RELICS

Reionization Lensing Cluster Survey

Dan Coe

STScI ESA/AURA Astronomer

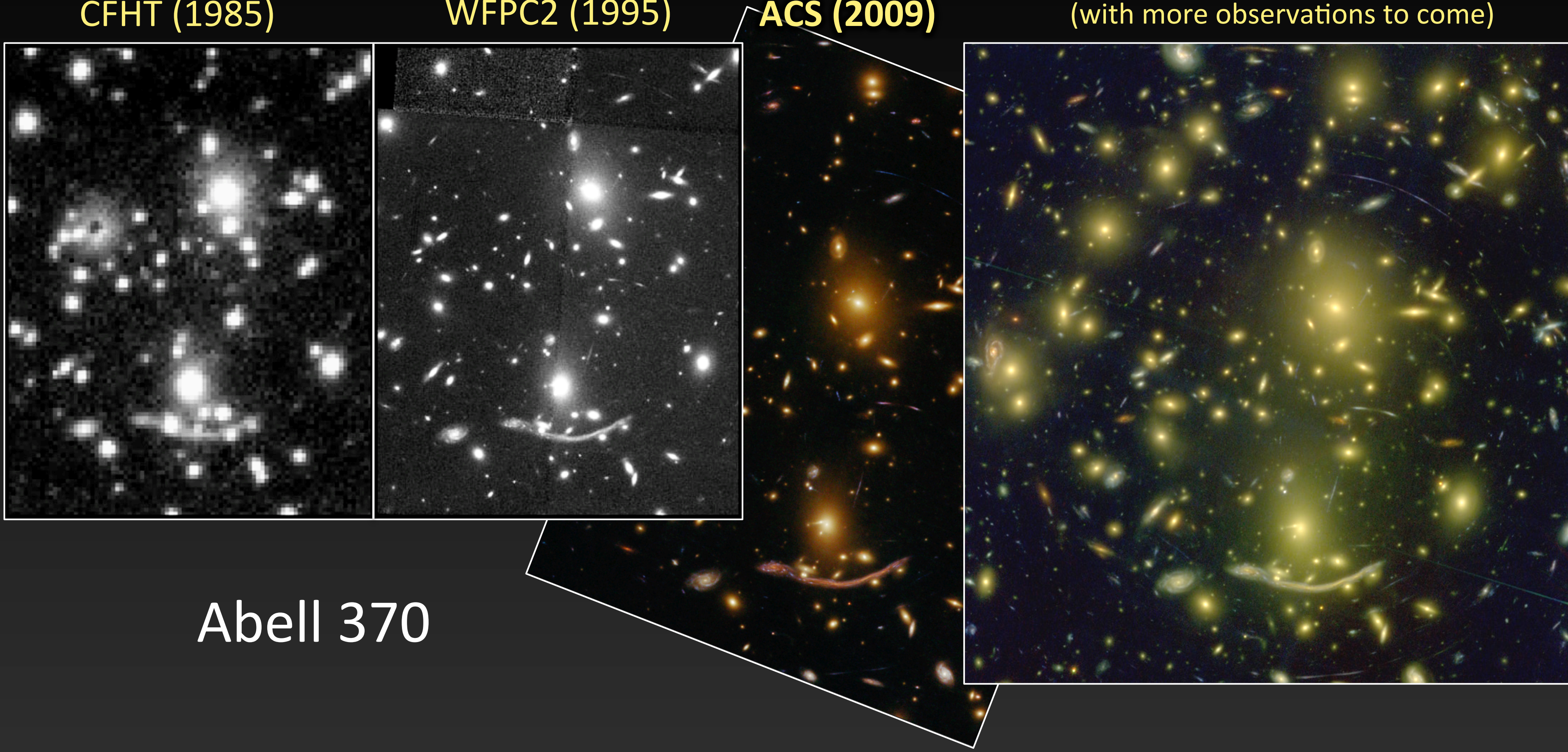
ACS & NIRCam Instrument Scientist

Abell 2163
archival ACS imaging
reduced by
Roberto Avlia and Sara Ogaz

Long history of gravitational lensing

see review by Kneib & Natarajan 2011

CFHT (1985) | WFPC2 (1995) | **ACS (2009)** | ACS + WFC3/IR (2016) (with more observations to come)



Large Hubble Cluster Lensing Programs

CLASH
Cluster Lensing And Supernova survey with Hubble
PI Marc Postman
25 clusters
524 Hubble orbits
HST Cycles 18 – 20
Nov. 2010 – July 2013

1. cluster science
2. high-z galaxies

Frontier Fields
Directors' Discretionary Time

PI Jennifer Lotz
6 clusters
840 Hubble orbits
HST Cycles 21 – 23
Oct. 2013 – Sept. 2016

faint high-z galaxies

RELICS
Reionization Lensing Cluster Survey

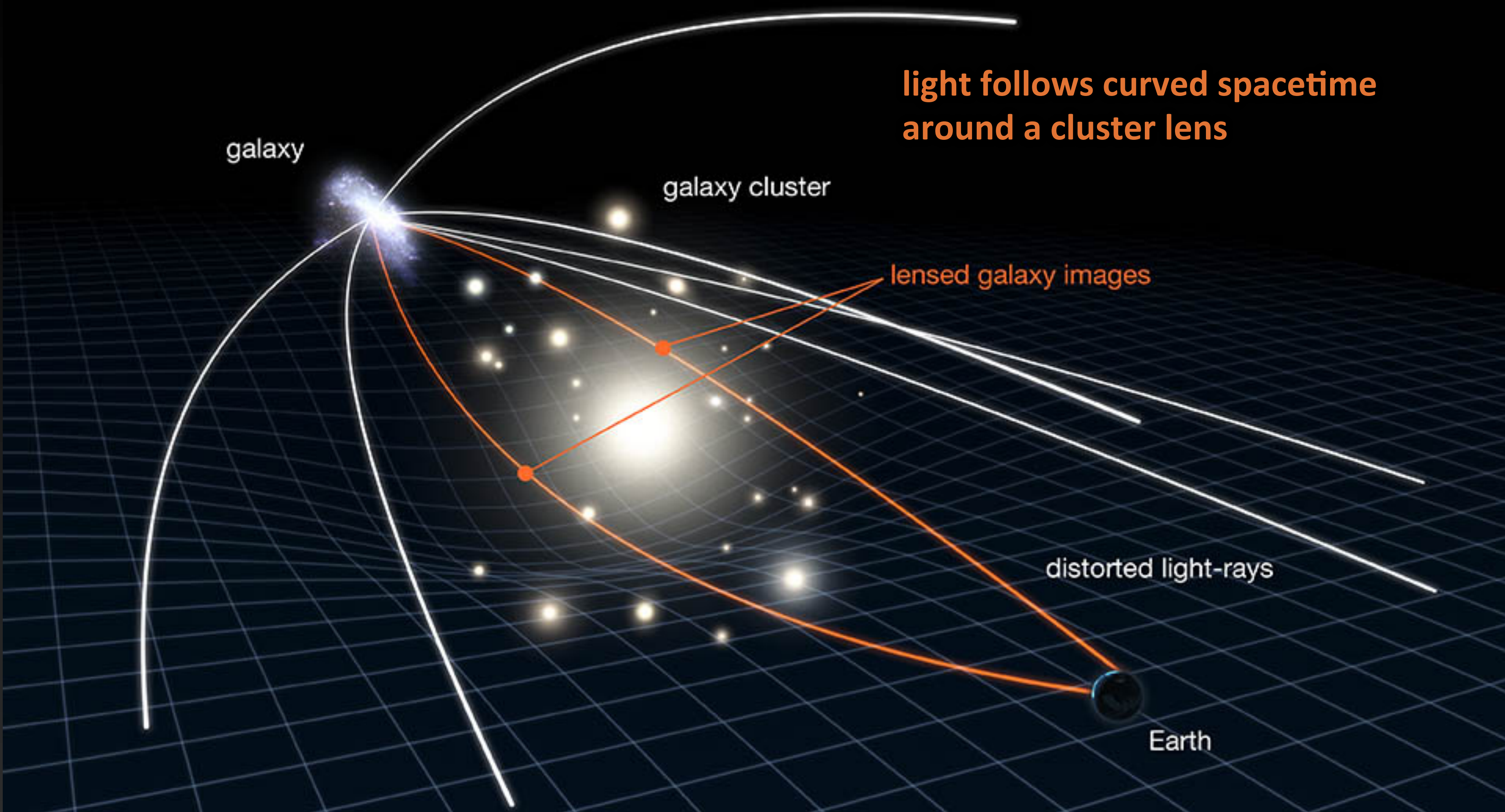
PI Dan Coe
41 clusters
190 Hubble orbits
HST Cycle 23
Oct. 2015 – April 2017

bright high-z galaxies

Also GLASS, SGAS, LoCuSS, Ebeling, Kochanek…

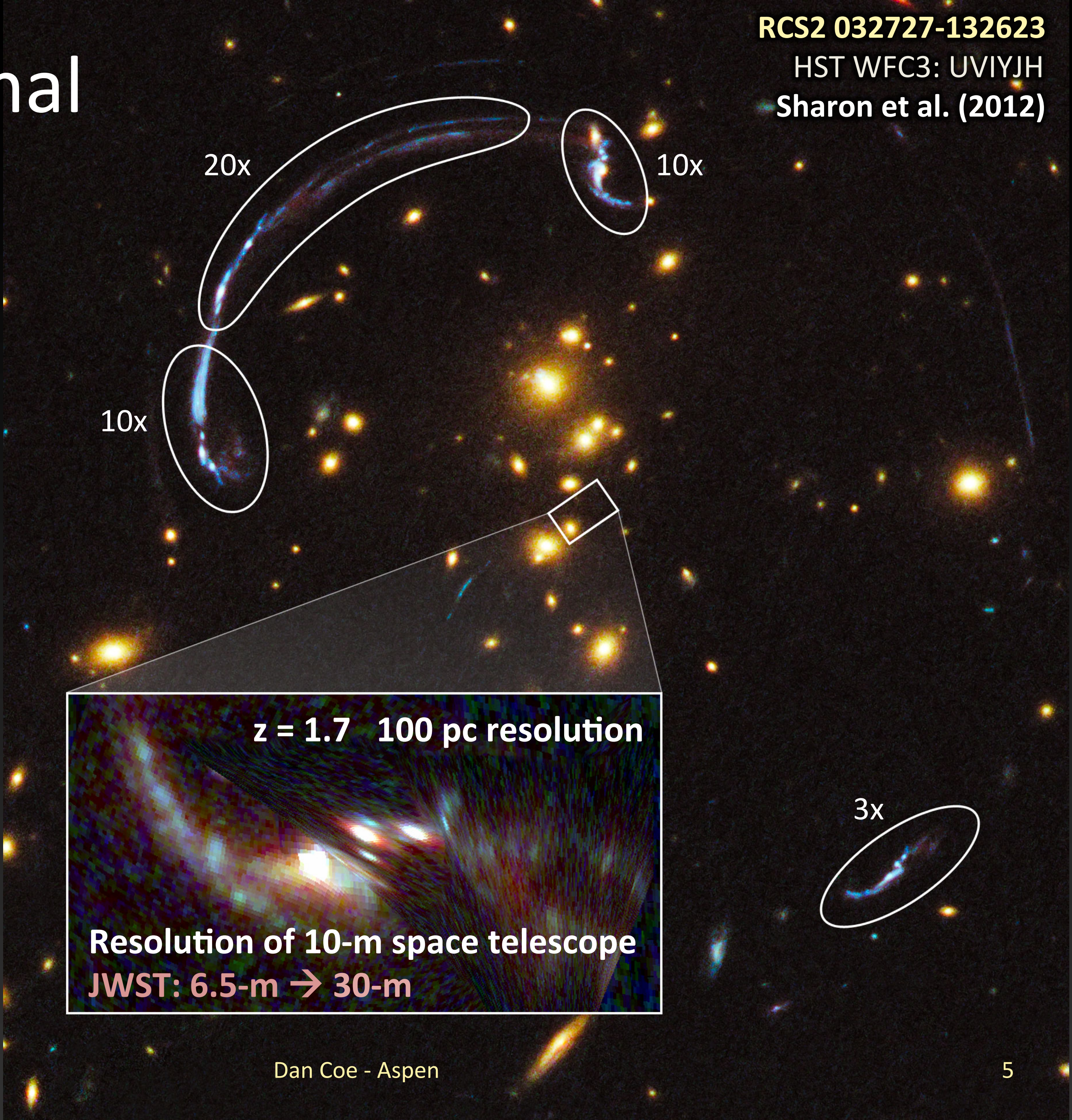
Gravitational lensing magnifies distant galaxies

enabling more efficient discovery and detailed analysis

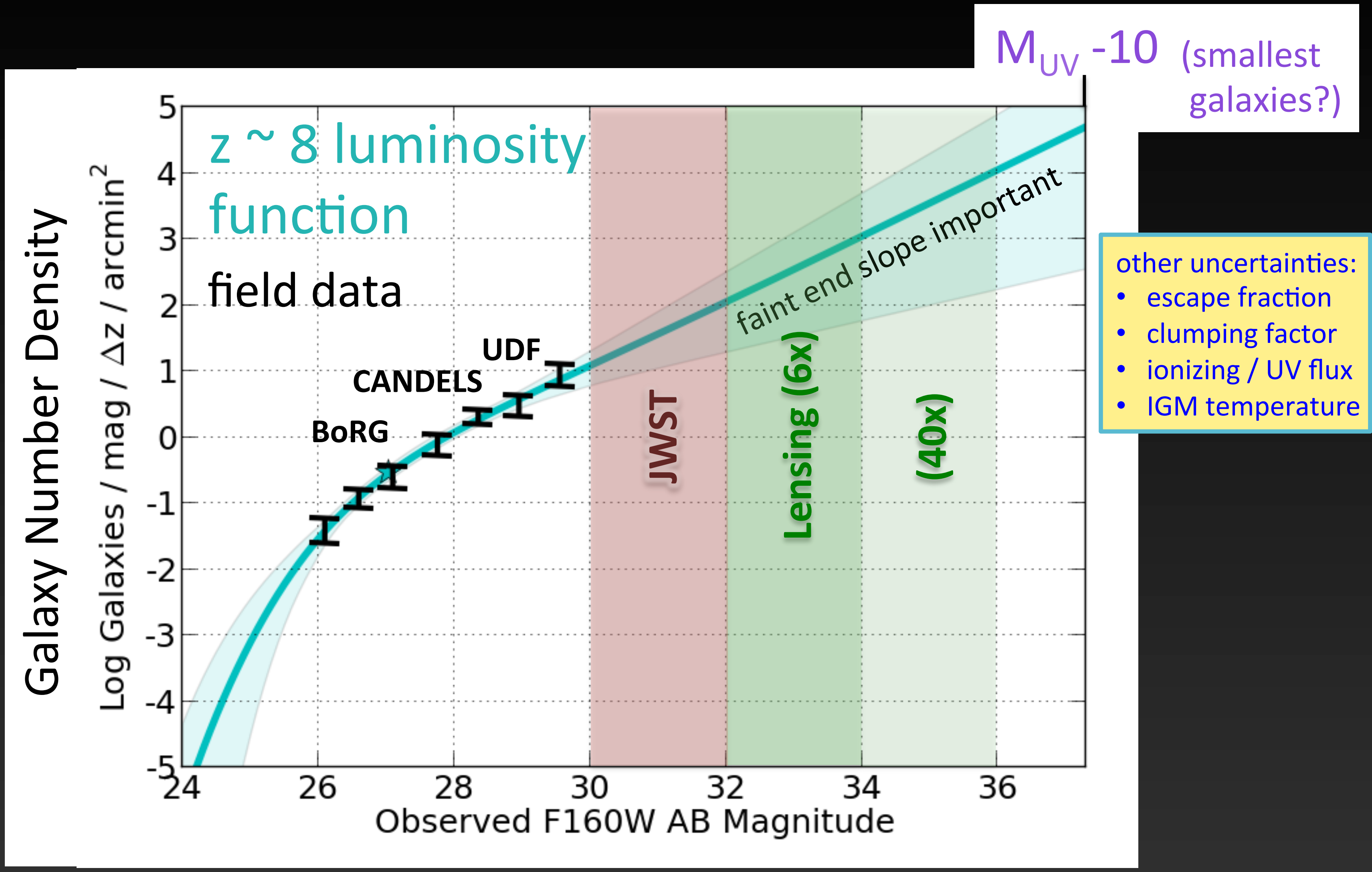


Animation: http://www.spacetelescope.org/videos/heic1106a/ – NASA, ESA & L. Calçada

