



Hunting the First Galaxies with Gravitational Lensing

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ESA/AURA Astronomer**

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

Nov 20, 2014

Dan Coe - Kavli IPMU

Hubble has observed galaxy evolution over 13 billion years

Hubble Sequence

Elliptical



Abell S0740
Blakeslee

Spiral



M74
Chandar

Irregular,
Starburst

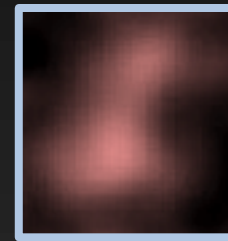


Antennae
Whitmore

Clump clusters, chains



in CANDELS
 $z = 2.05$
Wuyts12
3 Gyr



A1689-zD1
 $z \sim 7.8$
Bradley08
650 Myr

Single
clump?
 $r < \sim 100$ pc



in CLASH
MACS0647-JD
 $z \sim 10.8$
Coe13
420 Myr

time
←

all images from Hubble

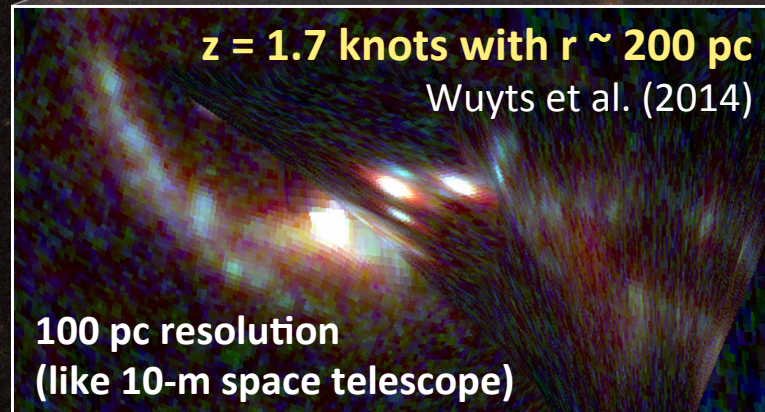
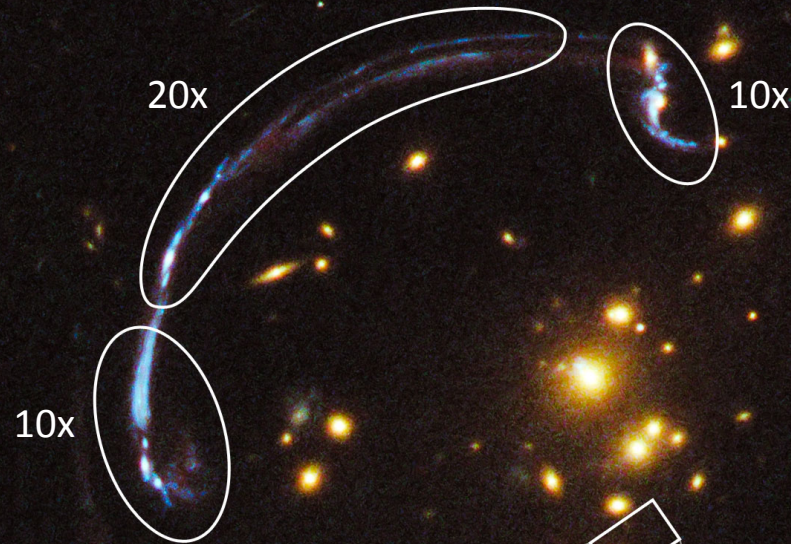
lensed galaxies

Gravitational lensing magnifies the distant universe

RCS2 032727-132623

HST WFC3: UVIIYJH

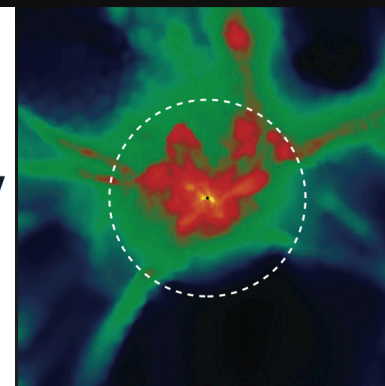
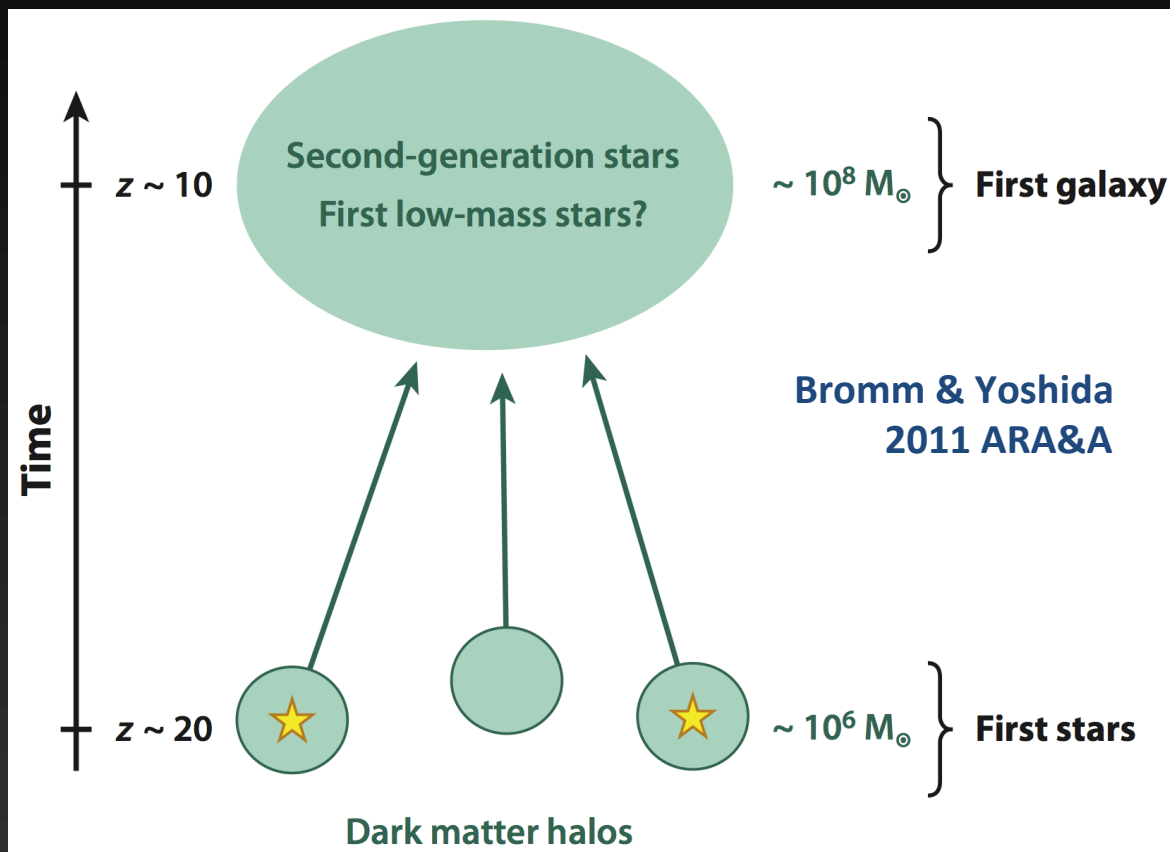
Sharon et al. (2012)



Nov 20, 2014

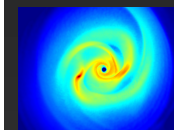
Frontier questions about galaxy evolution

- When did the first galaxies form? $z \sim 10$ (465 Myr)
– 30 (100 Myr)



Greif et al.
(2010)

Hubble:
 $z < 13$ (325 Myr)

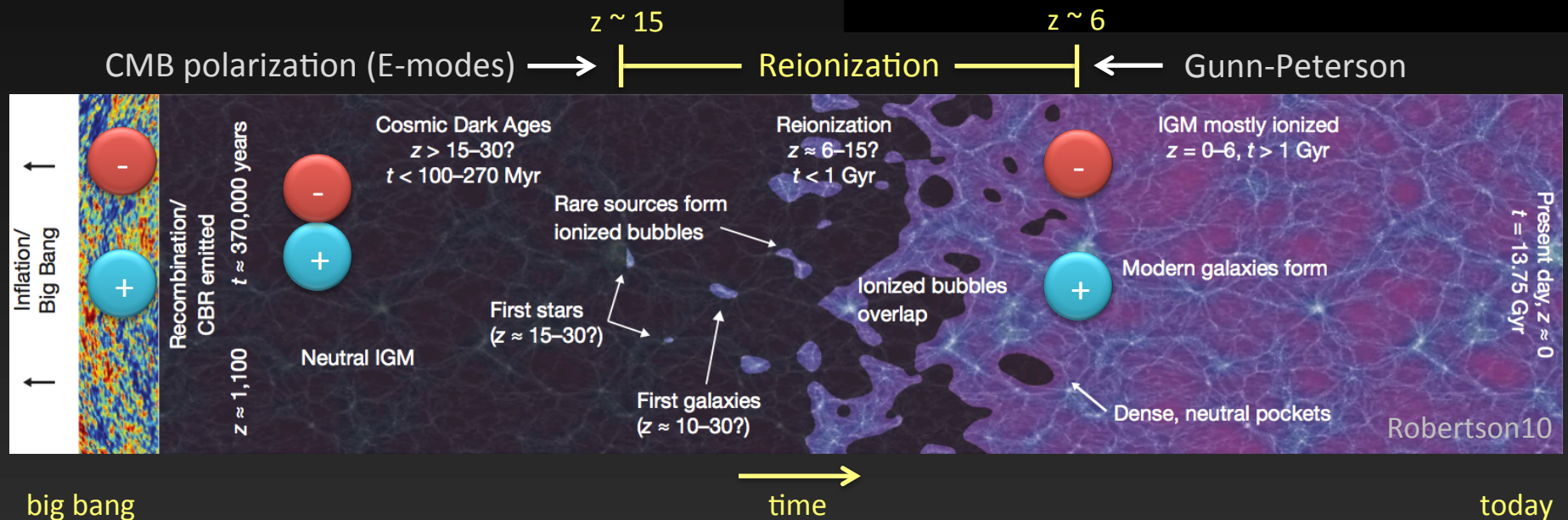


Clark et al.
(2011)

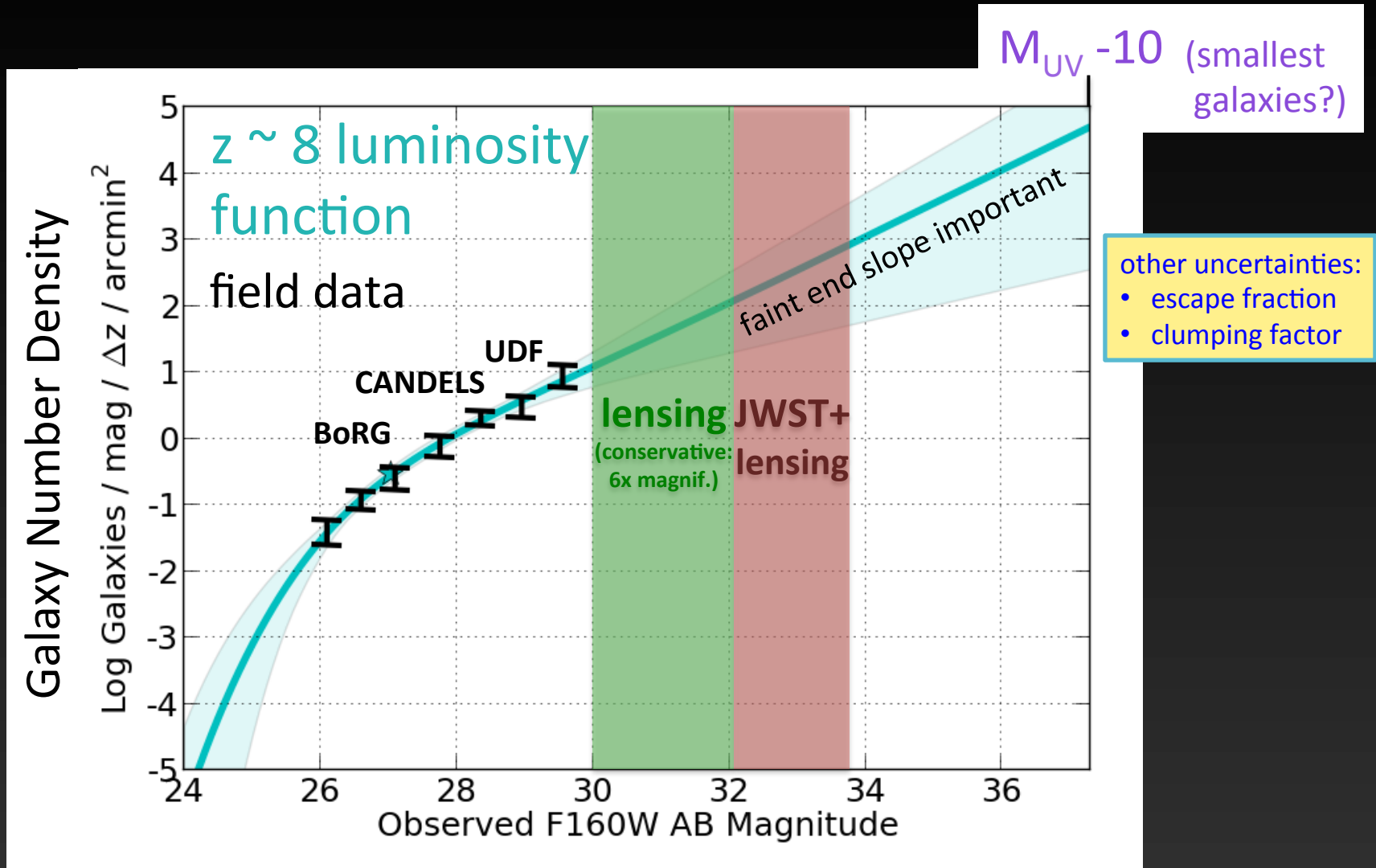
Frontier questions about galaxy evolution

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

We are observing galaxies during the epoch of reionization



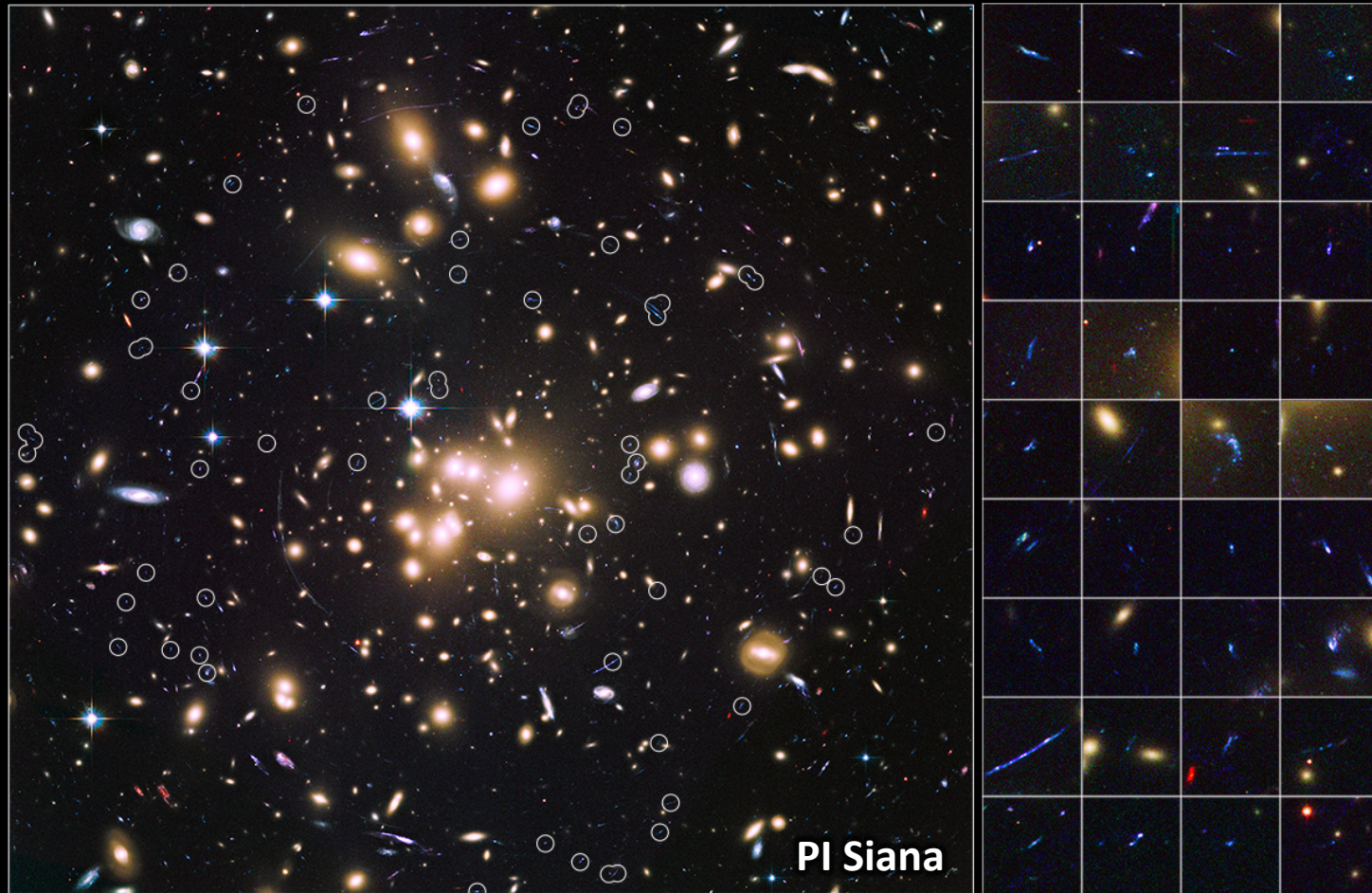
Large extrapolations required to estimate faint galaxy contribution to reionization



Deep (60 orbit) HST UVIS observations reveal many faint lensed $z \sim 2$ galaxies

Galaxy Cluster Abell 1689

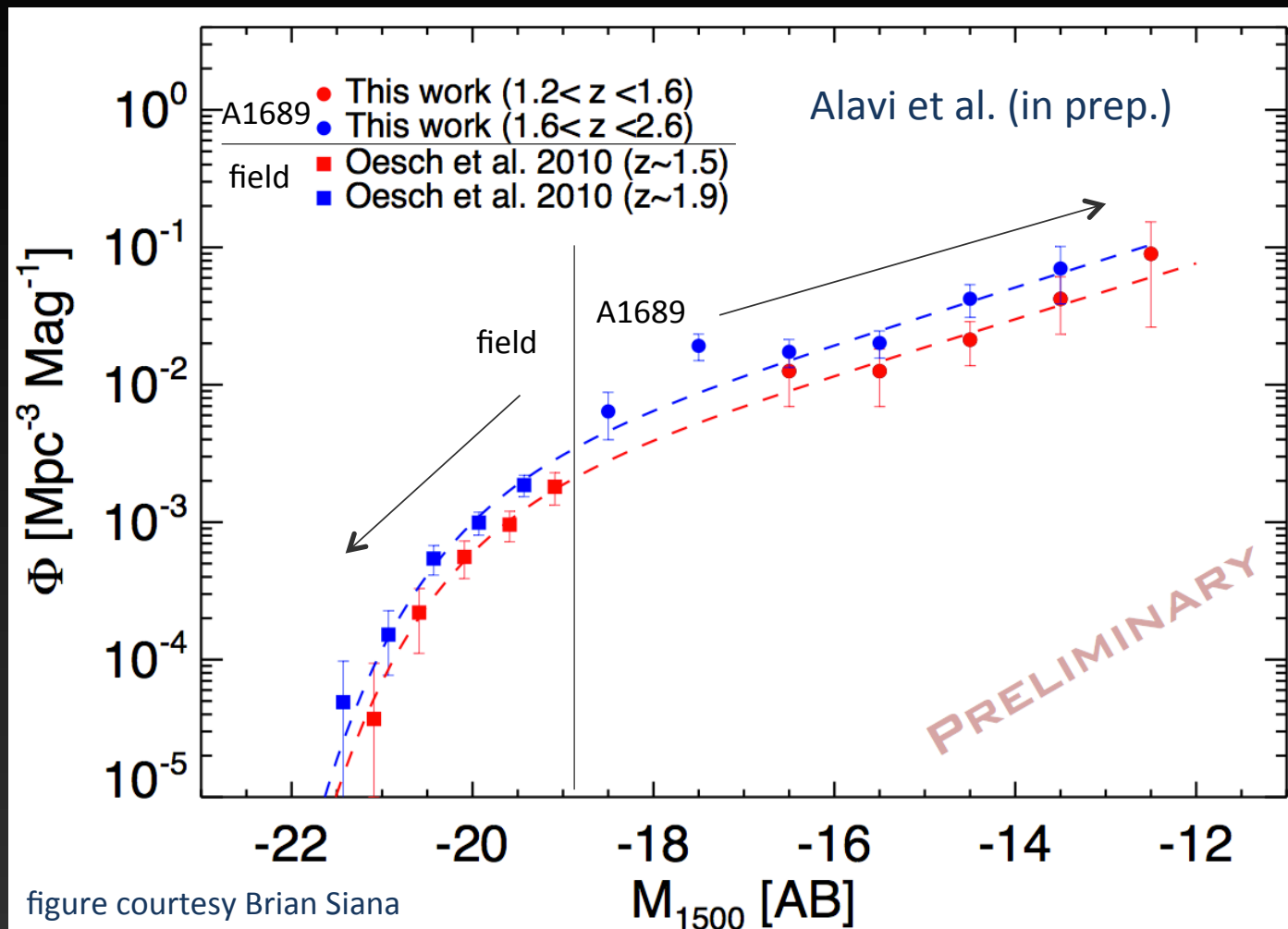
Hubble Space Telescope ■ ACS/WFC ■ WFC3/UVIS



