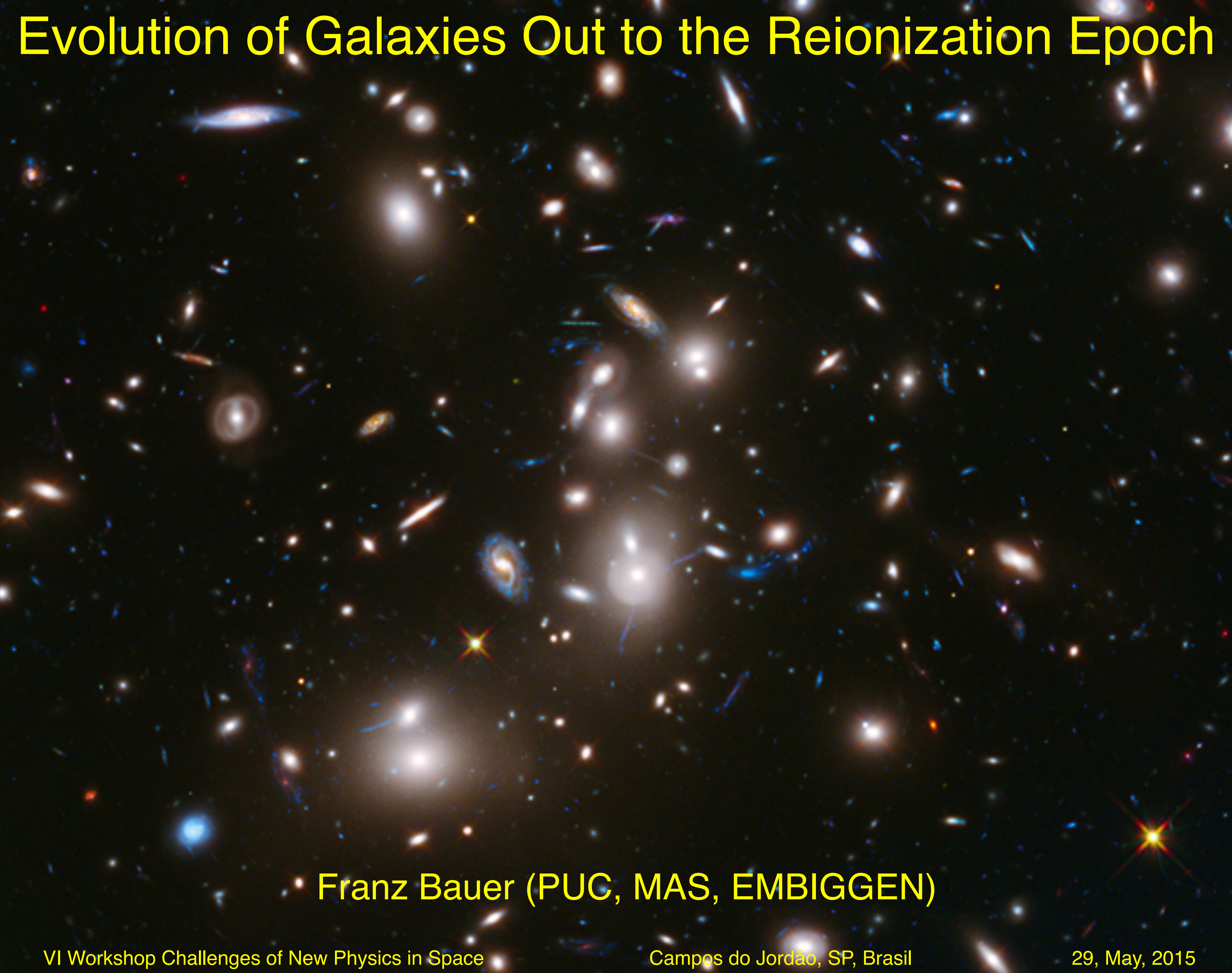


Evolution of Galaxies Out to the Reionization Epoch

Franz Bauer (PUC, MAS, EMBIGGEN)

VI Workshop Challenges of New Physics in Space Campos do Jordão, SP, Brasil 29, May, 2015

A talk about…


THE
STEREO
COSMIC DROPOUTS
Groovy Things


I WAS A TEENAGE COSMIC FAN!!
The COSMIC DROPOUTS
THIS SPLENDID DISC GIVES YOU FOUR ULTRA WILD TUNES, ESSENTIAL FOR TRUE BELIVERS EVERYWHERE!
ATTACK OF THE CRAB MONSTERS