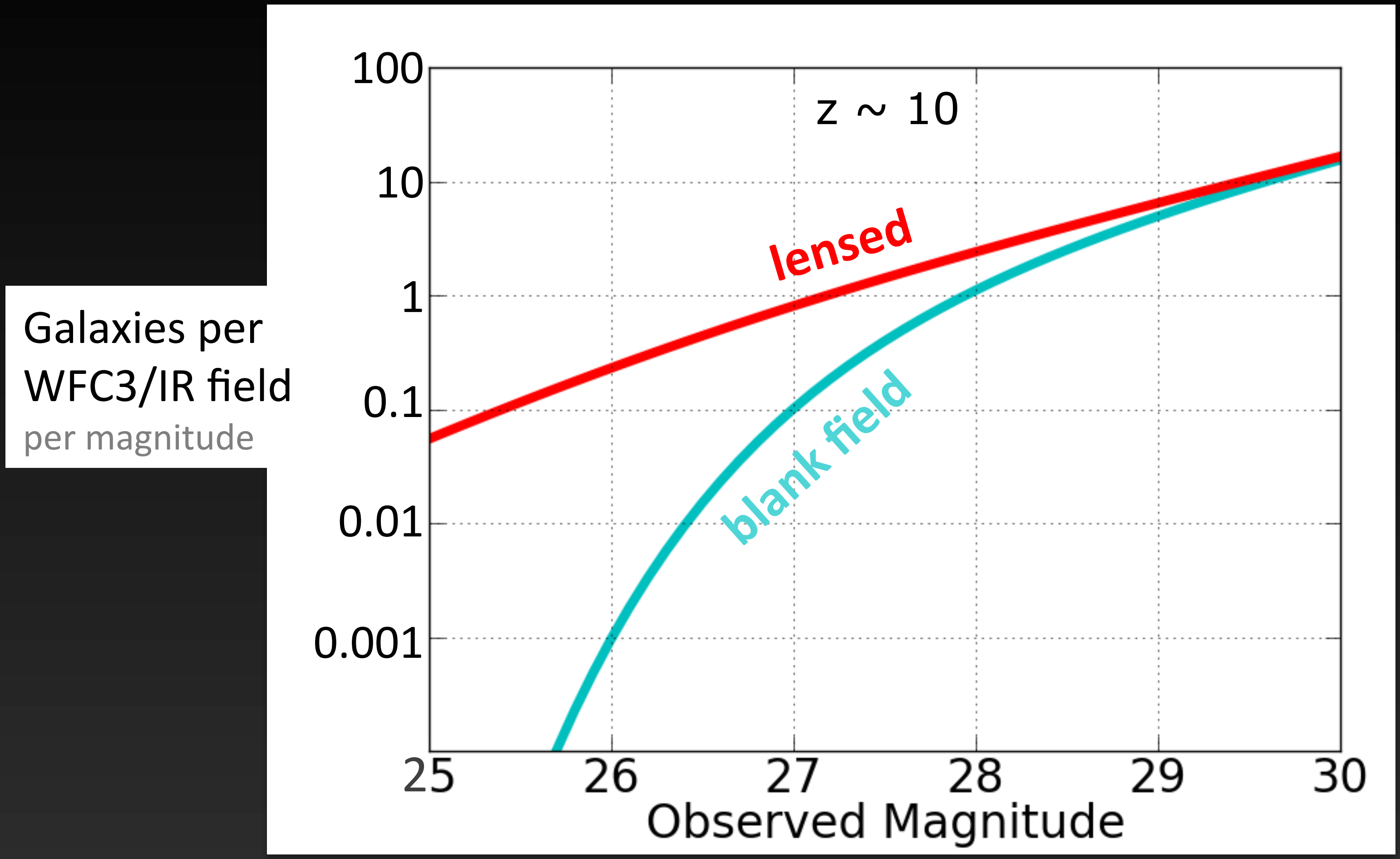
Gravitational lensing magnifies the distant universe



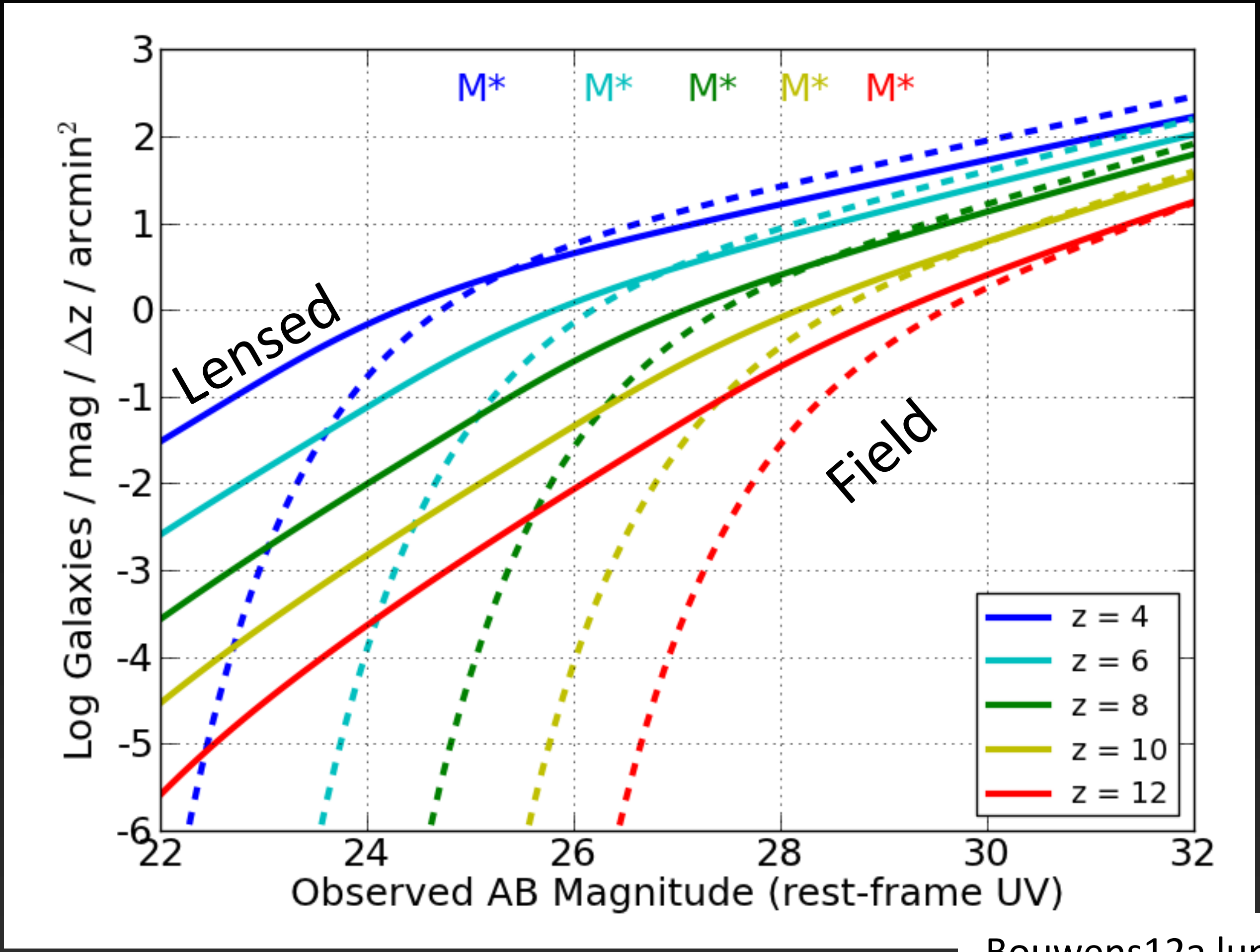
Large extrapolations required to estimate faint galaxy contribution to reionization



Cluster lensing enables more efficient discovery of the most distant galaxies

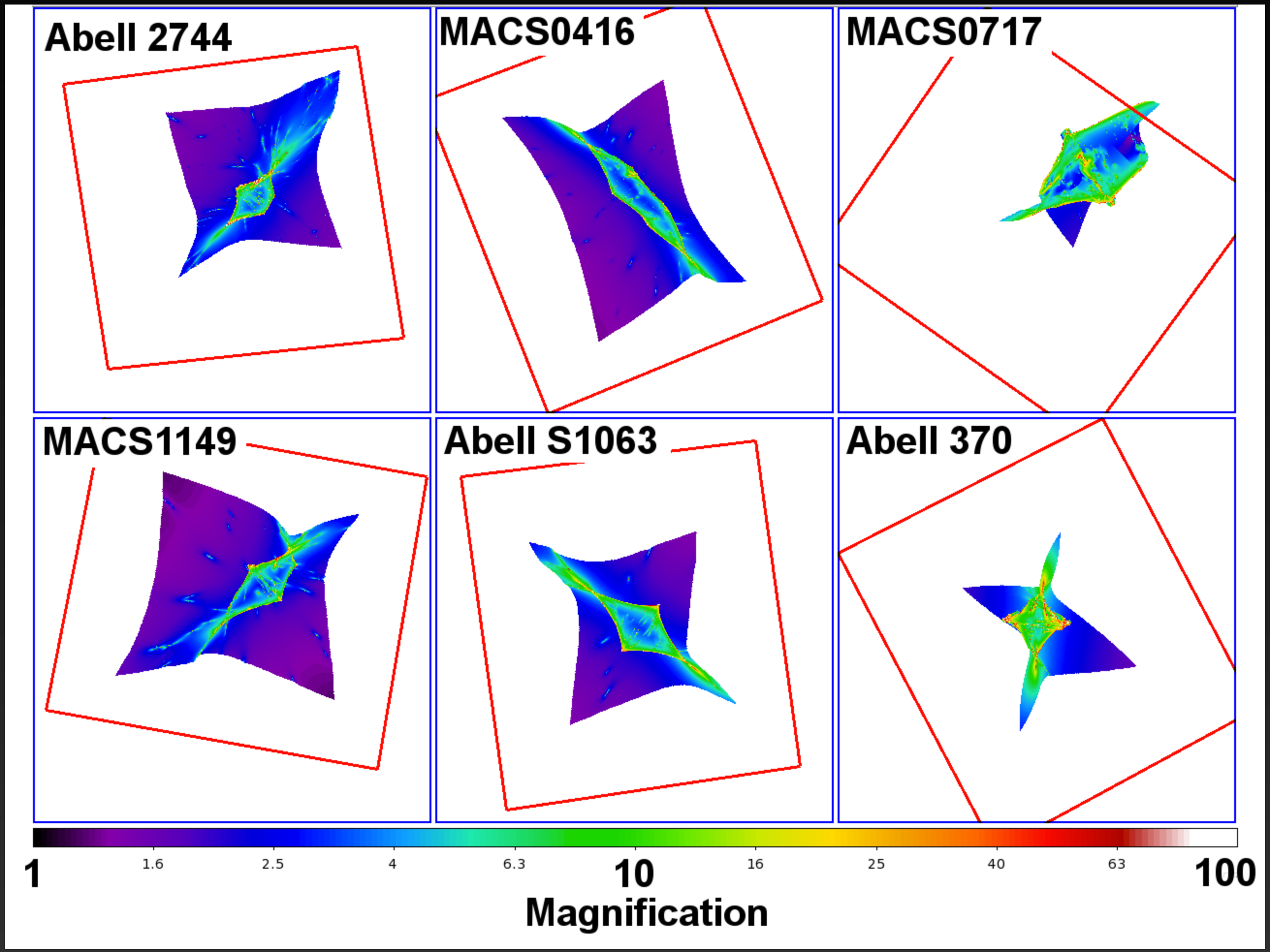


Cluster lensing wins at brighter magnitudes / higher redshifts



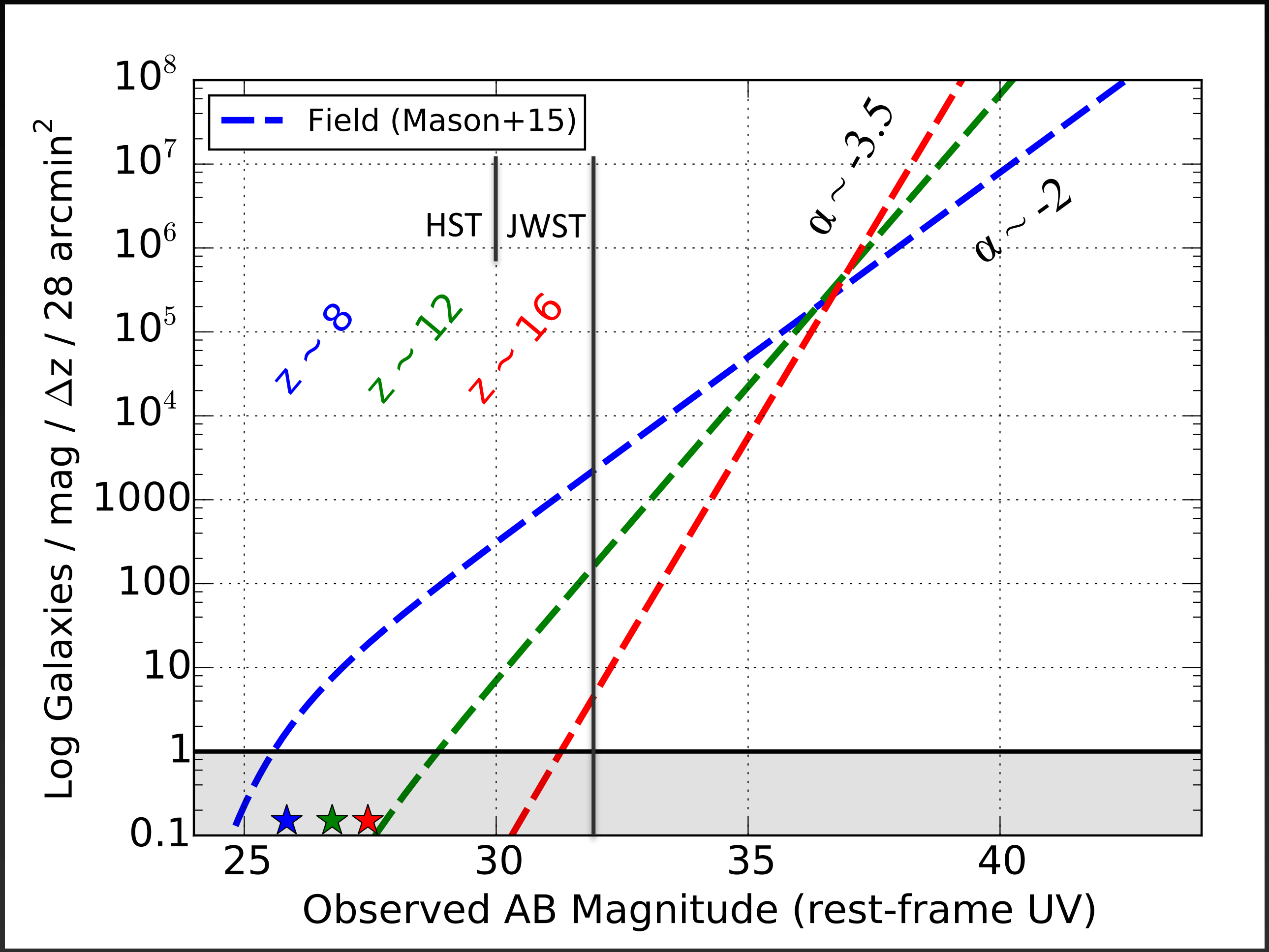
Bouwens12a luminosity function evolving all 3 parameters