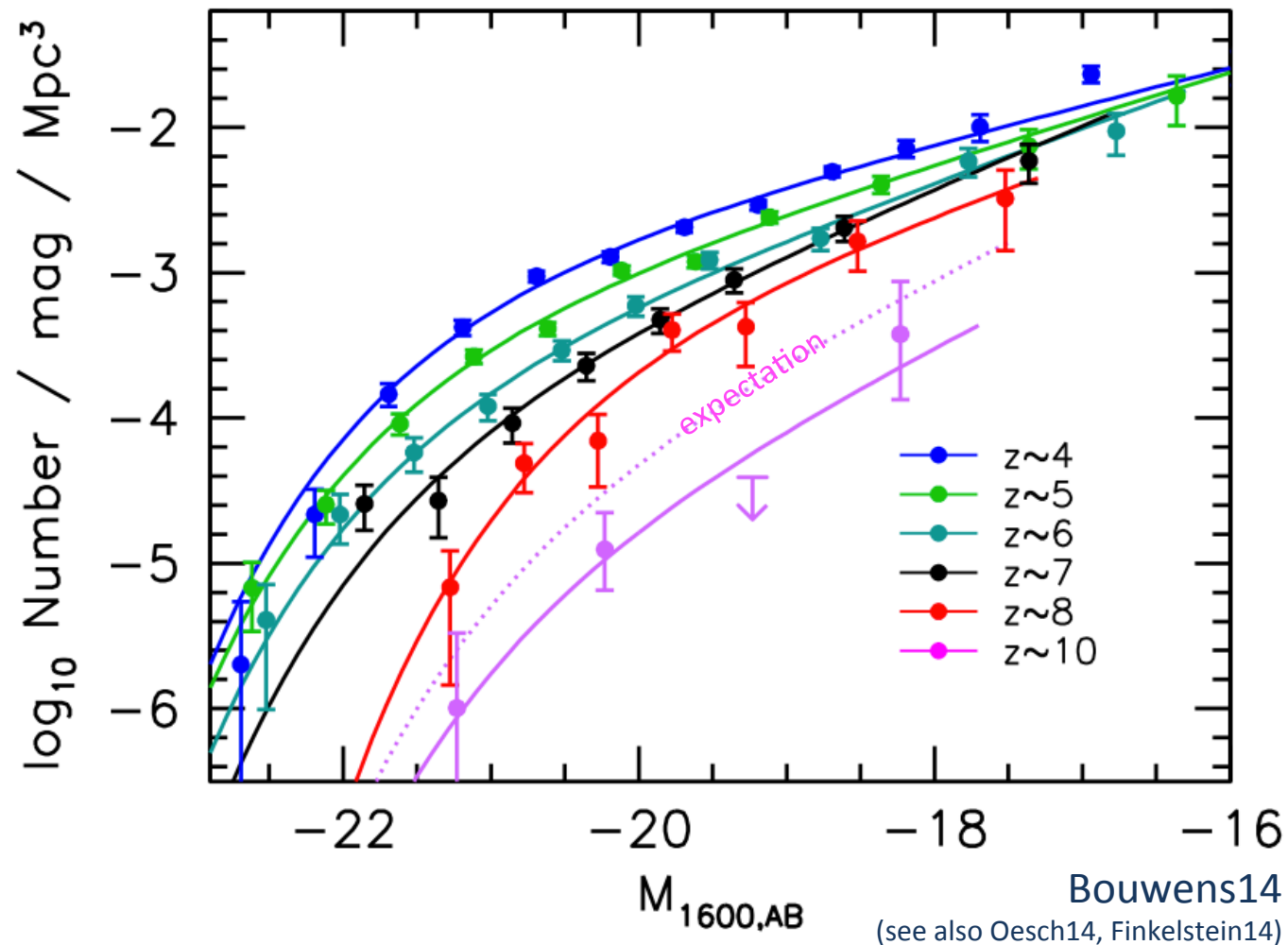
NASA and ESA

STScI-PRC14-07a

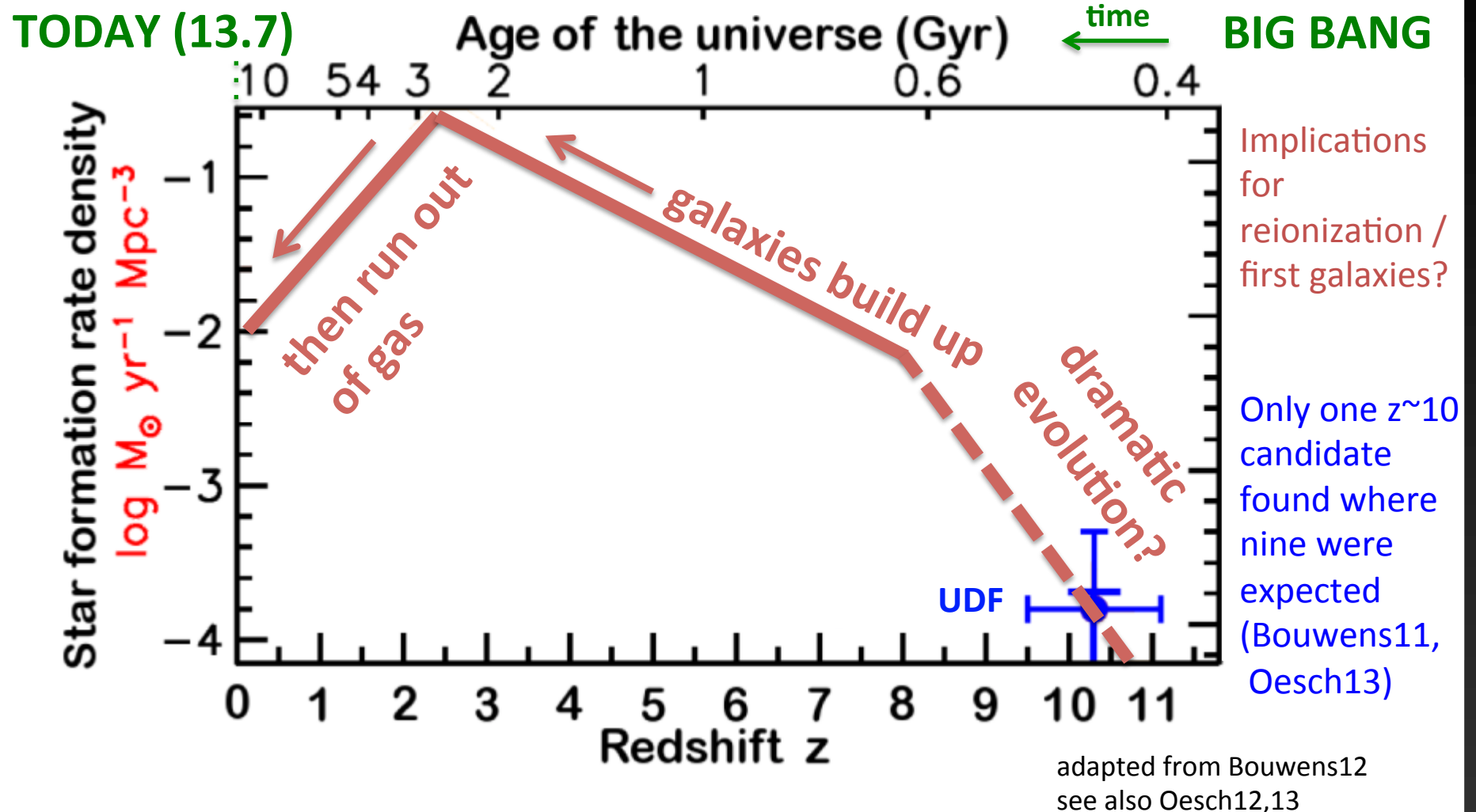
Lensing extends $z \sim 2$ luminosity function constraints to very faint magnitudes



Field luminosity functions are constrained out to $z \sim 8$



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





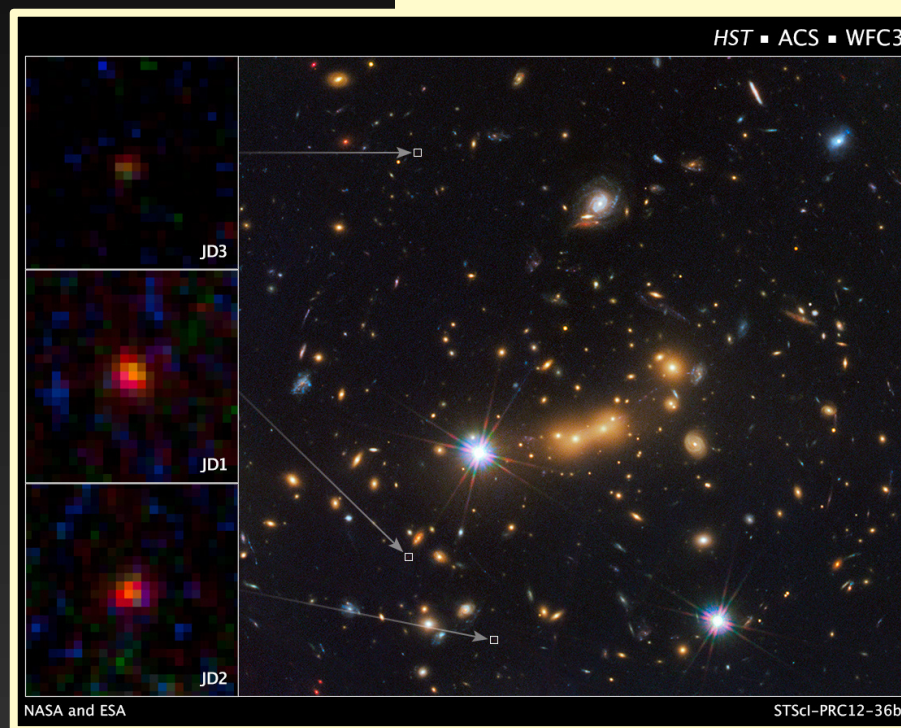
CLASH revealed two robust candidates in the first 500 Myr



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

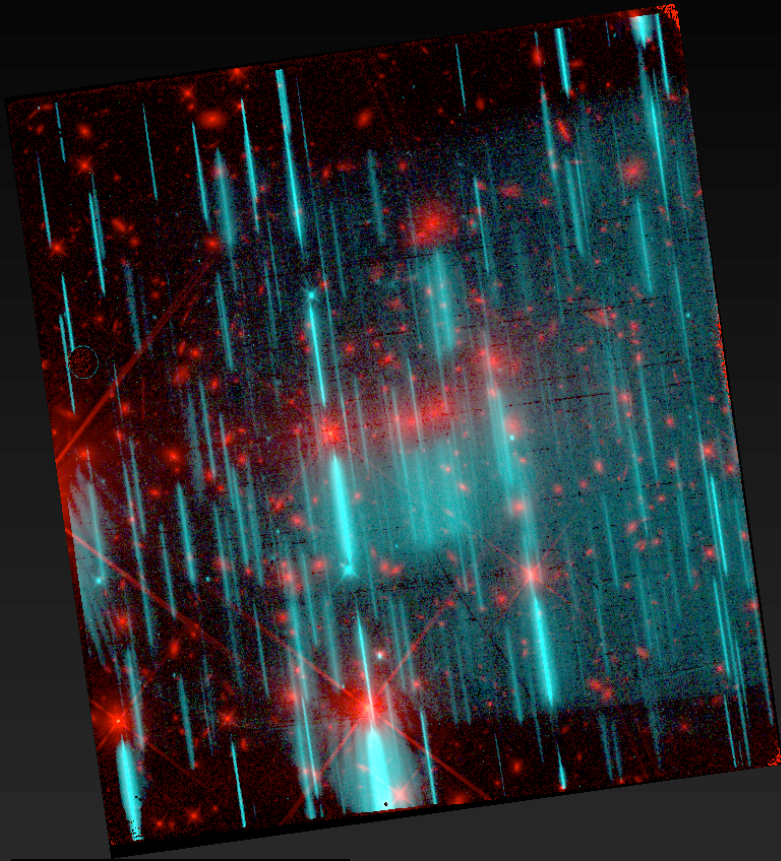
MACS0647-JD
 $z \sim 10.8$ (420 Myr)
 Dan Coe et al. (2013)
 ApJ 762, 32

in 2 / 5 “high-magnification” CLASH clusters



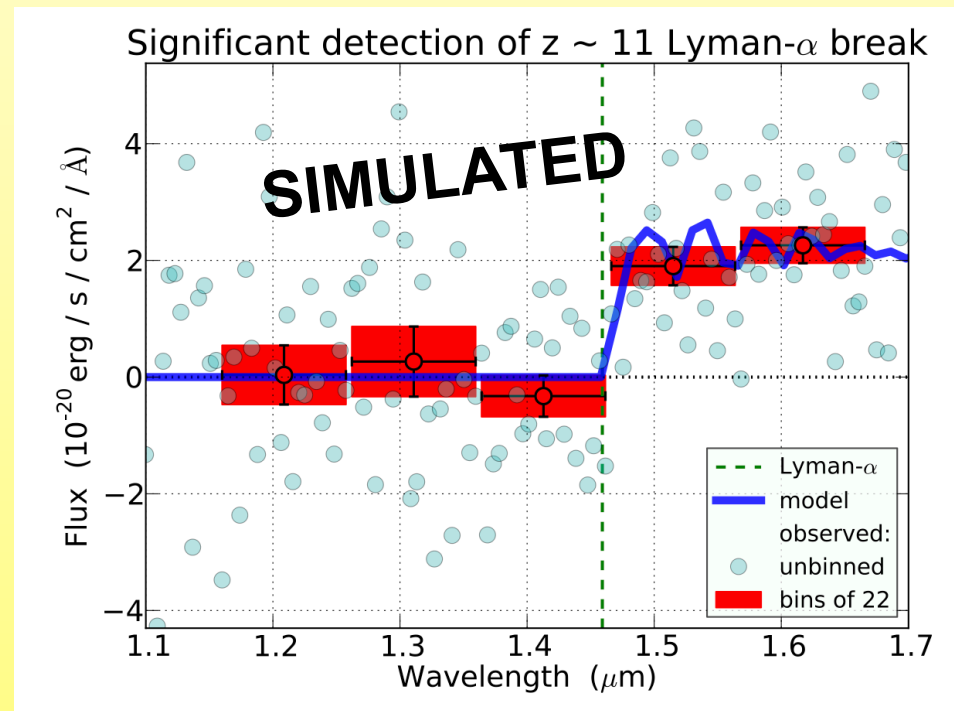
HST WFC3/IR grism z~11 confirmation expected

12 orbits G141 + F140W (PI Coe; 2/3 complete)



F140W image
G141 grism

Goal: Detect Lyman continuum break.
No prominent Lyman- α emission expected.

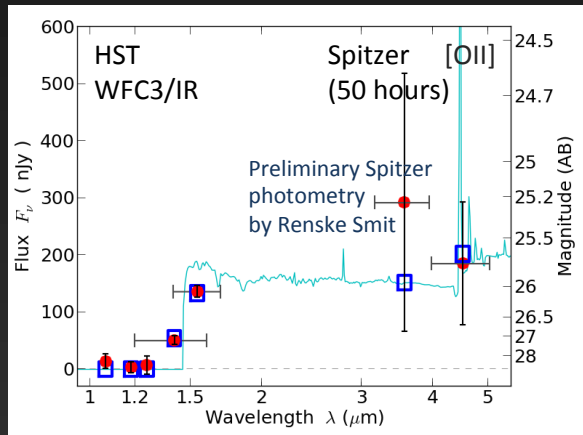


Deep Spitzer imaging (100 hours, PI Coe) to constrain $z \sim 11$ galaxy properties (age, stellar mass, UV slope)

first half of data
obtained and shown

3.6 μm

4.5 μm

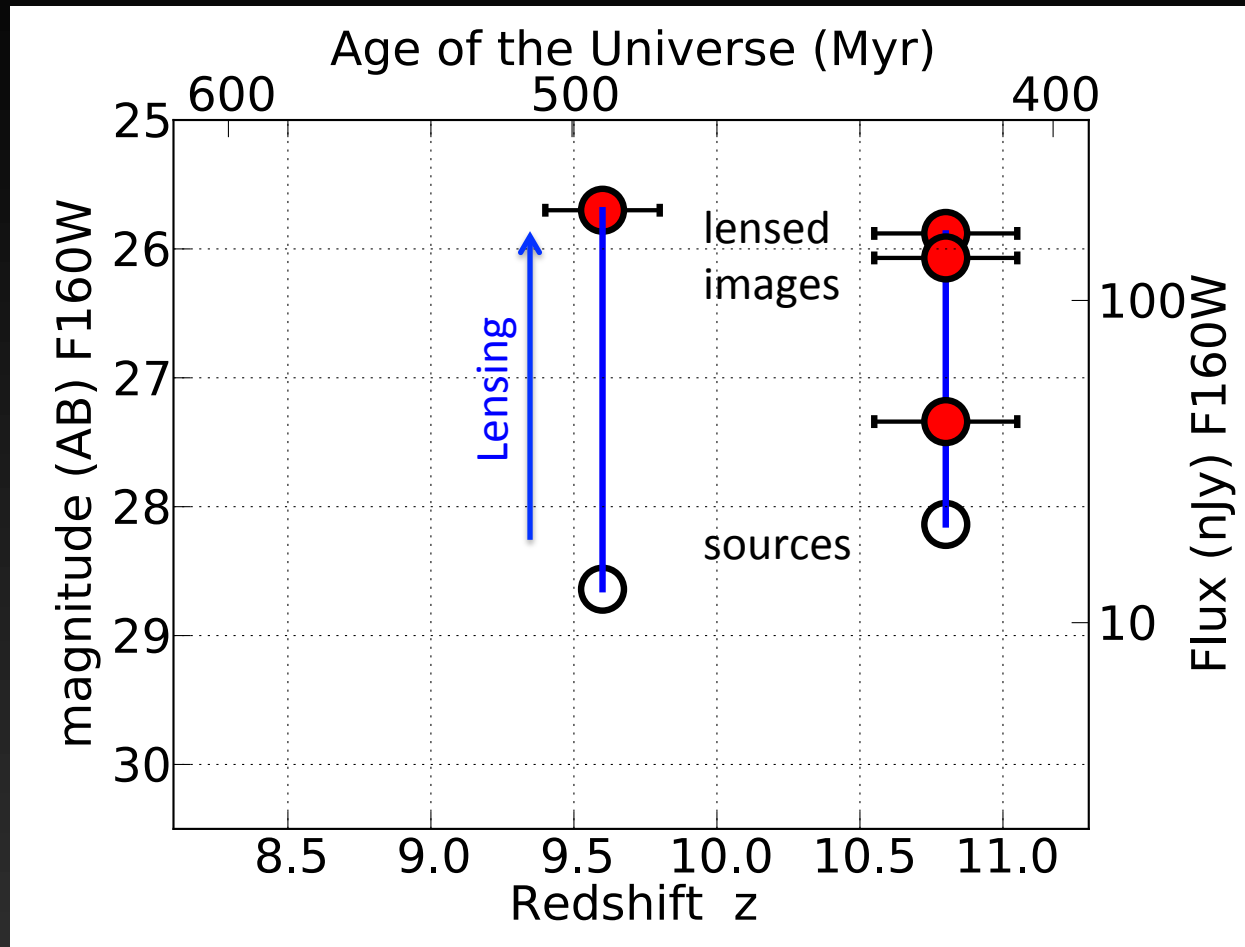


$z \sim 11$



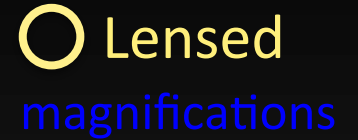
New deeper imaging
avoids stars,
mitigates artifacts

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



○ Lensed
magnifications

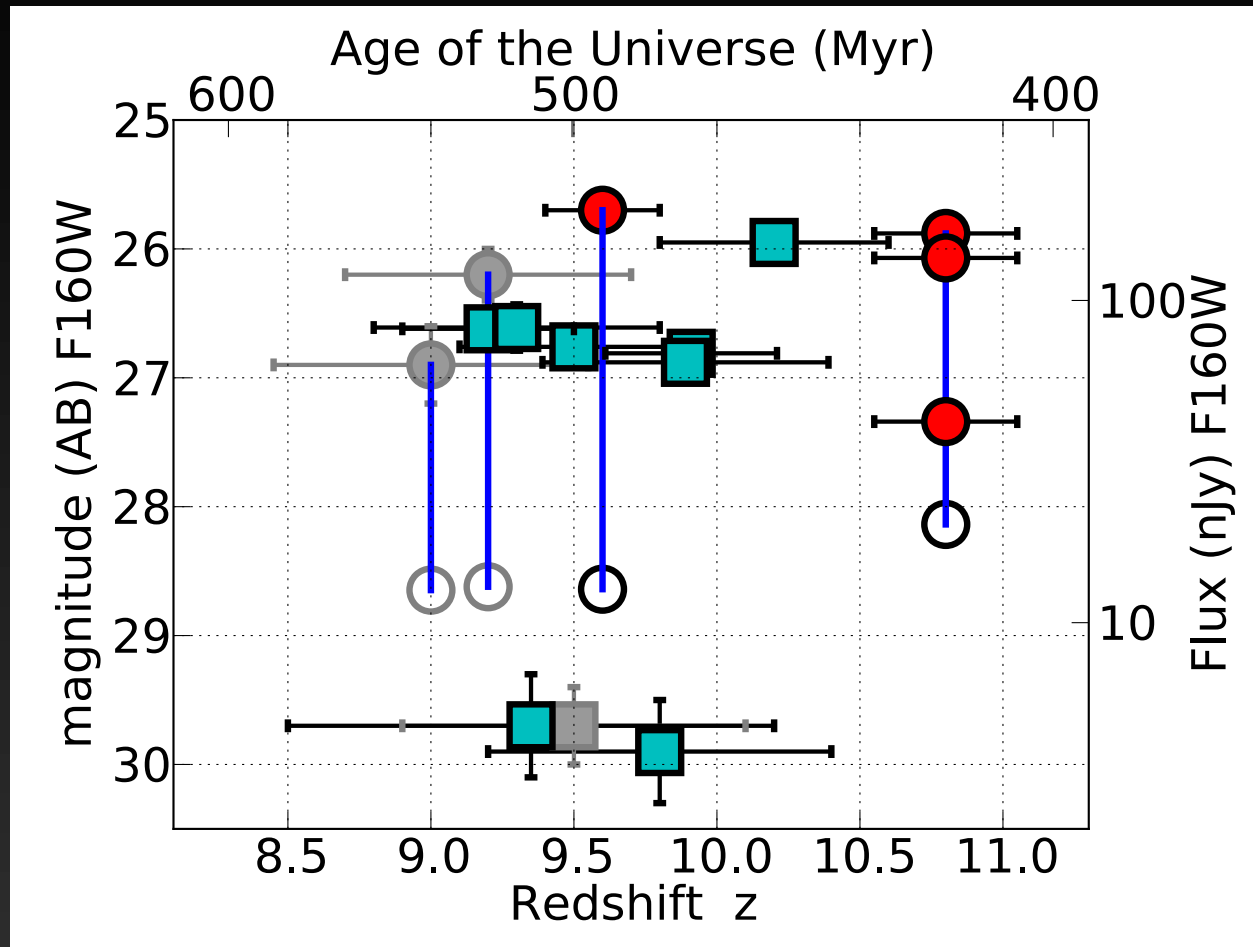
(Zheng12, Coe13)



Less secure

(Zheng12, Coe13,
Bouwens13)

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



Lensed
magnifications

Robust
Less secure
(Zheng12, Coe13, Bouwens13)

UDF **CANDELS**

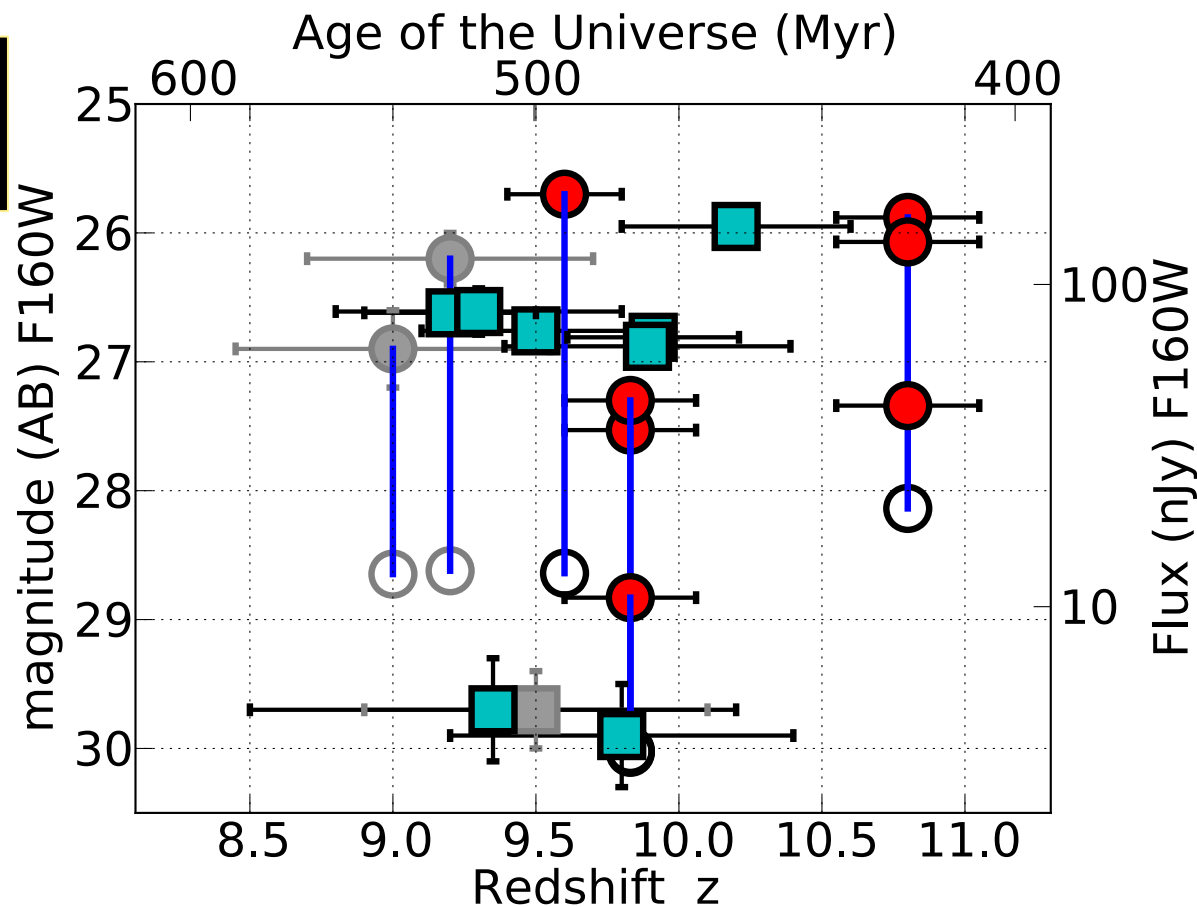
Field

Robust
Less secure
(Ellis13, Oesch13, Oesch14)