STEREO
THE
COSMIC DROPOUTS
CRASHED CADILLACS
AND
BROKEN HEARTS
EP

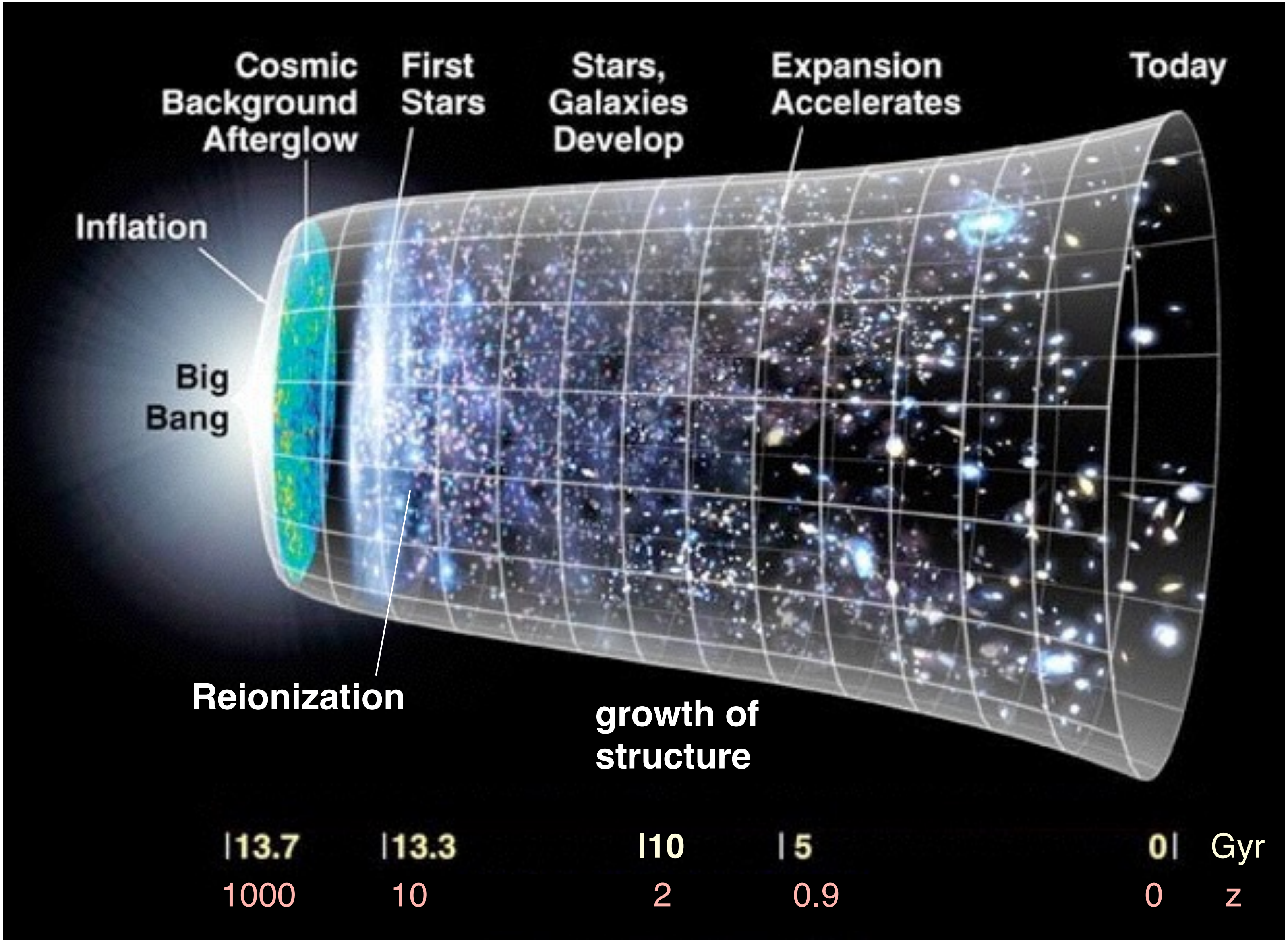

THE
COSMIC DROPOUTS
HOOLABALOO!


THE
STEREO
COSMIC DROPOUTS
LET'S GO TO THE BEACH


MY MIND'S EYE
PRÄSENTIERT
THE WHAT...FOR! – Chicago
THE KLIEK – Why Do I Cry?
THE TIMELAPSE – I'm Gonna Make You Mine

history of the universe

As z increases, less objects and less information to interpret with, so often must interpret liberally (and occasionally incorrectly)