Cluster lensing trades search area for high magnifications

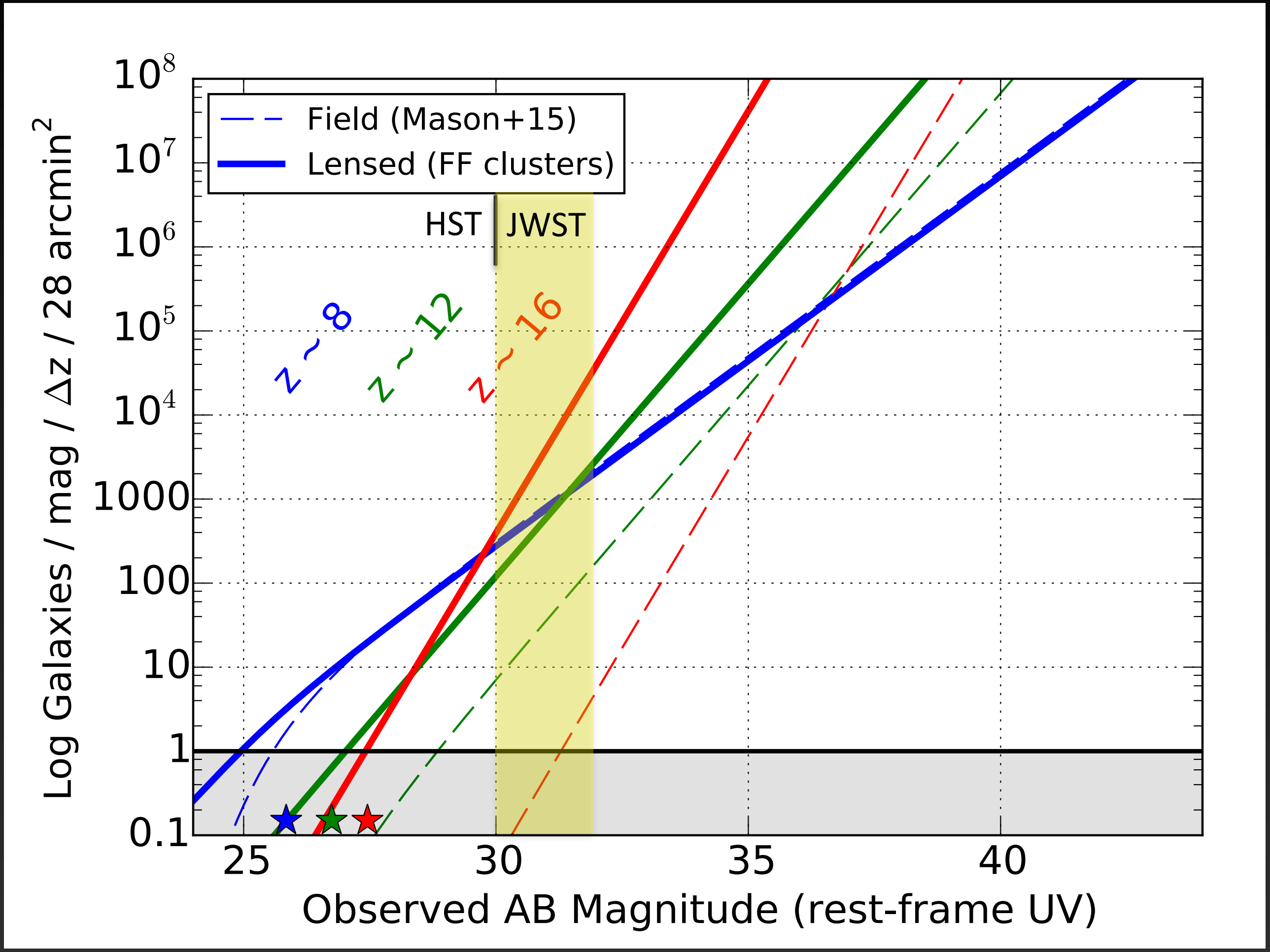


"CATS" team lens models of the Frontier Fields galaxy clusters

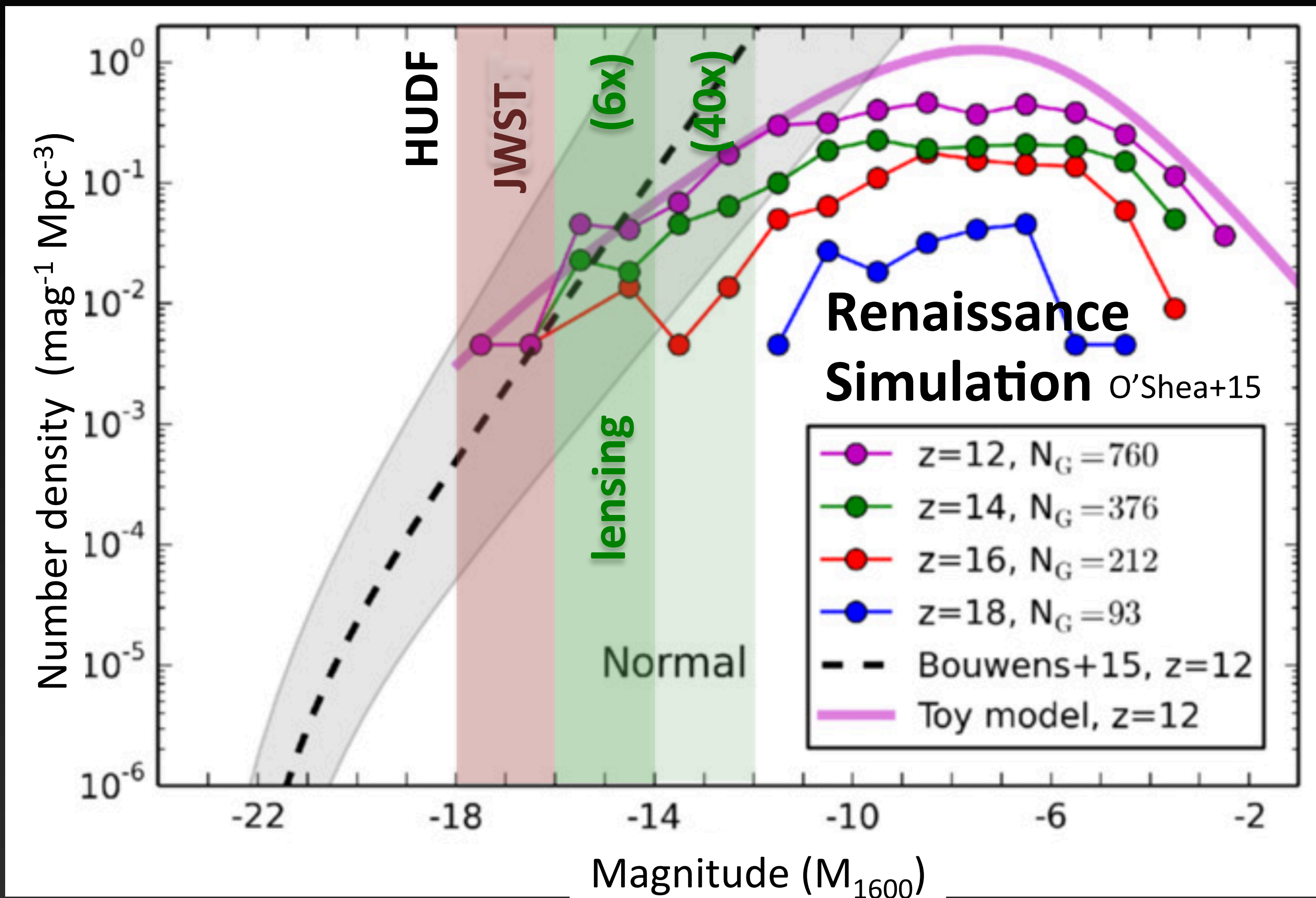
At even higher redshifts, steeper faint end slopes expected



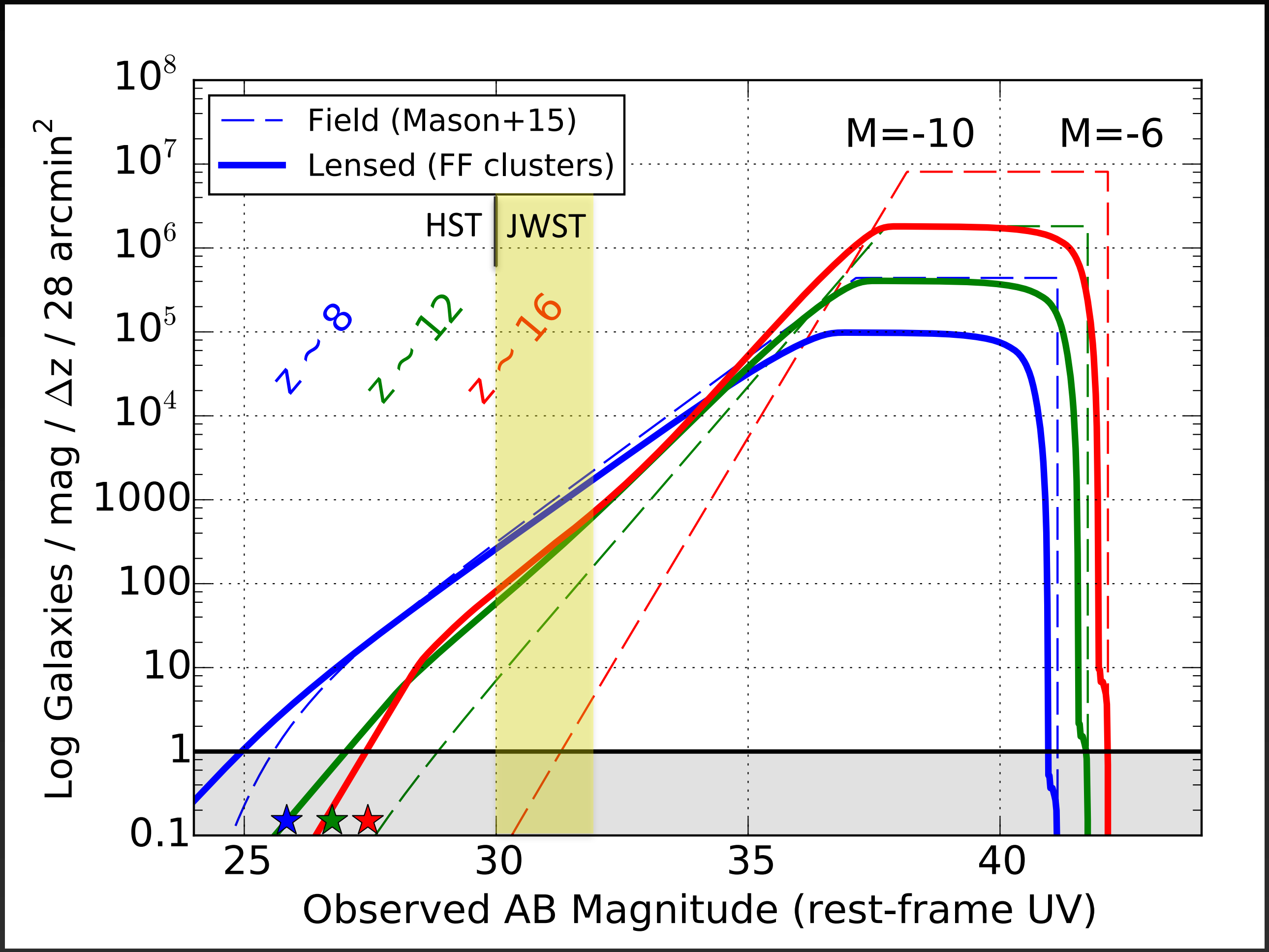
Lensing advantage increases at z > 10 thanks to steep faint end slopes



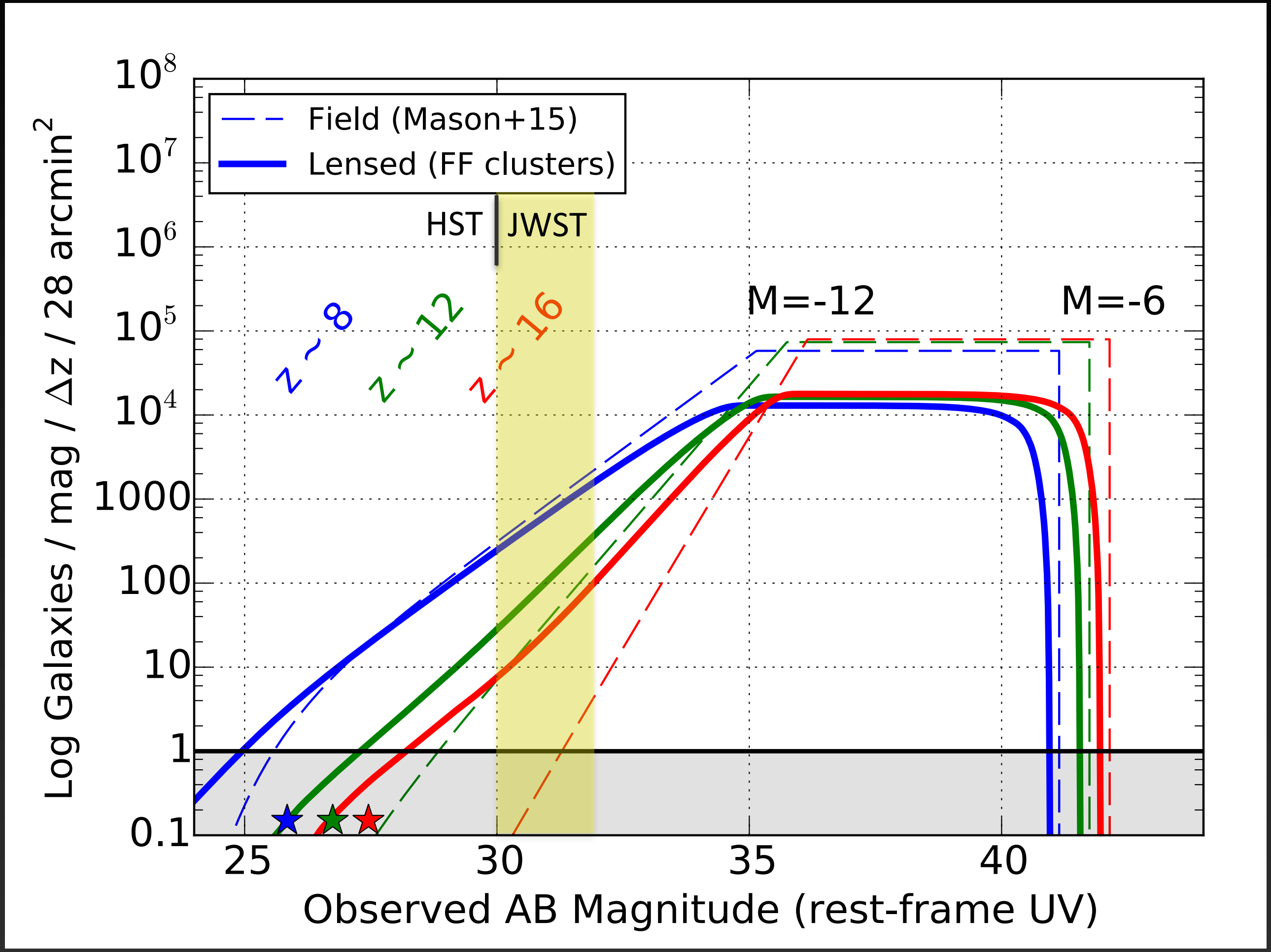
Faint end flattening predicted



Lensing advantage increases at z > 10 even if LF is truncated



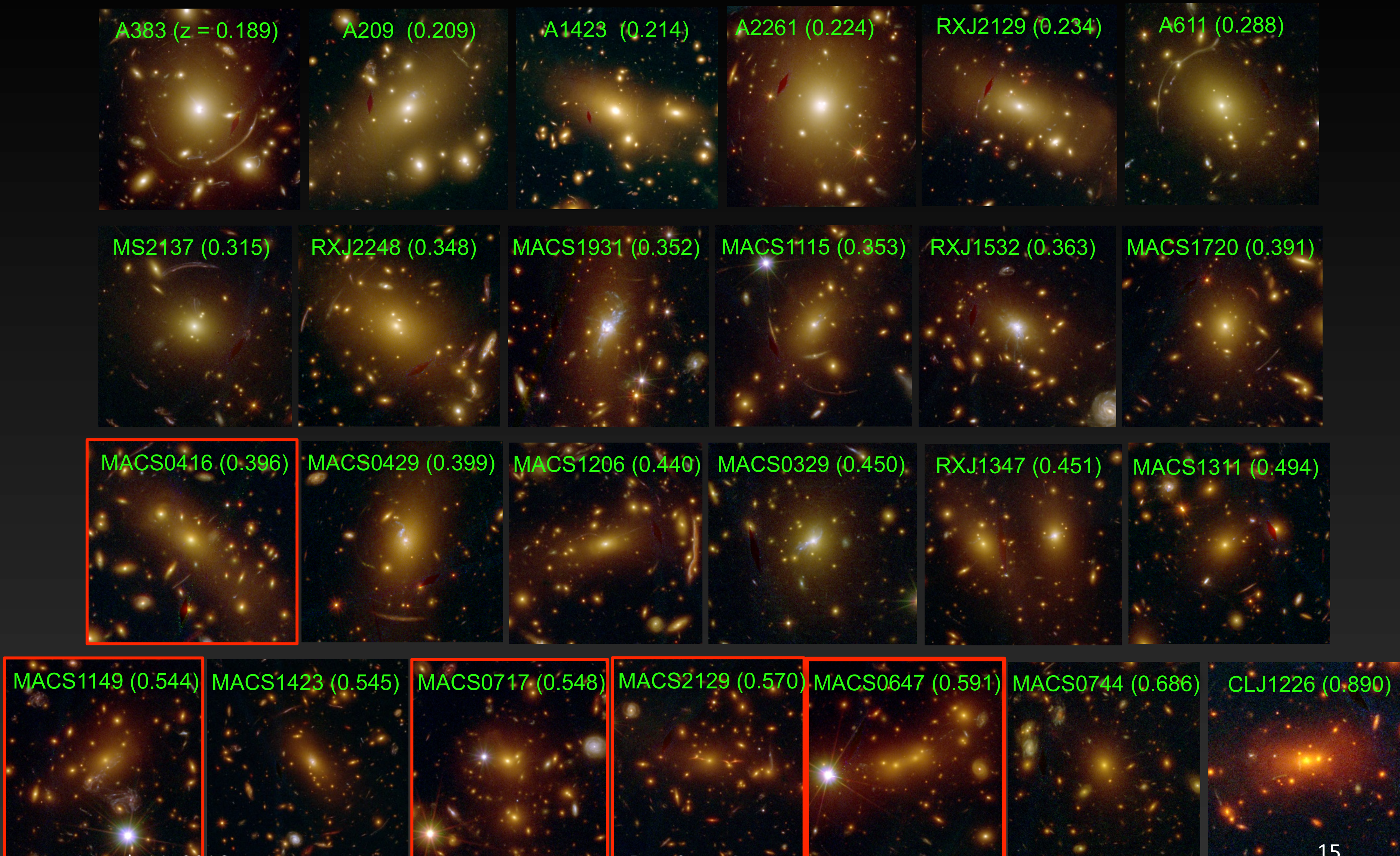
Lensing advantage increases at z > 10 even if LF is truncated