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

~14 $z > 9$
candidates

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



 Lensed
magnifications

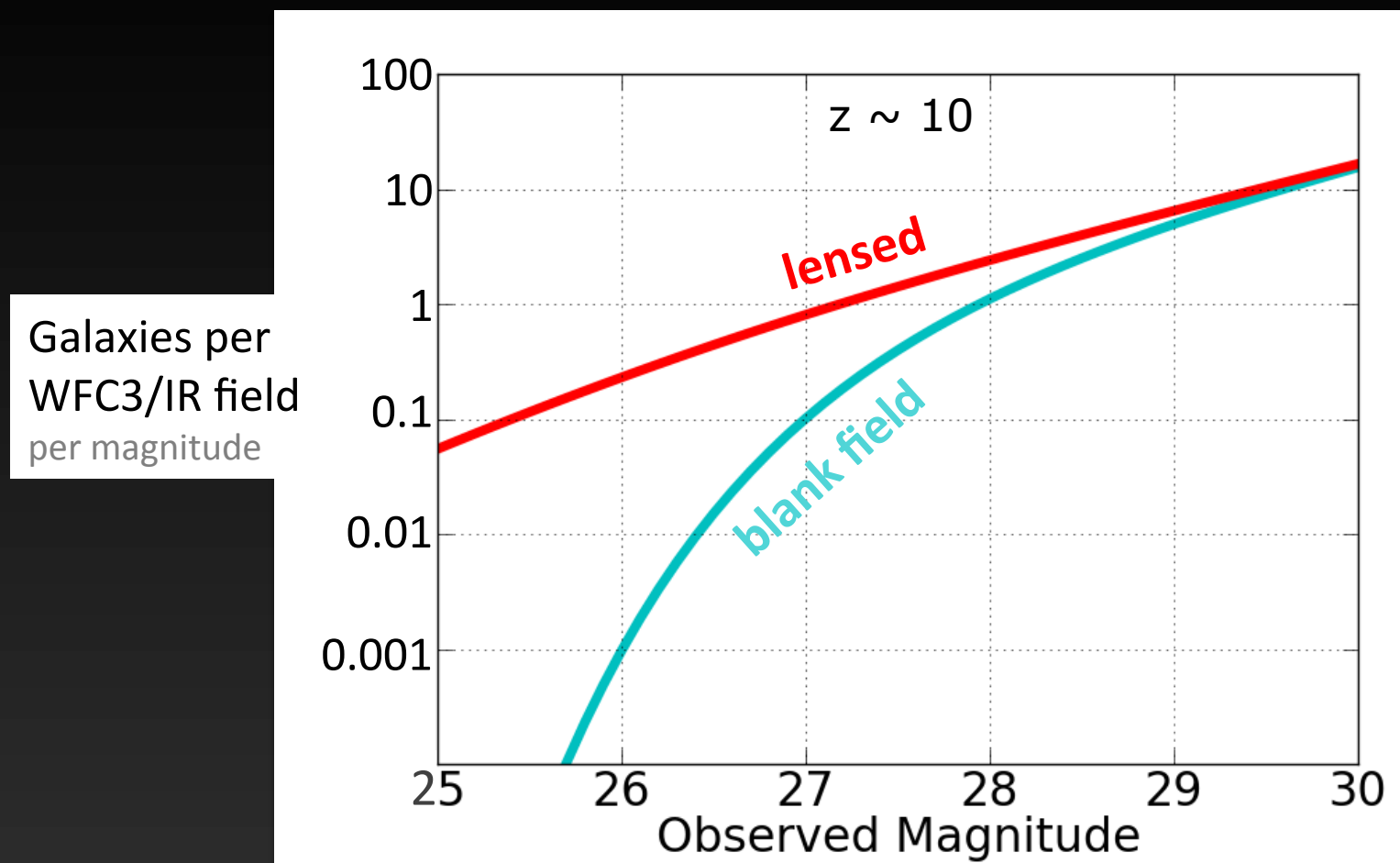
Robust
Less secure
(Zheng12, Coe13,
Bouwens13, Zitrin14)

UDF CANDELS

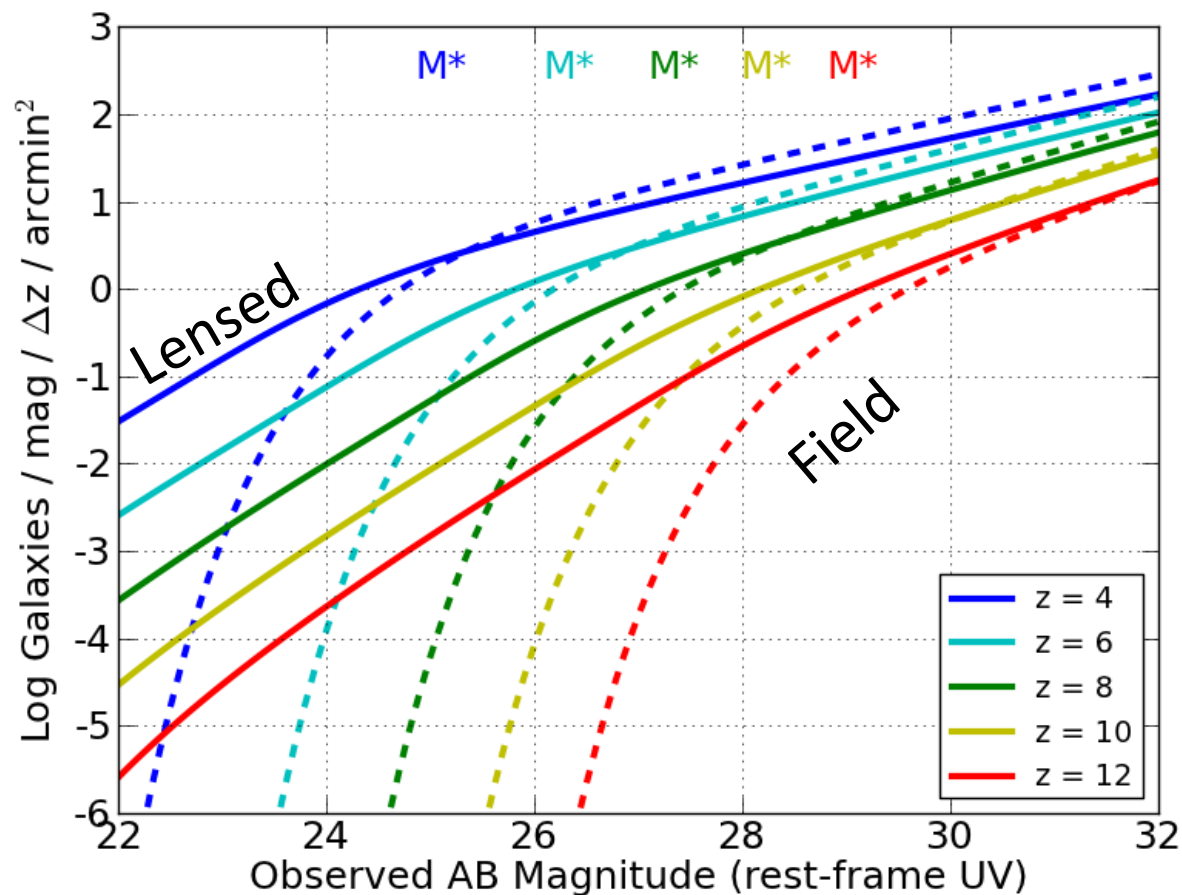
 Field

Robust
Less secure
(Ellis13, Oesch13,
Oesch14)

Cluster lensing enables more efficient discovery of the most distant galaxies



Cluster lensing wins at brighter magnitudes / higher redshifts

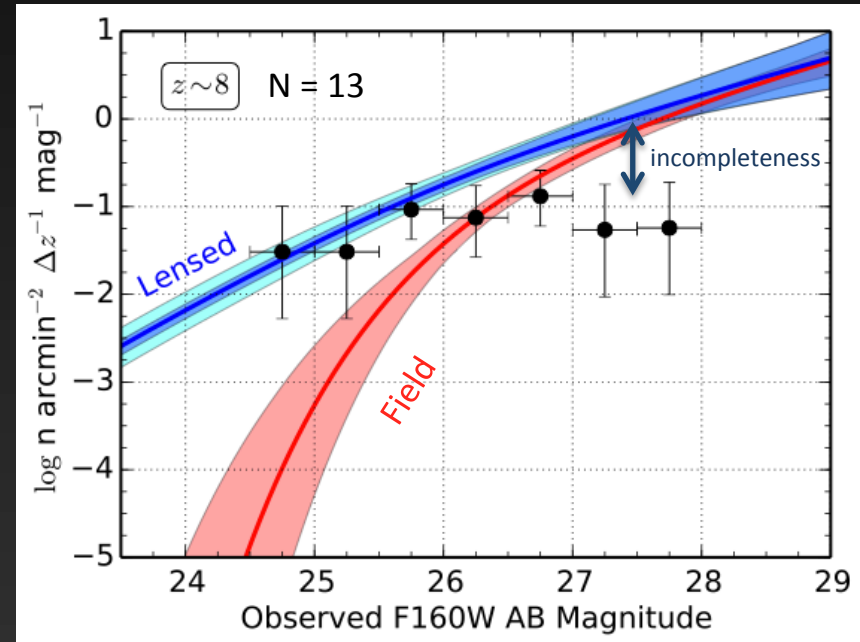
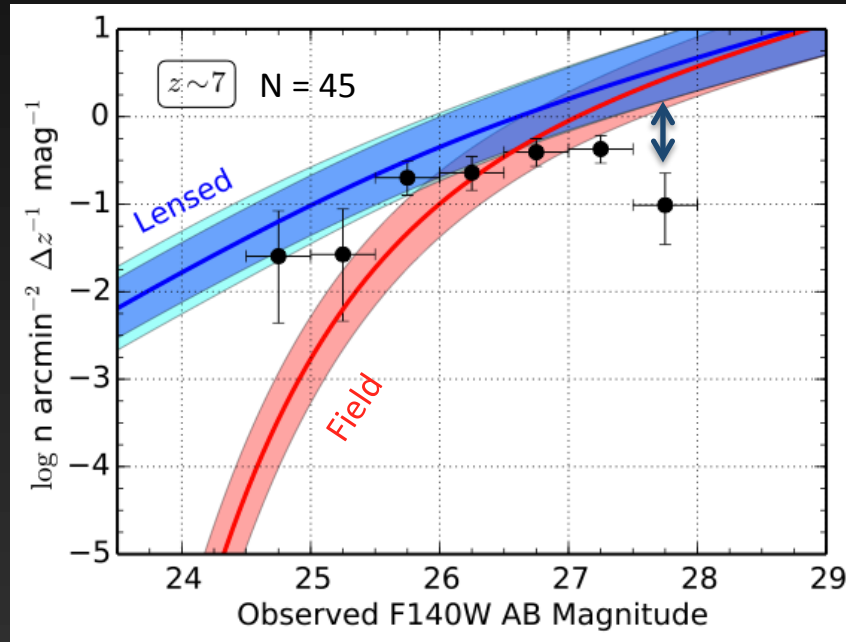
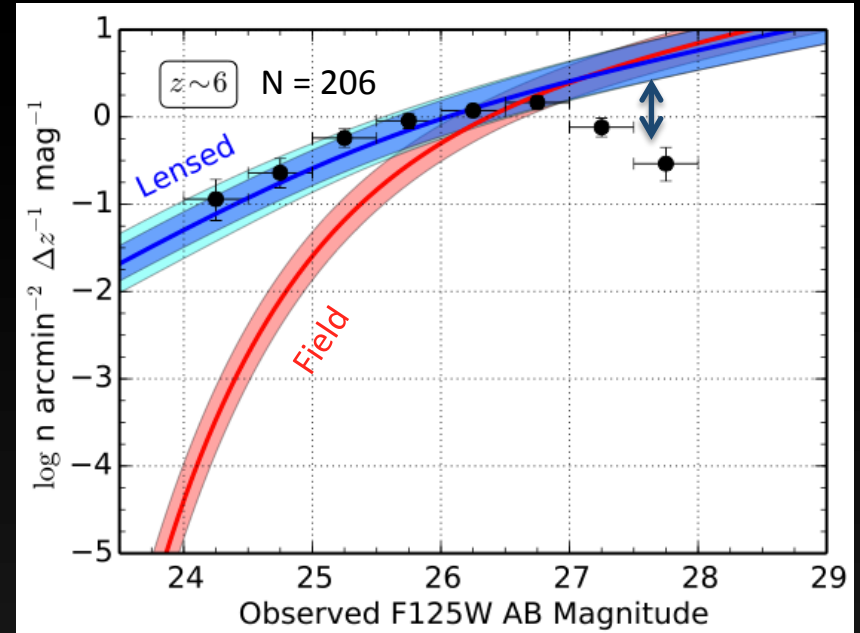


Bouwens12a luminosity function
evolving all 3 parameters



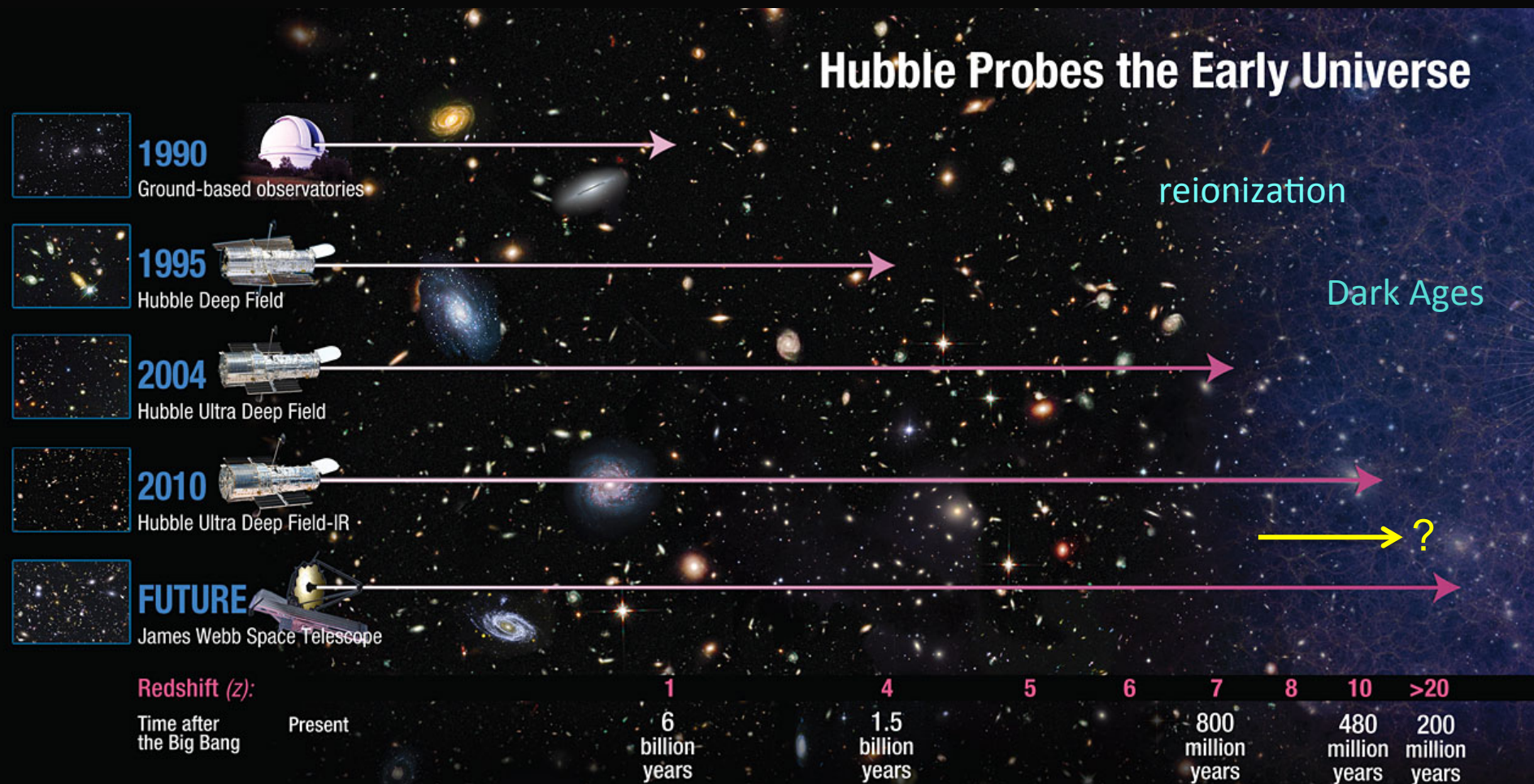
Lensed high-redshift galaxies discovered efficiently

Bradley et al. (2013): 18 / 25 CLASH clusters



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

-Matt Mountain
STScI director



Suggestions for a new Hubble Deep Fields Initiative were solicited from and deliberated over by members of the community

White paper recommendations included
deep imaging / spectroscopy
of “blank” / lensed fields

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

A Preview of JWST: Measuring Cosmic Evolution from $z \sim 8$ to $z \sim 11$ 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 $z \sim 10$ candidate, suggesting dramatic evolution in the <200 Myr between $z \sim 10$ 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 $z \sim 9 - 11$ candidates to date, more consistent with an evolving luminosity function ($dM^*/dz \sim 0.3$) as extrapolated from lower redshifts ($z \sim 4 - 8$) 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 $z \sim 10$ SFRD and galaxy formation models, providing one of the keys to understanding the source and epoch of reionization.

The buildup of stars from $z \sim 10 - 8$: CLASH observations to date have yielded one lensed candidate each at $z \sim 9.6$ (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 $z \sim 8$ luminosity function (Bradley12) extrapolated to higher redshifts assuming $dM^*/dz \sim 0.3$ (as observed between $z \sim 4 - 8$) and magnified through our lens models (cropped to the WFC3/IR FOVs and with foreground galaxies masked out). In the field, the single $z \sim 10$ candidate detected to date (Bouwens11) suggests a lower number count density by a factor of ~ 6 (Oesch12). The implication from this latter work is that SFRD increased by an order of magnitude over the ~ 200 Myr between $z \sim 10$ and 8, a greater increase than observed over the following ~ 800 Myr to $z \sim 4$ (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 $z \sim 9 - 11$: 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 $z \sim 9 - 11$ (Fig. 2). This is conservative with respect to the extrapolation from $z \sim 4 - 8$ (which suggests ~ 20) but optimistic based on the single field $z \sim 10$ 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 $z \sim 10$ for the first time and providing an important new test for galaxy formation models.

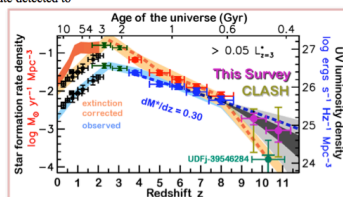


Fig. 1 – This survey will provide the first robust constraints on the $z \sim 10$ SFRD (magenta and dark gray), significantly reducing the current uncertainties from CLASH (yellow and light gray) and the field (green). SFRD constraints from lower redshifts with and without correction for dust extinction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

HDFI science working group

James Bullock (UC Irvine) – chair
Mark Dickinson (NOAO)

Steven Finkelstein (UT Austin)
Adriano Fontana (INAF, Rome)
Ann Hornschemeier (Goddard)
Jennifer Lotz (STScI)

Priya Natarajan (Yale)
Alexandra Pope (U Mass)
Brant Robertson (Arizona)
Brian Siana (UC Riverside)
Jason Tumlinson (STScI)
Michael Wood-Vasey (U Pitt)



PI Jennifer Lotz

<http://www.stsci.edu/hst/campaigns/frontier-fields/>



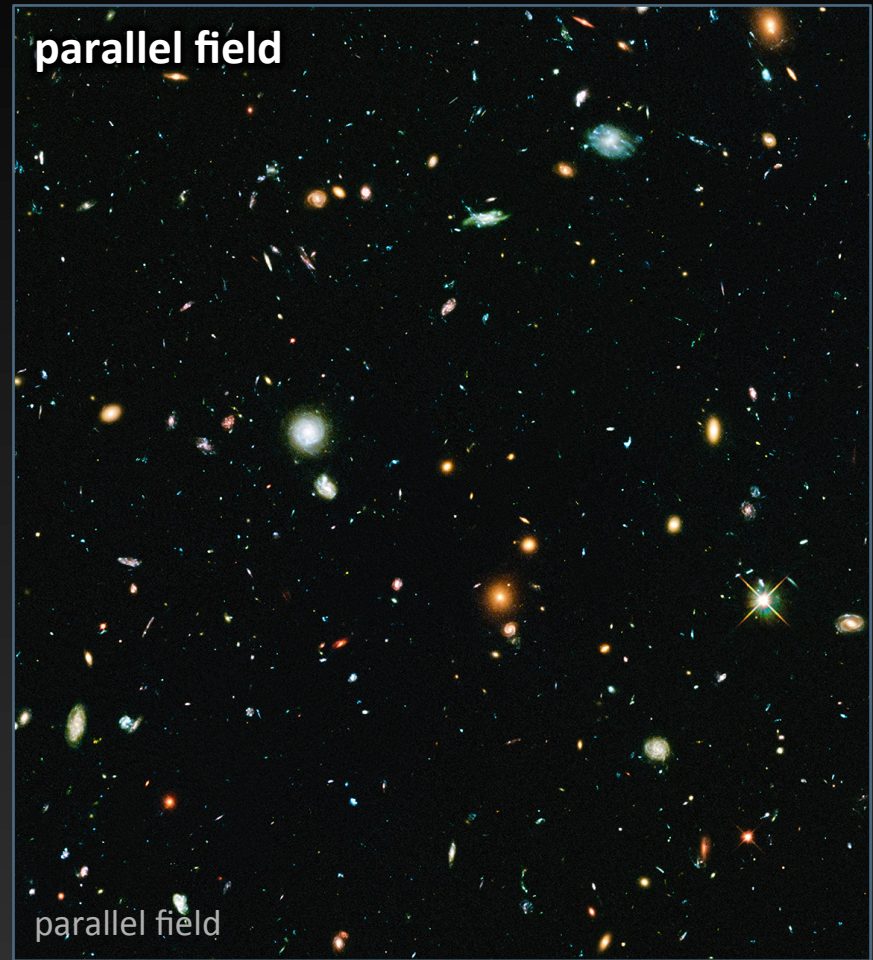
Up to 840 Hubble orbits
+ 1000 Spitzer hours
directors' discretionary time

