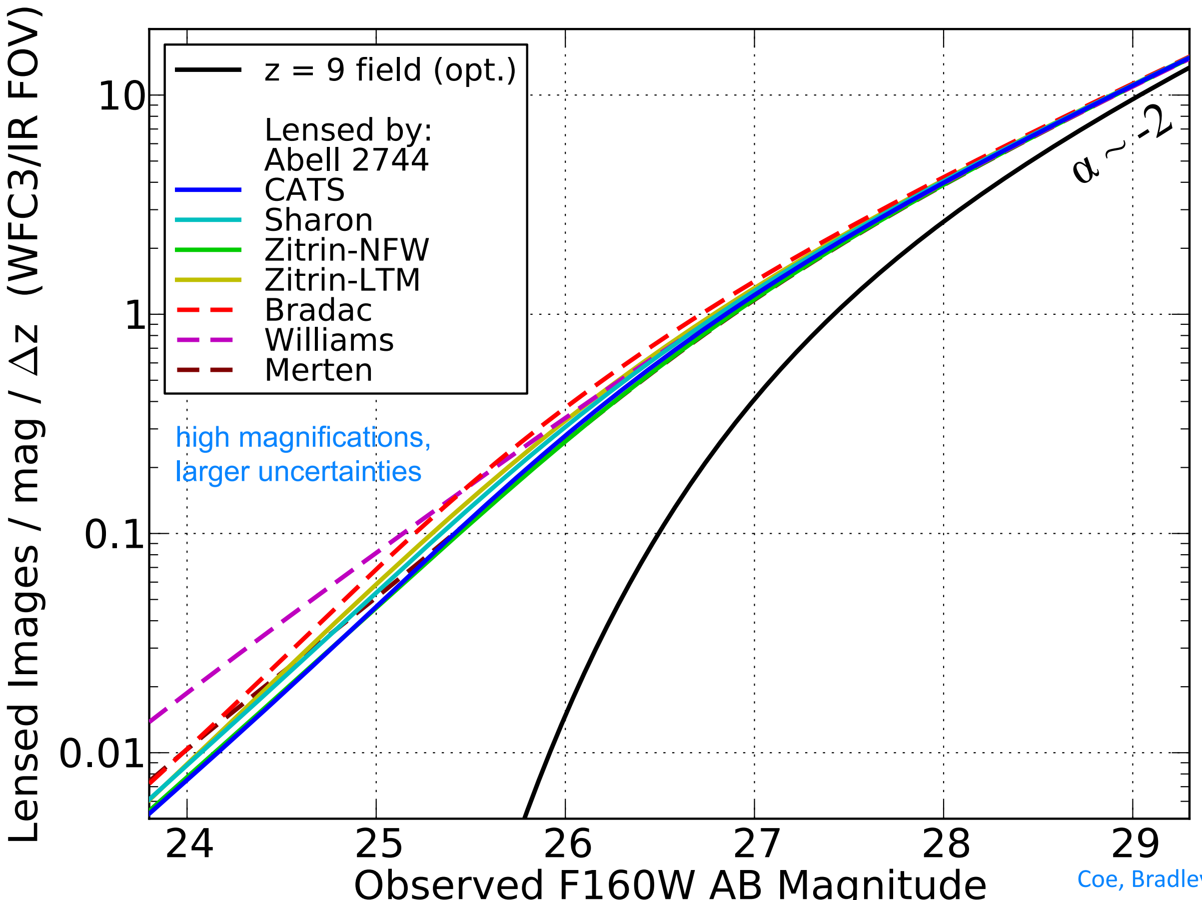
Magnification estimates with uncertainties

The lensed Frontier Fields are yielding the faintest galaxies yet observed



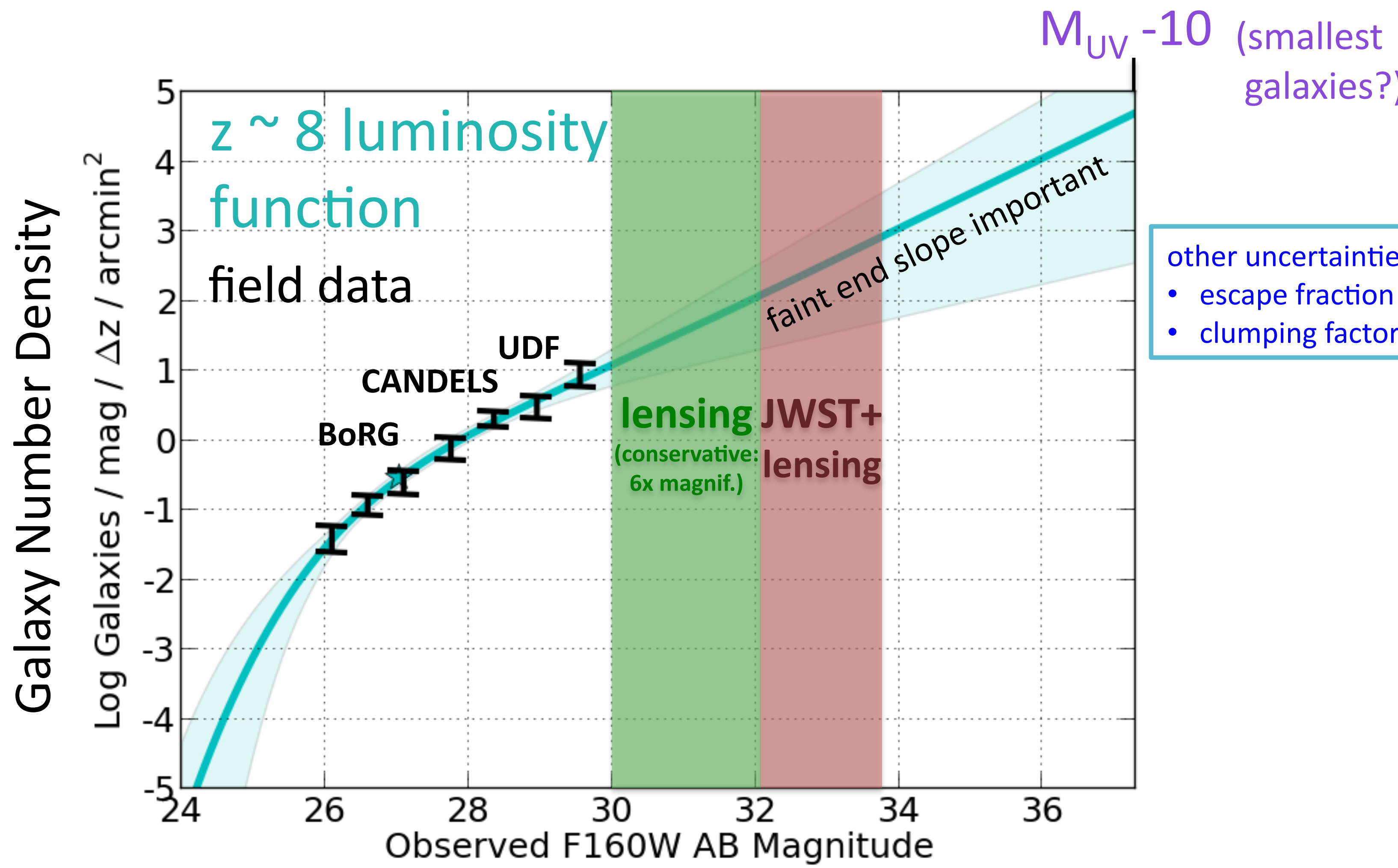
Lens models yield consistent predictions

Lens models yield consistent predictions for faint lensed number counts



Coe, Bradley, & Zitrin (2014)

Large extrapolations required to estimate faint galaxy contribution to reionization