HST observations of 25 clusters

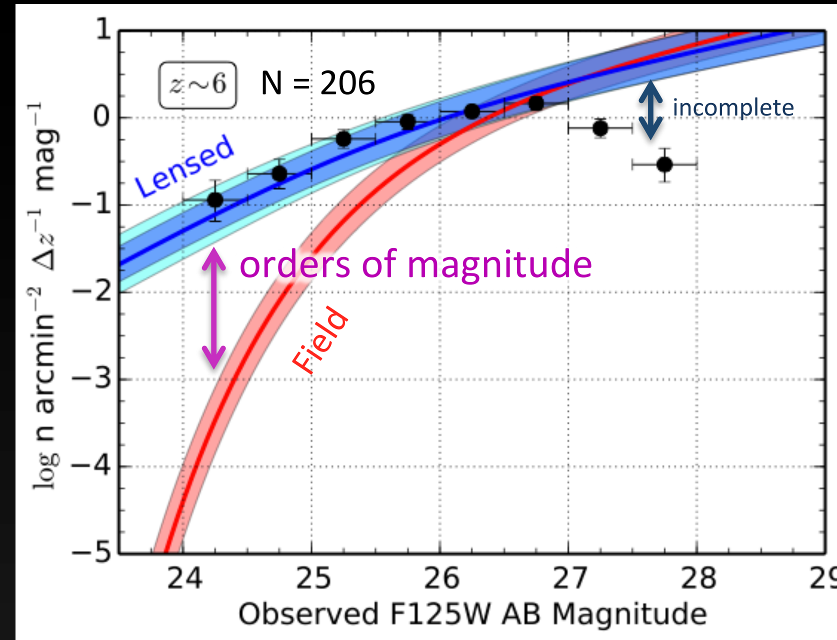
each 20 orbits, 16 filters

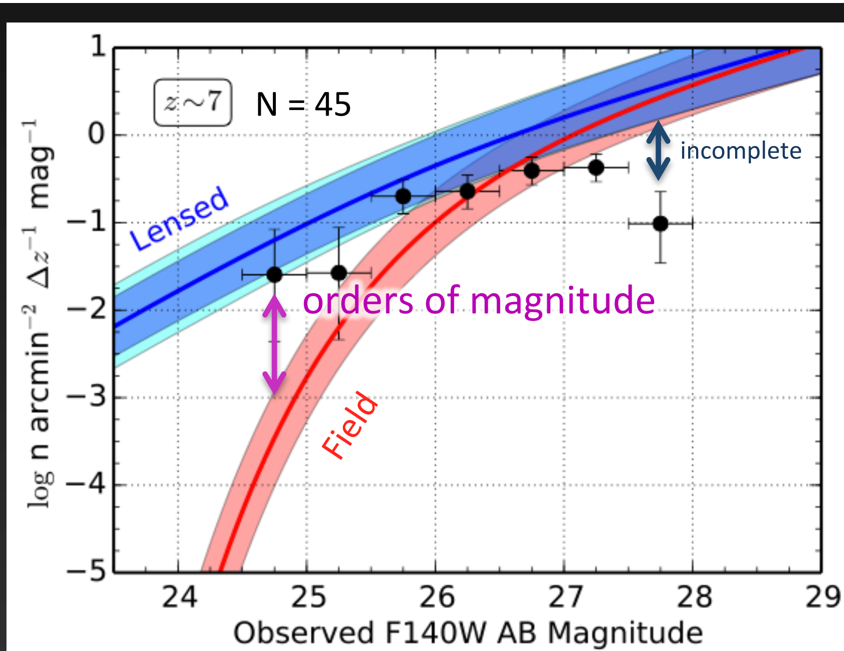
5 selected for lensing strength

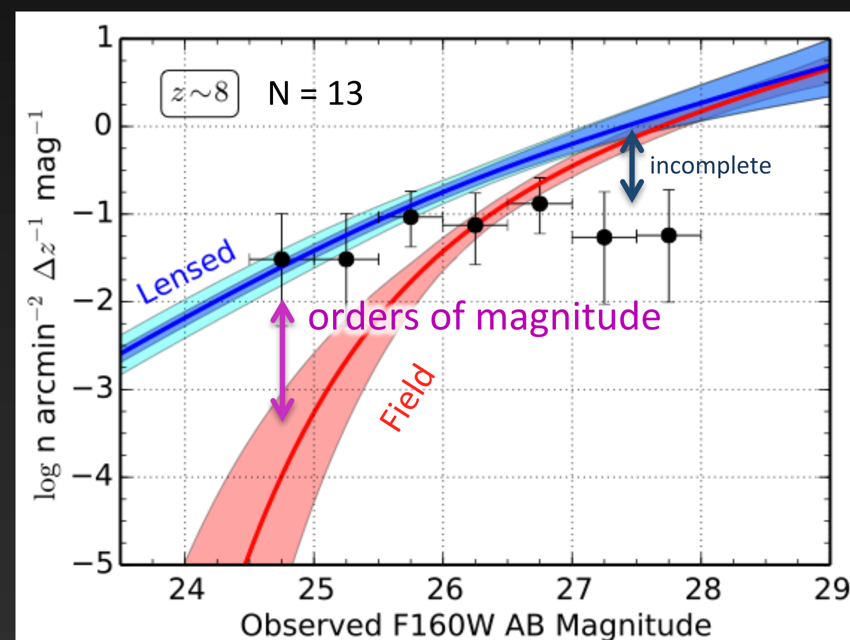


Lensed high-redshift galaxies discovered efficiently

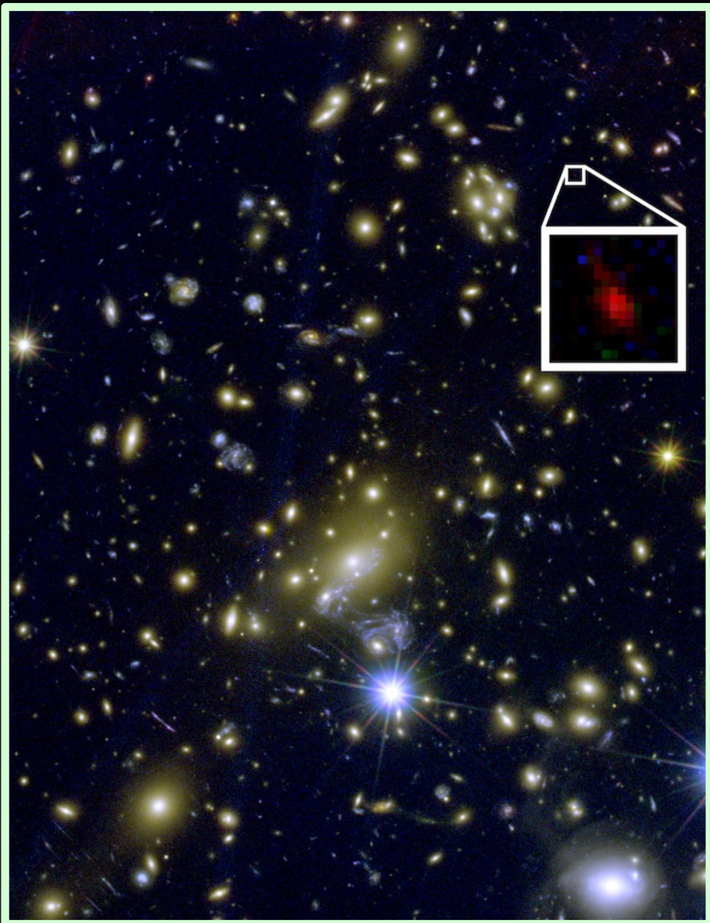
Bradley et al. (2013): 18 / 25 CLASH clusters





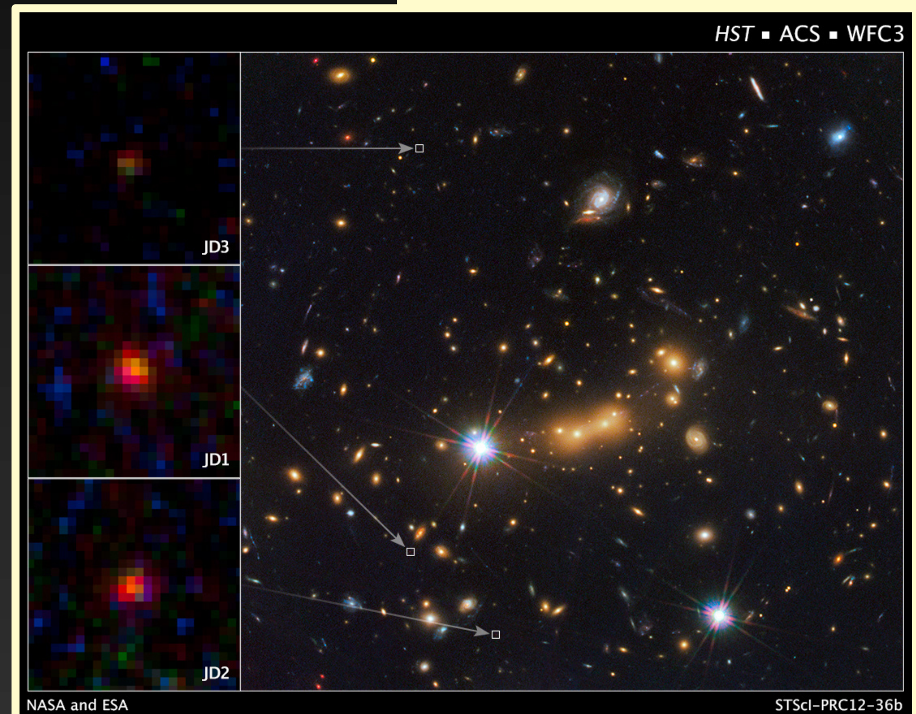


CLASH revealed two robust candidates in the first 500 Myr



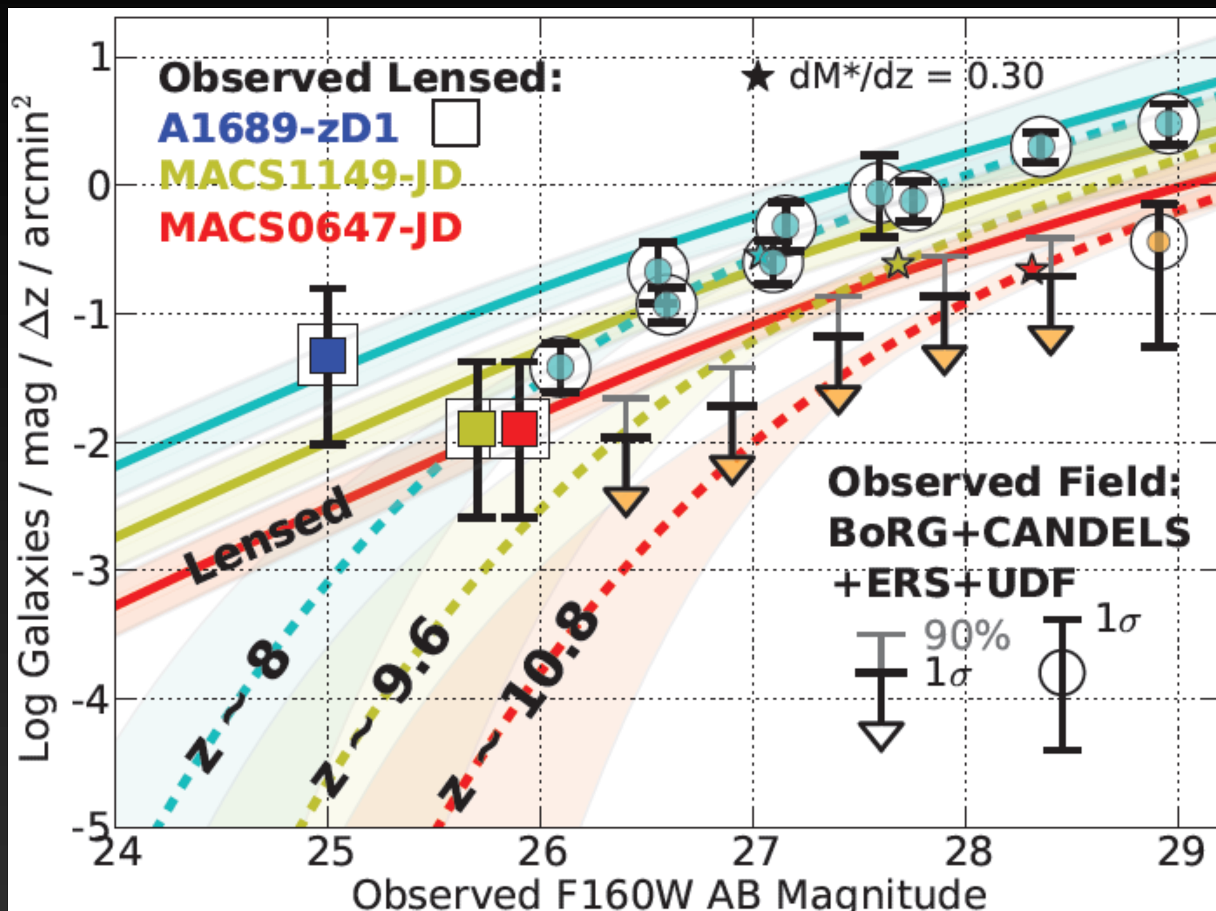
MACS1149-JD
z ~ 9.6 (490 Myr)
Wei Zheng et al. (2012)

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



in 2 / 5 “high-magnification” CLASH clusters

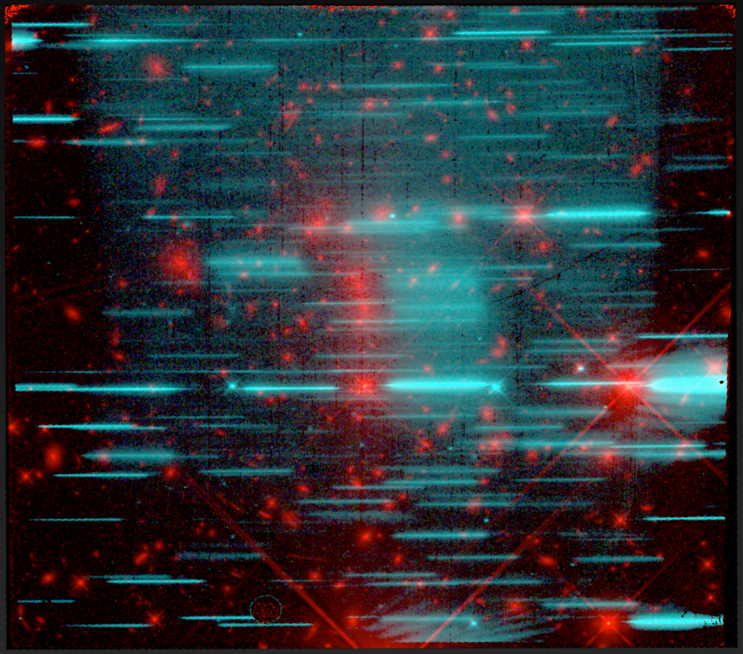
z ~ 11 detection consistent with extrapolated lensed LF



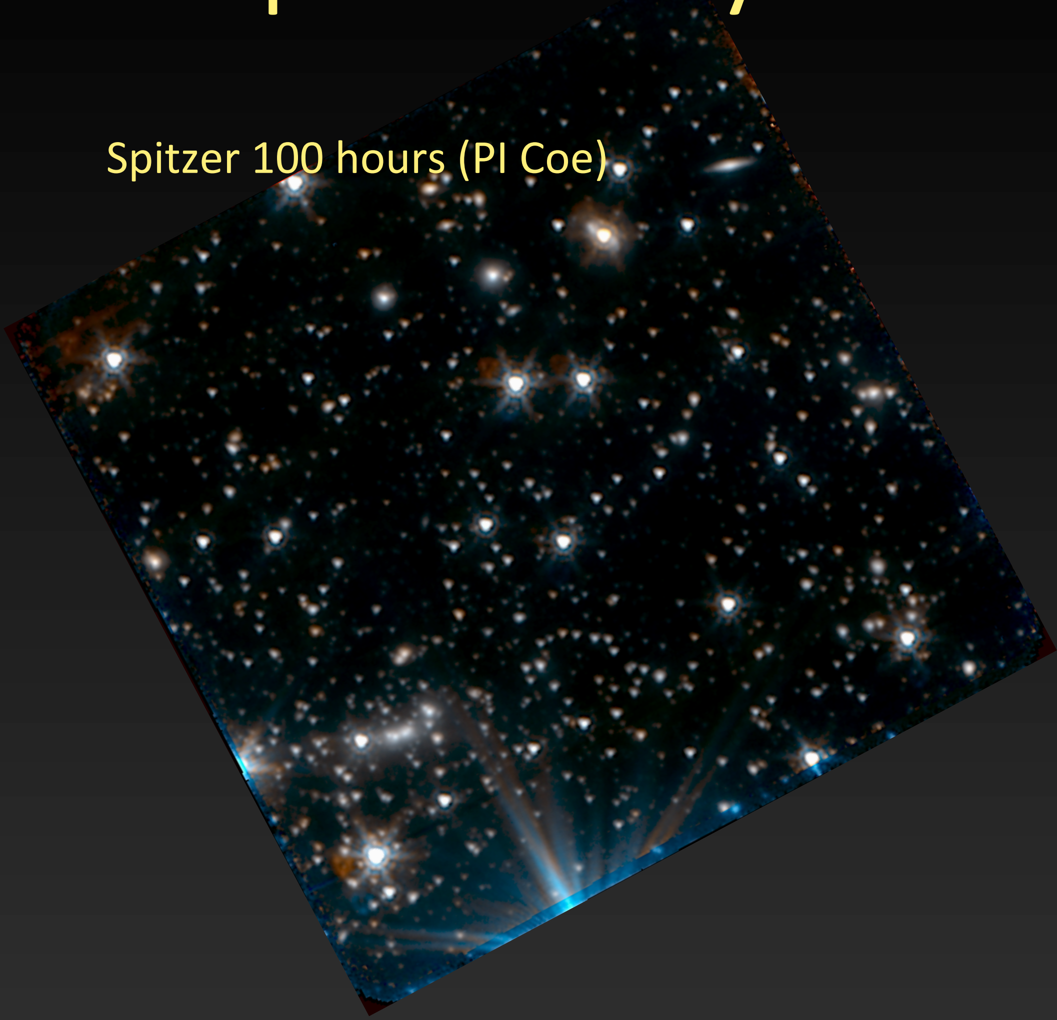
Coe+13

See talks by Pirzkal and Lam on z ~ 11 HST grism and Spitzer analyses

HST grism 12 orbits (PI Coe)



Spitzer 100 hours (PI Coe)