Abell 2744



Abell 2744

parallel field



parallel field

6 clusters + 6 “blank” parallel fields being observed over 3 years

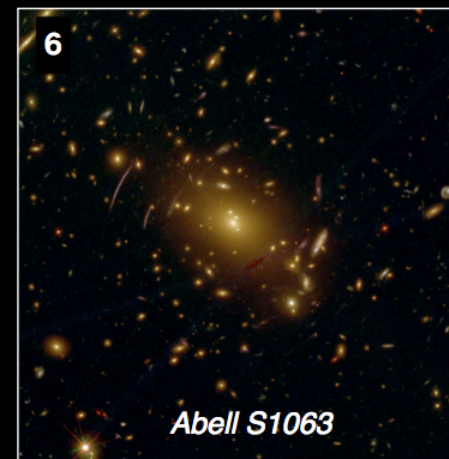
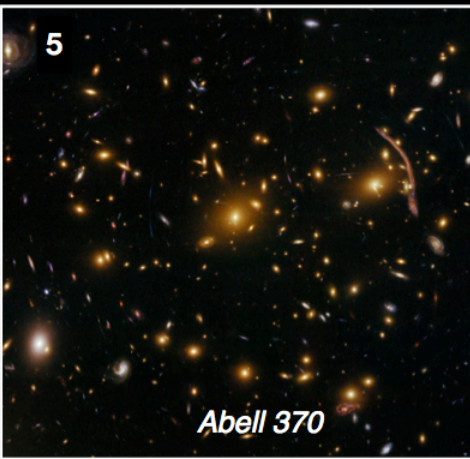
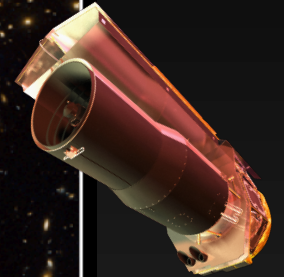
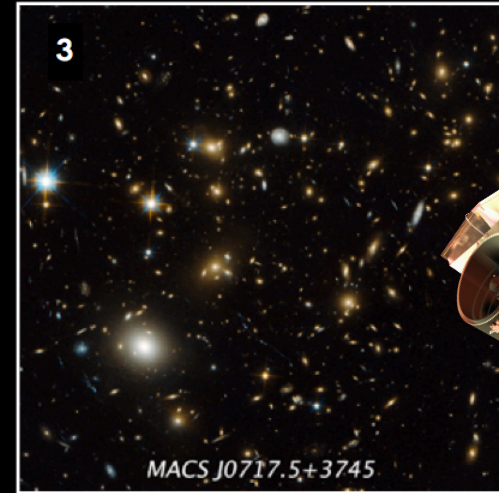
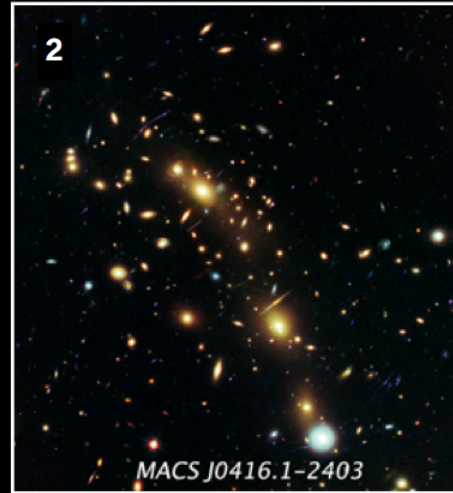
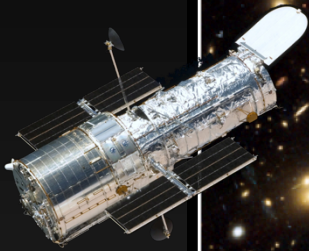
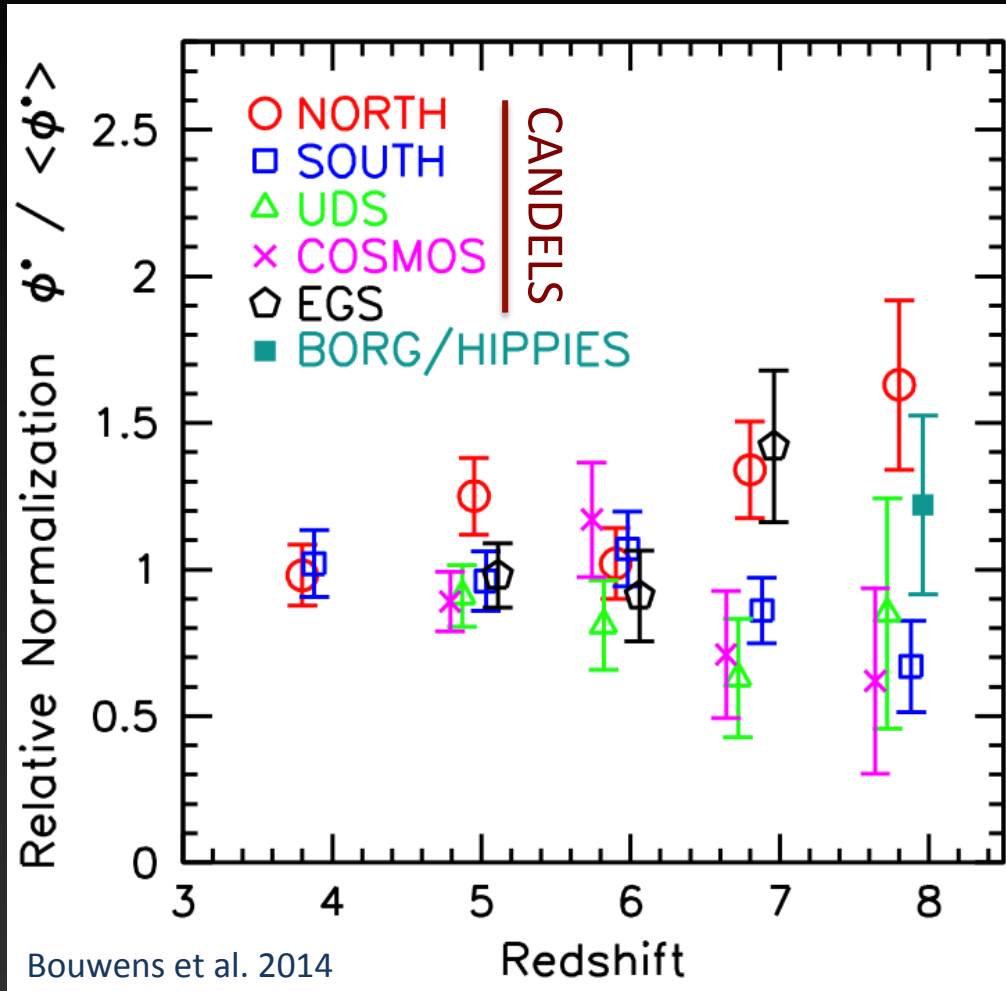
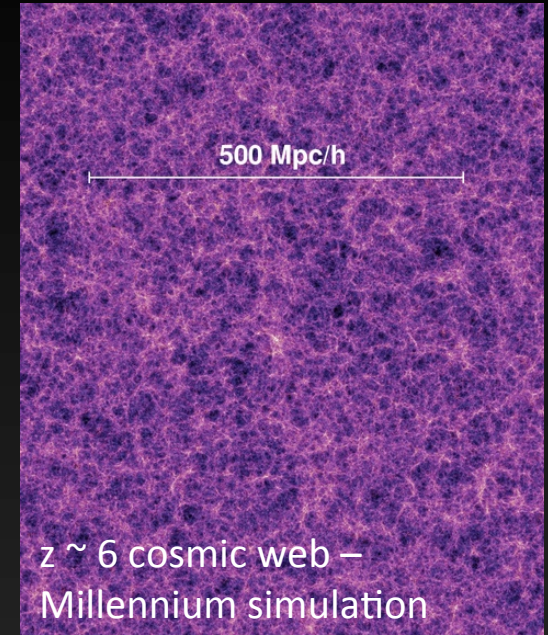


figure courtesy
Jennifer Lotz

The need for 6 sightlines: Cosmic Variance



factor
of 3
(+/- 50%)

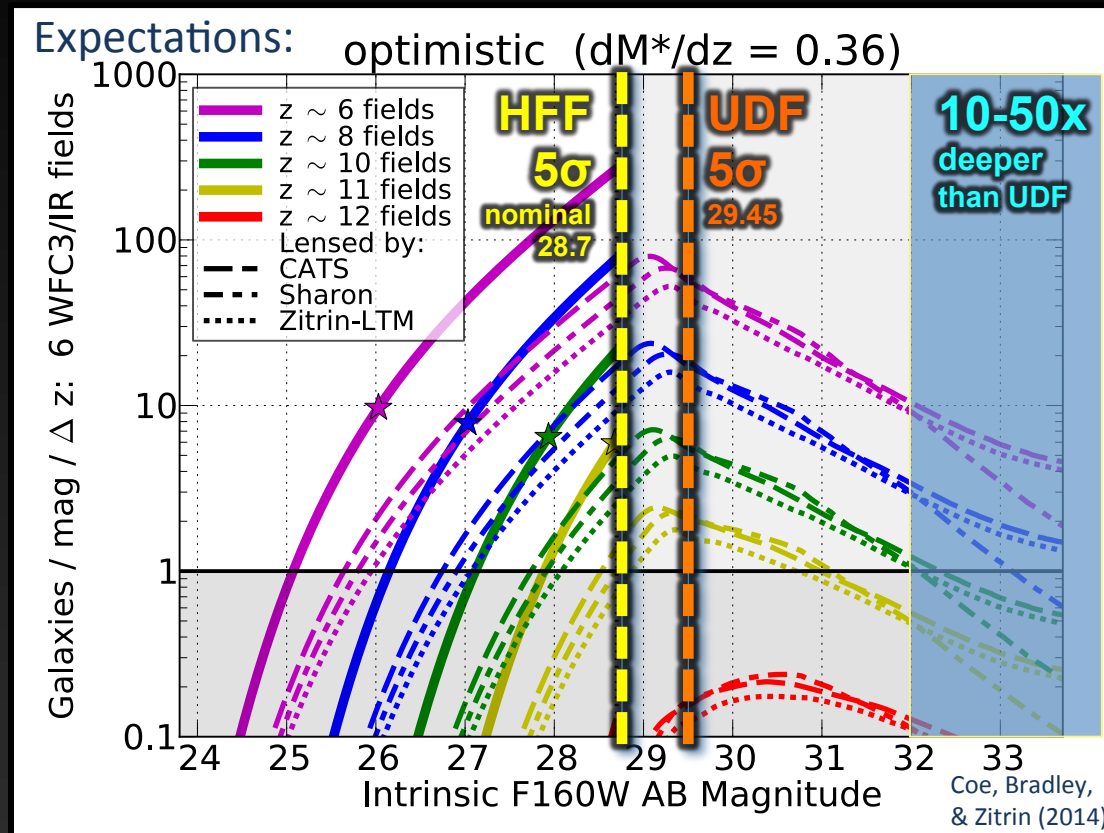


see also Robertson14
for lensing effect on cosmic variance

Recent large Hubble programs observing galaxy evolution with complementary strategies

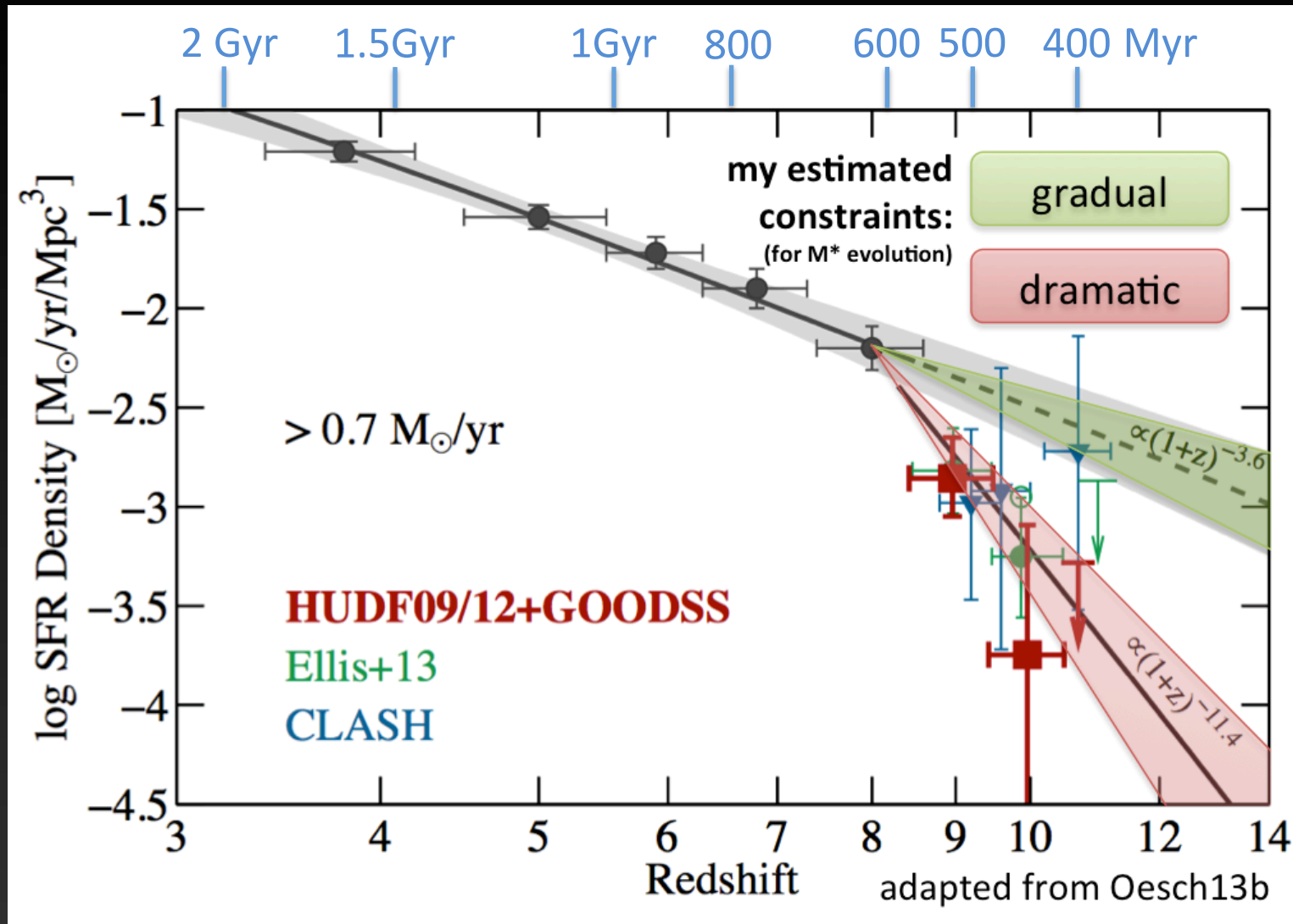
	“Blank” Fields	Gravitational Lensing
“shallow” surveys (AB magnitude 26-27)	CANDELS, BoRG, HIPPIES	
deep fields (AB magnitude 29-30)	Ultra Deep Field, 	

The lensed Frontier Fields are yielding the faintest galaxies yet observed



Lens models
yield
consistent
predictions

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



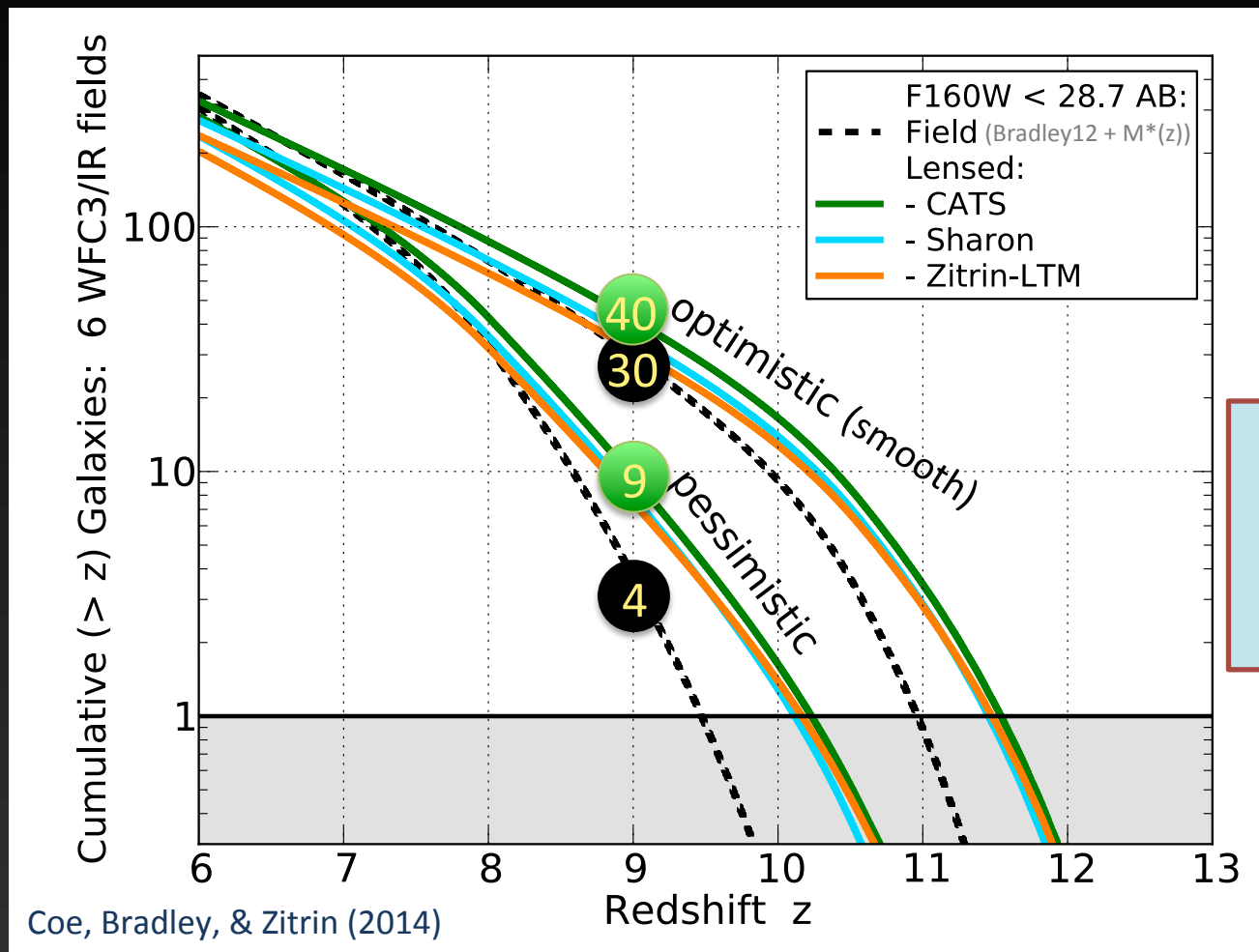
Full FF:
6 lensed +
6 blank
fields:

~70 $z > 9$
galaxies

(F160W < 28.7)

~13 $z > 9$
galaxies

We predict up to ~ 70 $z > 9$ galaxies
in the Frontier Fields (6 per field)
not accounting for incompleteness



Lens models
yield
consistent
predictions

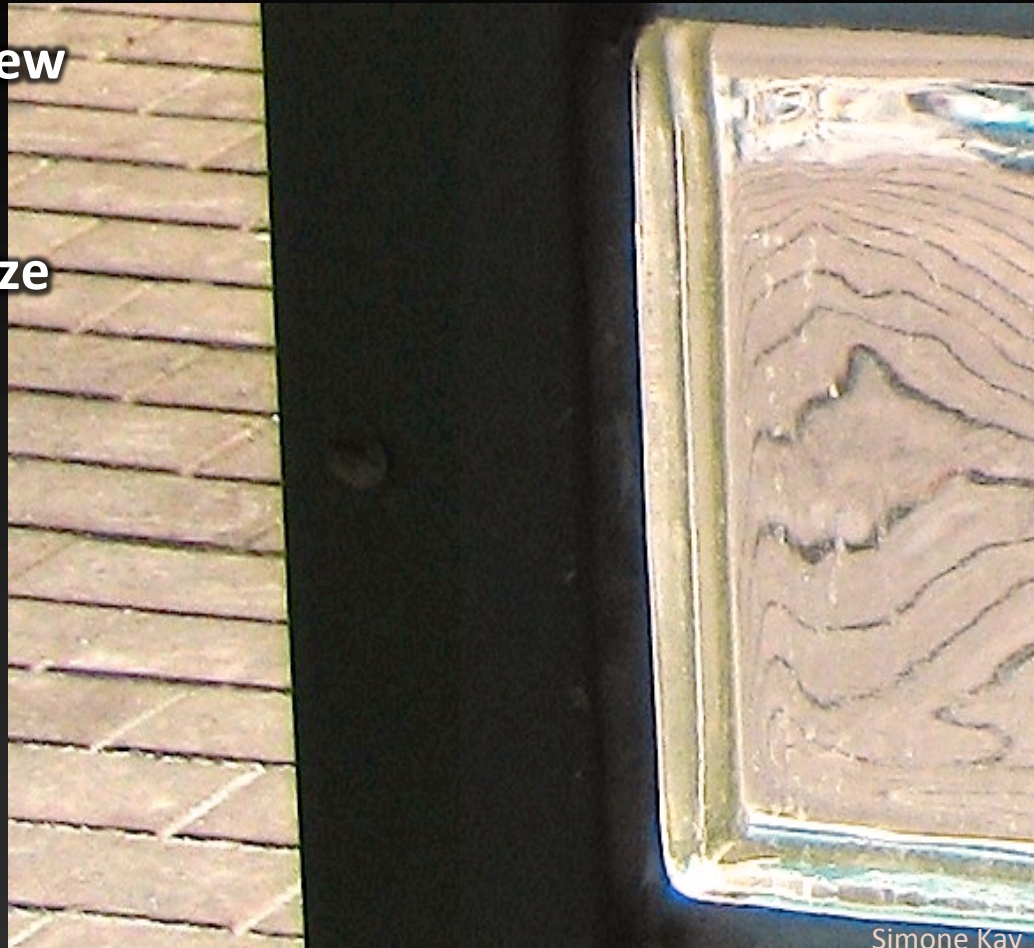
To lens or not to lens?

“Blank” Field

Lensed

Unobstructed view

- luminosities more certain
- easier to analyze (lensing expertise not required)
- no cluster “in the way”



Simone Kay

Magnified:

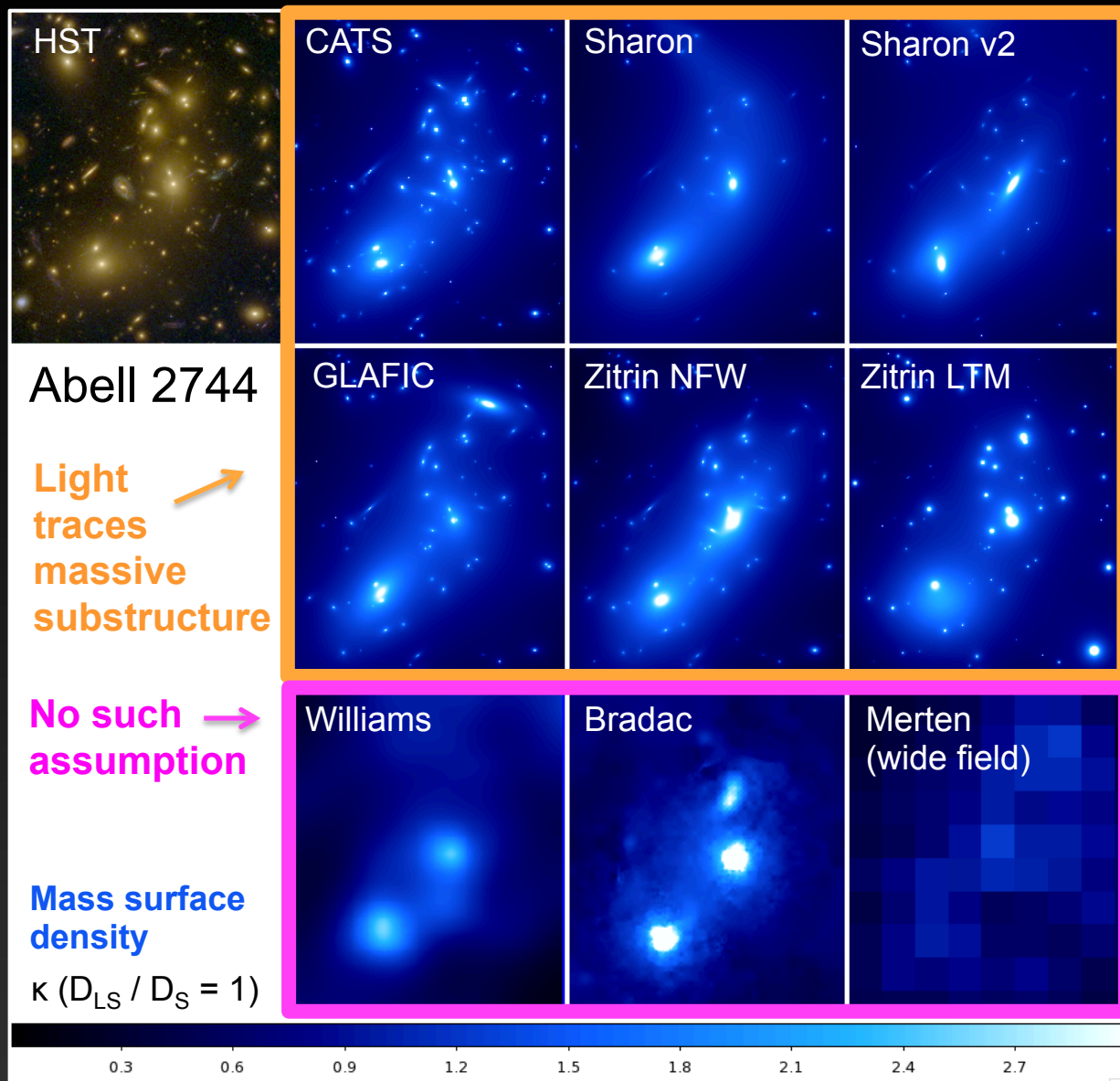
- More efficient bright detections
- Intrinsically fainter sources
- Higher resolution