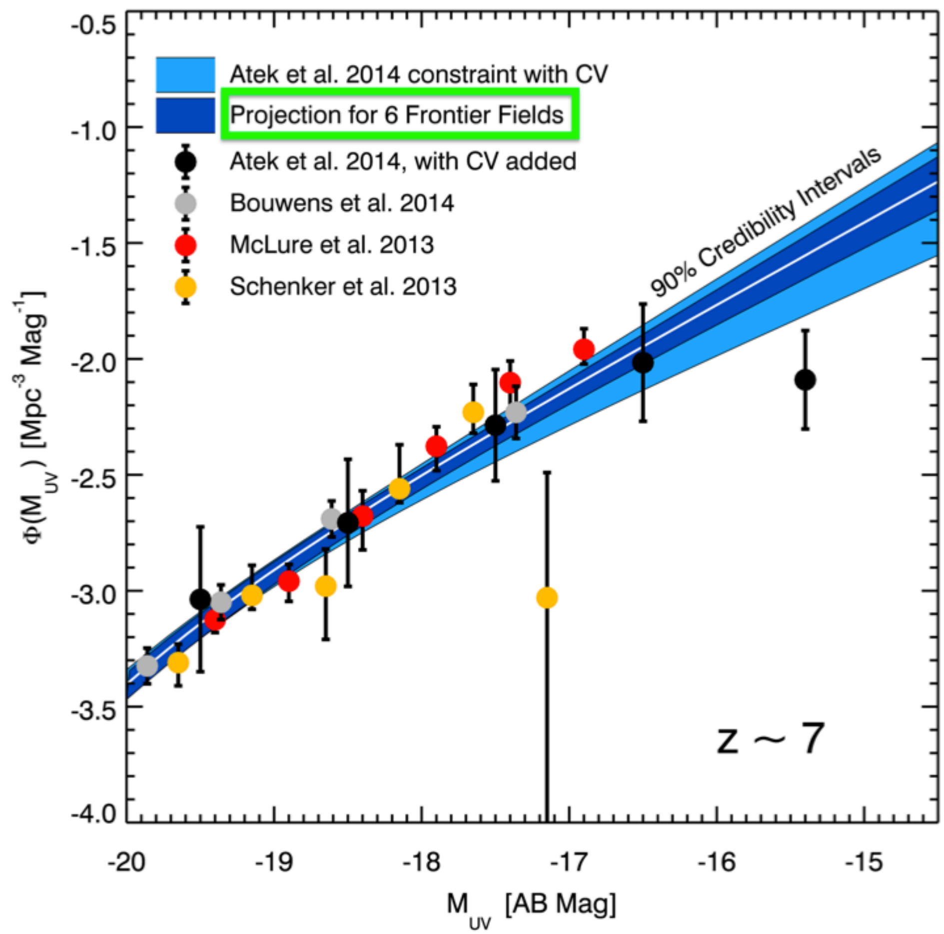
other uncertainties:
- escape fraction
- clumping factor

The Frontier Fields will tightly constrain high-z luminosity function faint end slopes

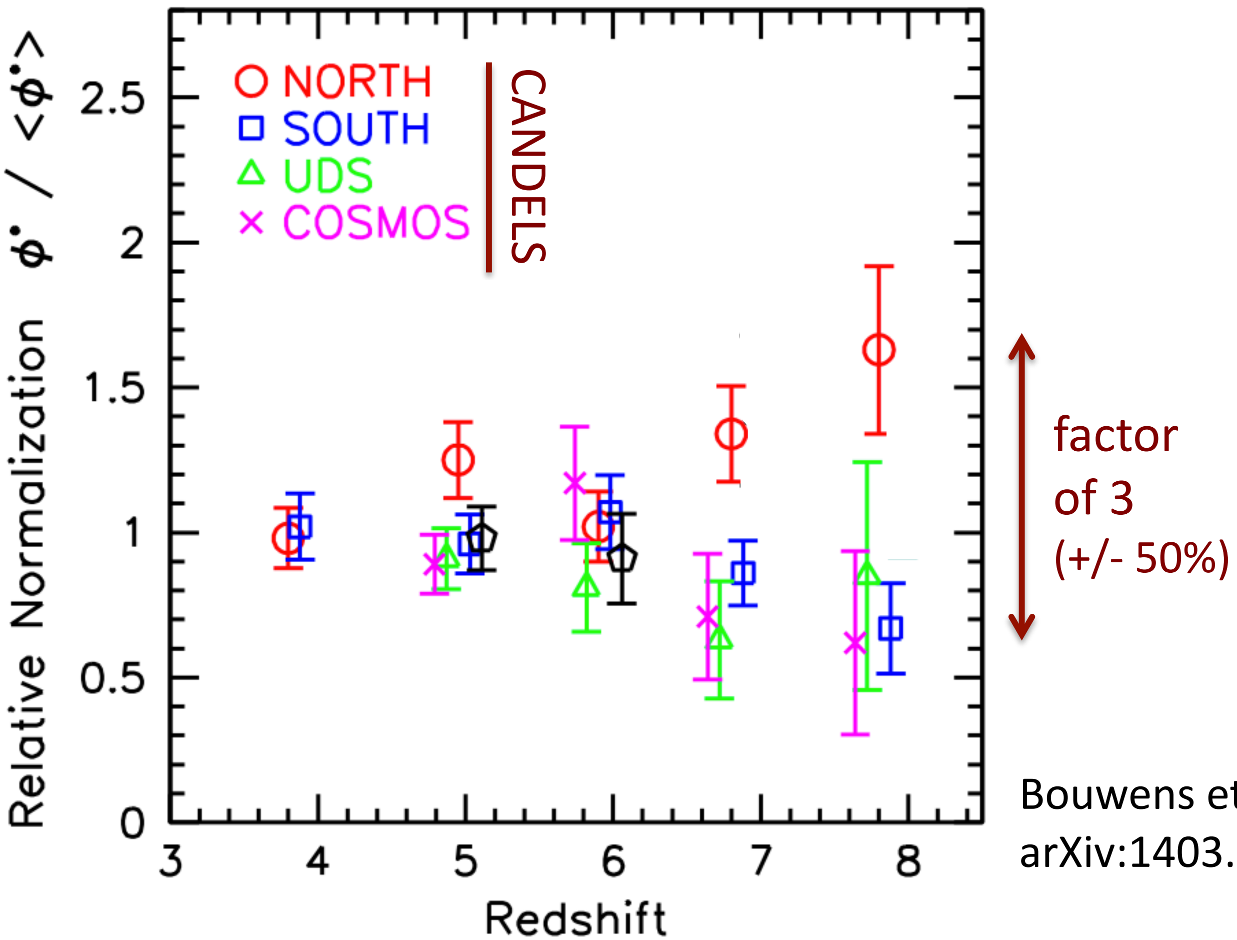
z ~ 7 LF faint end slope:
precision ➔ 0.05

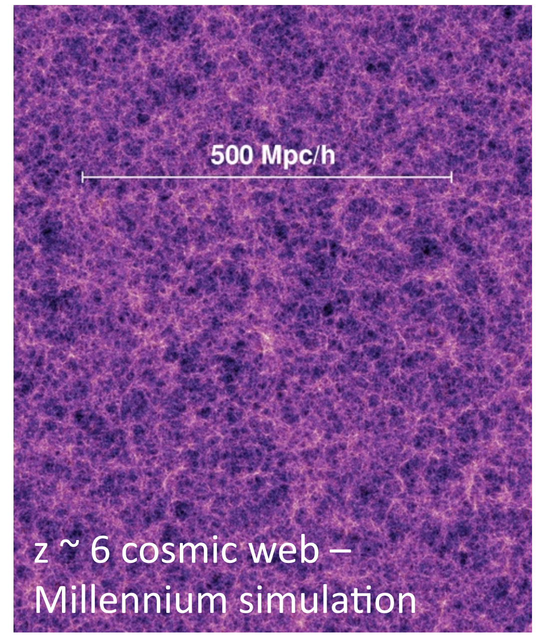
UV luminosity density:
2x precision ➔ 30%

Robertson et al. (2014)