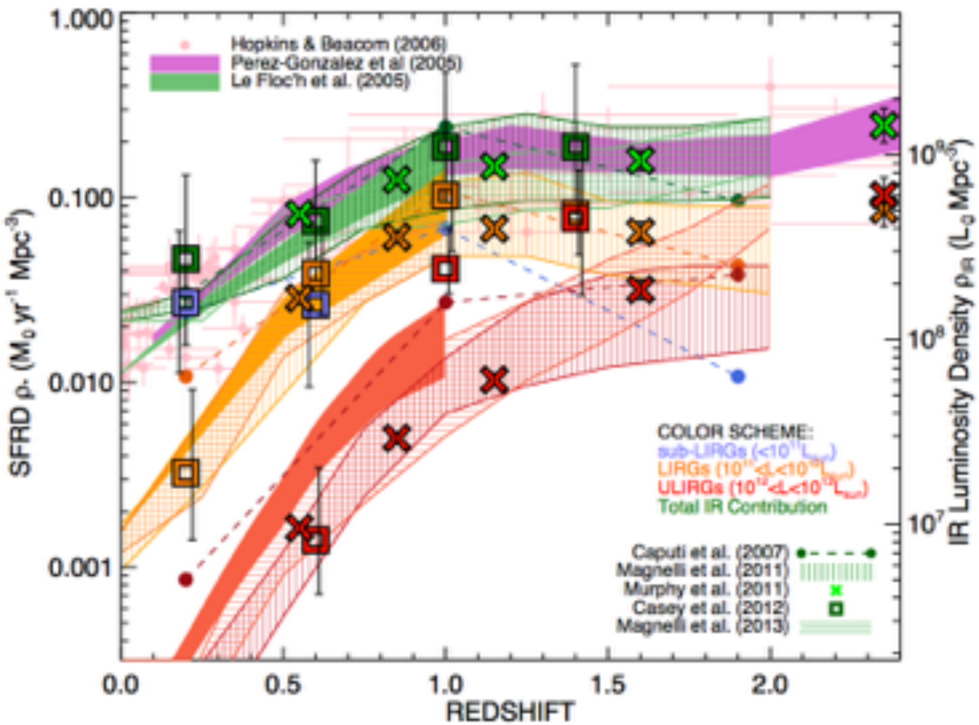


why z > 1?

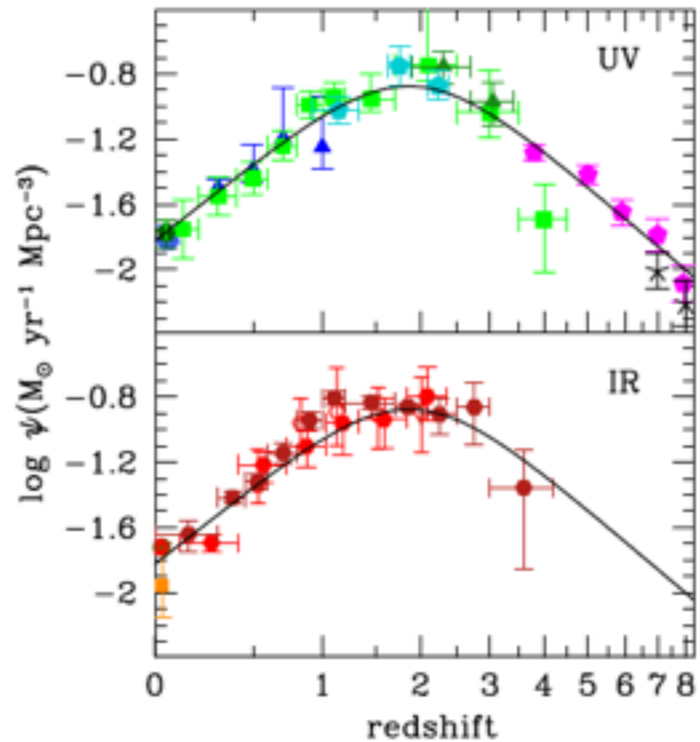
- Difficult to reconstruct detailed formation history of the Milky Way, let alone for a large sample of local galaxies to infer their assembly and SF histories directly.
  - *Need proxies ("photo albums") for what these galaxies looked like at younger stages.*
- Most local laws (e.g., Schmidt-Kennicutt, color-magnitude sequence/ cloud, SFR MS, MZR, …) hold out to z~2-3, although with significant evolution. Galaxies and SMBHs seem to grow in step most of the way.
  - *Main drivers of galaxy variation seem to be growth of structure (density) and variable SFR + SFE.*
  - *Still need few other fundamental `ingredients' (**availability of gas**) in order to reconcile the panoply of local relations*
  - *Evolution of these relations has major implications for how galaxies assemble and create stars.*
- A census of youngest forming objects (z > 6-10) provide strong constraints on theoretical predictions related to cosmic reionization and the formation of the first stars, galaxies, and black holes
  - *Want to understand these fundamental building blocks.*