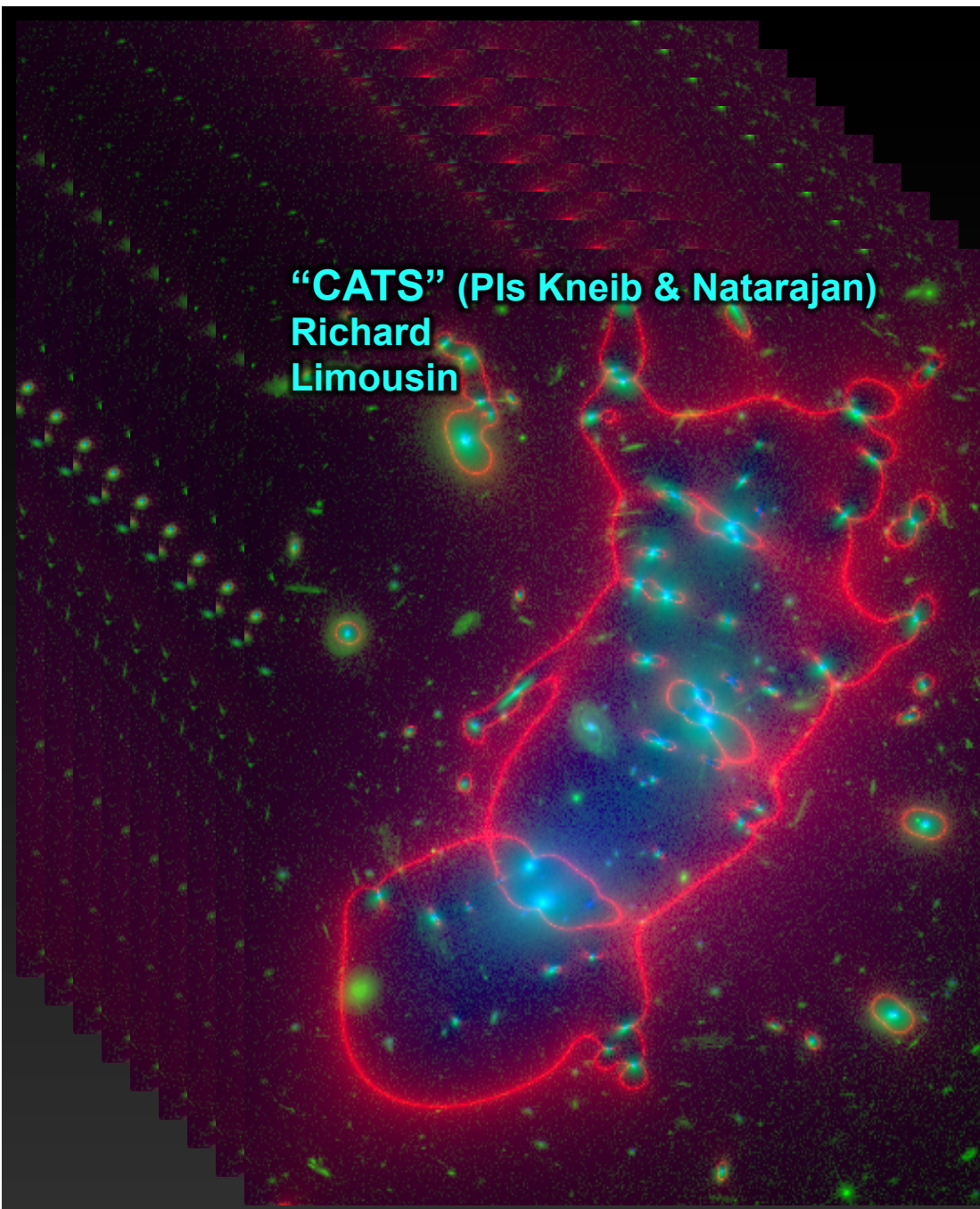


Lens models solicited and available for all Frontier Fields clusters

New submissions
are welcome

Available via MAST at:
[http://archive.stsci.edu/
prepds/frontier/lensmodels/](http://archive.stsci.edu/prepds/frontier/lensmodels/)





“CATS” (PIs Kneib & Natarajan)
Richard
Limousin

**Each team
submitted
~100 models
per cluster,
enabling
uncertainty
estimates**

Abell 2744

red = magnification for a
lensed galaxy at $z = 9$

green = HST

blue = mass

Interactive model magnification web tool

Hubble Frontier Fields lens model magnification estimates

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

Calculated at your input redshift(s) based on the mass and shear maps submitted by each team (see [lensing primer](#)). (Not interpolated / extrapolated from the magnification maps pre-calculated at $z = 1, 2, 4, 9$ available for download.) [Lens model main page](#)

☒ Single lensed galaxy:

RA:

Dec:

$z =$

observed radius (arcseconds):

☐ 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:

(* = Based in part on Frontier Fields imaging. All models are "version 1" unless otherwise noted.)

[Models: \(availability\)](#) % confidence, calculated from a range of models provided by each group
[\(README\)](#) ☐ show all results from each range of models, yielding likelihood distributions

☒ CATS	with uncertainties ☒
☒ CATS (version 2)*	with uncertainties ☒
☒ Sharon	with uncertainties ☒
☒ Sharon (version 2)	with uncertainties ☒
☒ Zitrin-NFW	with uncertainties ☒
☒ Zitrin-LTM	with uncertainties ☒
☒ Zitrin-LTM-Gauss	with uncertainties ☒
☒ GLAFIC*	with uncertainties ☒
☒ Williams	with uncertainties ☒
☒ Williams (version 2)*	with uncertainties ☒
☒ Bradac	with uncertainties ☒
☒ Merten	with uncertainties ☒

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

Input
RA, Dec, redshift
of lensed galaxies

archive.stsci.edu/prepare/frontier/lensmodels/webtool/output_000879_JD1C.html

Hubble Frontier Fields lens model magnification estimates

Output saved to [output_000879_JD1C.html](#)

Lensing cluster: Abell 2744 ($z = 0.308$)

Lensed source ($z = 9.8$):
RA, Dec = (00:14:18.607, -30:24:31.36) = (3.57753, -30.40871)
observed radius = 0.0 arcseconds

Output
Magnification estimates
with uncertainties

CATS	2.95 best;	$2.99^{+0.06}_{-0.05}$	[2.93, 3.05]	median and 68.3% confidence range
CATSv2				
Sharon	2.81 best;	$2.70^{+0.20}_{-0.11}$	[2.60, 2.90]	median and 68.3% confidence range
Sharonv2	2.92 best;	$2.86^{+0.16}_{-0.08}$	[2.78, 3.02]	median and 68.3% confidence range
Zitrin-NFW	2.95 best;	$3.65^{+1.13}_{-0.76}$	[2.89, 4.78]	median and 68.3% confidence range
Zitrin-LTM	37.07 best;	$5.41^{+4.60}_{-1.81}$	[3.60, 10.01]	median and 68.3% confidence range
Zitrin-LTM-Gauss				
GLAFIC	3.08 best;	$3.02^{+0.17}_{-0.18}$	[2.84, 3.18]	median and 68.3% confidence range
Williams	1.48 best;	$1.52^{+0.17}_{-0.19}$	[1.33, 1.69]	median and 68.3% confidence range
Williamsv2				
Bradac	4.59 best;	$3.45^{+0.37}_{-0.41}$	[3.04, 3.82]	median and 68.3% confidence range
Merten	2.76 best;	$7.76^{+14.29}_{-3.03}$	[4.74, 22.05]	median and 68.3% confidence range

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

Full uncertainties

Luminosity:

- Mass
- Star formation rate

Size (radius)

Reduced uncertainties

(integrated quantities)

Number counts:

- Luminosity function

Lensed Volume:

- Star formation rate
cosmic density

No added uncertainties

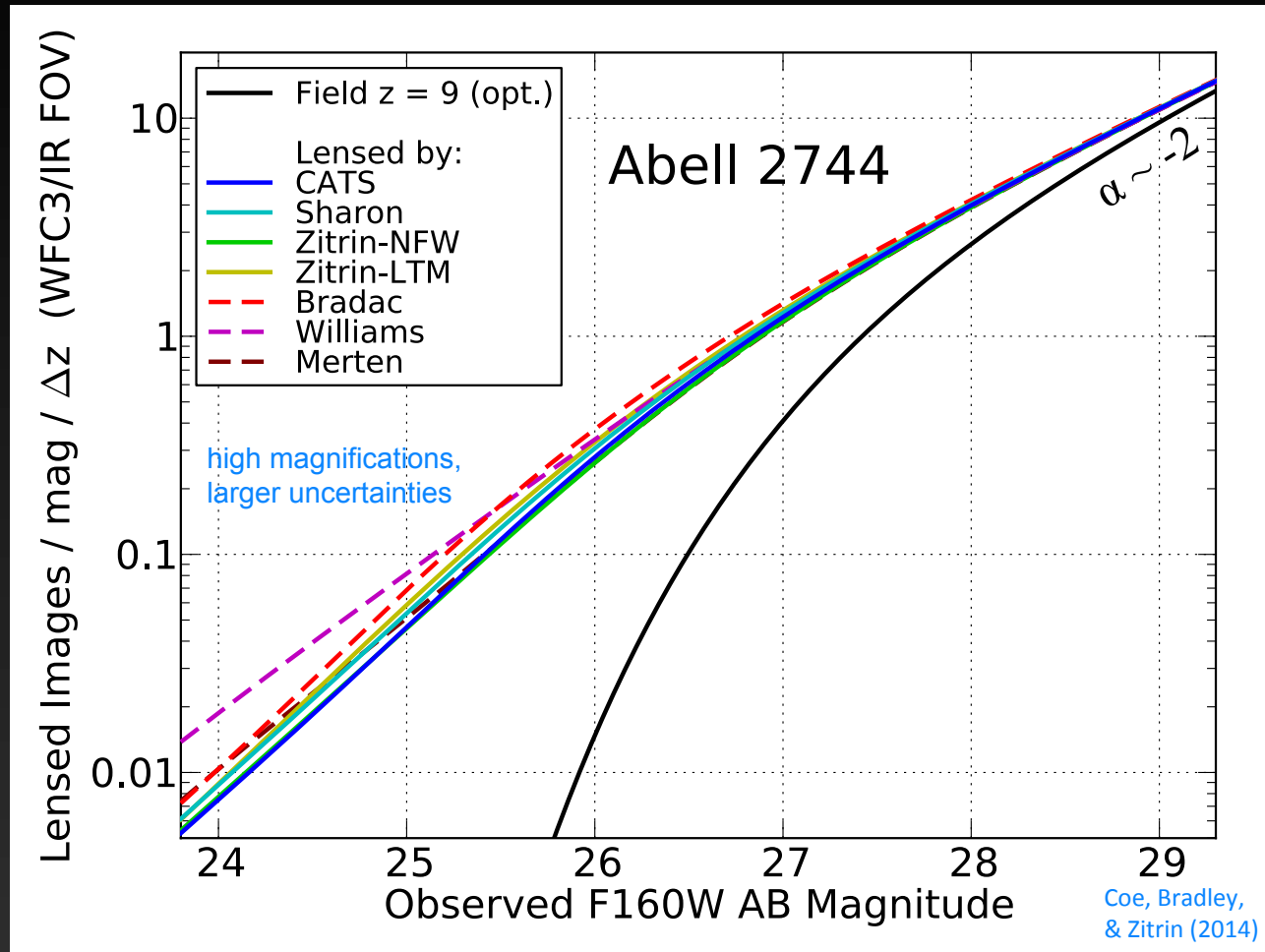
Colors:

- Redshift
- Age (Balmer break)
- Metallicity
- Equivalent Width (EW)
- UV slope β

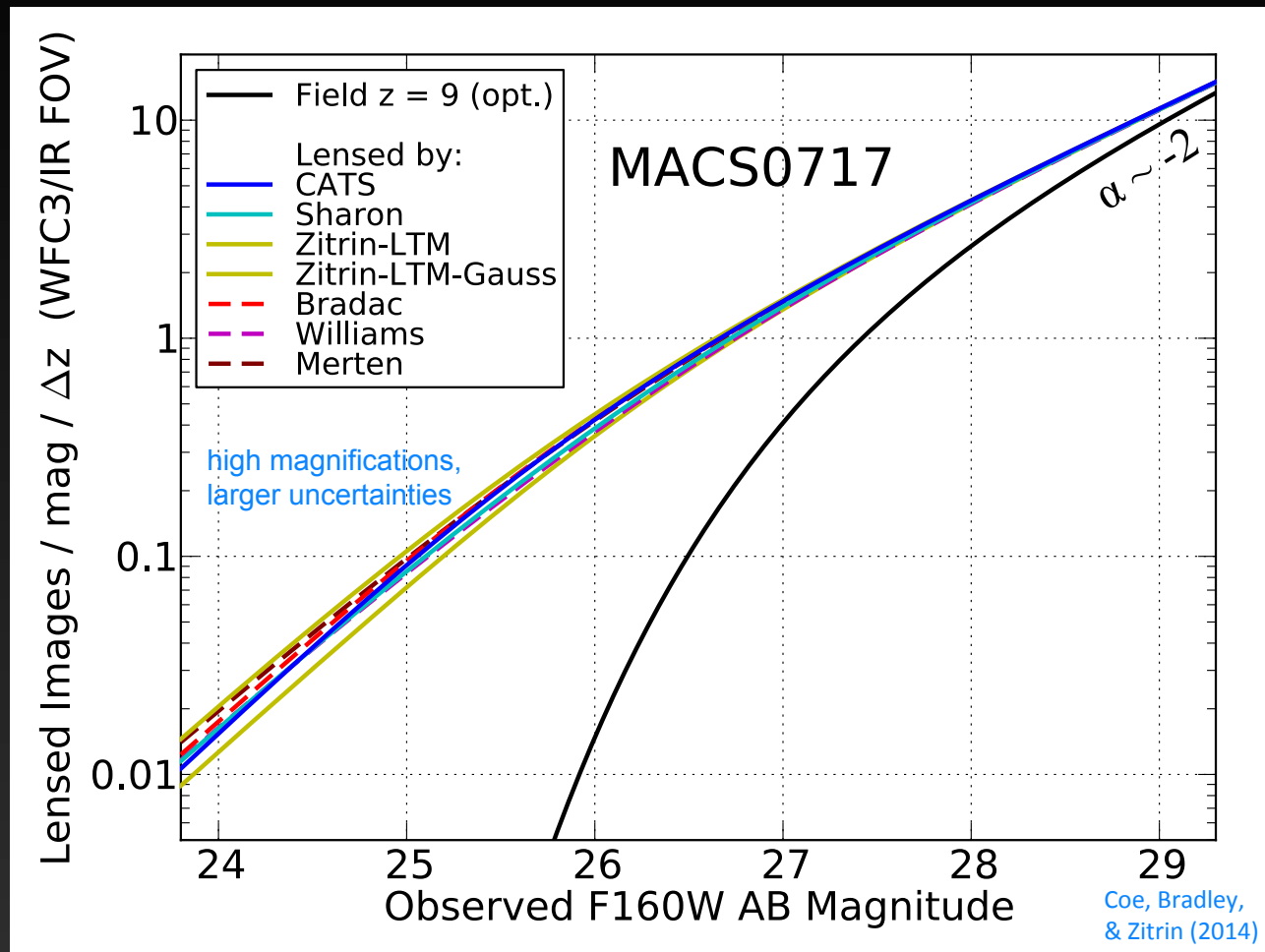
Specific star formation rate
(SFR / stellar mass)

Did galaxies reionize the early universe?

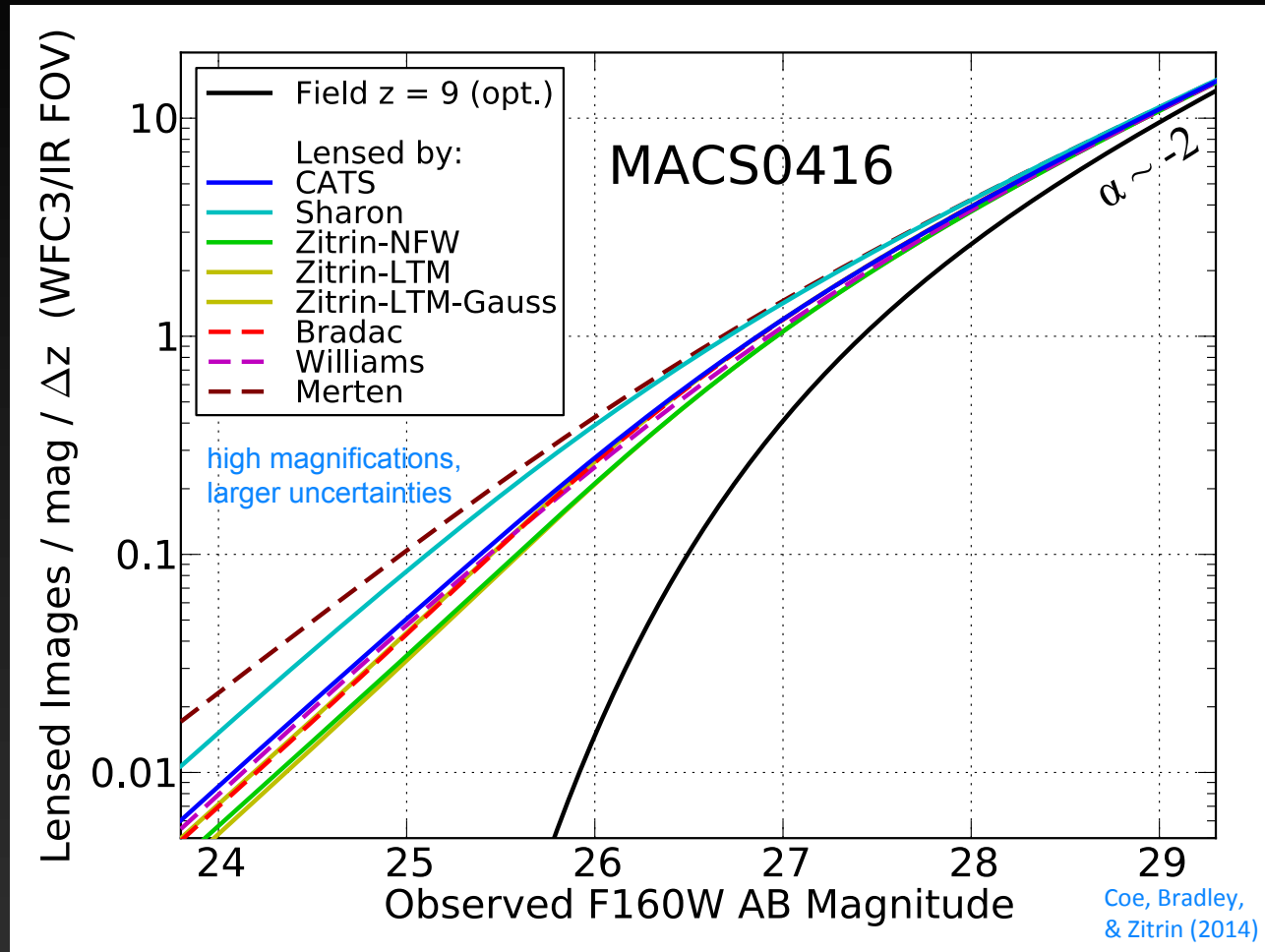
Lens models yield consistent predictions for faint lensed number counts



Lens models yield consistent predictions for faint lensed number counts

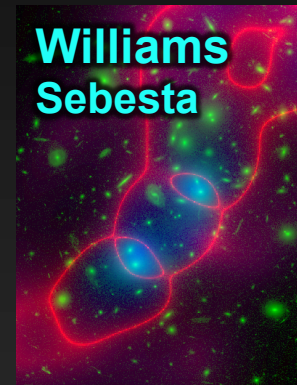
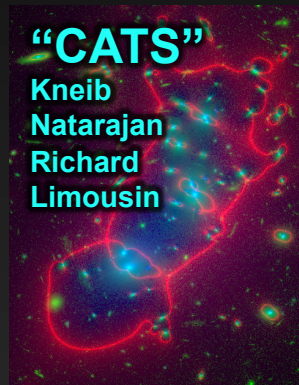
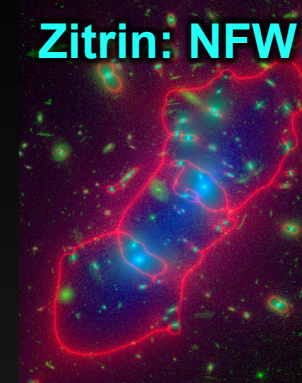


Lens models yield consistent predictions for faint lensed number counts



Lens models of the Frontier Fields clusters

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



Abell 2744

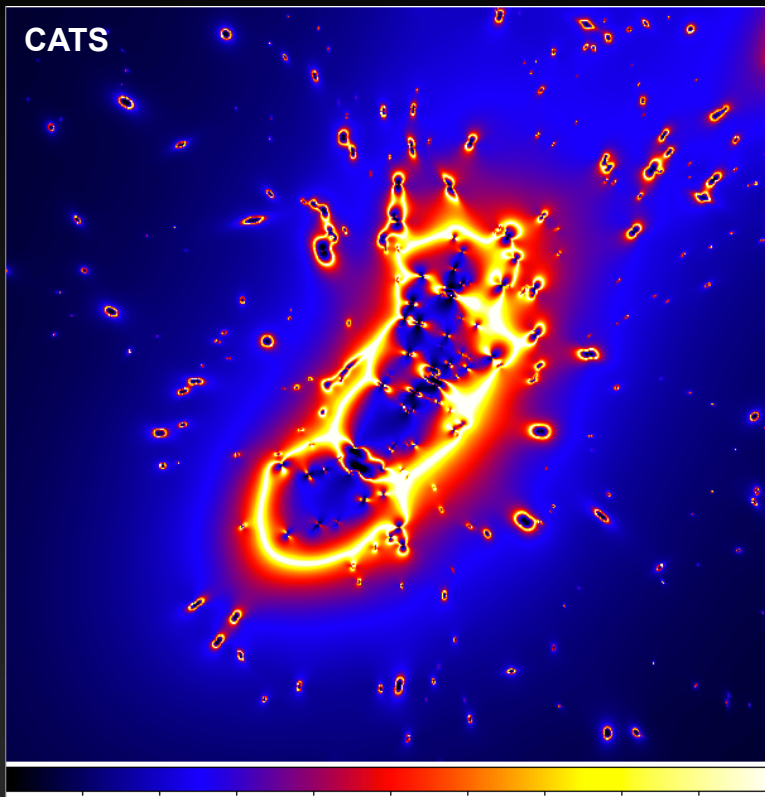
red = magnification for a lensed galaxy at $z = 9$

green = HST

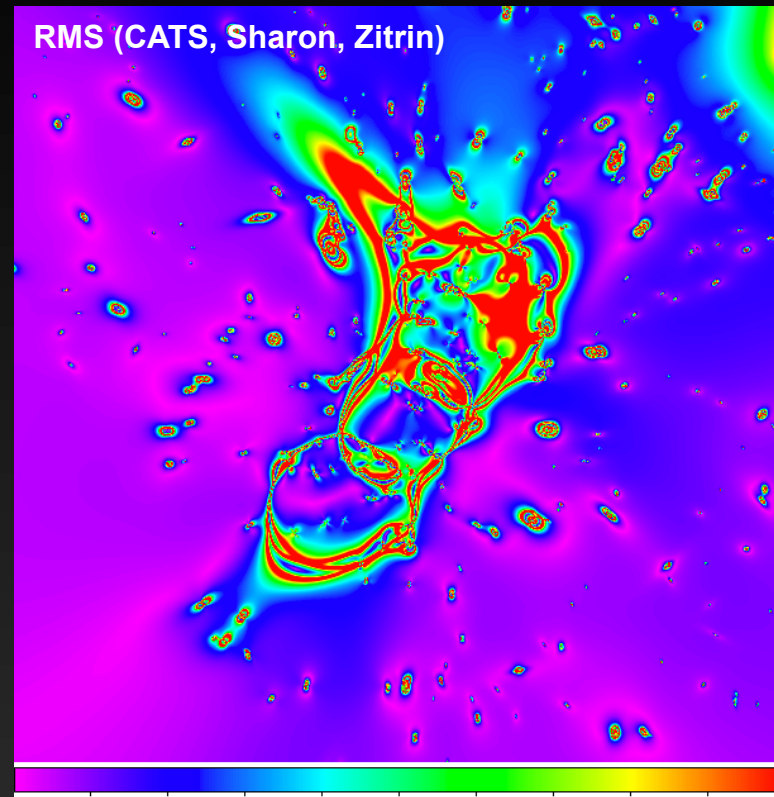
blue = mass

Magnification estimates for individual galaxies

Larger scatter in higher magnification regions

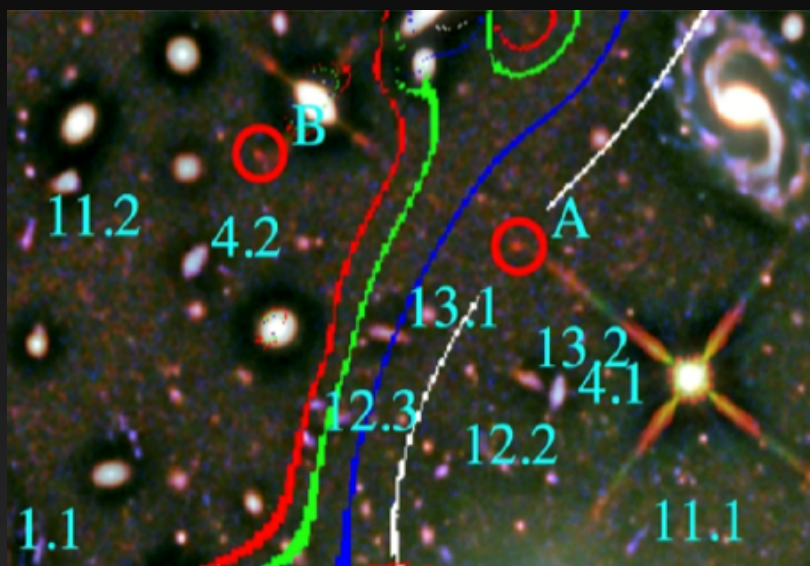


0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
z = 9 magnification in magnitudes