FRONTIER FIELDS

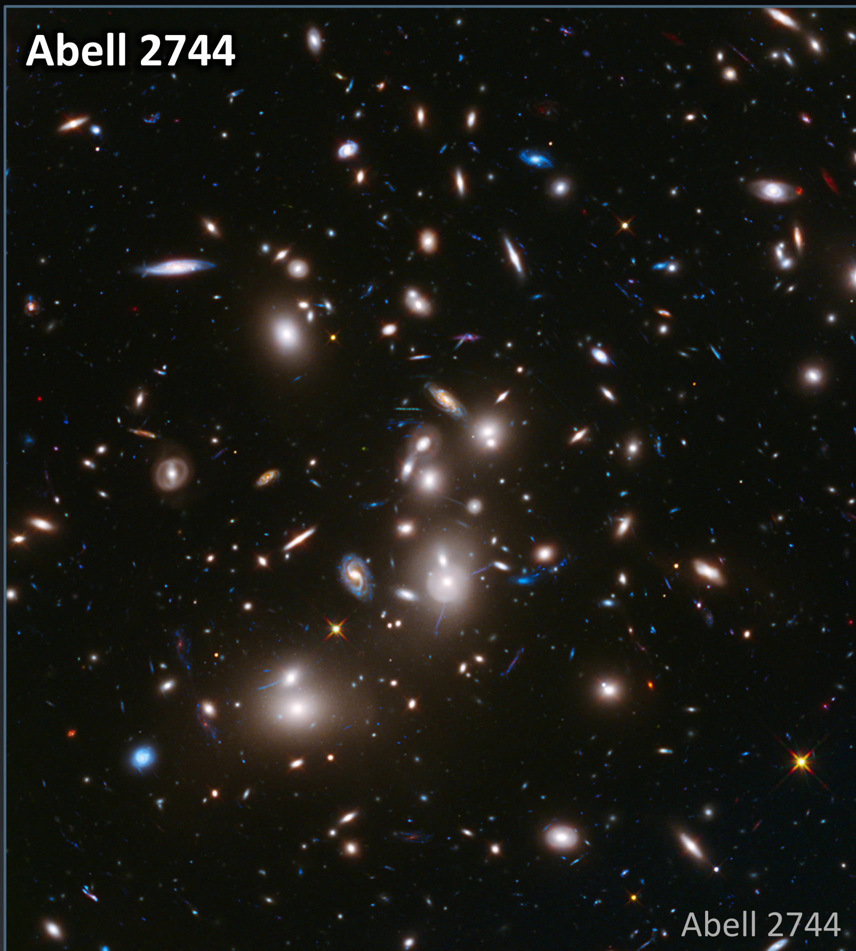
PI Jennifer Lotz

SPACE TELESCOPE SCIENCE INSTITUTE
Operated for NASA by AURA

SSC

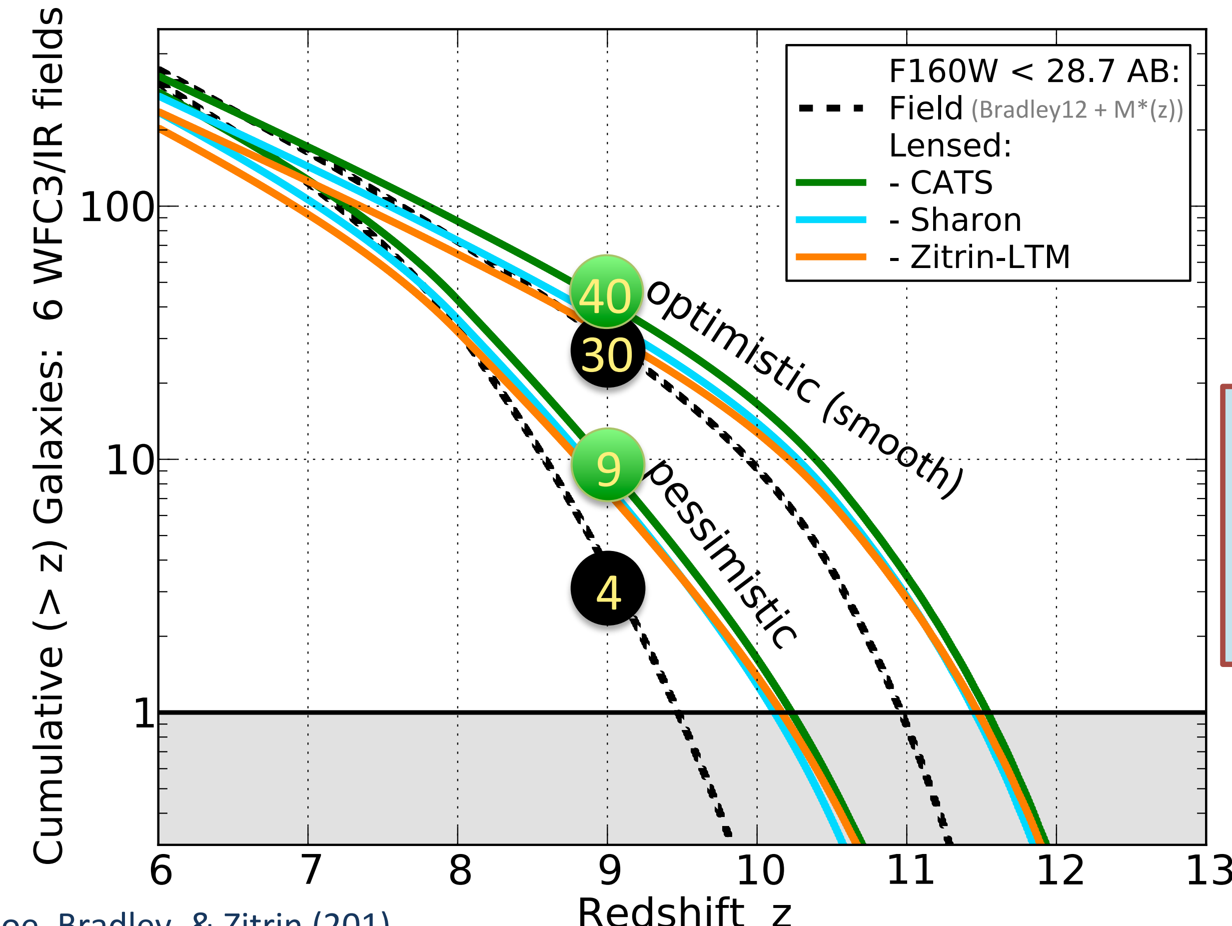
http://www.stsci.edu/hst/campaigns/frontier-fields/

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



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

not accounting for incompleteness



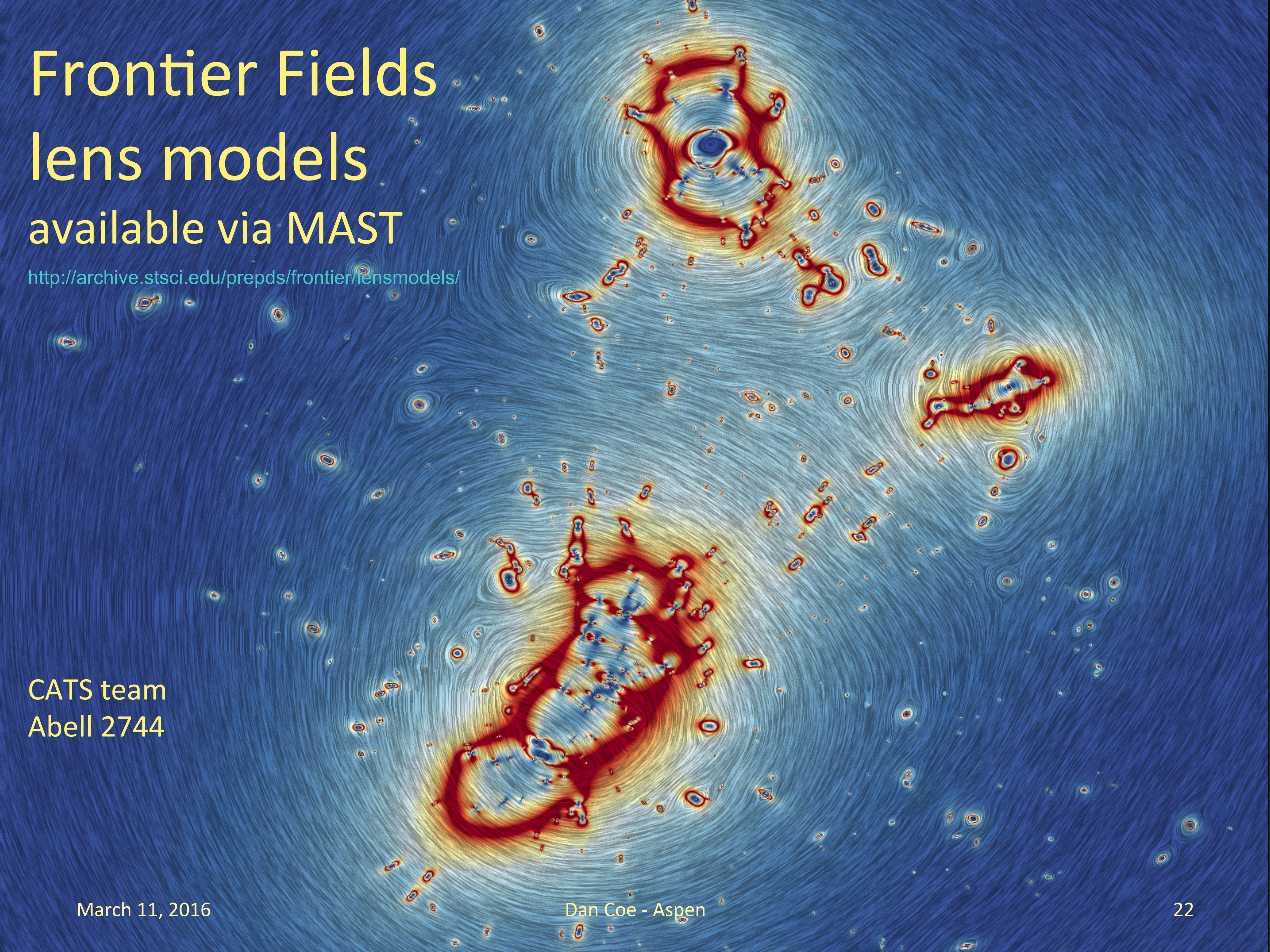
Coe, Bradley, & Zitrin (201)

Lens models yield consistent predictions

Frontier Fields lens models

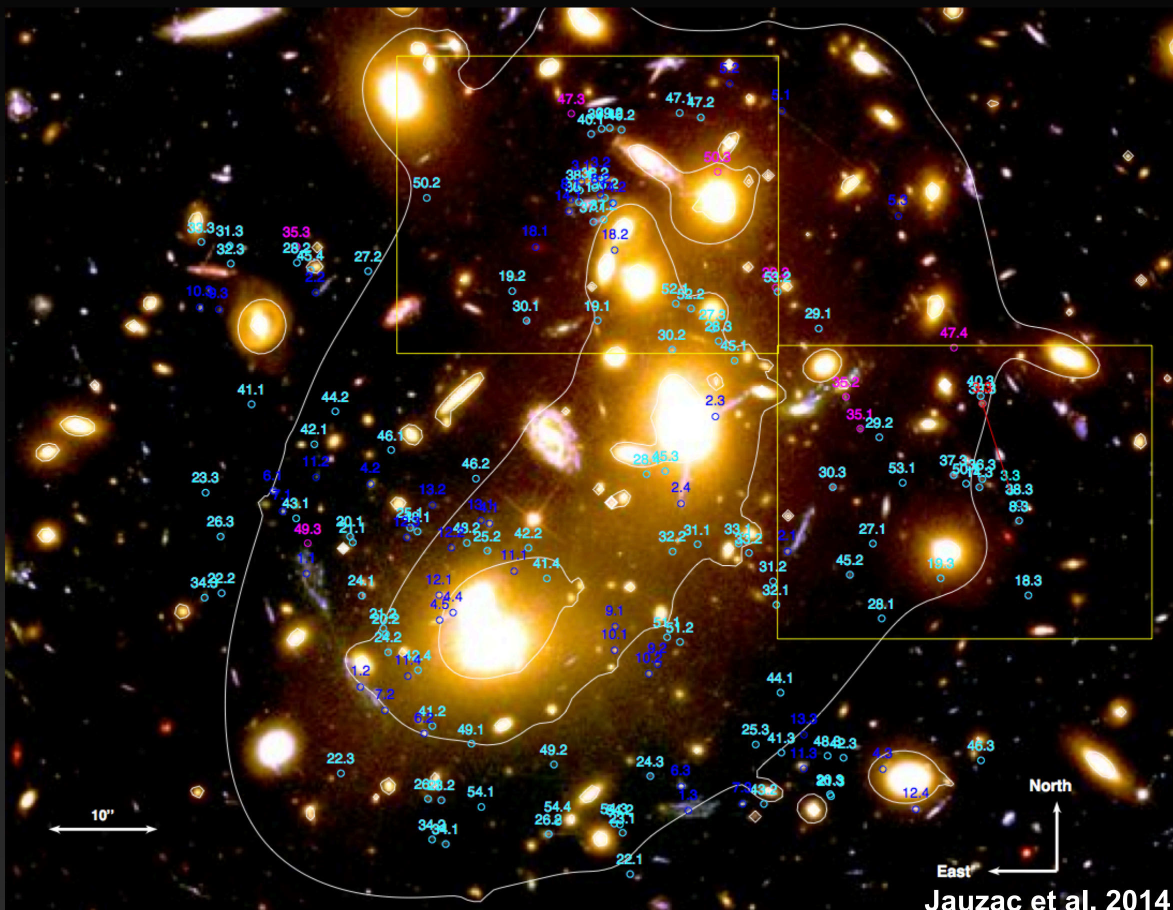
available via MAST

http://archive.stsci.edu/prepds/frontier/lensmodels/



CATS team
Abell 2744

Best constrained lens models



Abell 2744:

30 pre-FF multiple images

120 new multiple images

7 new but less confident

similar results for other clusters

Interactive model magnification web tool

FRONTIER FIELDS

Used ~2x / day (~1900x)
in first 2+ years
(Nov. 2013 – Mar. 2016)

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 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

Input
RA, Dec, redshift of lensed galaxies

- (•) Single lensed galaxy:
  - RA: 00:14:18.607
  - Dec: -30:24:31.36
  - z = 9.8
  - 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: JD1C

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

Models: (availability) (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 ☑
☑ 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 ☑
All None	All None

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

Retrieve magnification estimates

archive.stsci.edu/prepds/f...

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

Hubble Frontier Fields lens model magnification estimates

Output
Magnification estimates with uncertainties

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

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

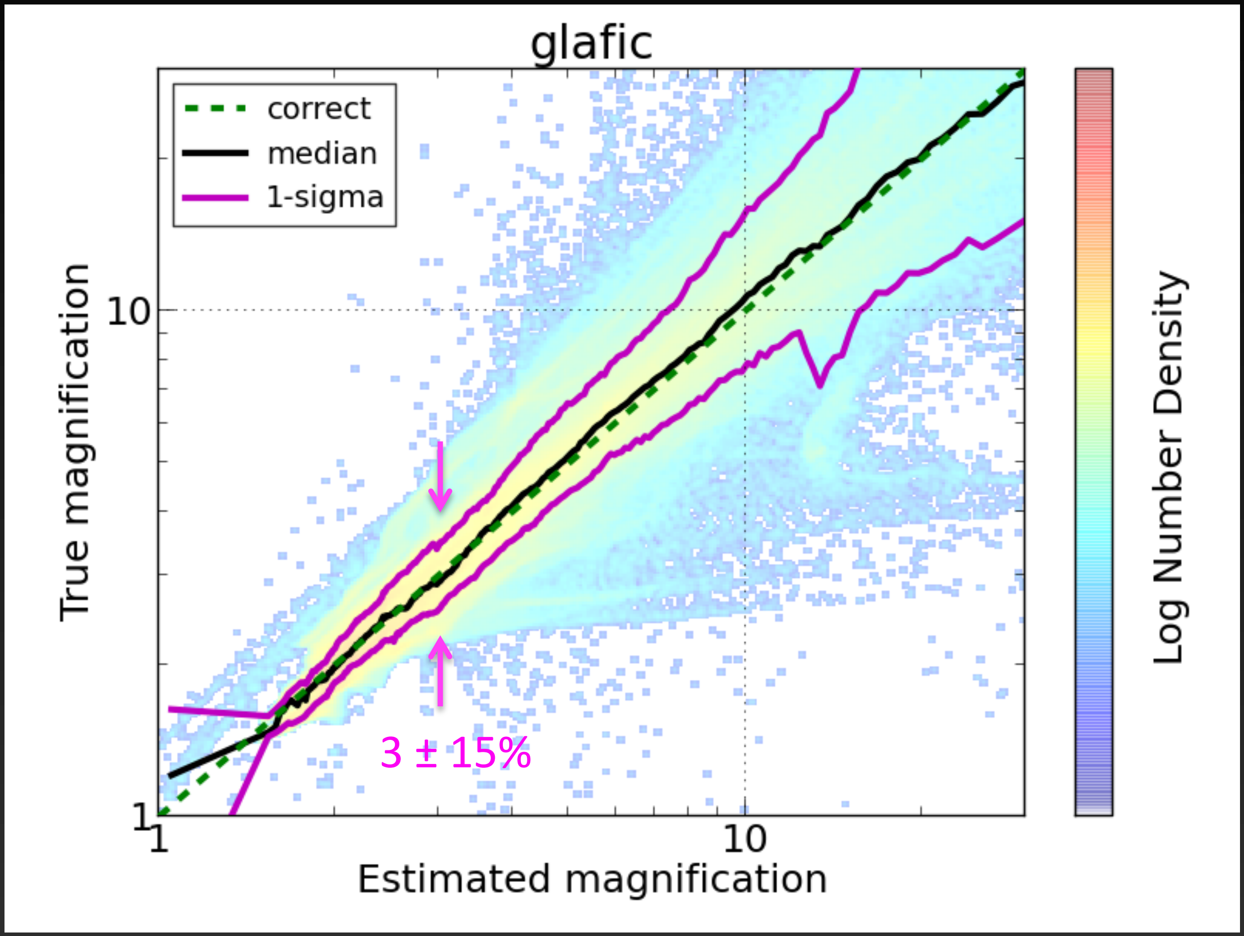
For a given (RA, Dec, z), outputs magnification estimates and uncertainties from all models