increasing SFR density with redshift

Casey et al. 2014

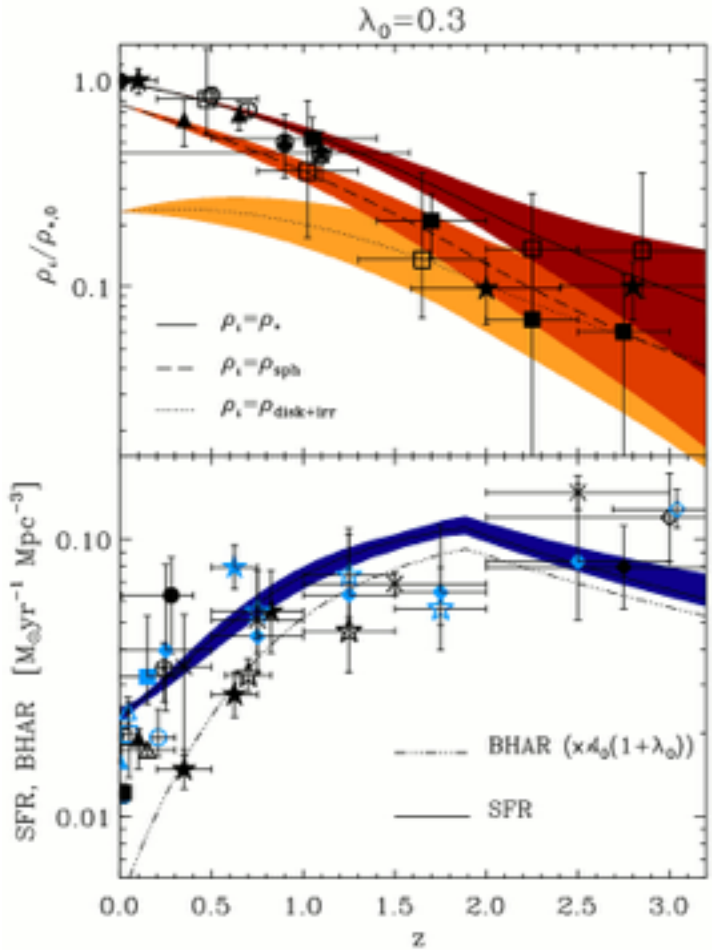


Madau + Dickinson 2014

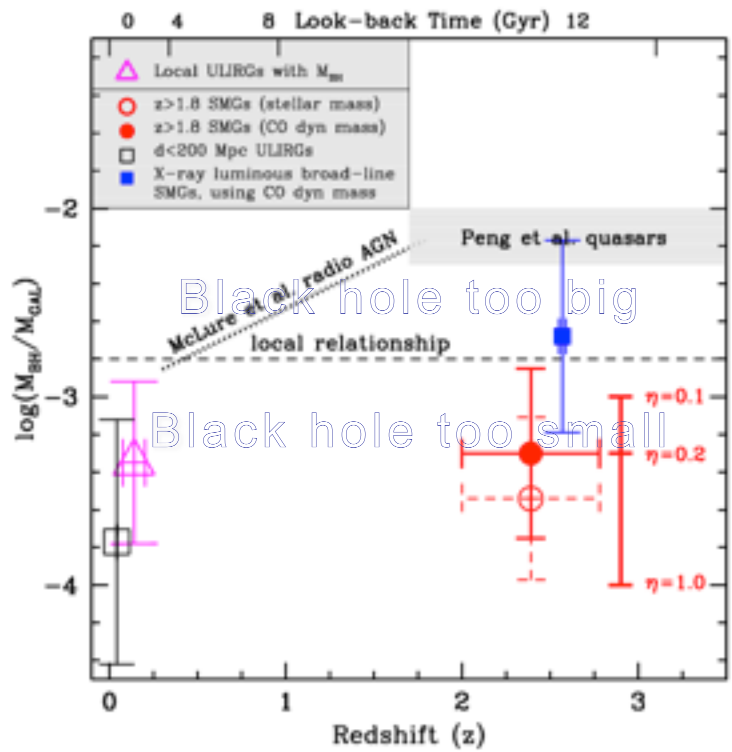


cosmological AGN-star formation activity

Merloni et al. 2004

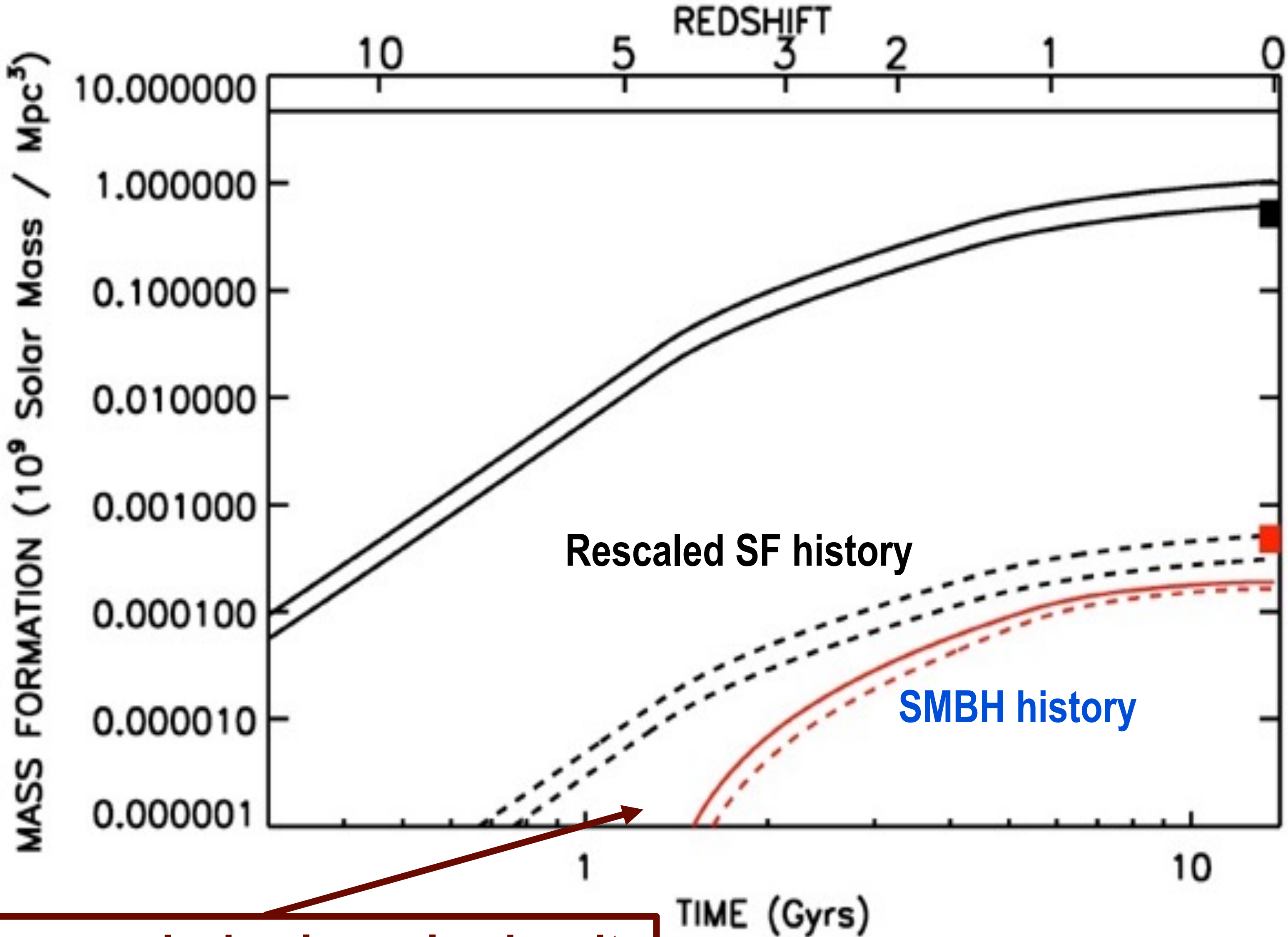


Star formation (scaled by factor of 1000) and mass accretion histories: concordant growth on average?



Alexander et al. 2008

But growth may sometimes be temporarily out of sync (e.g., objects with intense AGN or star-formation activity)… "unsynchronized co-evolution"



Are we missing lower luminosity AGN at high redshift?

why z > 1?

- at z~0.1-0.2, we have SDSS/GAMA/etc. (>1M objects w/ spec)
- at z~1, we have COSMOS/DEEP/etc. (~100k objects w/ spec)
- at z~2-4, we have many 1k of objects (galaxies + AGNs), which can be studied in detail with spectra from Keck, VLT, etc.
  - *but still probing tips of luminous populations with spectra*
- at z~4-7, something like 10k to 100 dropout candidates and narrow-band emitters are now known, respectively. Vast majority are expensive to confirm with Keck, VLT, etc.
  - *very limited detailed constraints as yet (only rare objs)*