The need for multiple sightlines: cosmic variance



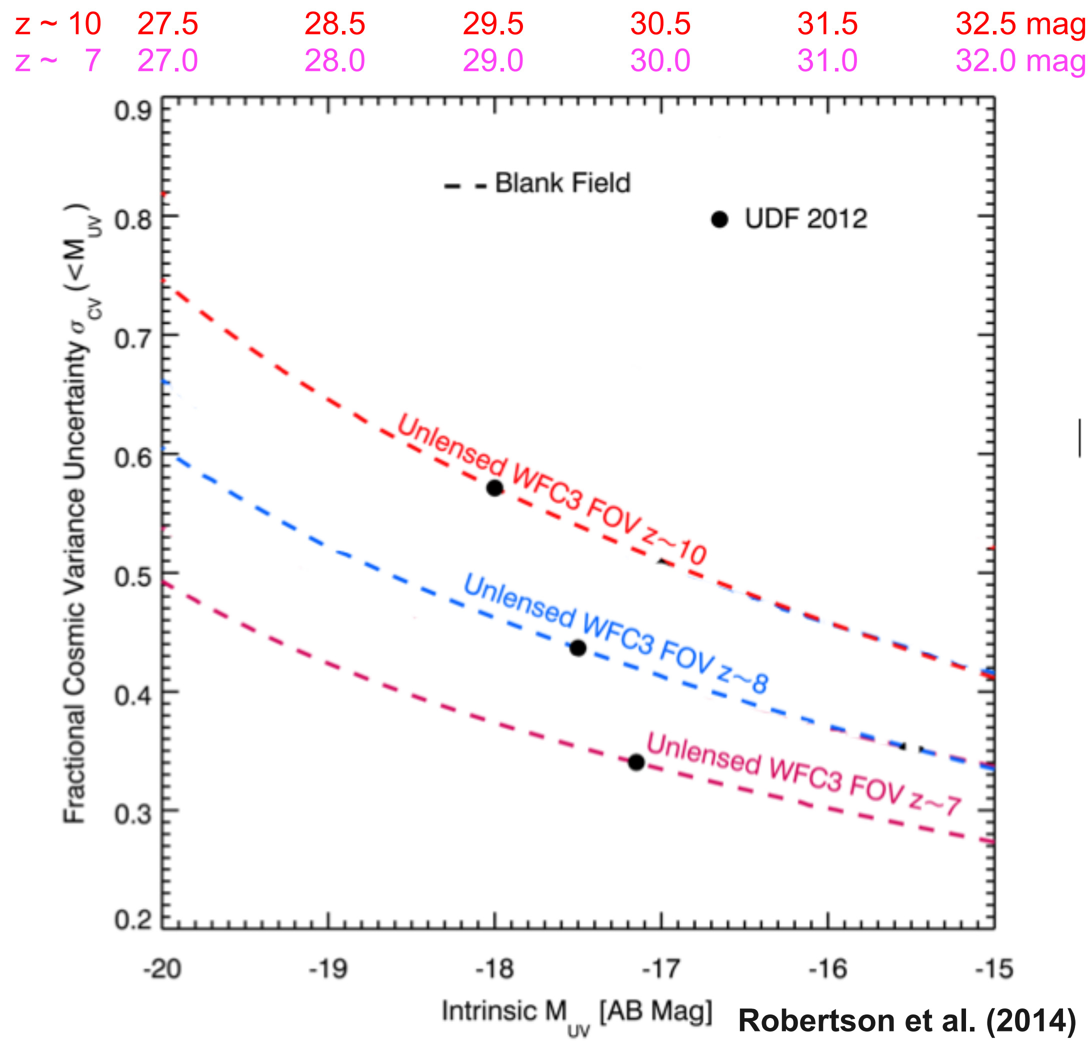


Bouwens et al. 2014
arXiv:1403.4295

Cosmic variance estimates for the Frontier Fields

Brighter galaxies are
more biased tracers of mass

Bias diminishes over time
as larger galaxies form



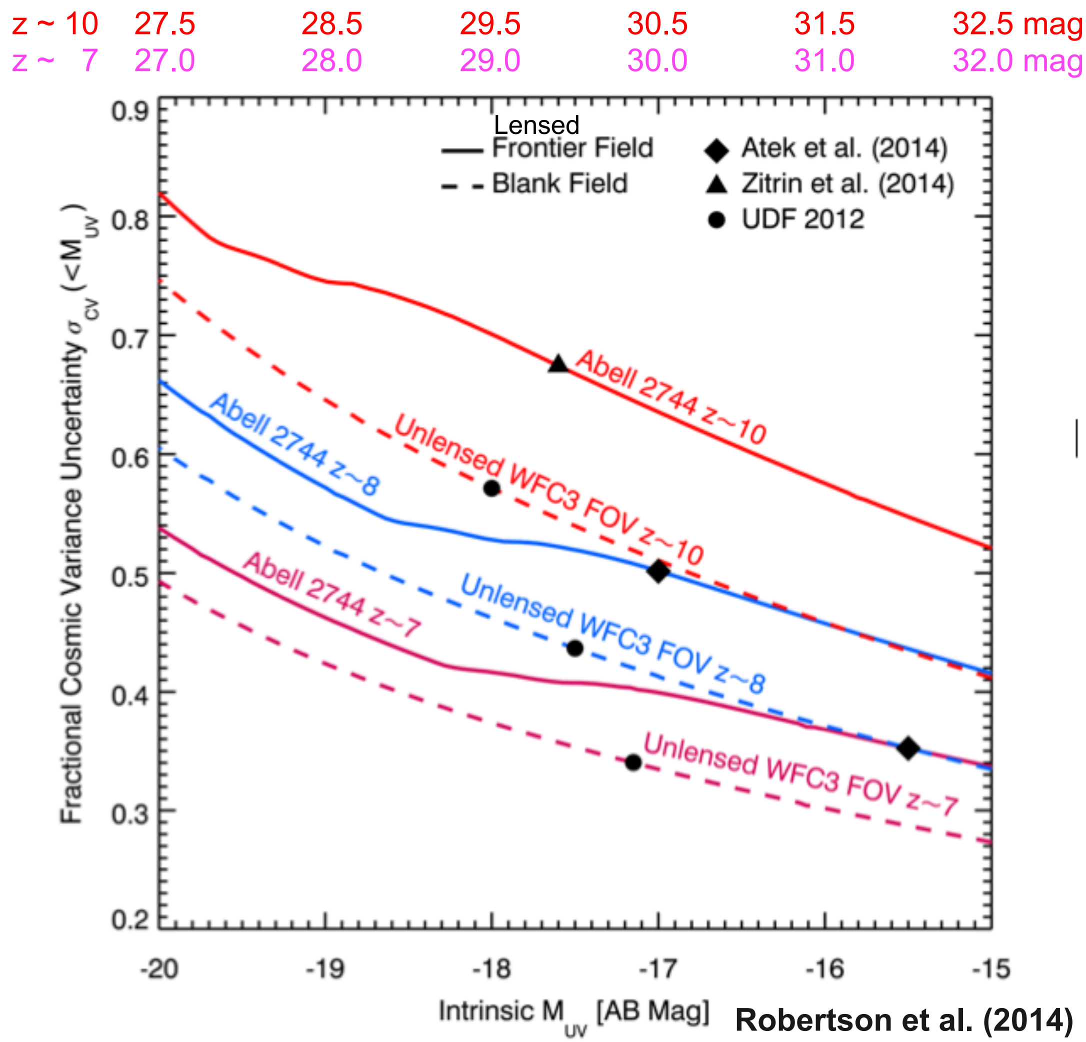
Robertson et al. (2014)

Lensing can increase cosmic variance

Lensing

decreases search volume: CV ↑

and probes fainter galaxies: CV ↓



Robertson et al. (2014)

Lensing can increase cosmic variance

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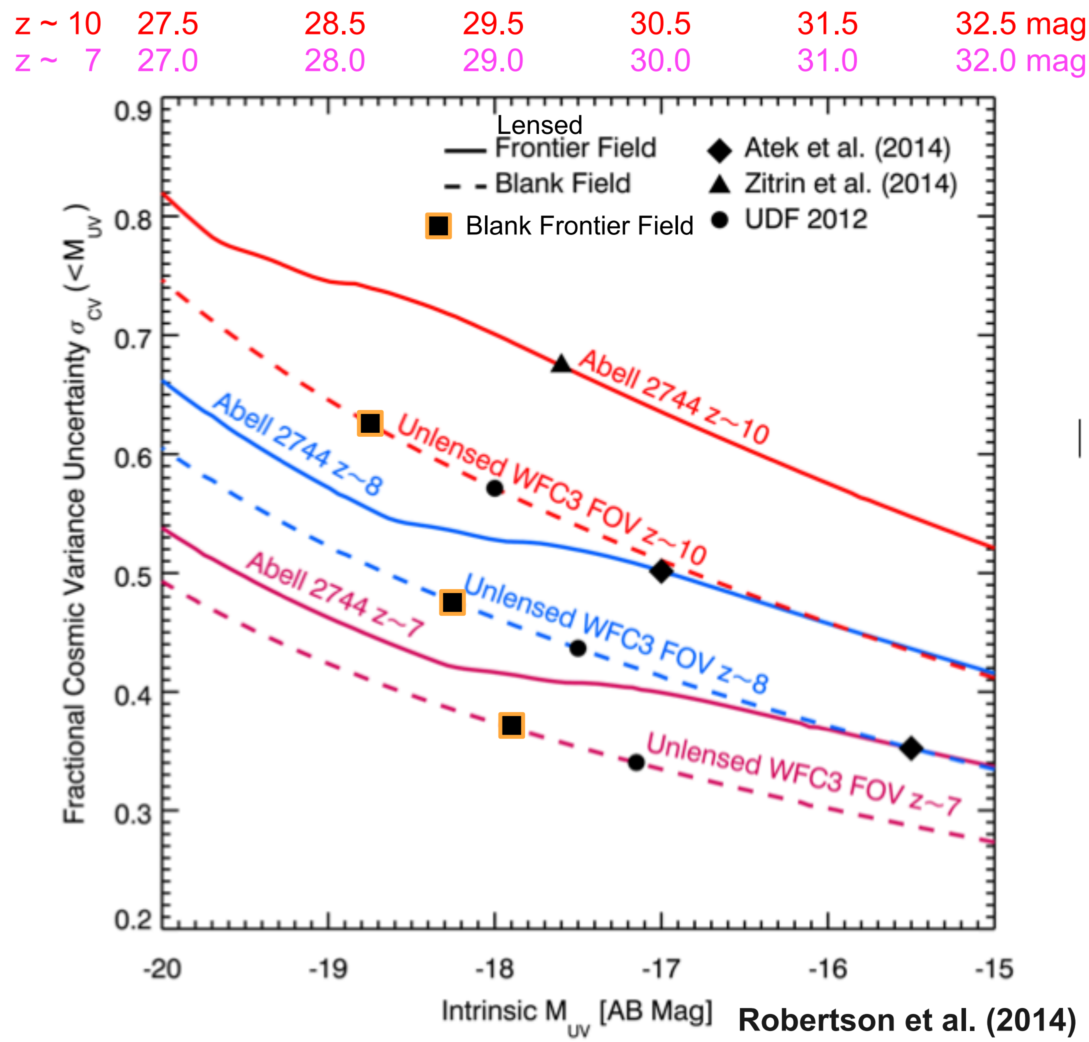