Simulated cluster lensing challenge to quantify model accuracies

"Hera" simulated by Meneghetti

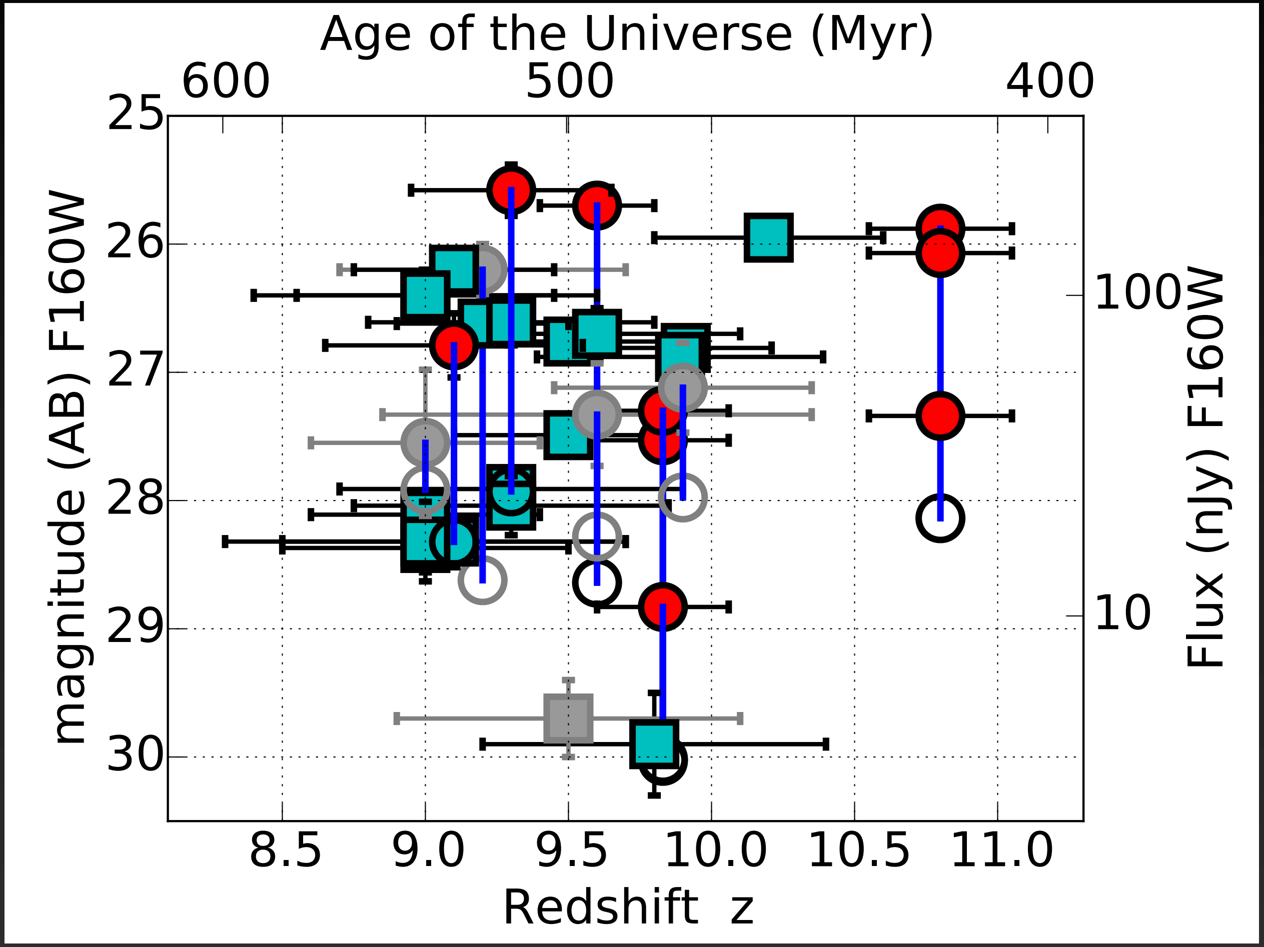
Project led by:
Priyamvada Natarjan
Massimo Meneghetti
Dan Coe

Magnification accuracies quantified; More tests required



"Only" 32 z > 9 candidates

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



Lensed
magnifications
Robust
Less secure
(Zheng12, Coe13, Bouwens13, Zitrin14, McLure16)

Field
Robust
Less secure
(Ellis13, Oesch13, Oesch14, Bouwens15, McLure16)

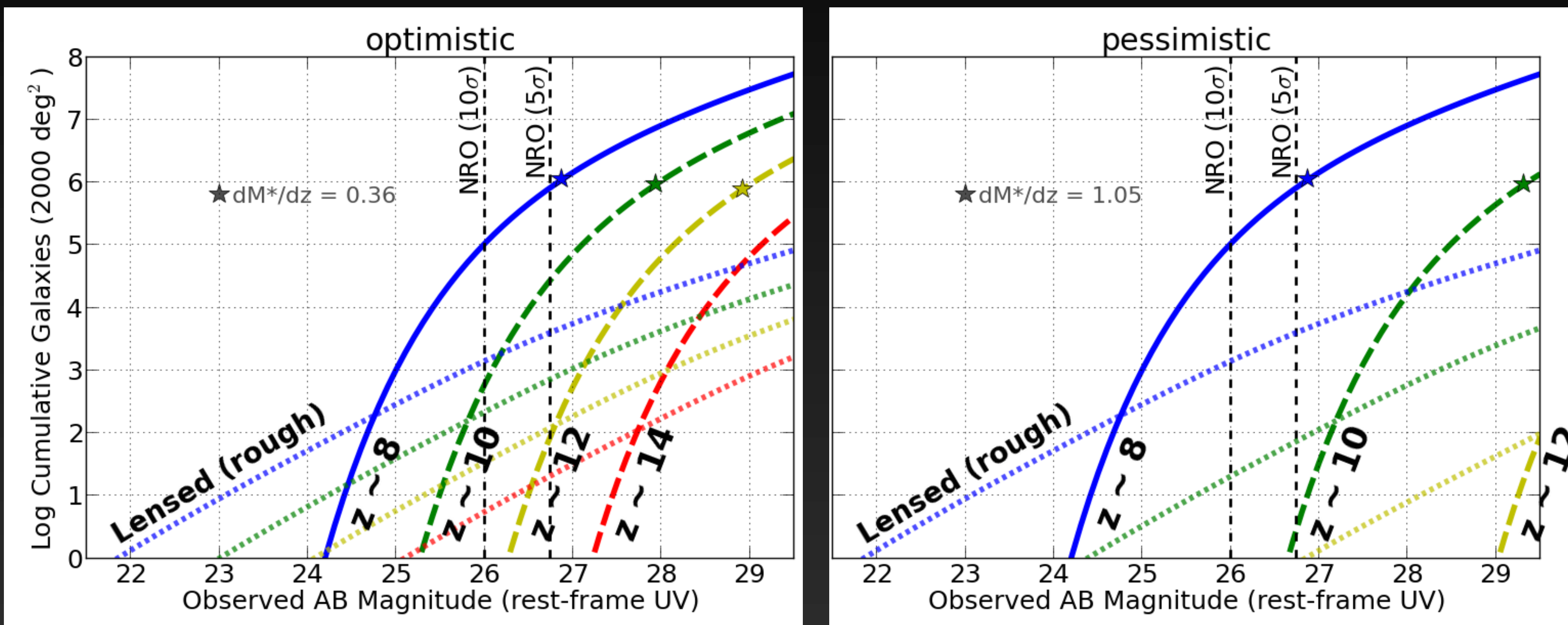
Beyond the Frontiers…

Euclid and WFIRST will yield many high-z candidates

Would be most useful before or during JWST's mission

WFIRST: 100,000's at z ~ 8 and perhaps some out to z ~ 15

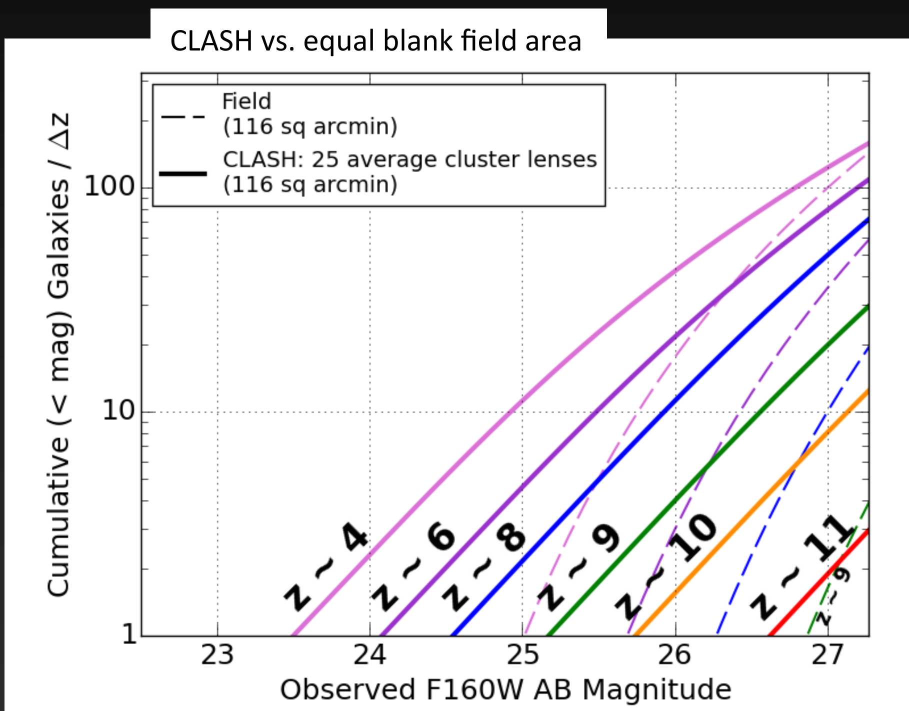
roughly assuming one strong lensing cluster per square degree

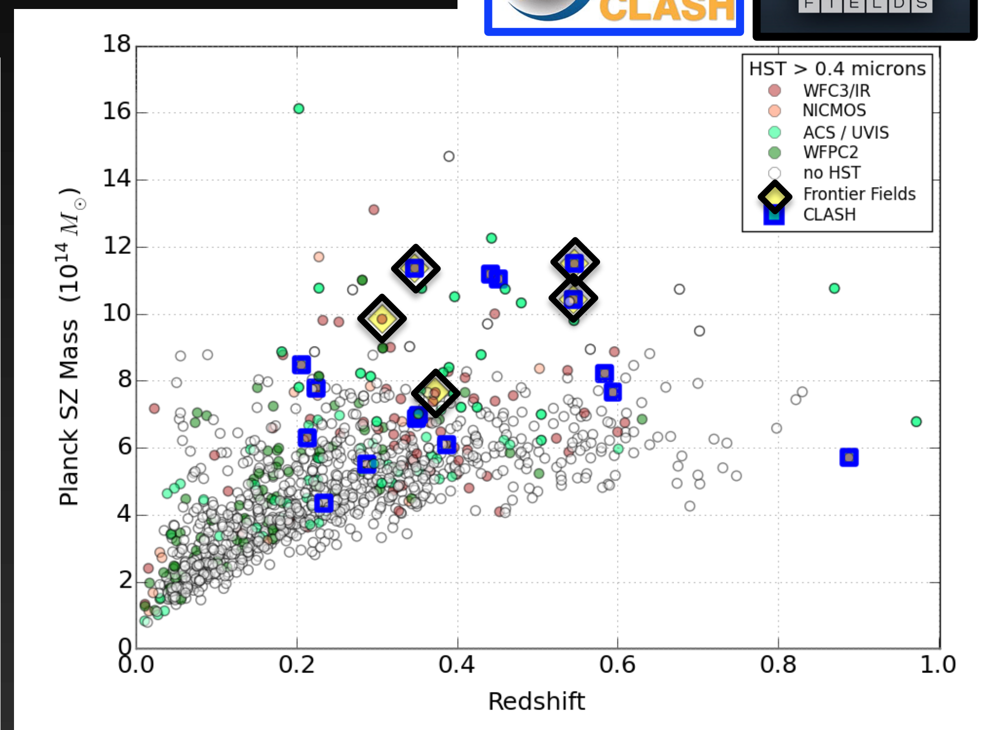


D. Coe & L. Bradley
WFIRST white paper submission

Beyond the Frontiers…

Hubble can discover the best and brightest high-redshift candidates in time for JWST with a large new cluster survey