  - *(must await future instruments).*

so can make numerous statistical characterizations, although as we go to higher z, run risk of making poor extrapolations to larger populations.

When we look at z > ~2-4, what do we see?

Several key galaxy populations whose studies are relevant:

- **color-selected star-forming galaxies: (LBGs, BzKs, dropouts, etc.)**
- **sub-mm galaxies (SMGs) via lensing and negative K-correction**
- **passively-evolving and dust-obscured sources via deep NIR data (EROs, DRGs)**
- **high-EW emitters via narrow-band imaging and spectroscopy (Lyα, Hα, OII/OIII emitters)**
- **AGN (optical + X-ray + IR)**
- **(GRB hosts)**

All have something to tell us about galaxy and SMBH growth, but many represent the tip of the population and can give us biased/misleading views

(many examples in Nature)

Want to probe 1) fainter more "typical" objects to confirm trends and 2) detected objects in more detail (higher S/N, spatial resolution)

When we look at z > ~2-4, what do we see?

Key questions:

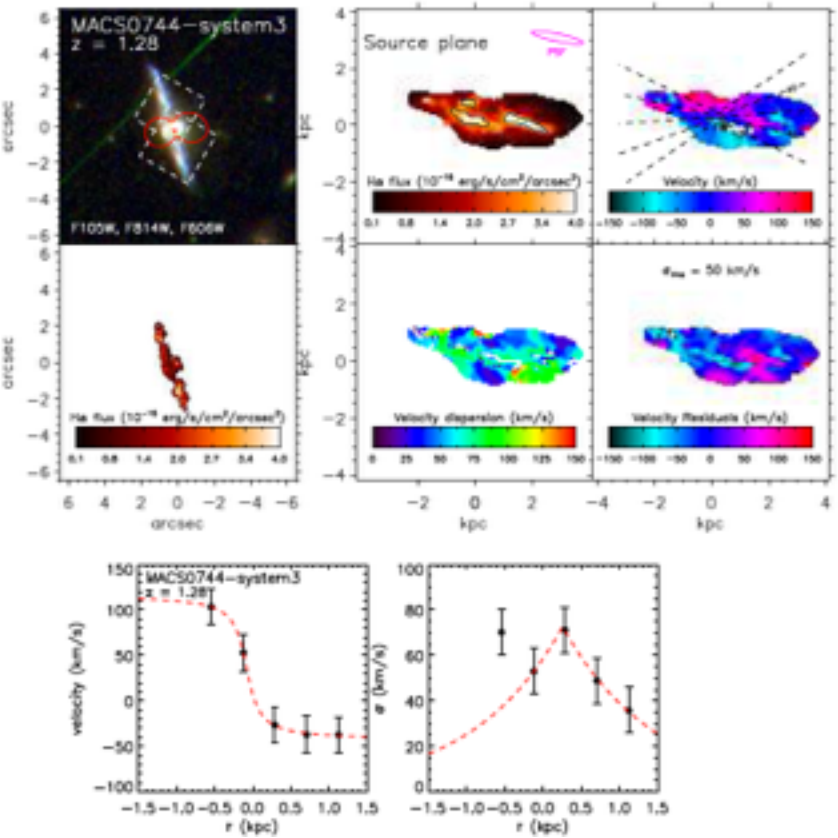
Given that all these populations co-exist at 2<z<4, interesting to know how they relate to each other in terms of