Robertson et al. (2014)

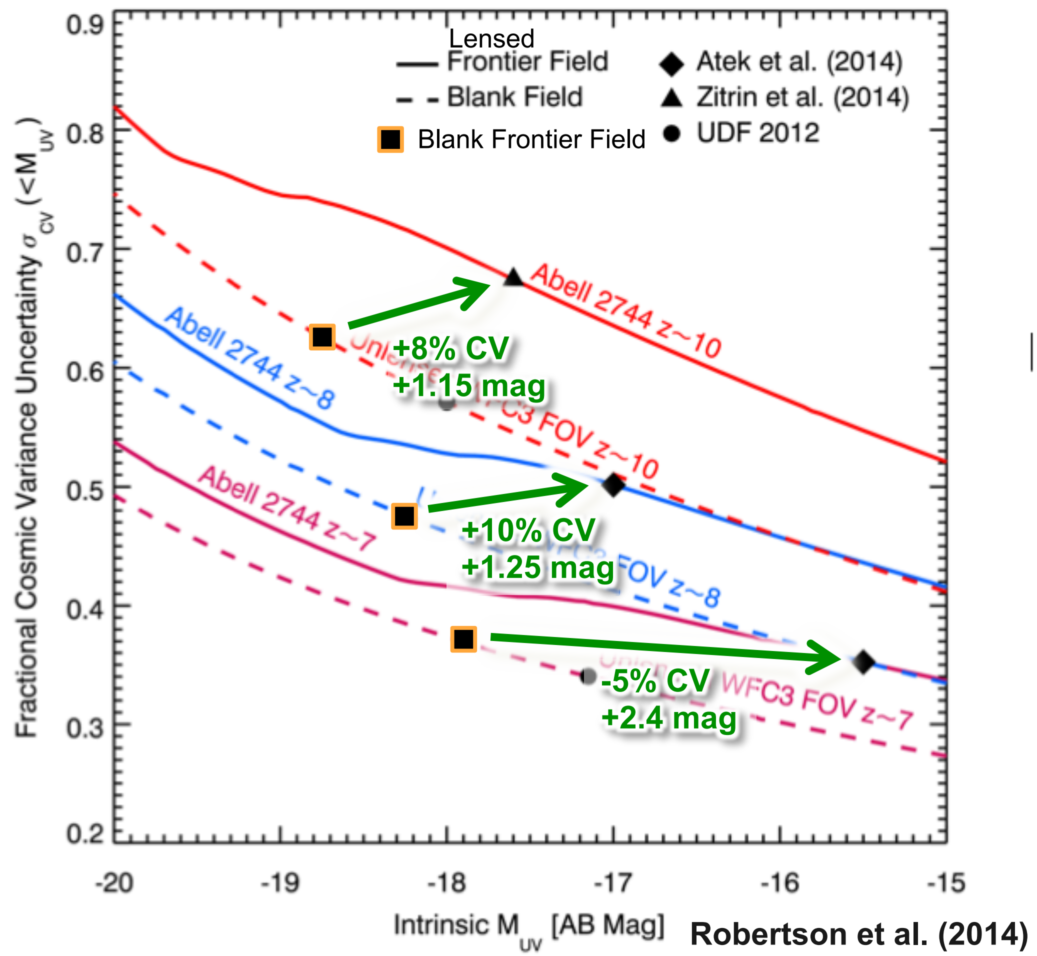
Lensing affects cosmic variance by ~10% wrt blank field at z = 7 – 10

Lensing

decreases search volume: CV ↑

and probes fainter galaxies: CV ↓

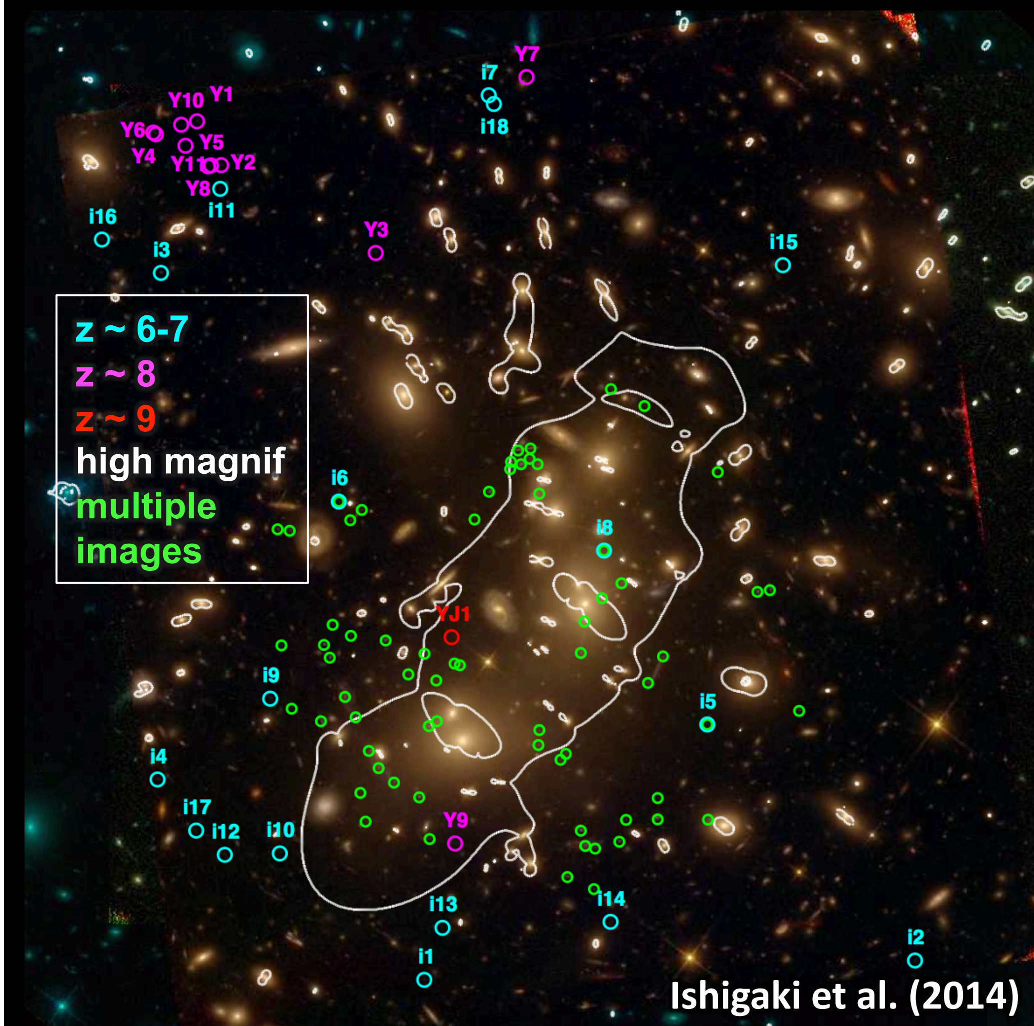
Brant cautions that
nonlinear halo bias
(not included here)
will be more significant
for the lensed fields
with their smaller volumes