0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
RMS magnification in magnitudes
(light traces mass models)

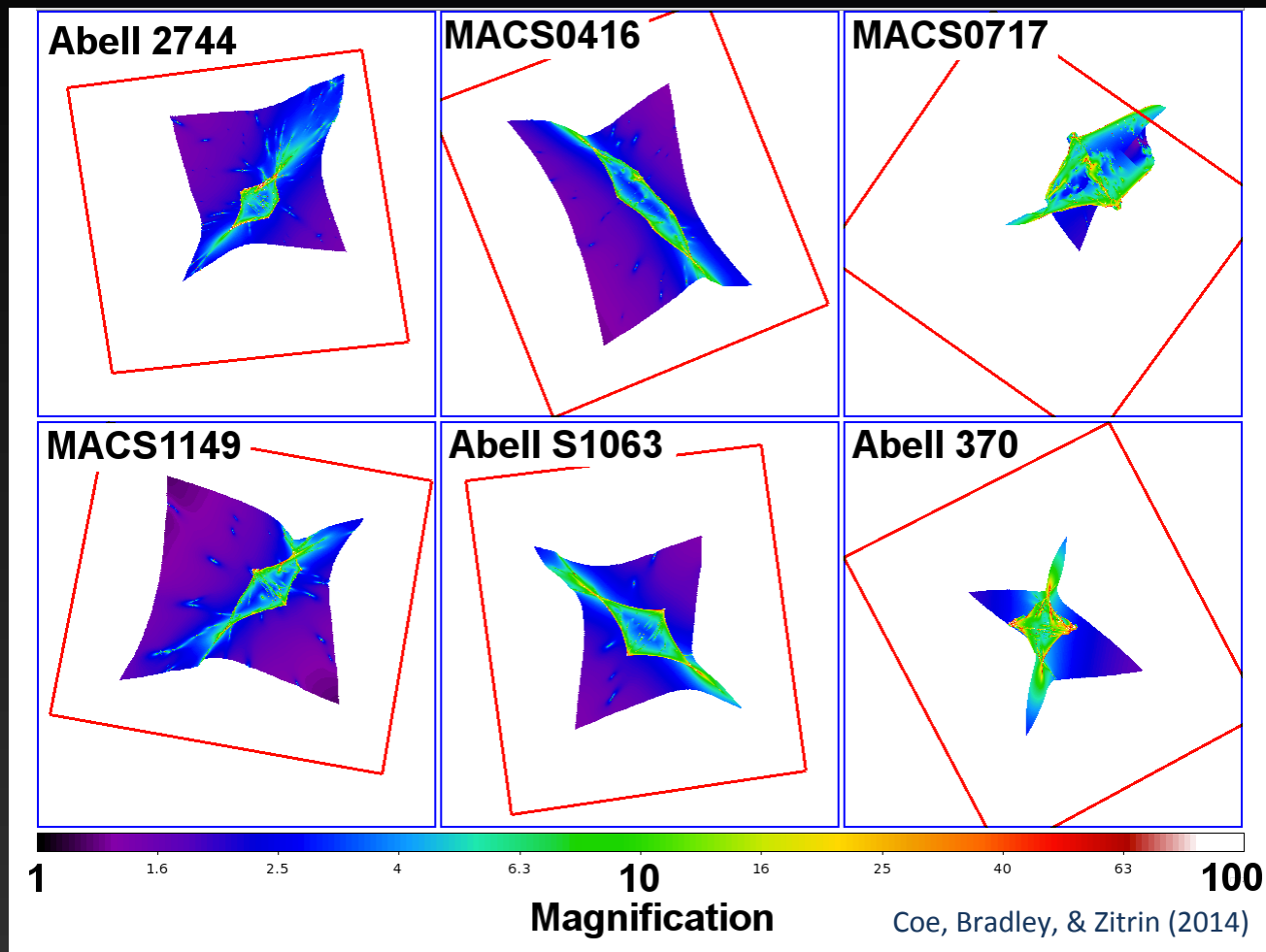
Highly magnified images are usually multiply-imaged yielding multiple estimates of the intrinsic flux



Zitrin et al. (2014)

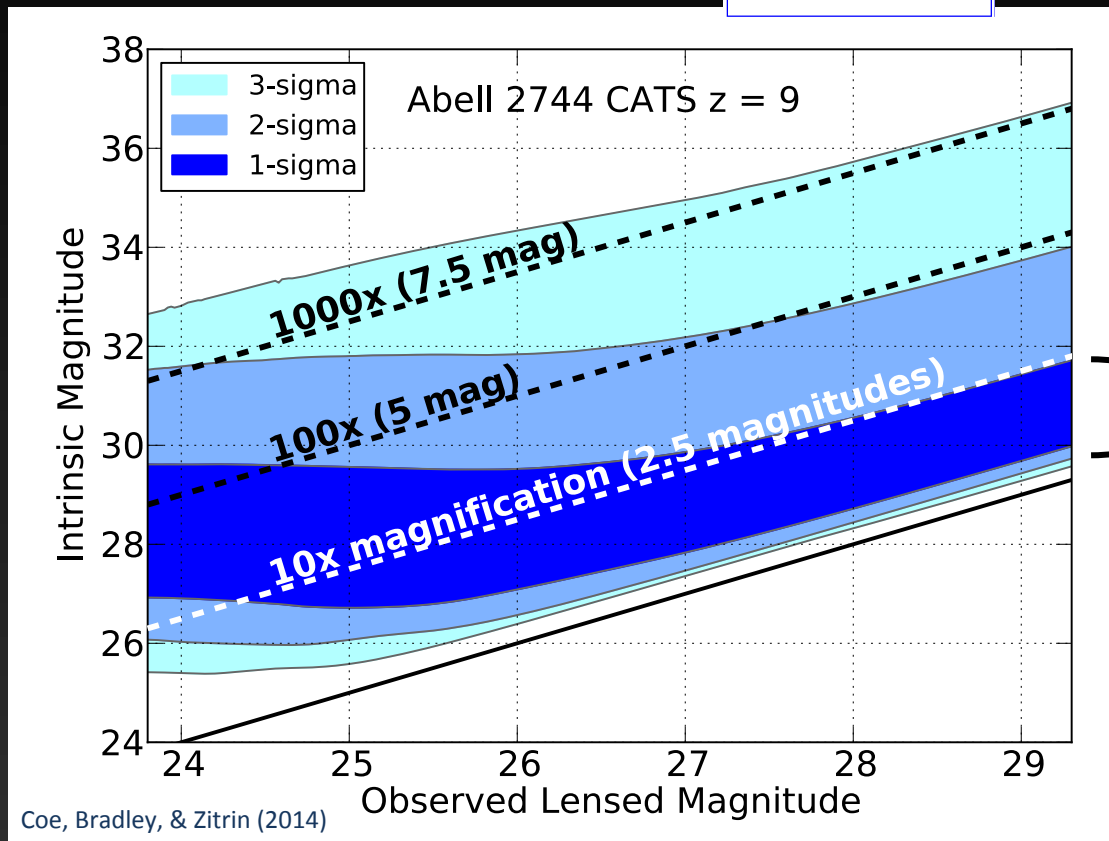
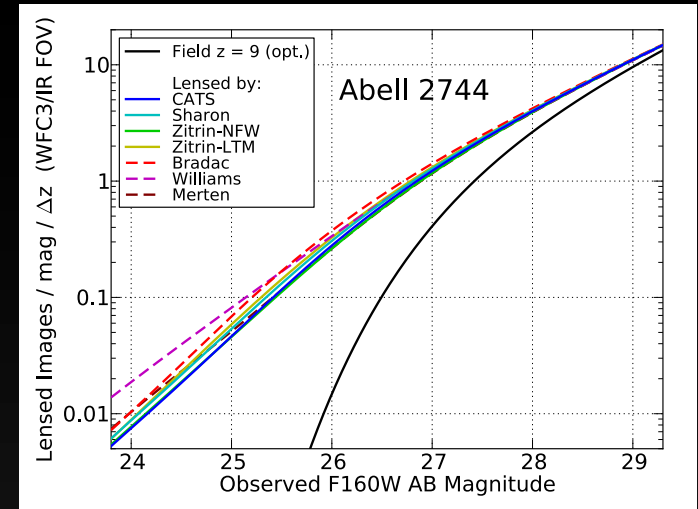
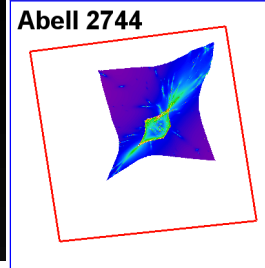
$z \sim 10$ candidate and high magnification critical curve

High magnification regions cover small source areas



“CATS” team
lens models
of the
Frontier Fields
galaxy clusters

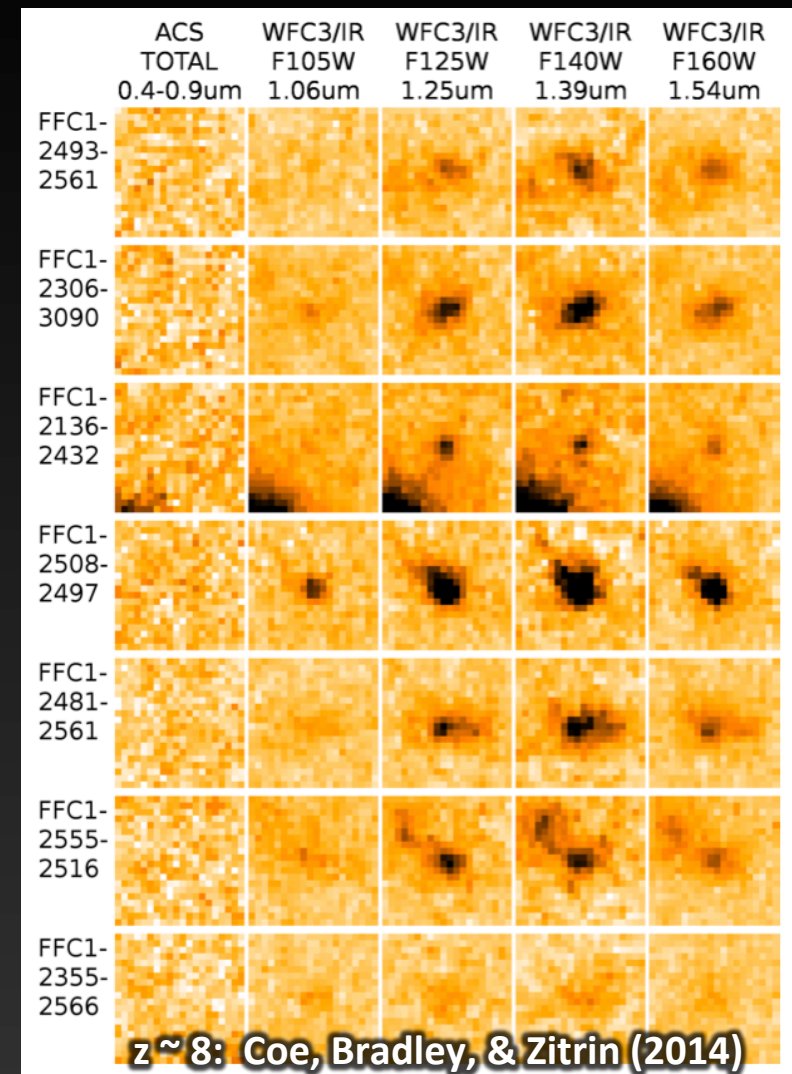
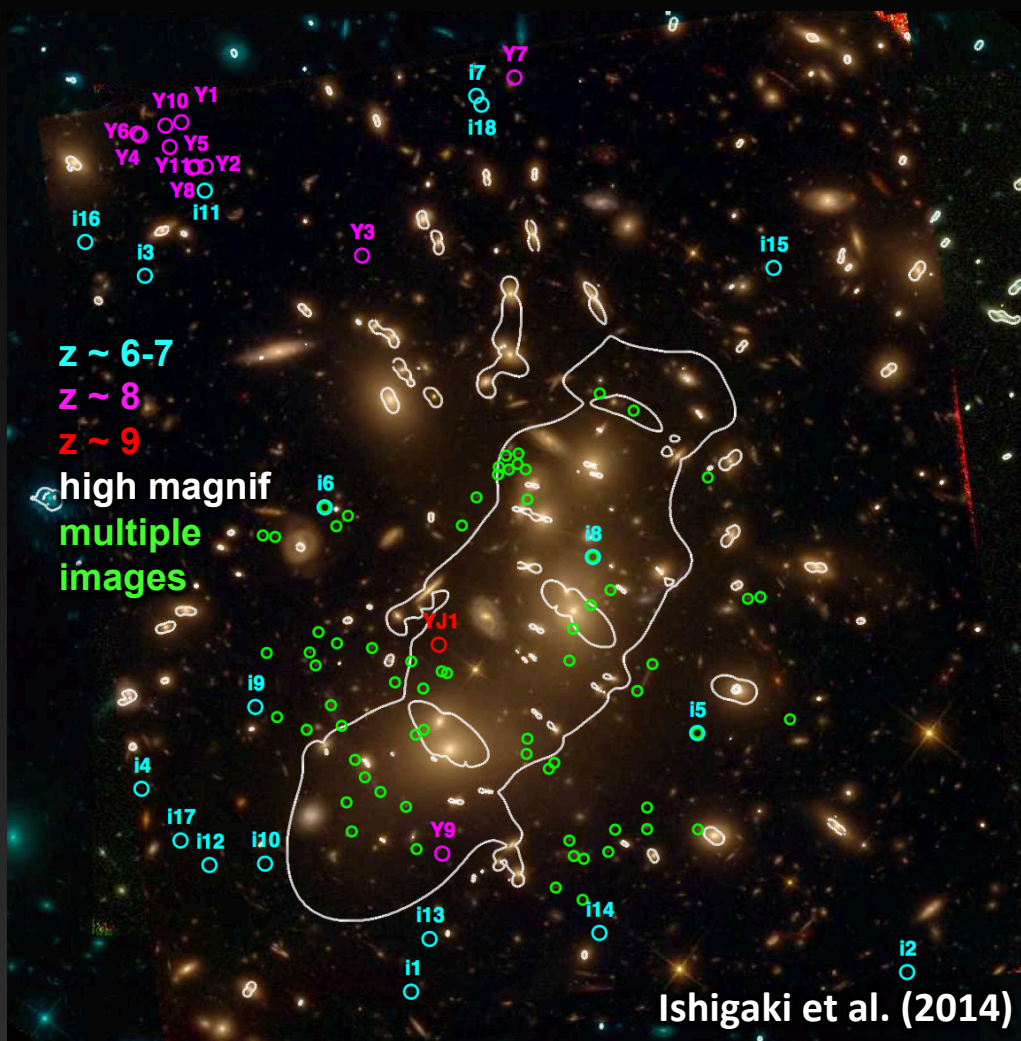
High magnifications are rare



~85% of faint lensed $z \sim 9$ galaxies are expected to have magnifications < 10

High-z candidates lensed by Abell 2744

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



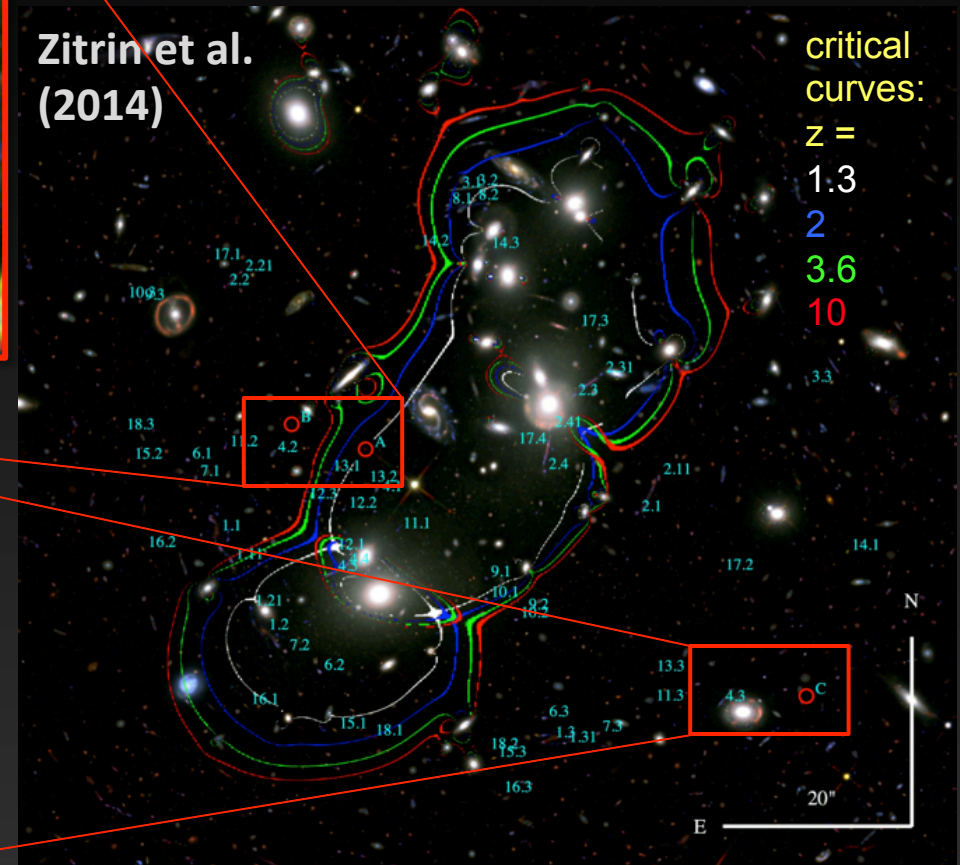
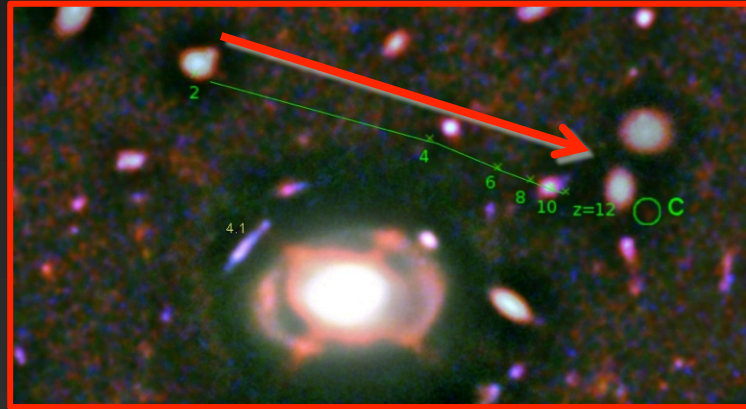
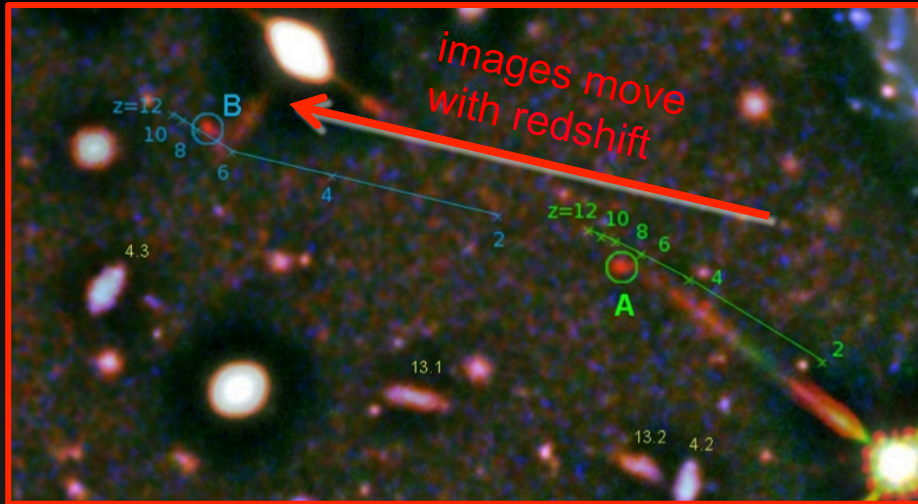
Triply-imaged $z \sim 10$ candidate

$z \sim 9.8$ based on photometry
and consistent with lens models

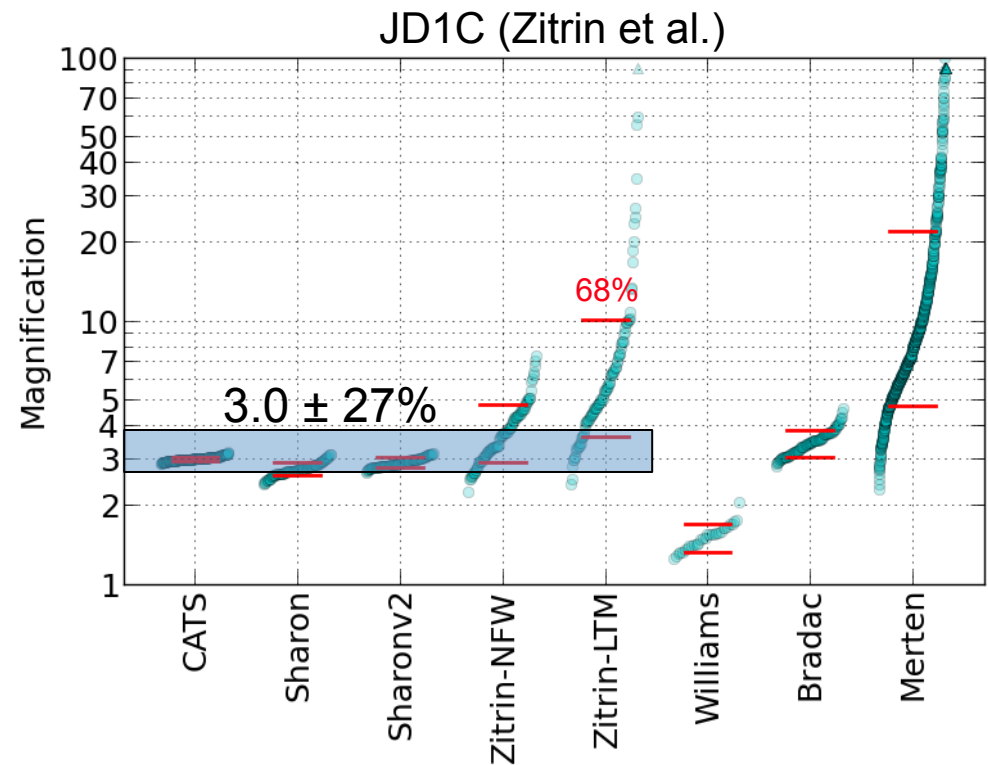
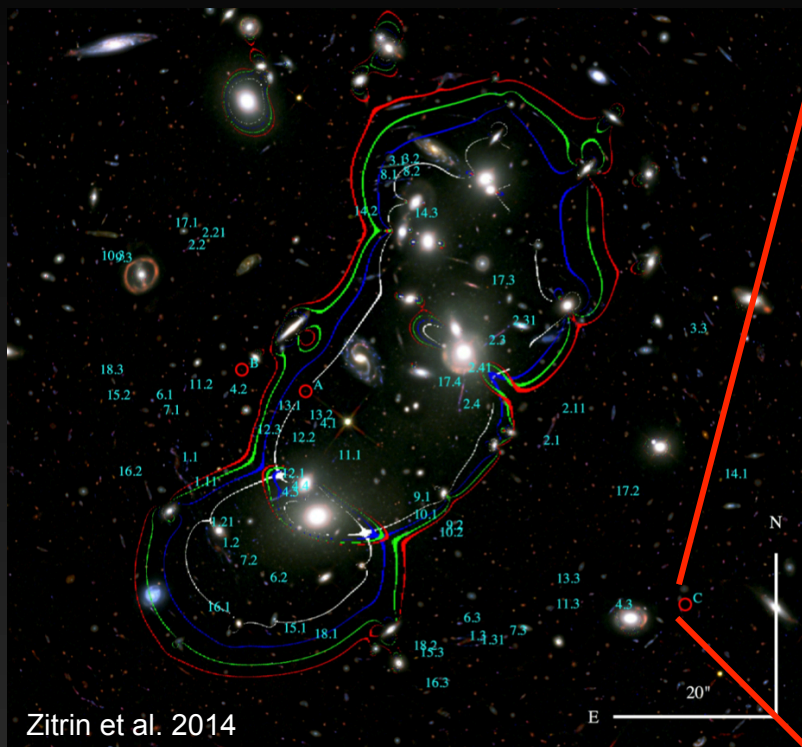
Zitrin et al.
(2014)

critical
curves:

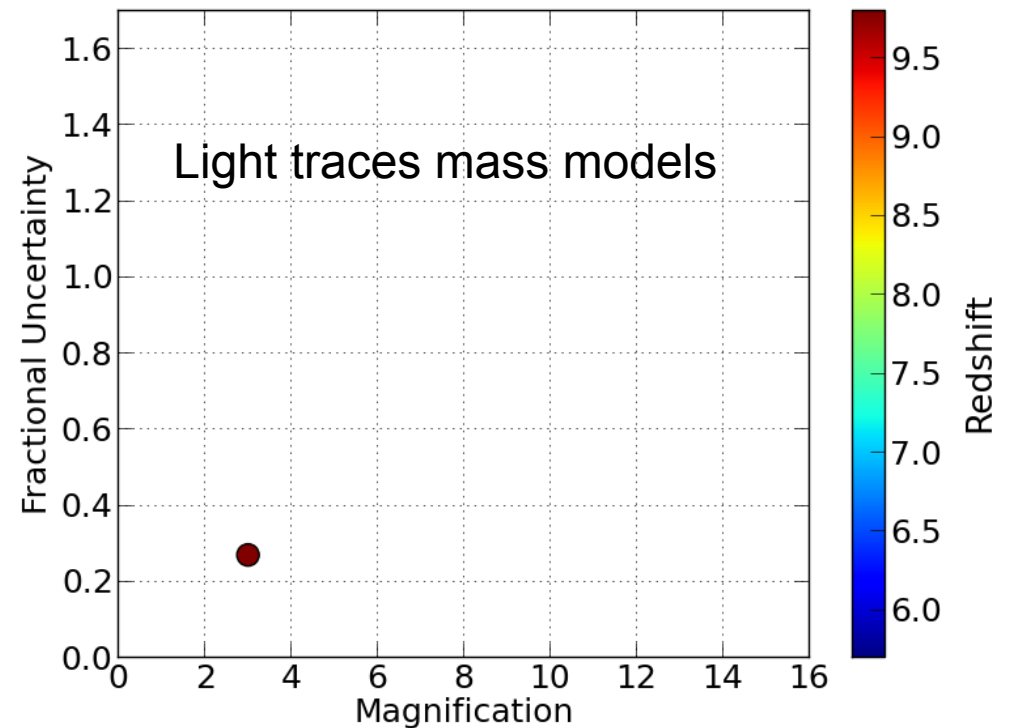
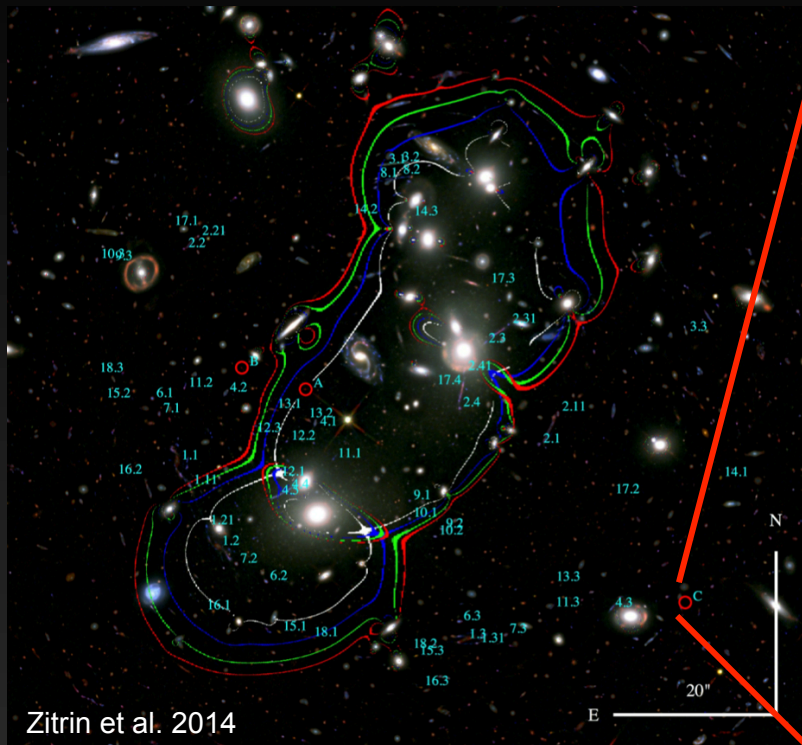
$z =$
1.3
2
3.6
10



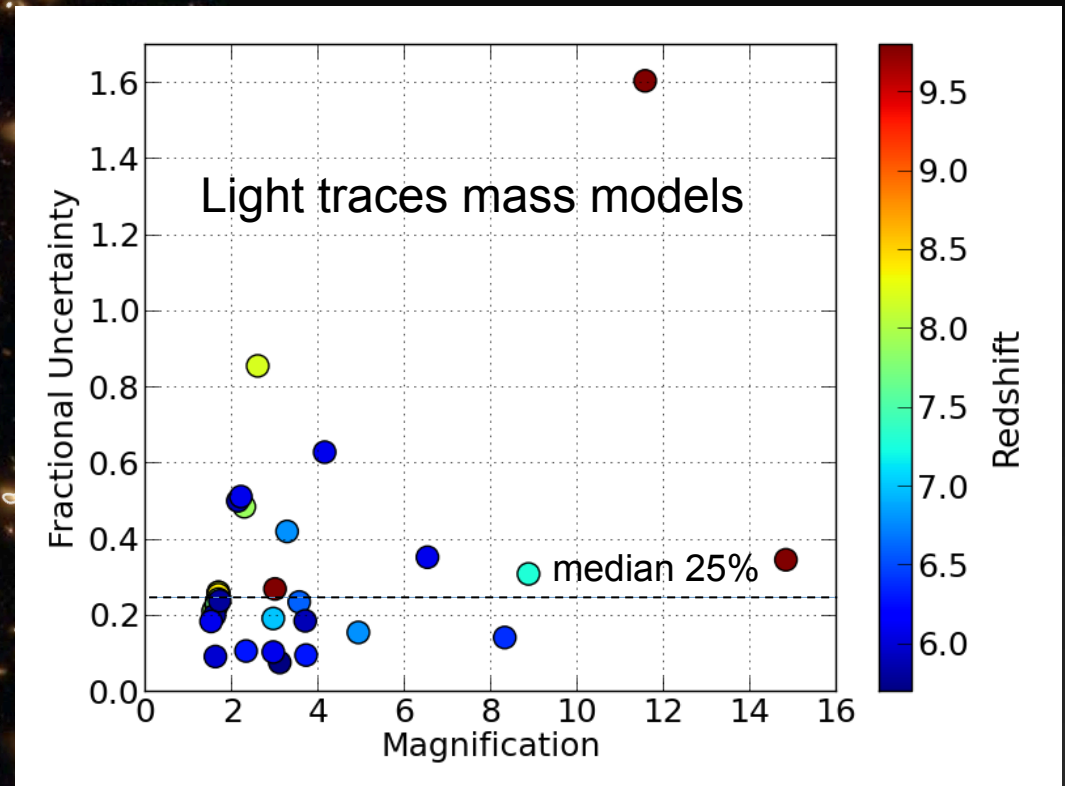
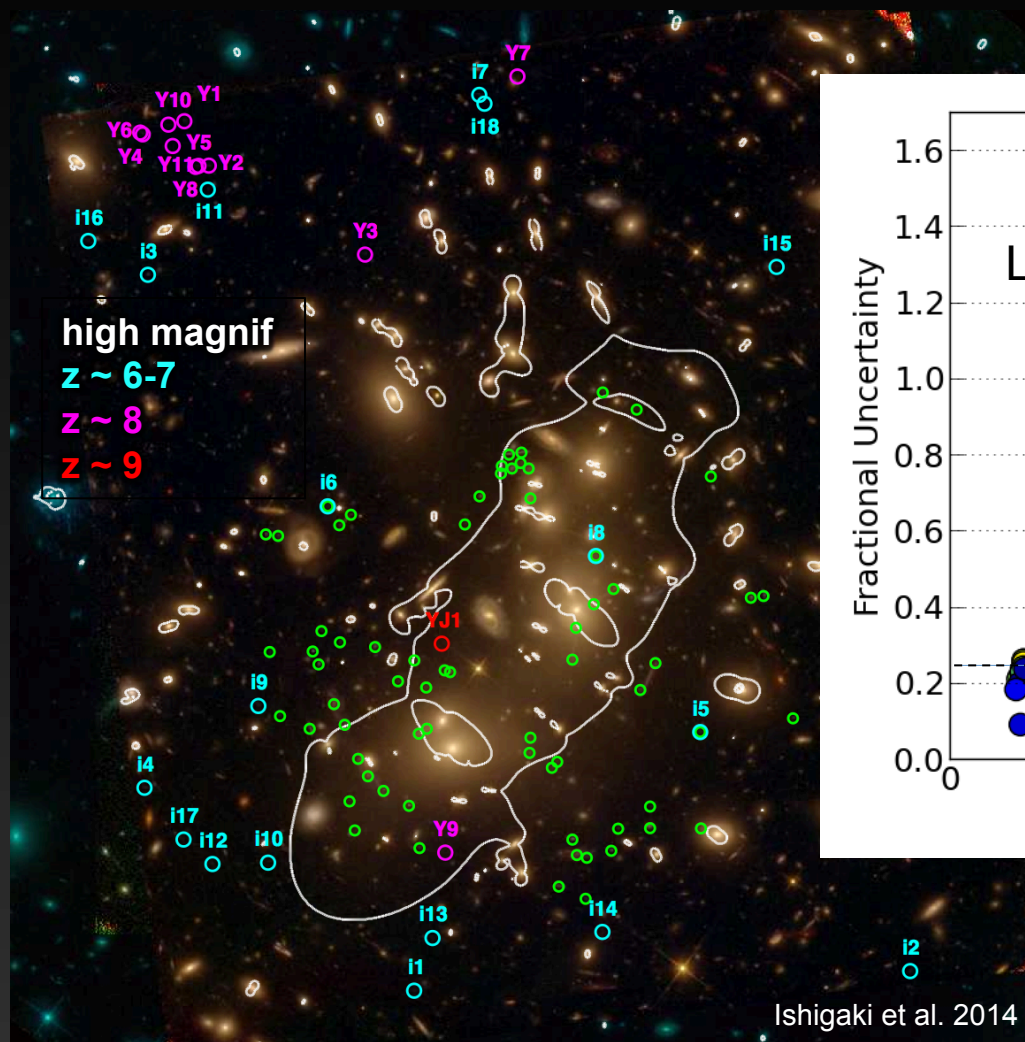
Magnification scatter for high- z candidates lensed by Abell 2744



Magnification scatter for high-z candidates lensed by Abell 2744



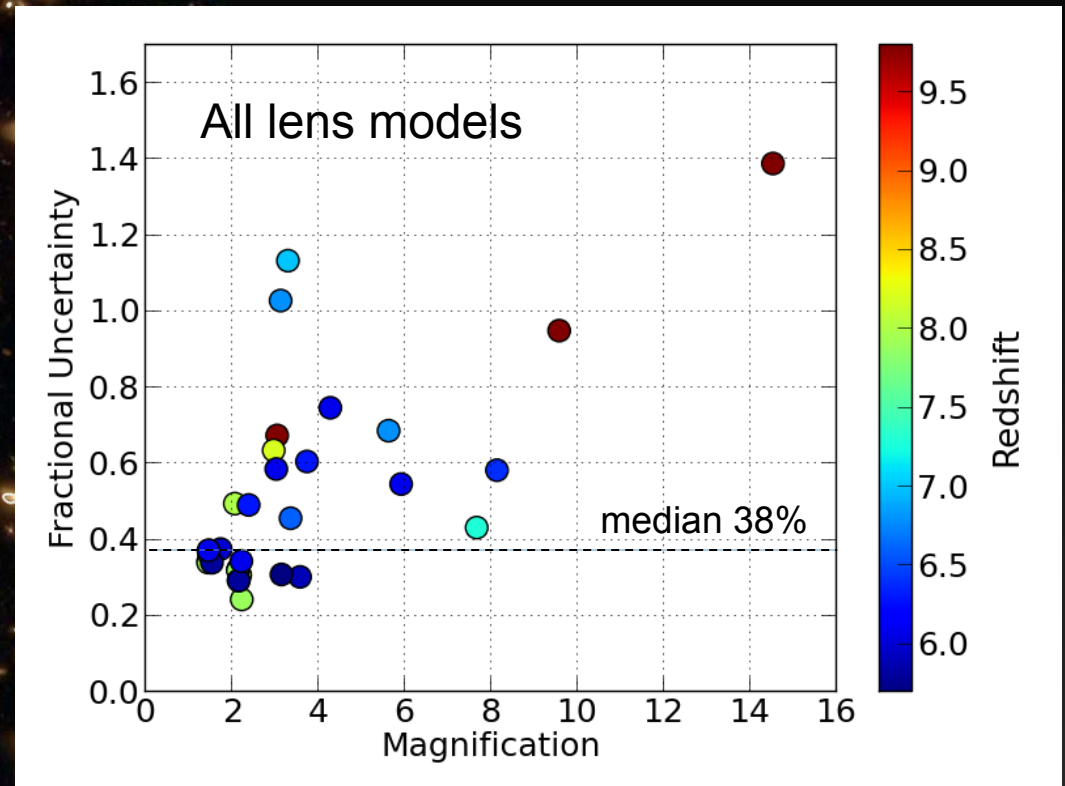
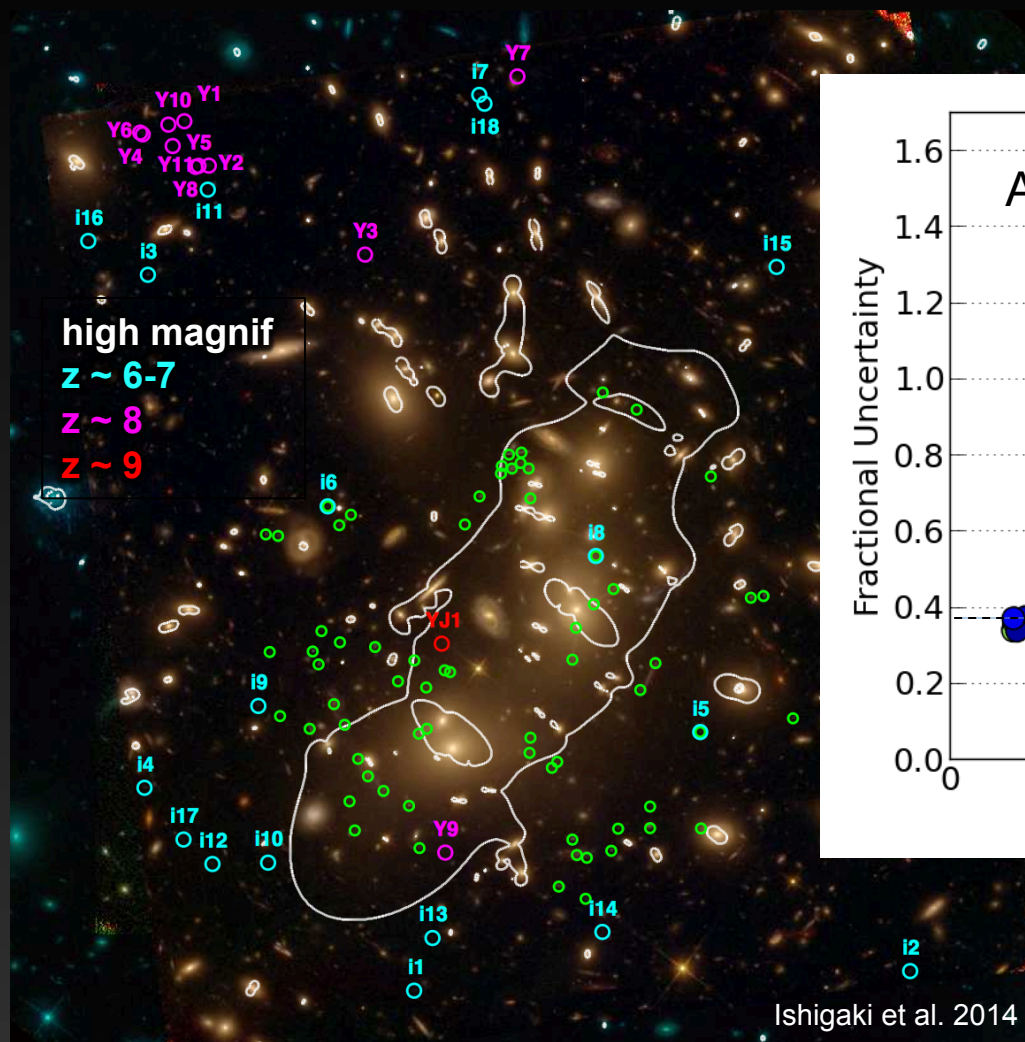
Magnification scatter for high- z candidates lensed by Abell 2744



Note most magnifications are < 10

Ishigaki et al. 2014 + Zitrin et al. 2014

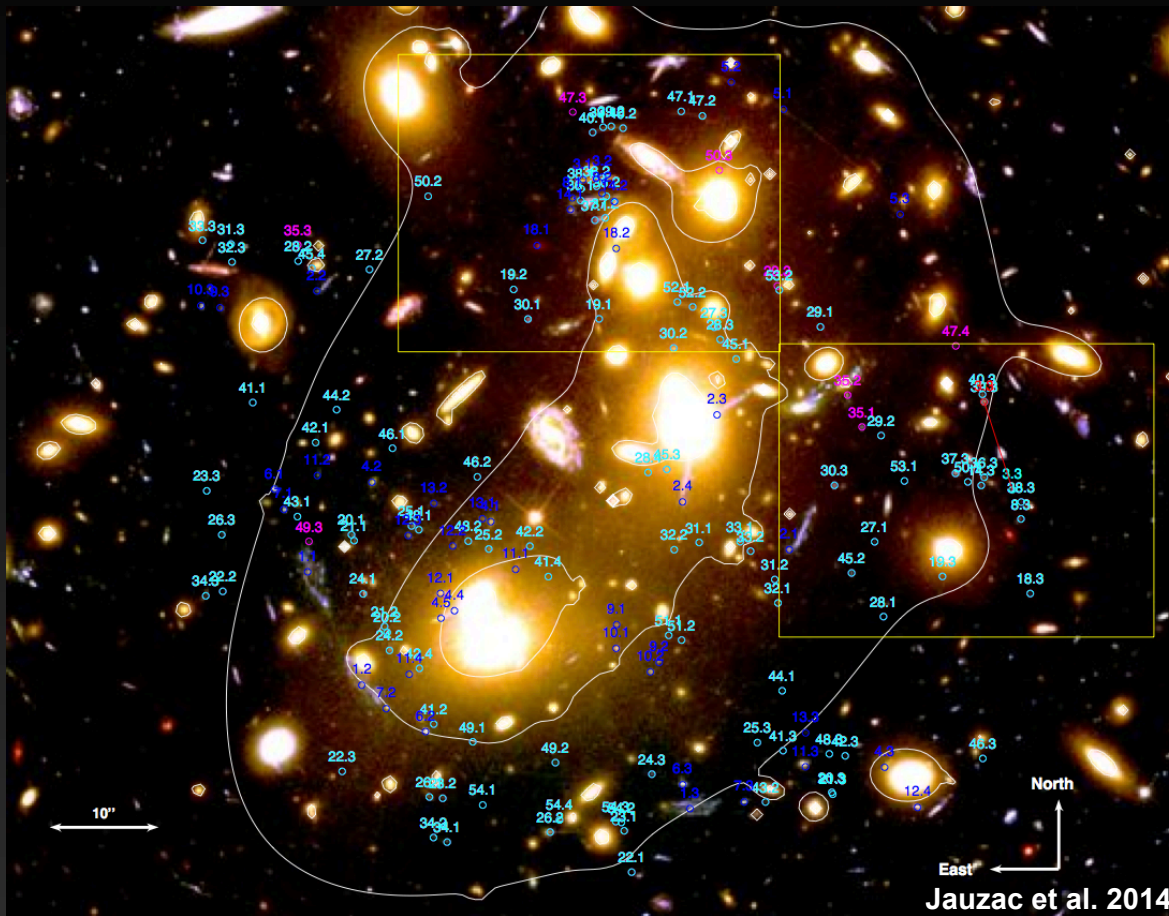
Magnification scatter for high- z candidates lensed by Abell 2744



Note most magnifications are < 10

Ishigaki et al. 2014 + Zitrin et al. 2014

Improved lens models forthcoming based on HFF imaging and other data



Abell 2744:

120 new multiple images

7 new but less confident

similar results for MACS0416

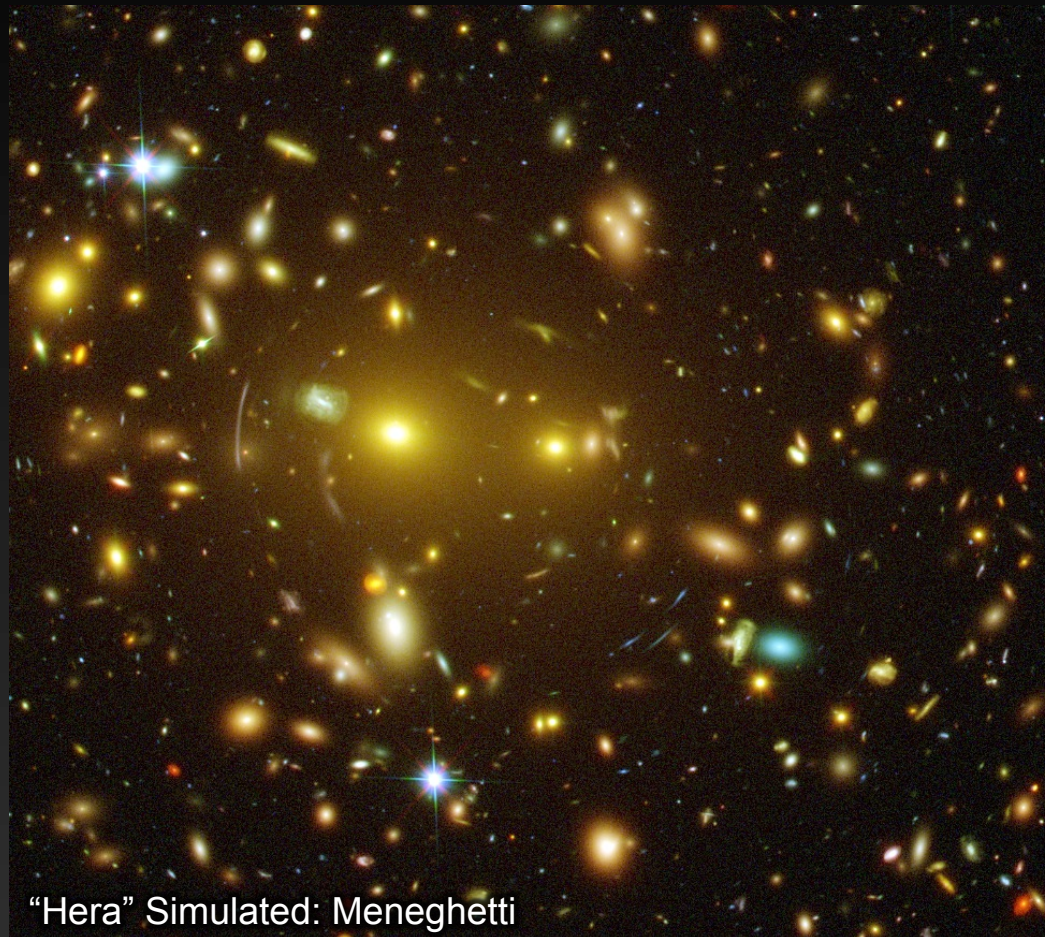
Updated models submitted by:

- Sharon, Johnson
 - Williams, Sebesta
 - Jauzac, CATS
 - Ishigaki, Kawamata, Oguri
- and forthcoming from:
- Diego, Lam, Broadhurst