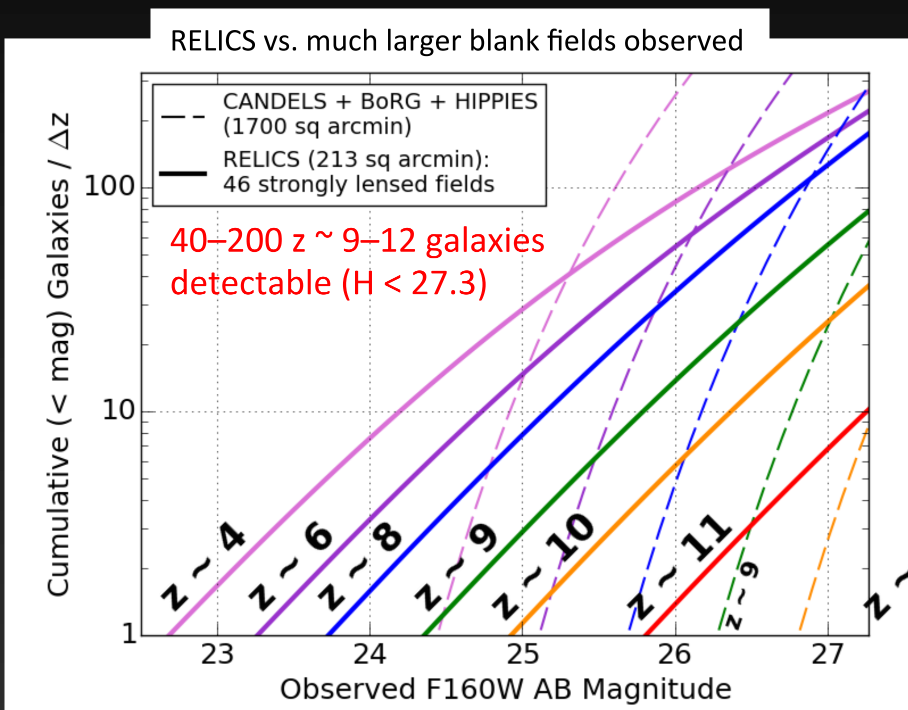


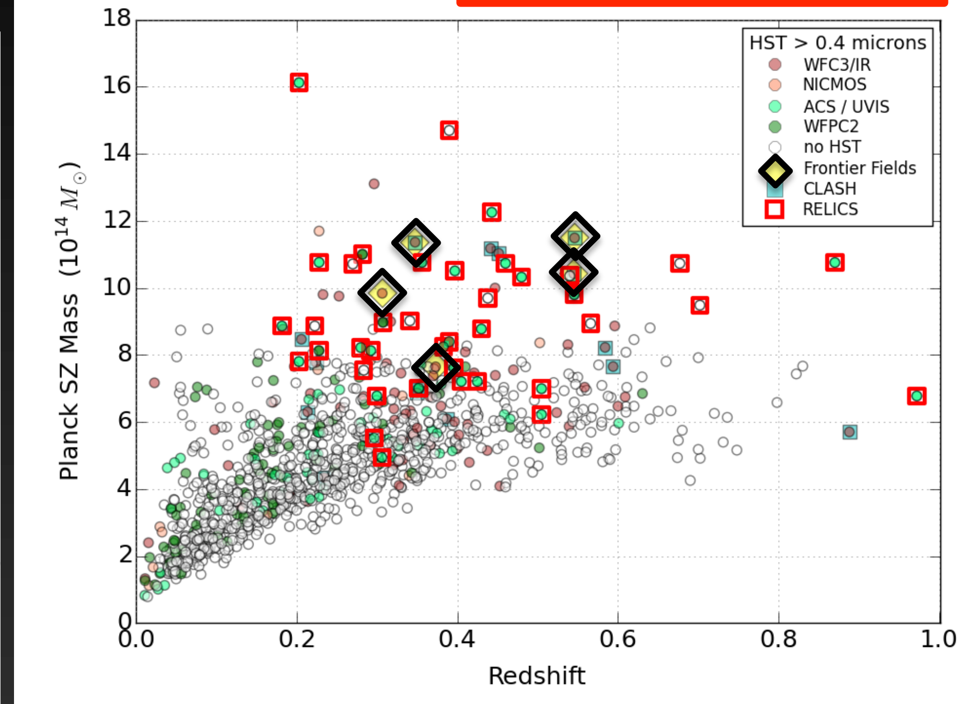


Beyond the Frontiers…

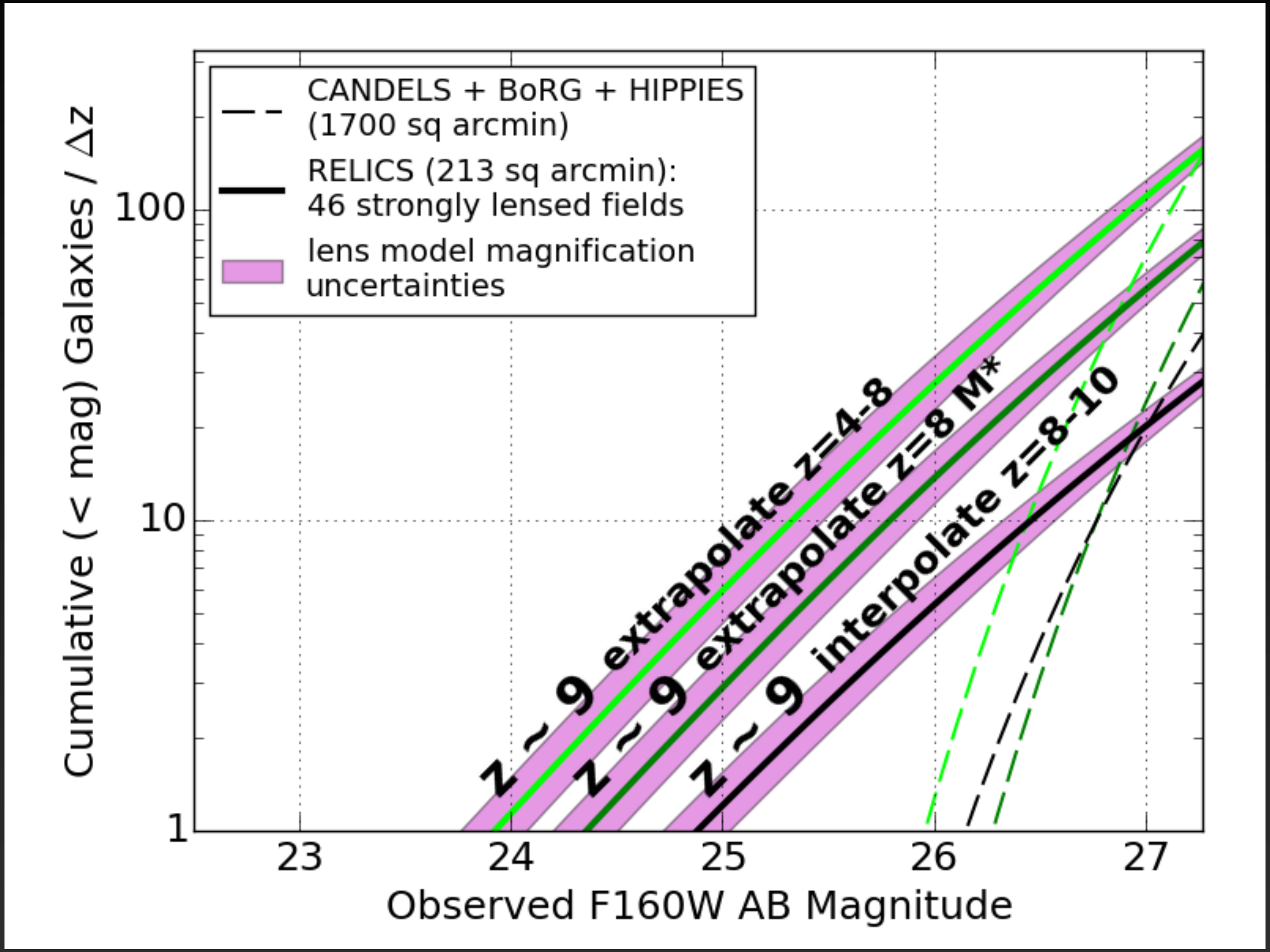
Hubble can discover the best and brightest high-redshift candidates in time for JWST with a large new cluster survey

RELICS
Reionization Lensing Cluster Survey





z ~ 9 efficiency and constraints



z ~ 9 – 12 galaxies
<u>if complete to H < 27.3</u>

200

100

40

http://relics.stsci.edu

RELICS: Reionization Lensing Cluster Survey

Dan Coe (PI)
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Roberto Avila
Rychard Bouwens
Maruša Bradač
Daniela Carrasco
Nicole Czakon
Will Dawson
Brenda Frye
Austin Hoag
Kuang-Han Huang
Traci Johnson
Christine Jones
Daniel Lam
Ramesh Mainali
Cordell Newmiller
Pascal Oesch
Sara Ogaz
Rachel Paterno-Mahler
Adam Riess
Steve Rodney
Russell Ryan
Brett Salmon
Irene Sendra-Server
Keren Sharon
Dan Stark
Lou Strolger
Michele Trenti
Keiichi Umetsu
Benedetta Vulcani
Adi Zitrin

Observations

46 fields lensed by 41 clusters
HST: 190 orbits + 77 parallel (incl. 20 for SN)
- 3 orbits ACS (minus archival)
- 2 orbits WFC3/IR   Frontier Fields filters

Spitzer: 390 hours (PIs Bradac, Soifer)

Science

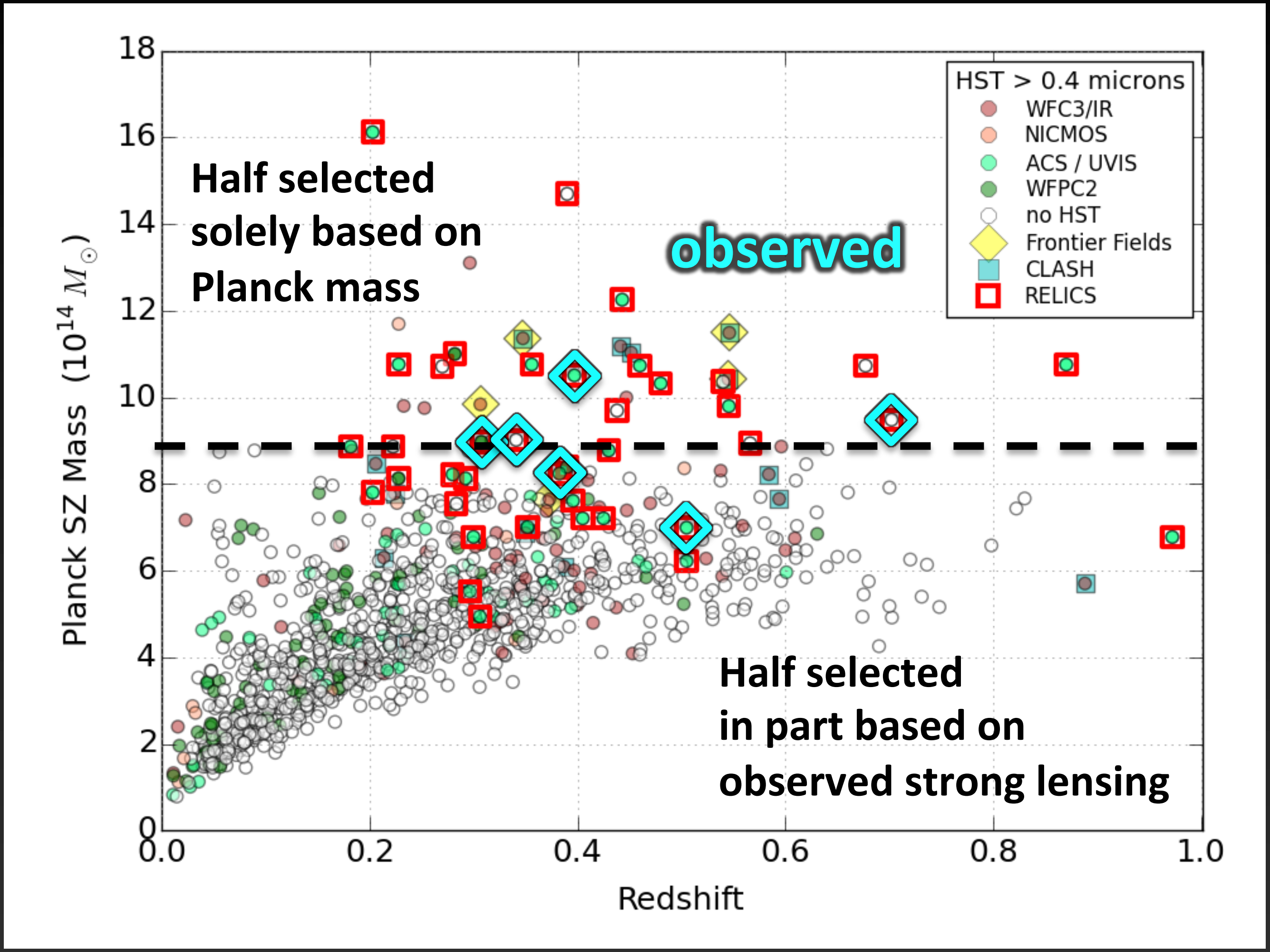
high-redshift galaxies
cluster mass scaling relations
merger physics + DM constraints
supernovae

Delivery

no proprietary period HST images
reduced images + catalogs
  2-3 months after completion of each field
final high-z candidates + lens models
  Nov. 2017 (JWST GO call for proposals)

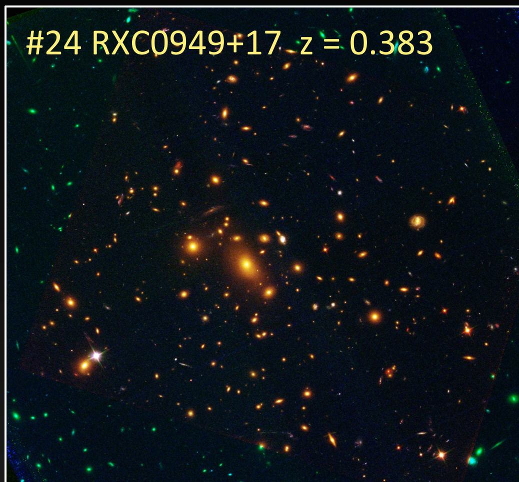
Example

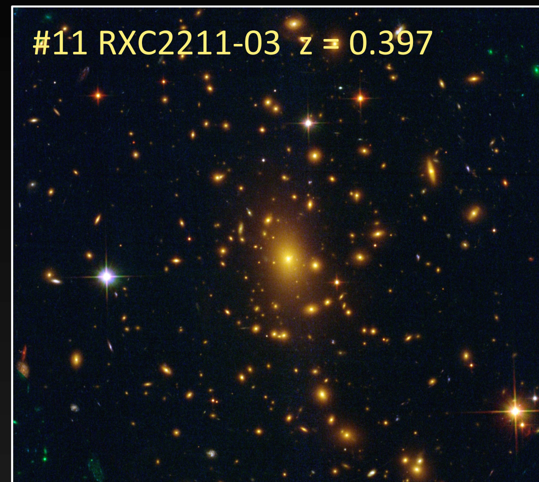
High Planck mass best for lensing?

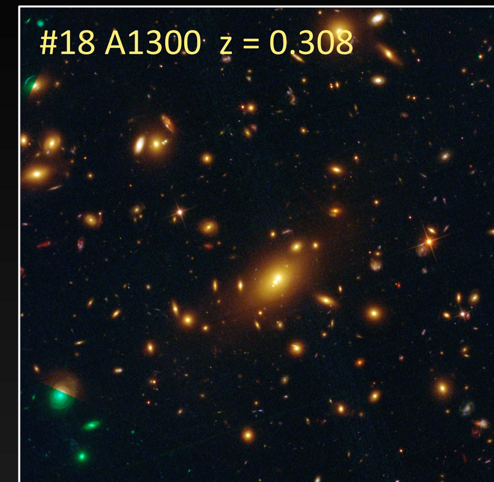


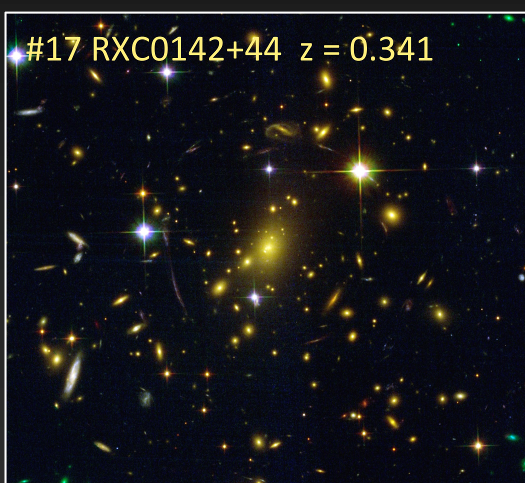
RELICS
Reionization Lensing Cluster Survey