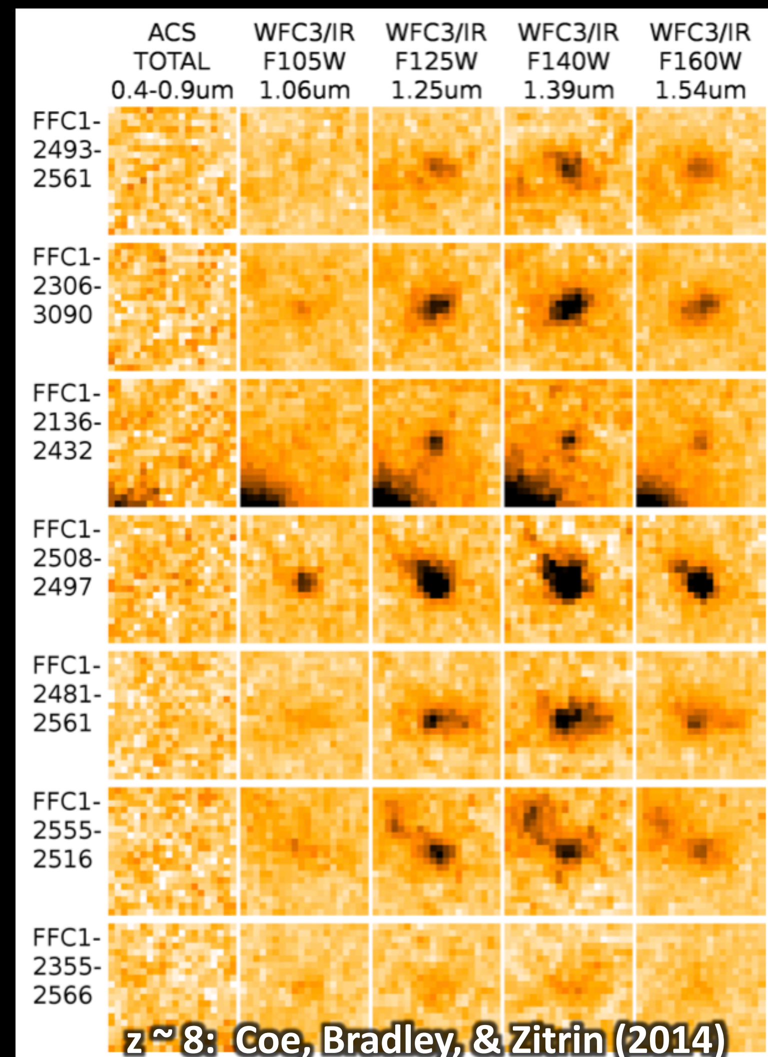


Robertson et al. (2014)

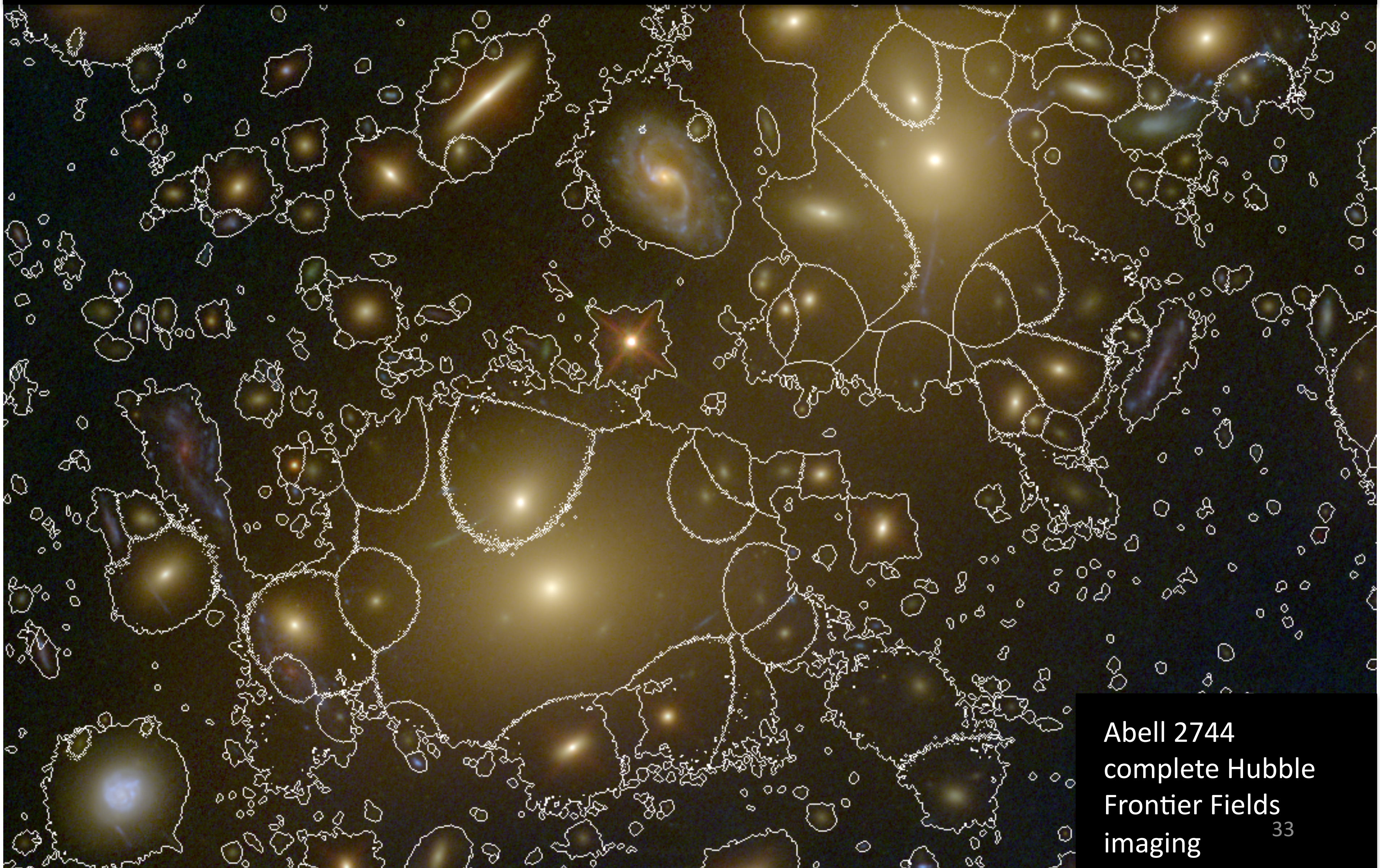
High-z candidates lensed by A2744

(see papers led by Zheng; Atek; Laporte; Coe; Zitrin; Ishigaki; Oesch…)