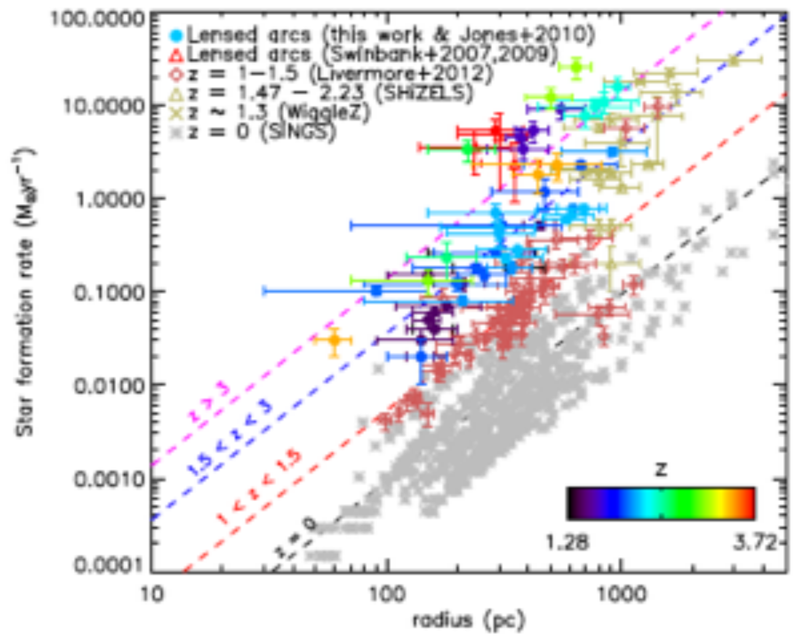
- **basic physical properties (mass, SFRs, Age, etc)**
- **relative contributions to SF rate at a given redshift**
- **degree of overlap (e.g. how many SMGs are LBGs, LAEs, etc)**
- **spatial clustering (relevant to halo bias)**
- **address puzzles (e.g., passive EROs are unexpectedly numerous with ~3/arcmin for K < 23…why?).**

When we look at z > ~2-4, what do we see?

For highly magnified systems behind lenses, can study spatial scales that are unattainable otherwise

Livermore et al. 2015





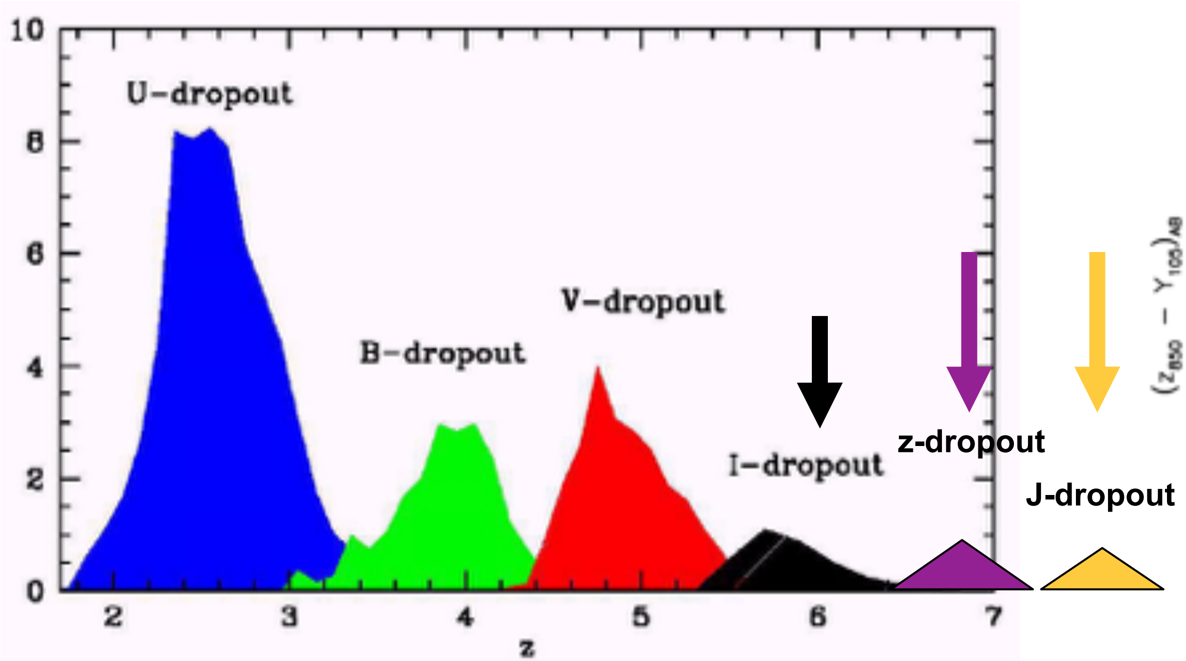
With IFUs and mm-arrays, can pick apart velocities, morphologies, ionizations, etc.