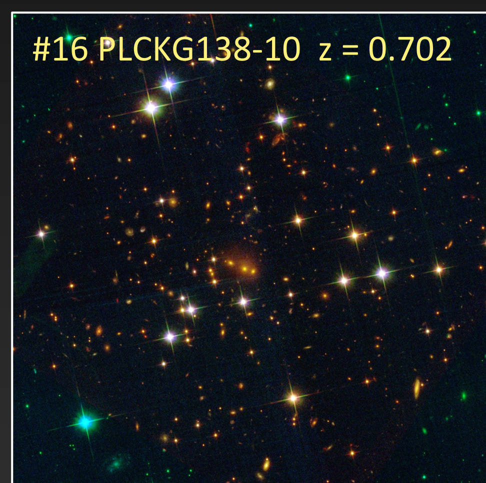
6 / 41 RELICS clusters observed so far

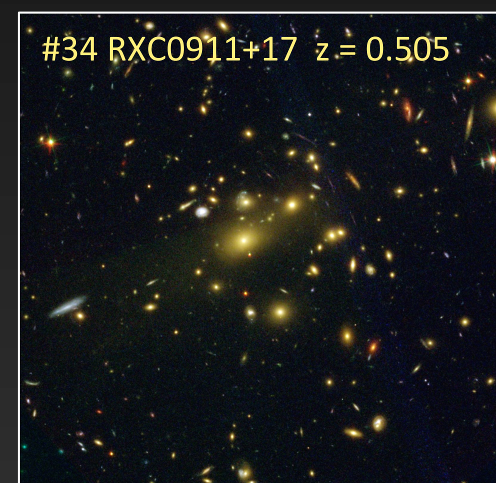




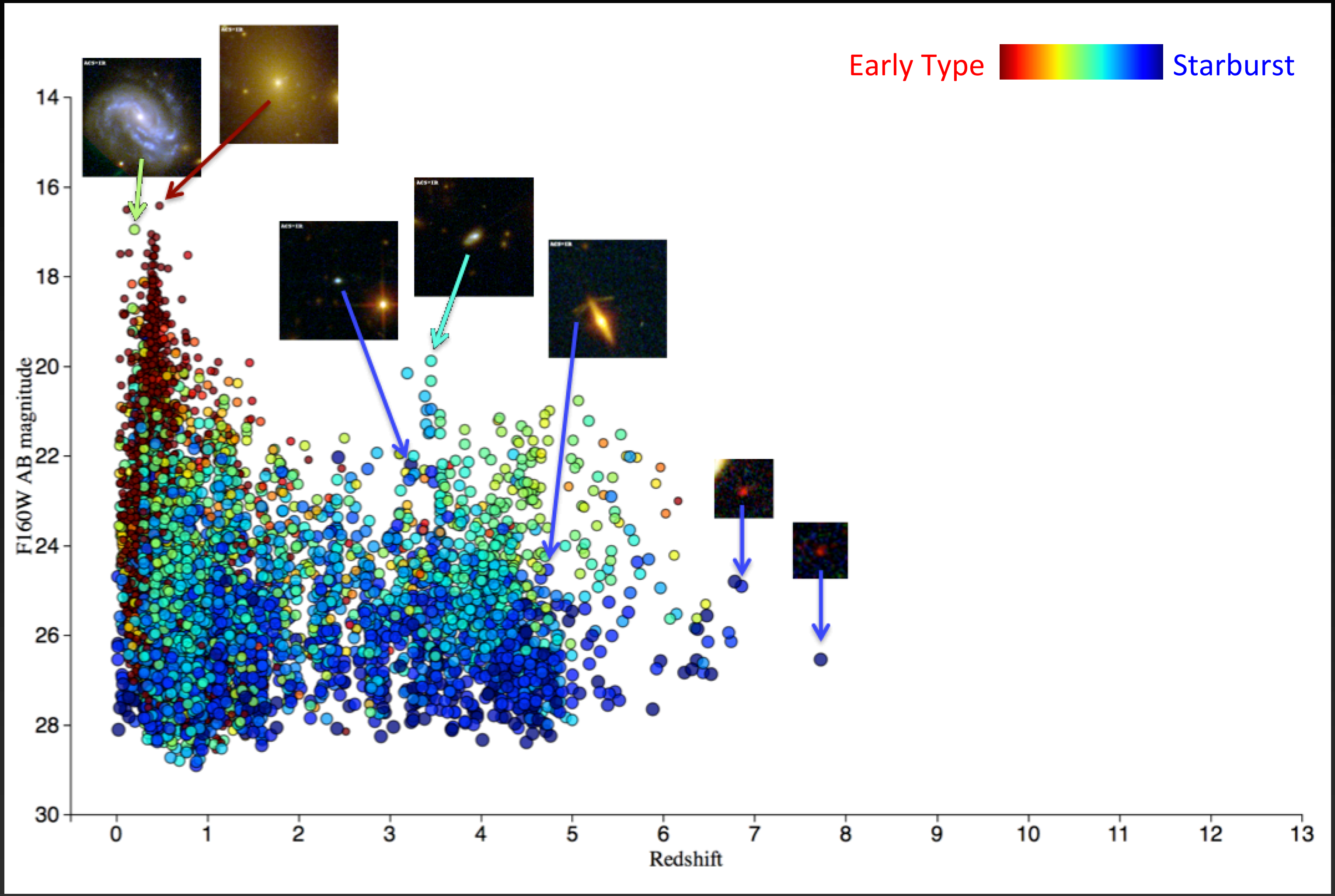






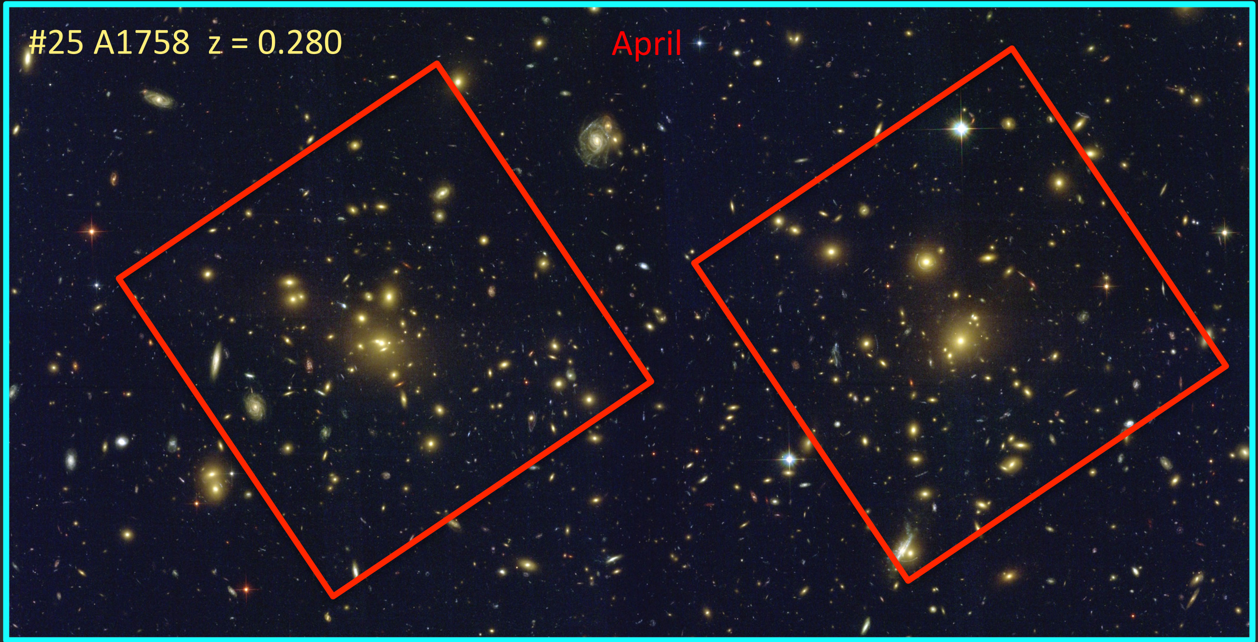


Galaxies in first 6 RELICS cluster images



RELICS
Reionization Lensing Cluster Survey

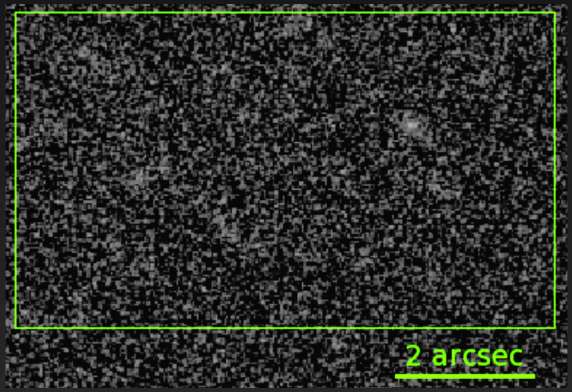
The best RELICS clusters are yet to come



Maximum Likelihood Detection

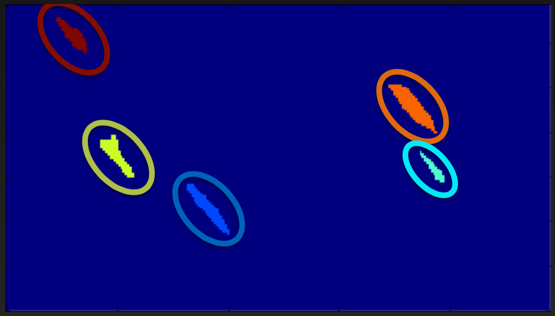
Will Dawson with Jim Bosch and Michael Schneider

2-orbit image

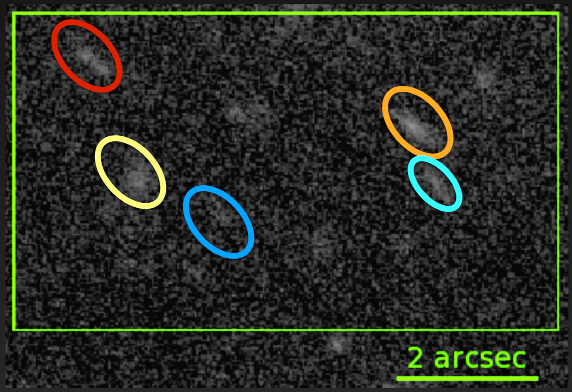


MACS1149: CLASH

Detection
using sheared kernel



15-orbit image



MACS1149: Frontier Fields

Find the best and brightest high-redshift candidates now in time for JWST

2015

2016

2017

2018

2019

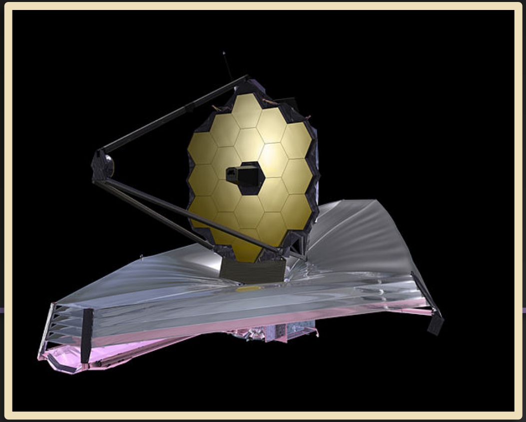
RELICS
Oct 2015
–
Apr 2017

GTO
Jan 2017 call
Apr 2017 deadline
Jun 2017 targets public

ERS (public data)
Mar 2017 call
Jul 2017 deadline
Sep 2017 TAC

(some proposal dates subject to change)

GO Cycle 1
Nov 2017 call
Feb 2018 deadline
May 2018 TAC



Launch! Oct 2018
commissioning 6 months

Science! Apr 2019
5 – 10 years

Oct 2015
Nov
Dec
Jan 2016
Feb
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Jan 2017
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Jan 2018
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Jan 2019
Feb
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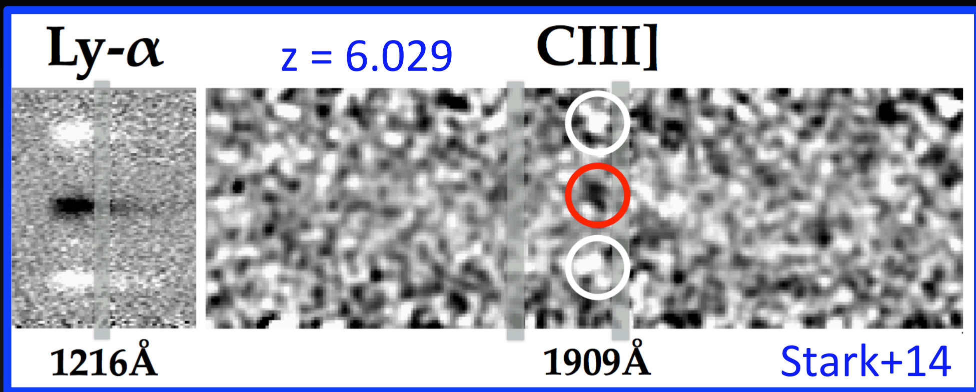
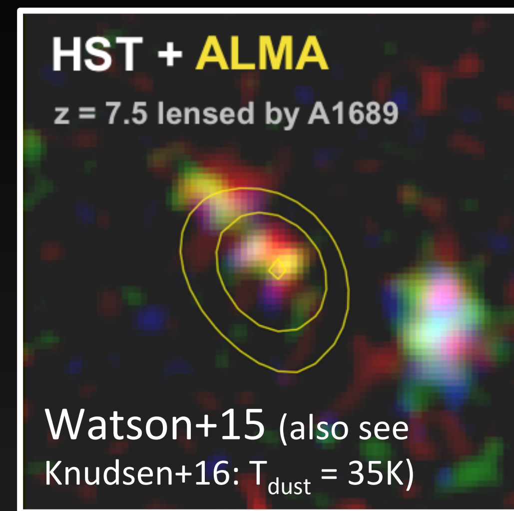
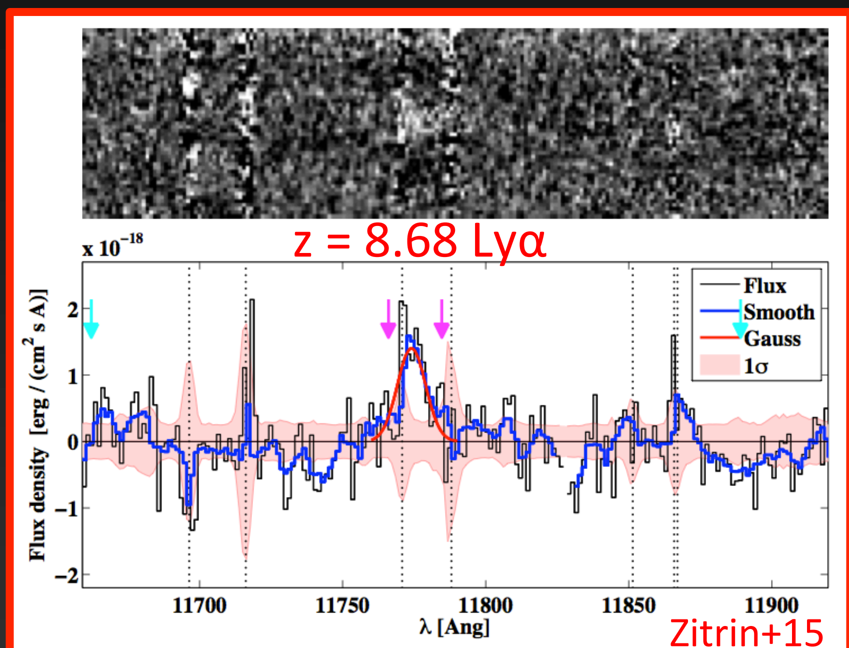
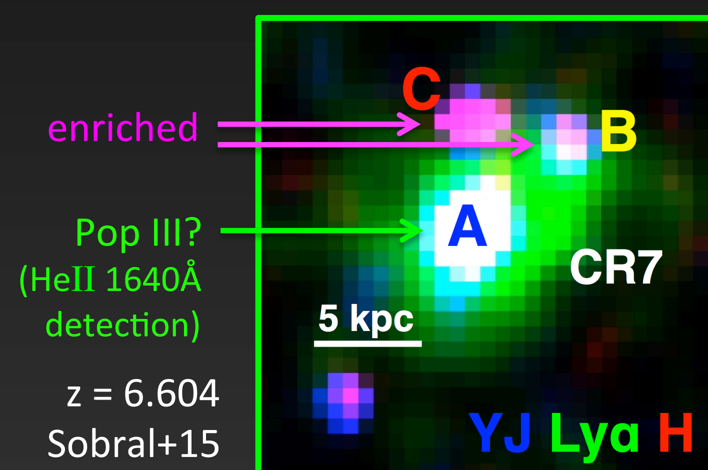
Confirmations and properties of brightly observed high-z galaxies







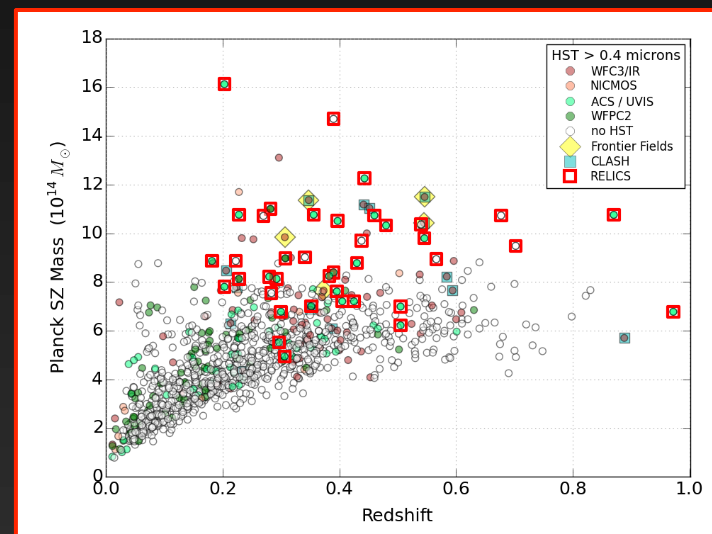


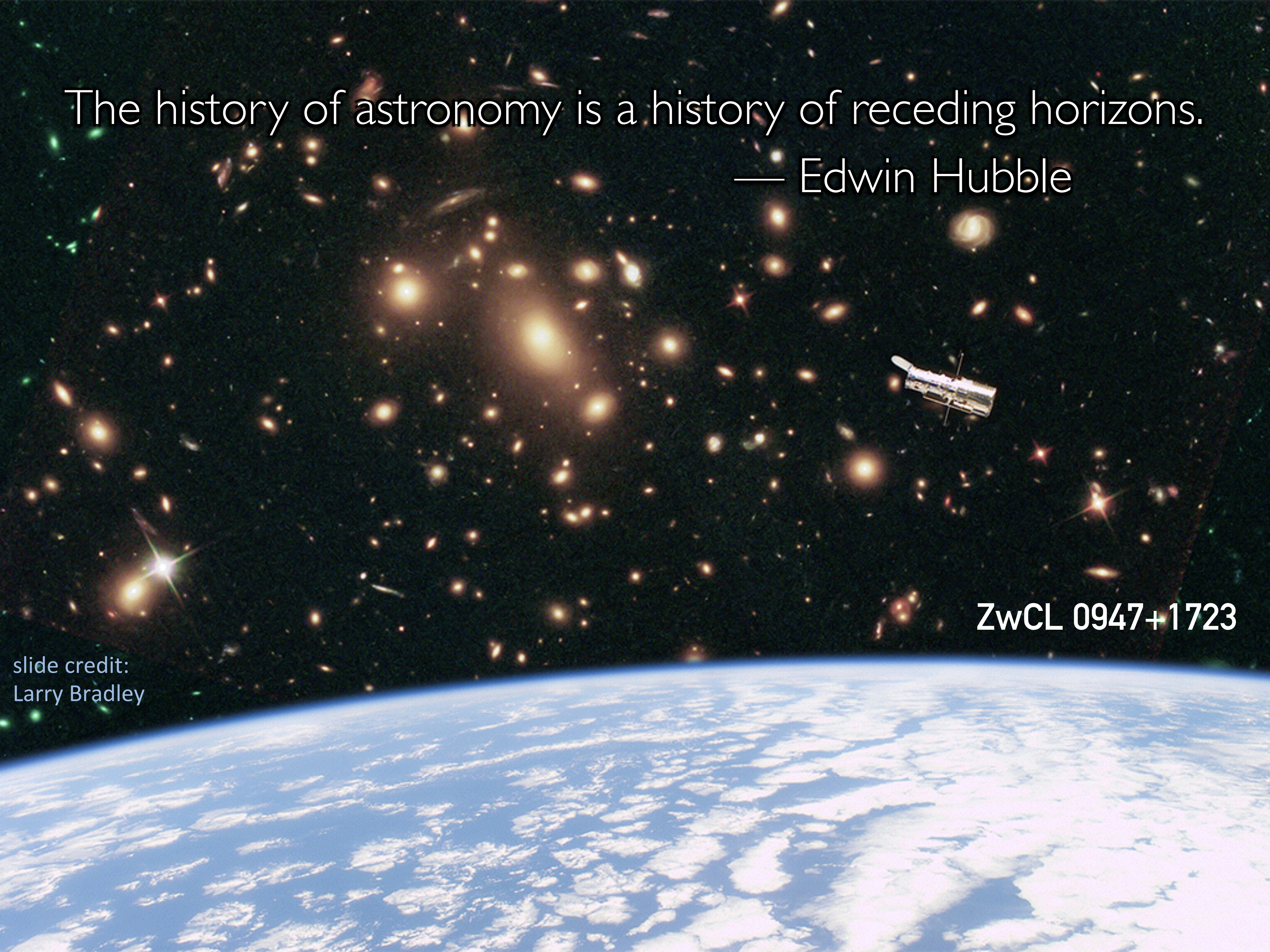
RELICS will deliver more of the "best and brightest" high-redshift candidates in time for JWST

Lensing delivers more, intrinsically fainter, and higher resolution z > 9 galaxies

RELICS
Reionization Lensing Cluster Survey

http://relics.stsci.edu




The history of astronomy is a history of receding horizons.
— Edwin Hubble
ZwCL 0947+1723
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Larry Bradley