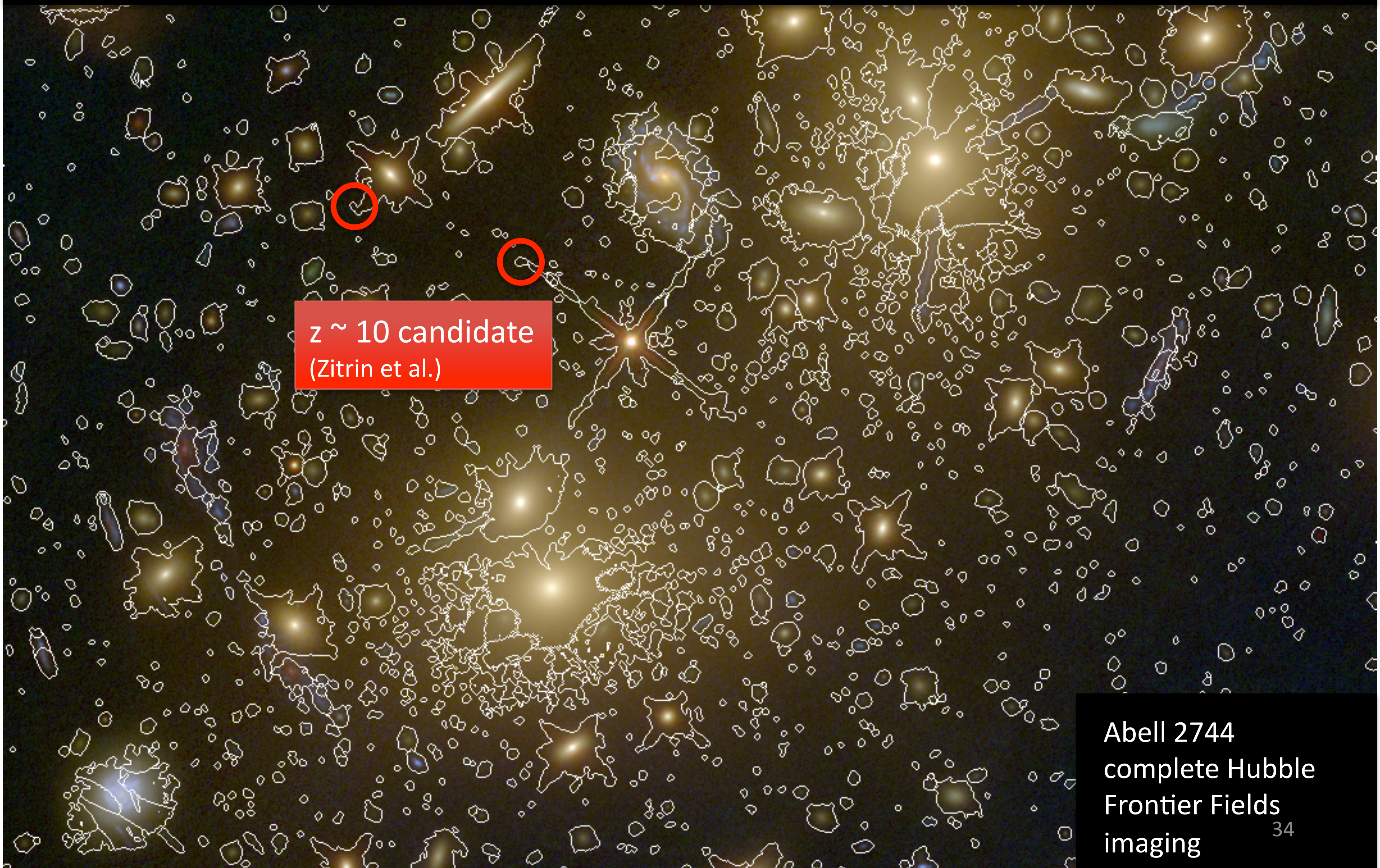


SExtractor detection with CLASH parameters



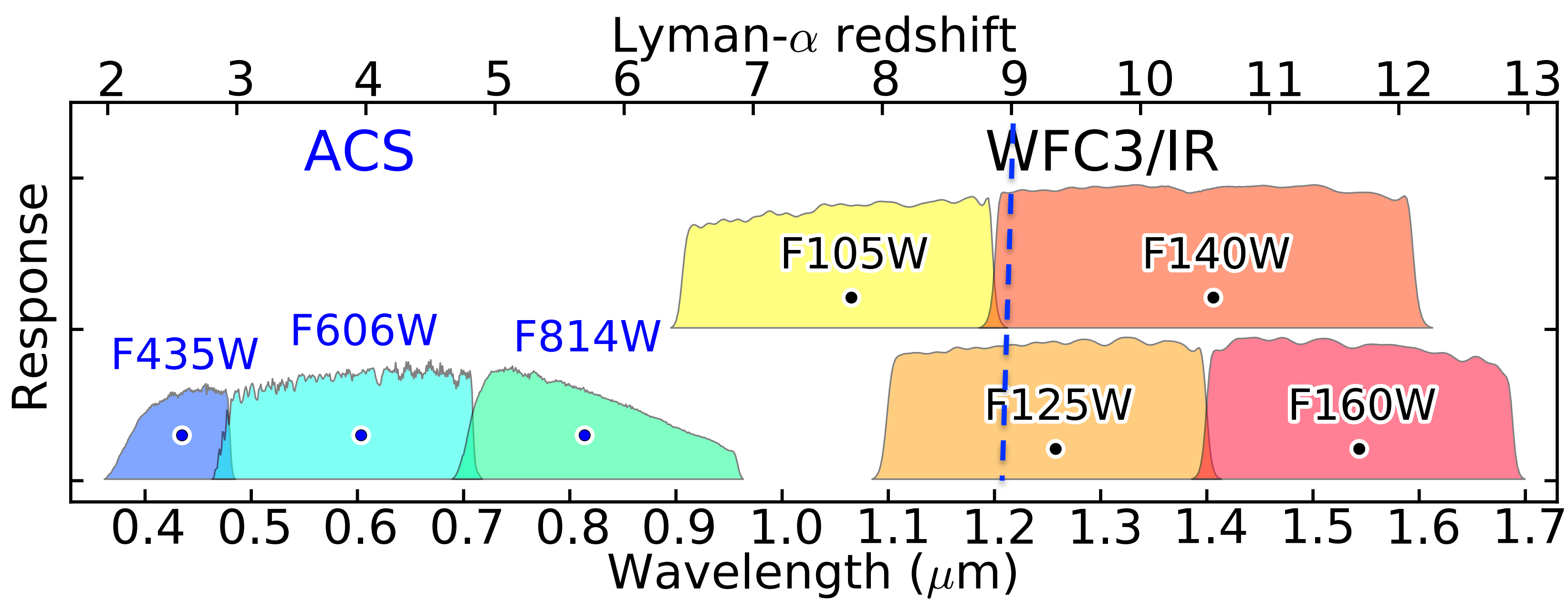
Abell 2744
complete Hubble
Frontier Fields
imaging