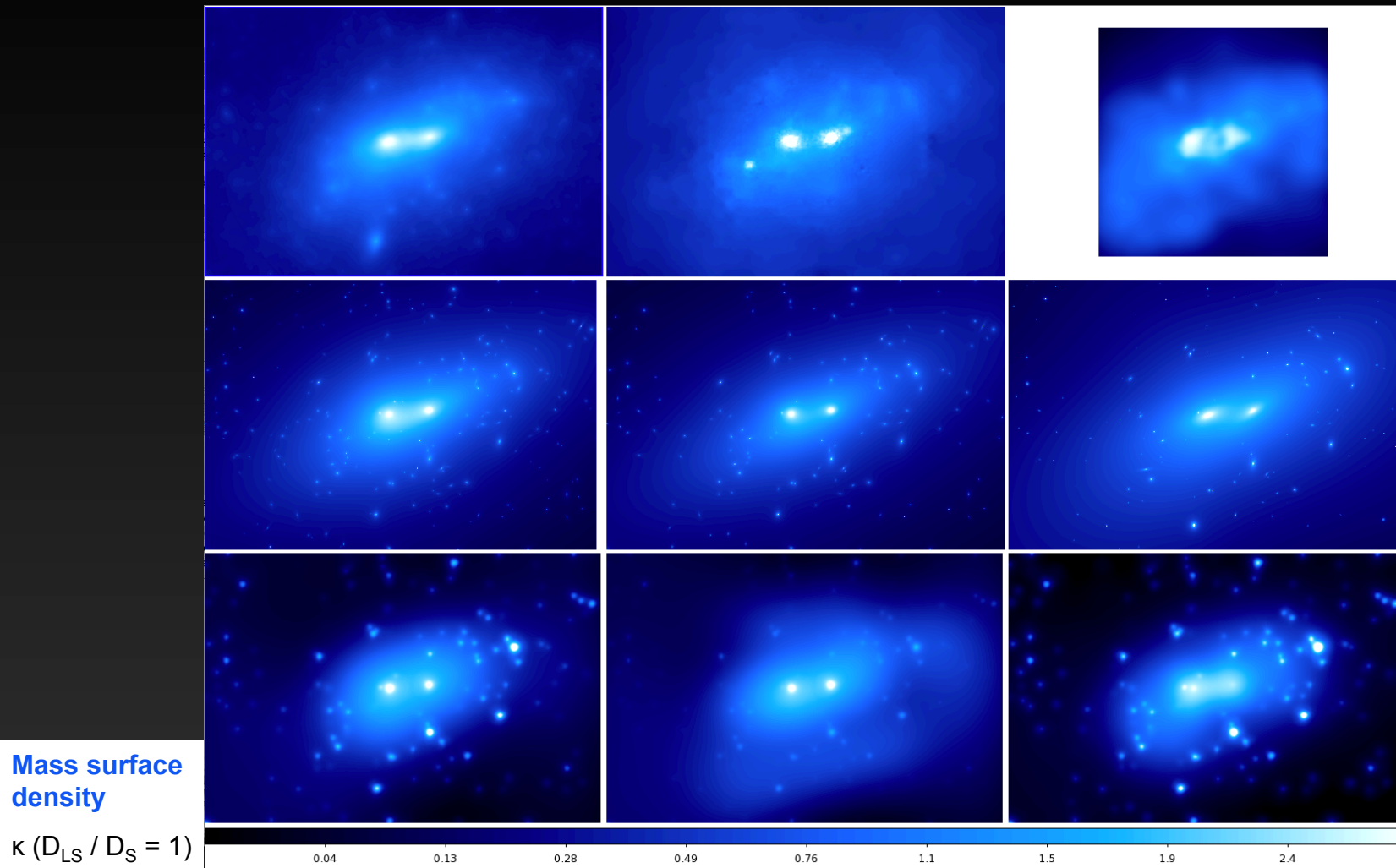
New data include:

- spec-z's from MUSE, GLASS
- A2744 Subaru BRz imaging

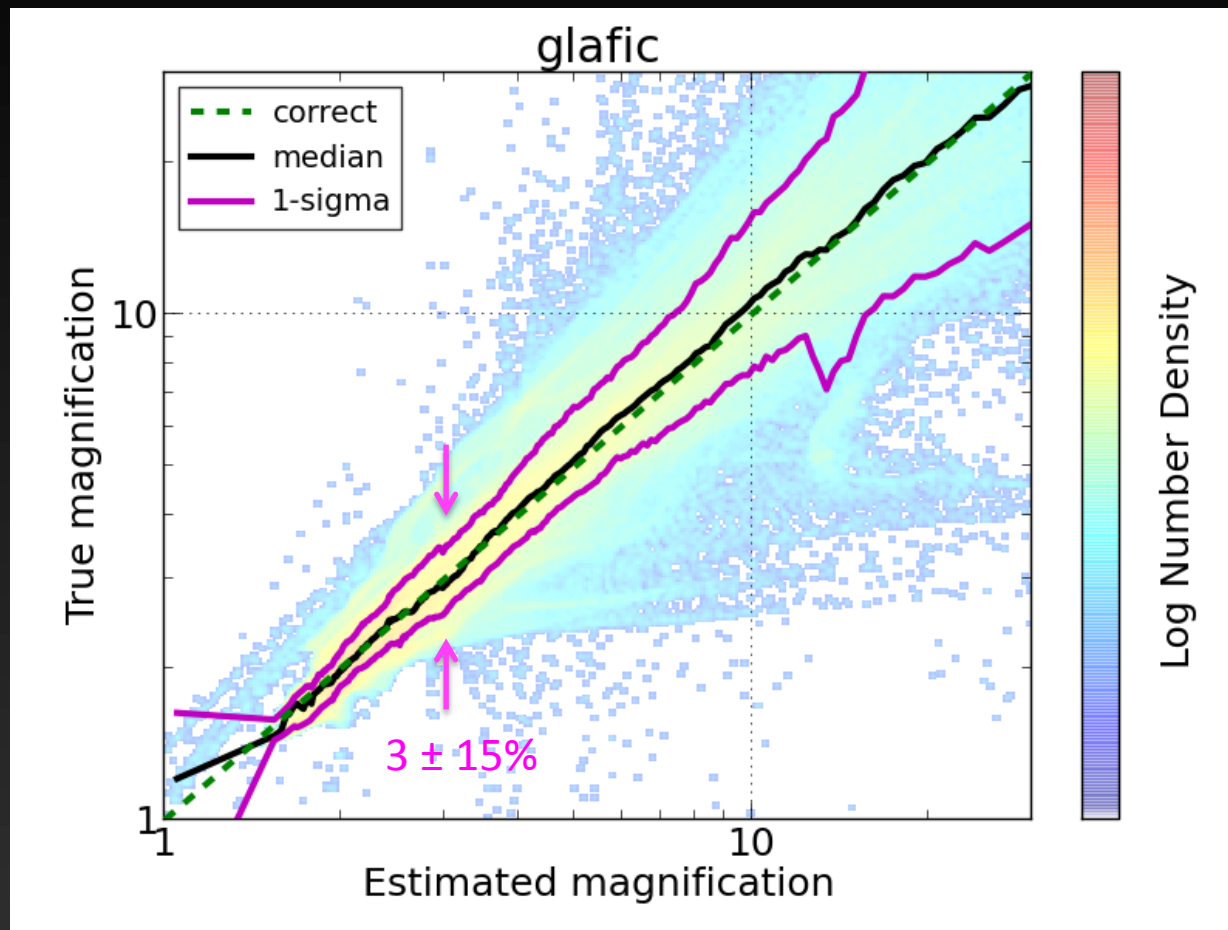
Simulated cluster lensing challenge to quantify model accuracies



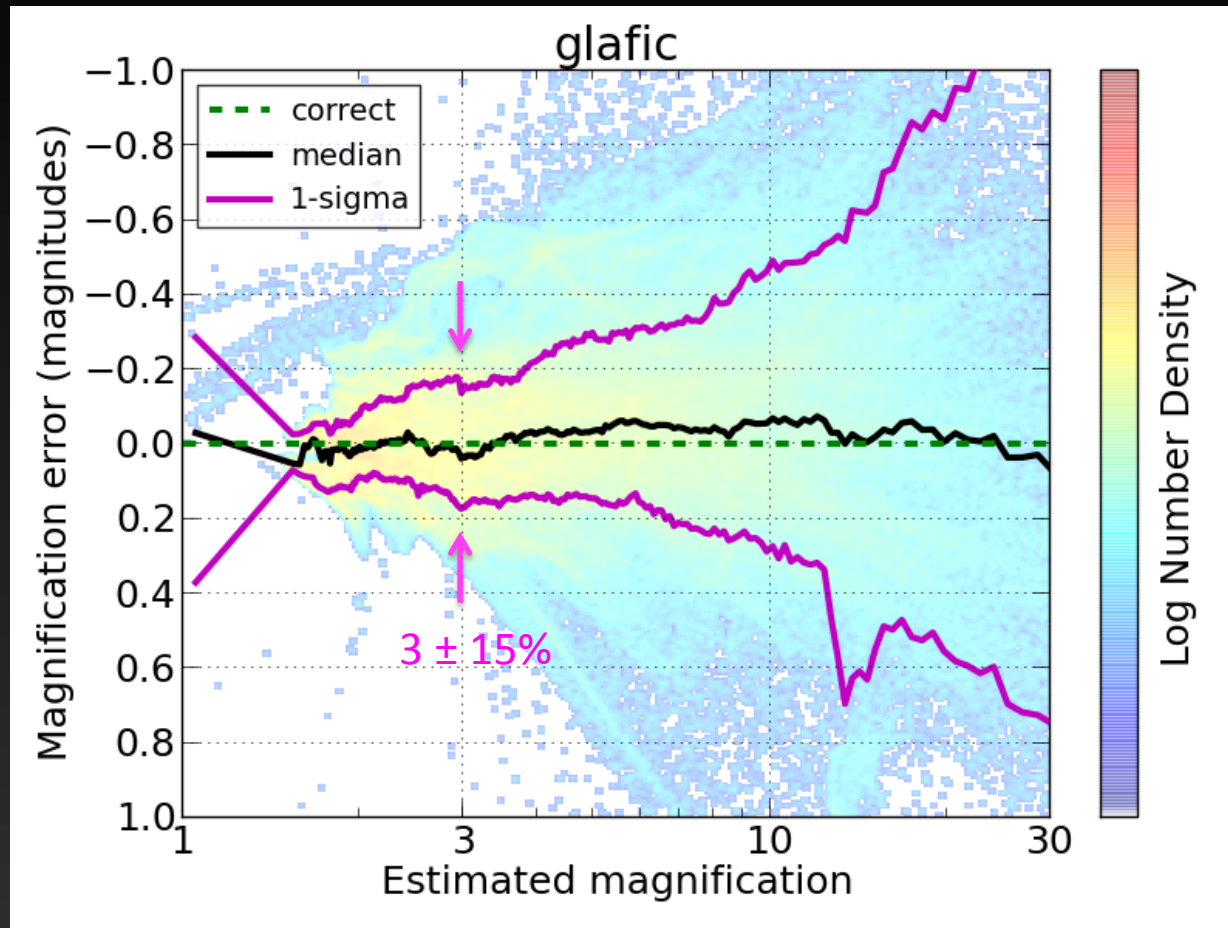
Hera mass models submitted



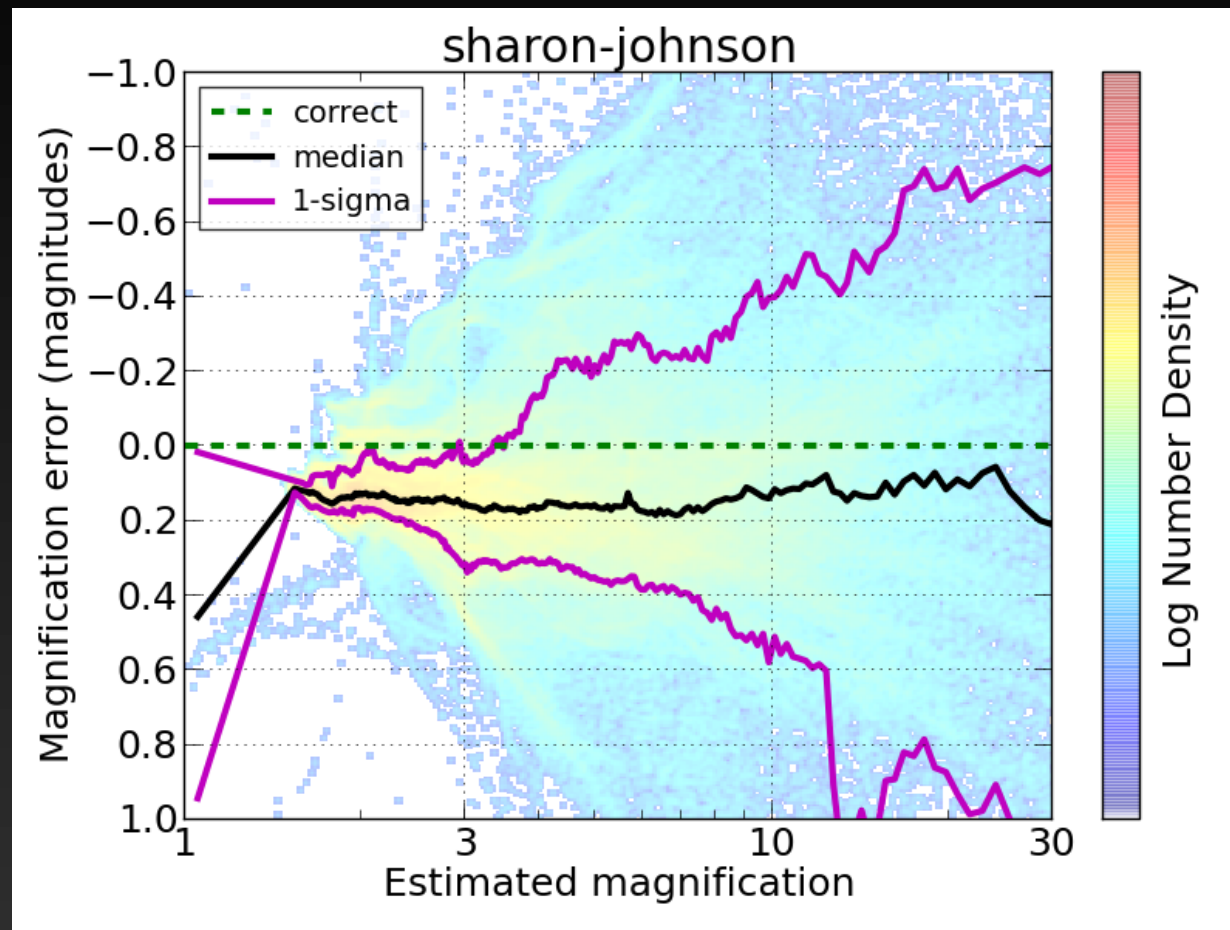
Magnification accuracies quantified



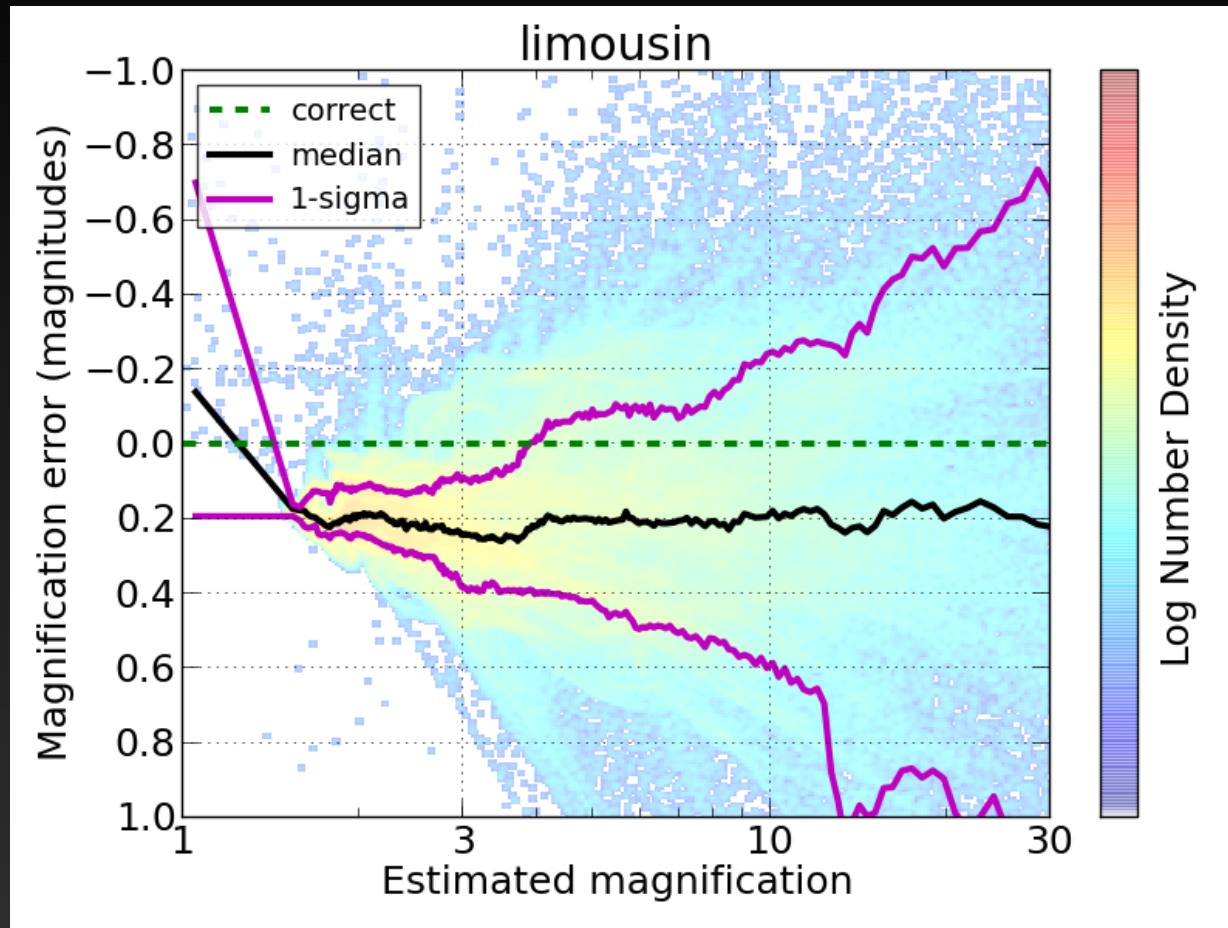
Magnification accuracies quantified



Magnification accuracies quantified

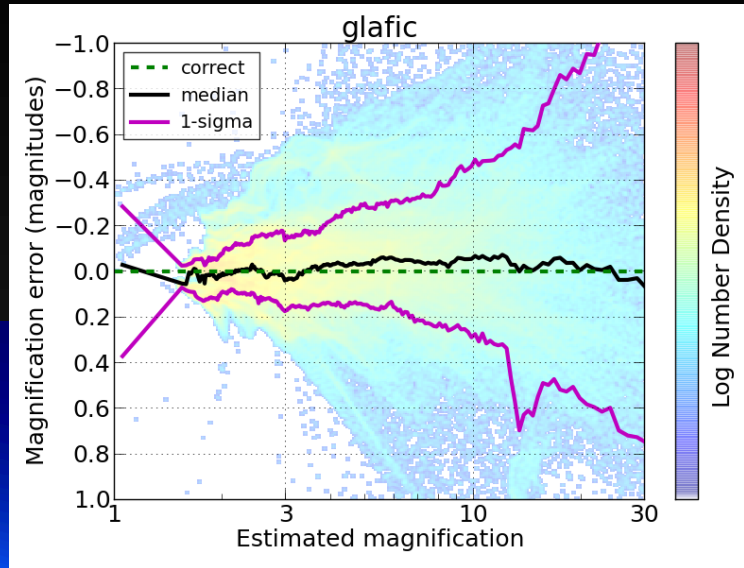
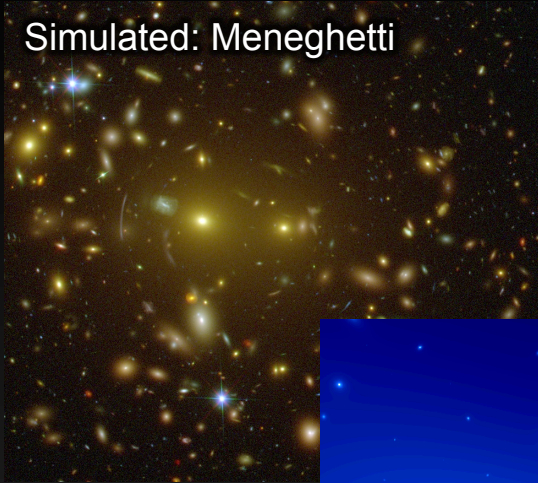


Magnification accuracies quantified

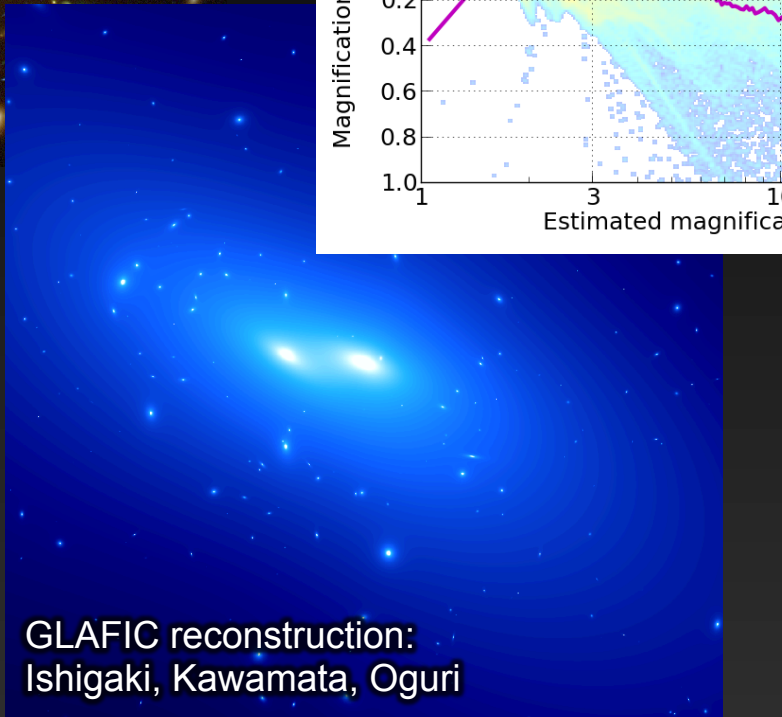


In this first test, GLAFIC performed best

Simulated: Meneghetti



GLAFIC reconstruction:
Ishigaki, Kawamata, Oguri



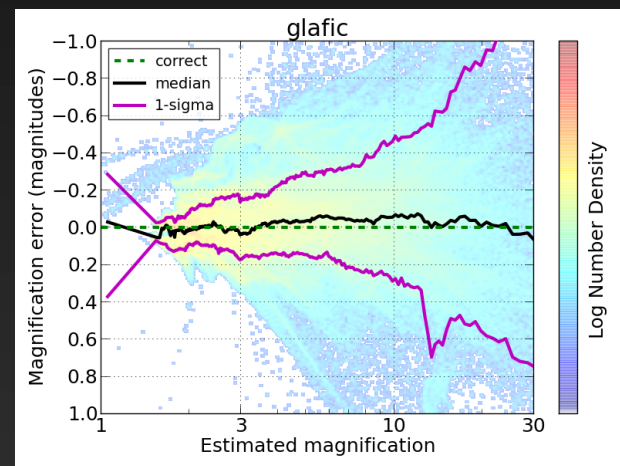
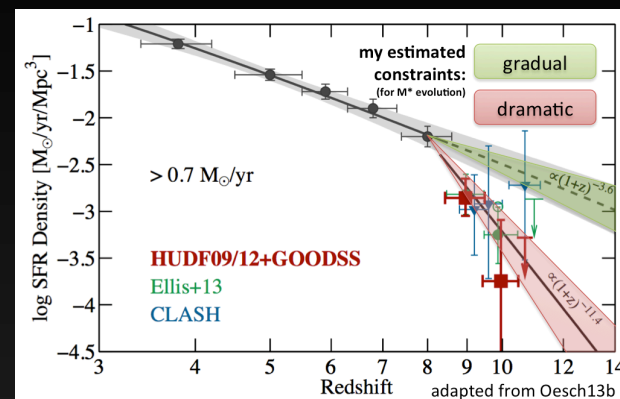
The Frontier Fields will strongly constrain high-z galaxy evolution and reionization

Simulations are beginning to quantify our accuracy of:

- lens model magnifications

and other challenging quantities:

- high-z detection completeness
- HST + Spitzer photometry



Thank you



Nov 20, 2014

Dan Coe - Kavli IPMU

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