More aggressive SExtractor parameters

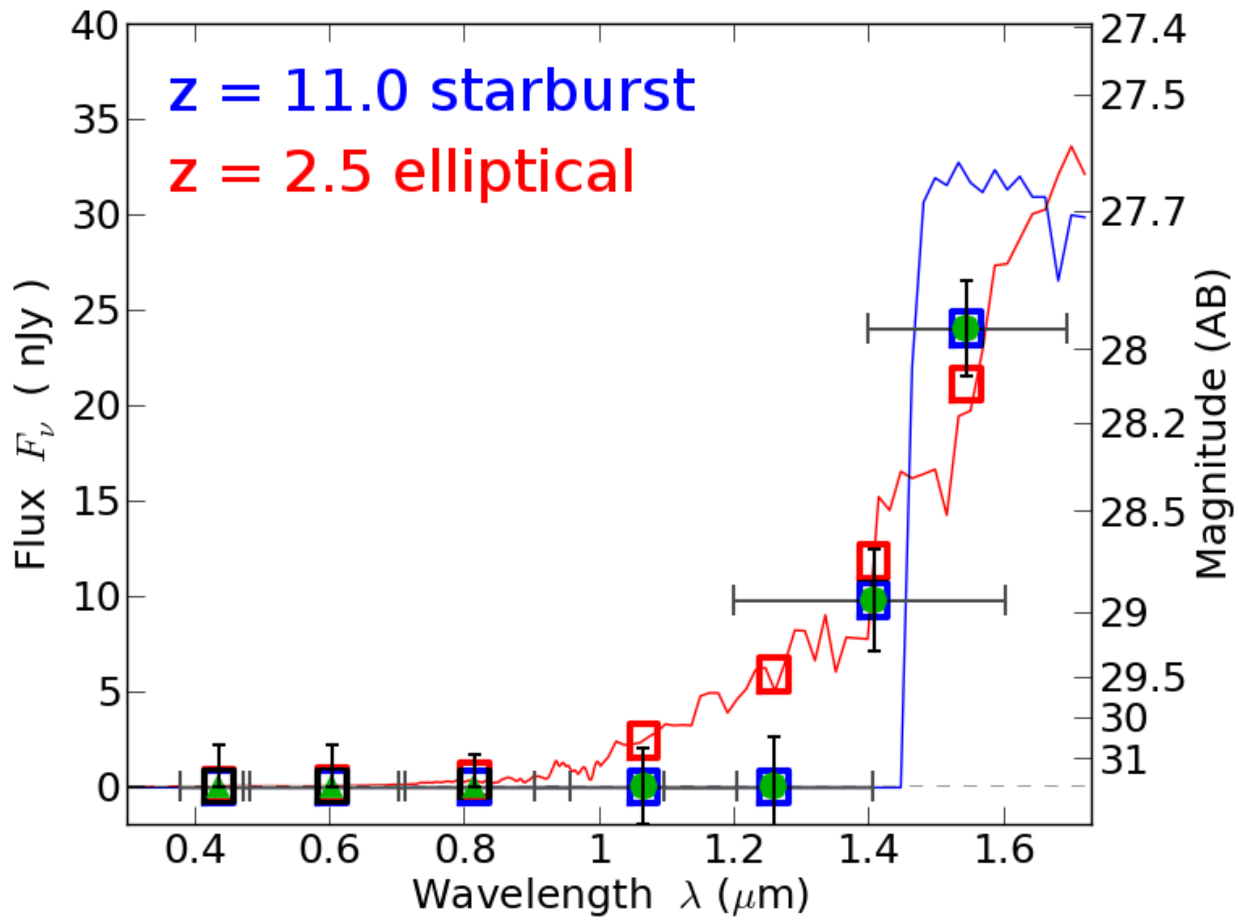


Abell 2744
complete Hubble
Frontier Fields
imaging

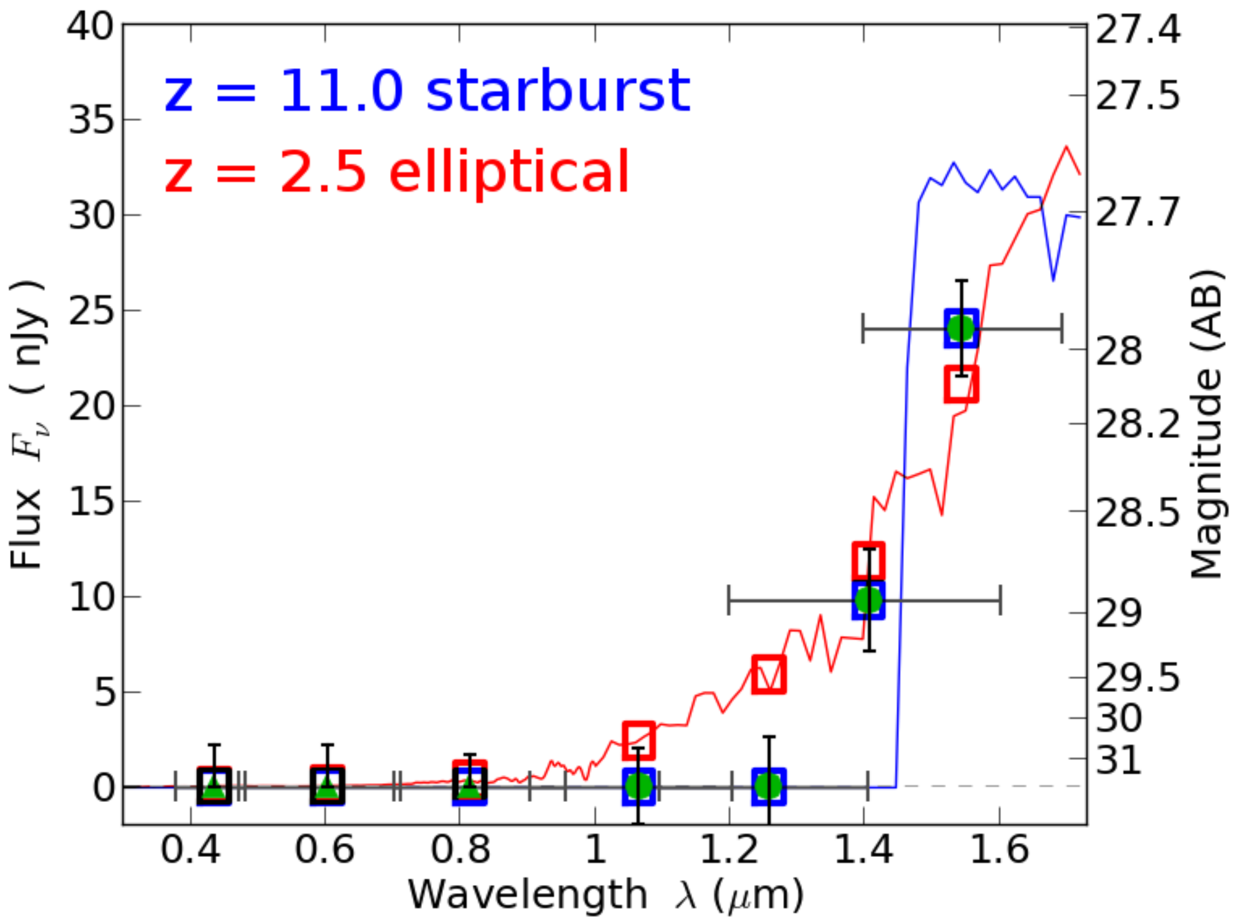
9 < z < 11 galaxies can look like red z ~ 2 galaxies in the FF HST filters



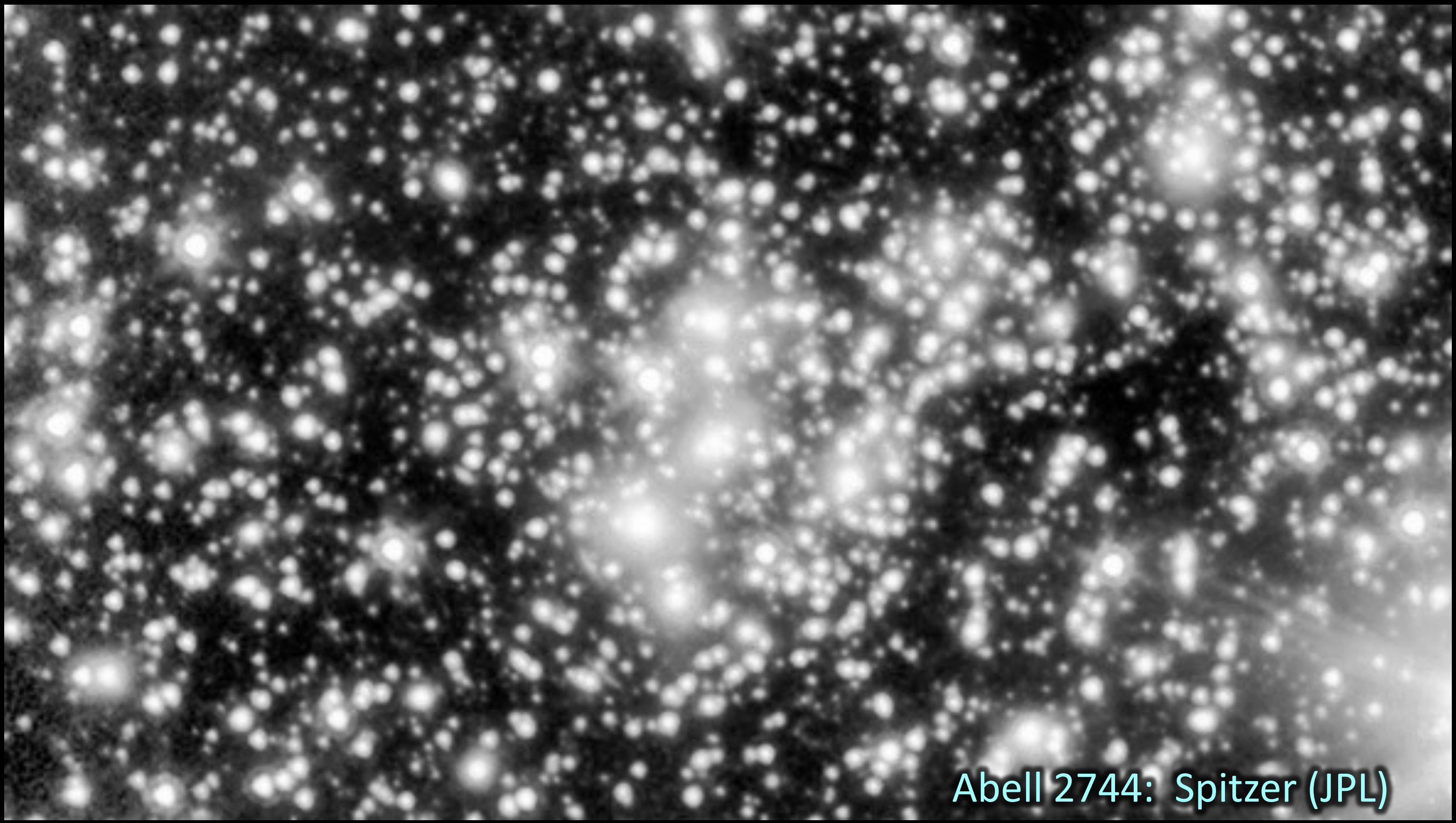
z ~ 10 galaxies can look like red z ~ 2 galaxies in the FF HST filters



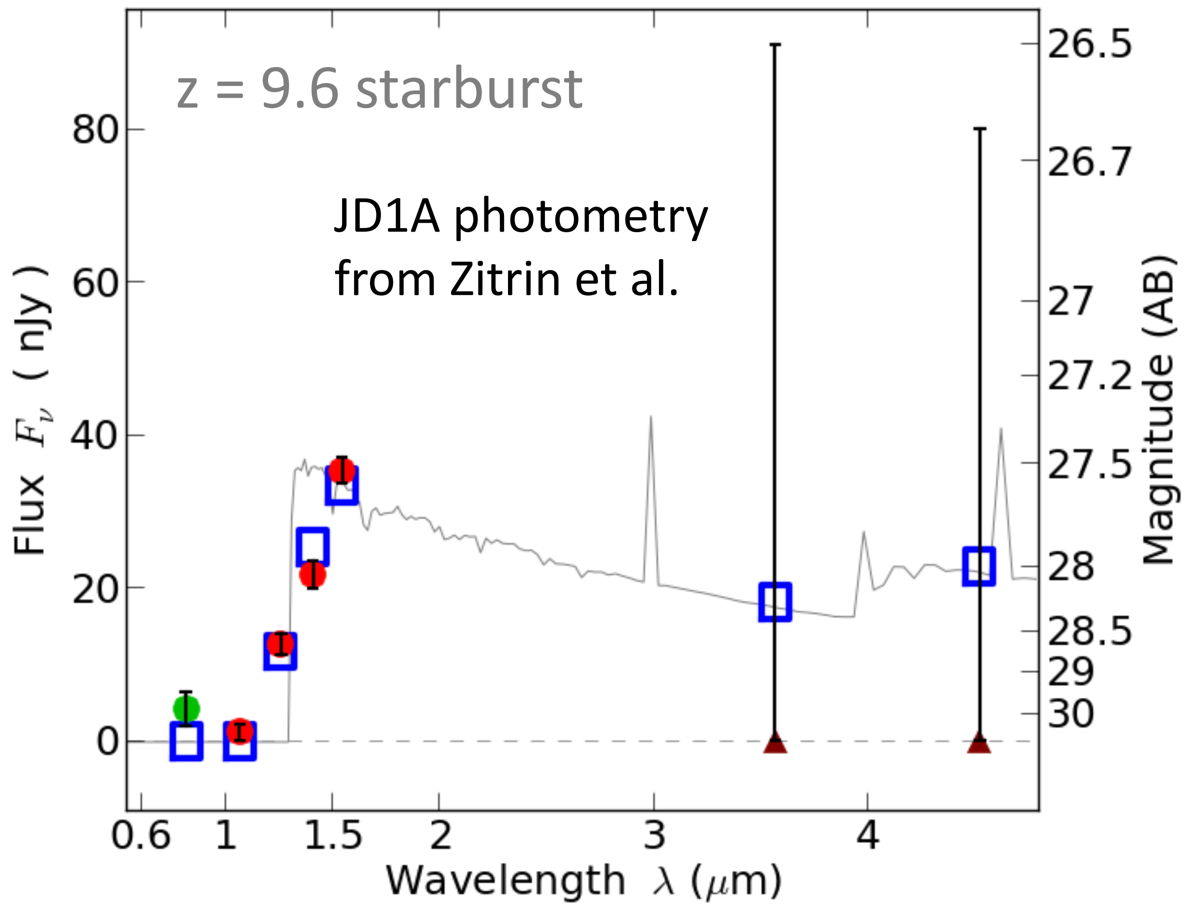
z ~ 10 galaxies can look like red z ~ 2 galaxies in the FF HST filters



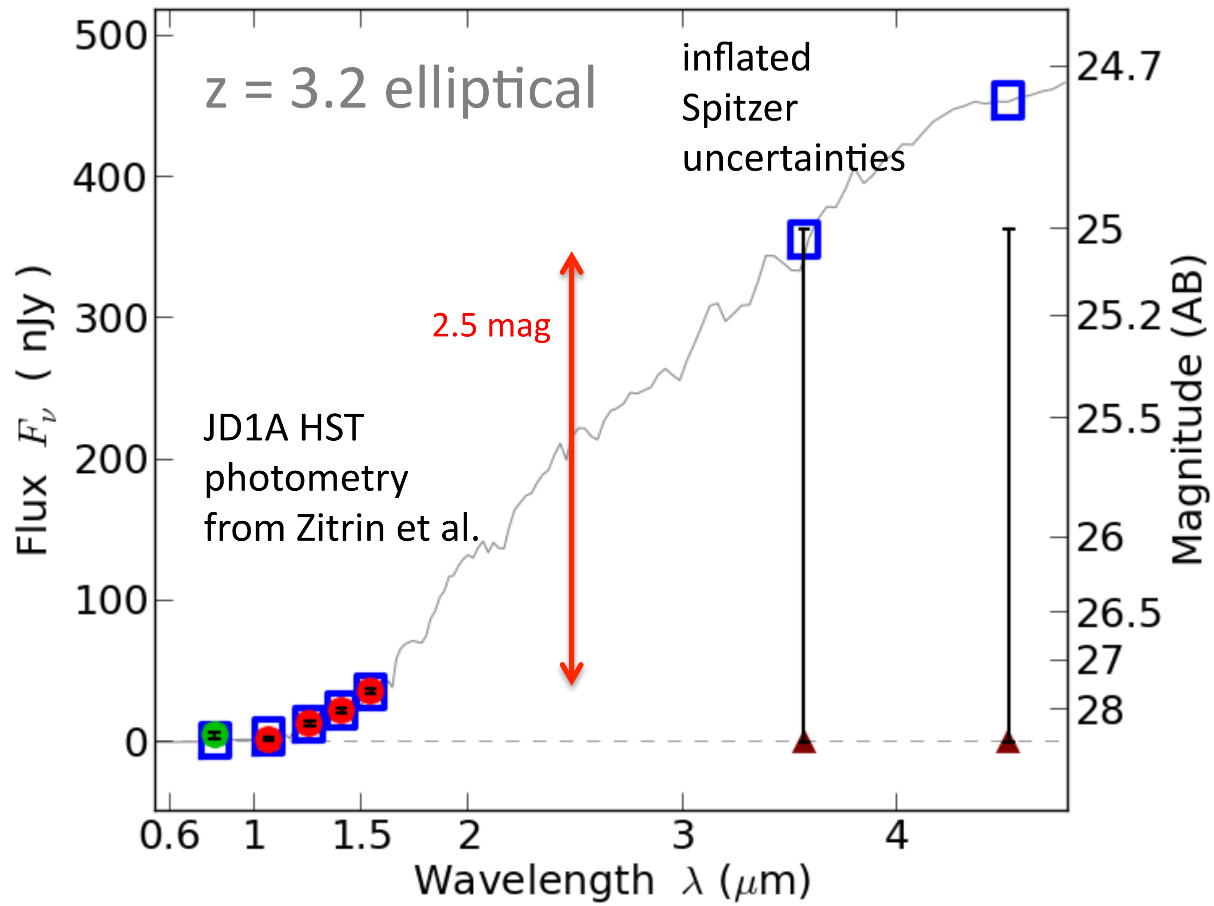
Hubble + Spitzer photometry can distinguish blue z ~ 10 galaxies from red z ~ 2 galaxies



Spitzer photometry adds confidence to z ~ 10 candidates

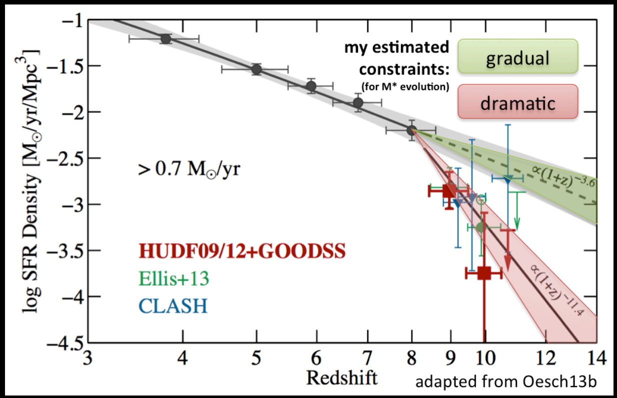


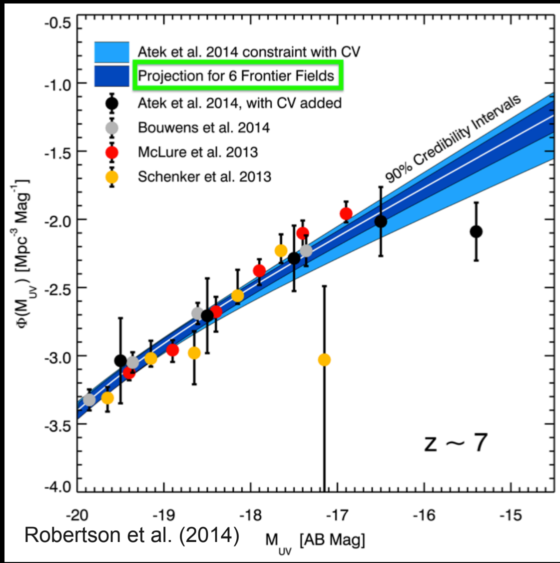
Spitzer detection limits within ~2 mag of HST flux add confidence to z ~ 10 candidates



The Frontier Fields will strongly constrain high-z galaxy evolution and reionization

I believe our biggest
current obstacles
(which are being overcome)
are detecting faint galaxies
and HST + Spitzer photometry,
not lensing uncertainties
nor cosmic variance






Thank you