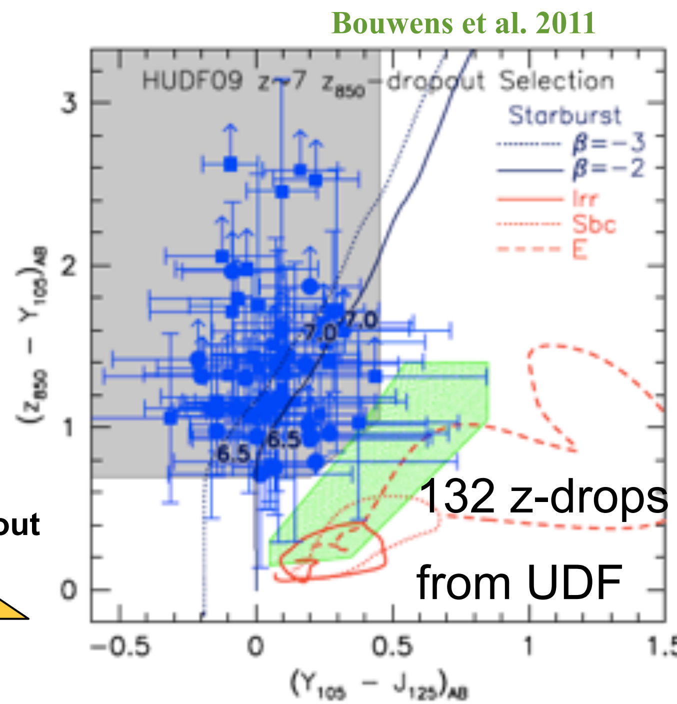
When we look at z > ~4-7, what do we see?

The same techniques apply, but here we are much more limited due to the rarity of objects (e.g., from the decline in SFR density, volume, time) and the FOVs over which we must search.

As always, mantra is to proceed with caution since only probing the tips of the populations.

lyman breaks or `dropouts' at higher z





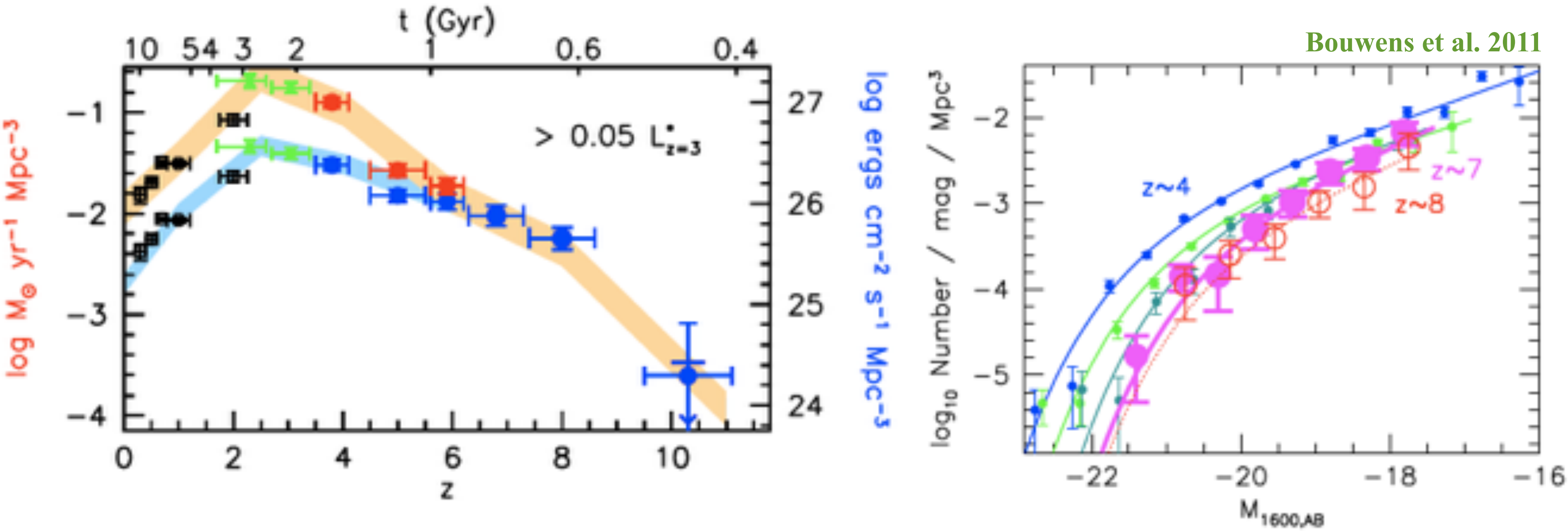
Dropout technique ill-suited to z > 5-6 galaxies because of:

- contamination from cool stars, z~2 passive galaxies (SEDs help here)
- spectroscopic follow-up impractical below ~few L* (i.e., bulk of objs)

i-drop volumes: UDF (2.6×10^4), GOODS-N/S (5×10^5), Subaru (10^6) Mpc^3

flux limits: UDF z<28.5, GOODS z<25.6, Subaru z<25.4

UV luminosity density in decline



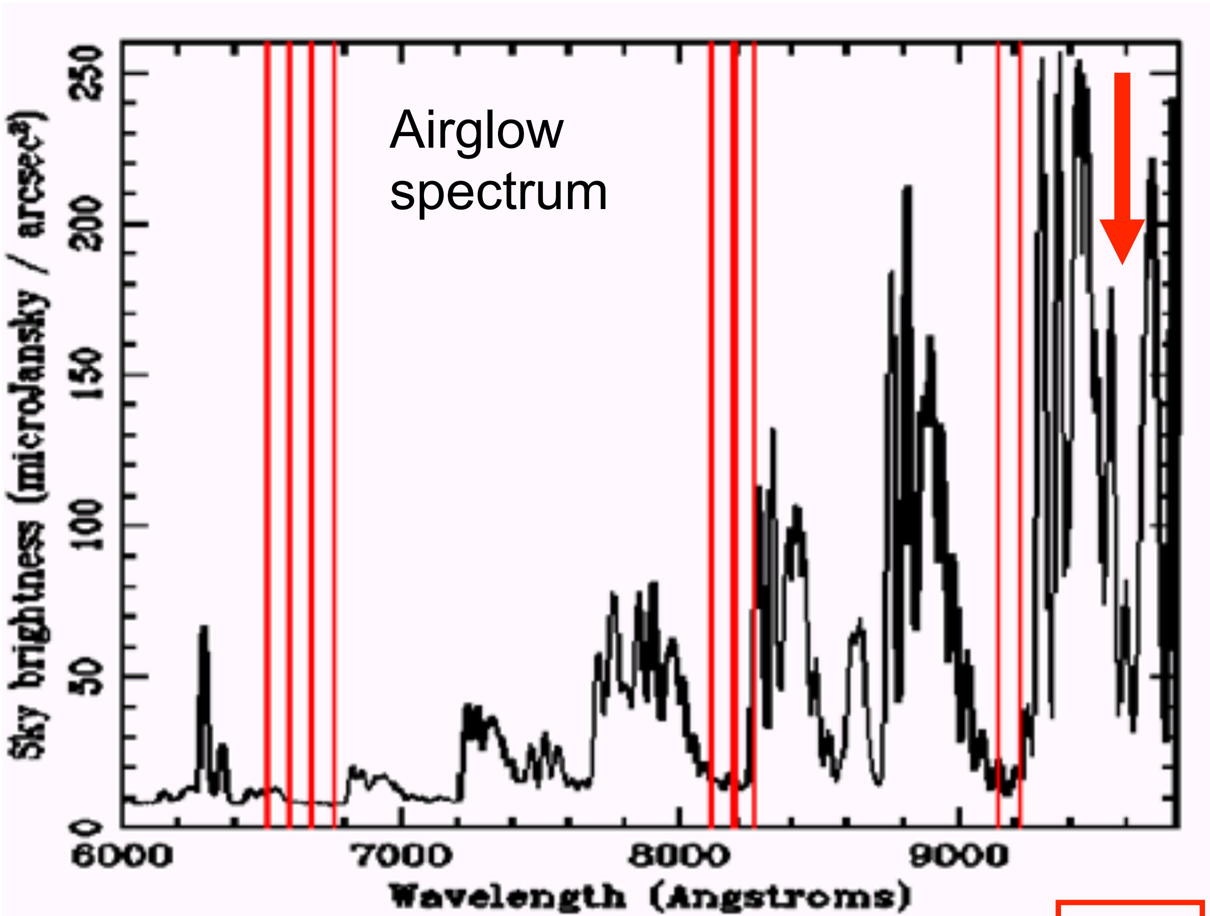
Rapid decline in UV luminosity density from 3<z<8, and possible sharper drop to z~10.

primary evolution is a shift in M* (0.7 mag in 0.7 Gyr over 4<z<6), steep faint-end slope α ~ -1.7 consistent throughout all samples.

Indicates elevated fraction of low-luminosity galaxies at high z.

confirmed in other fields and by other groups.

narrow bands in 'line-free' windows of sky spectrum



z(Lα) = 4.7 5.7 6.6 6.9

Pushing into J+H

HiZELs

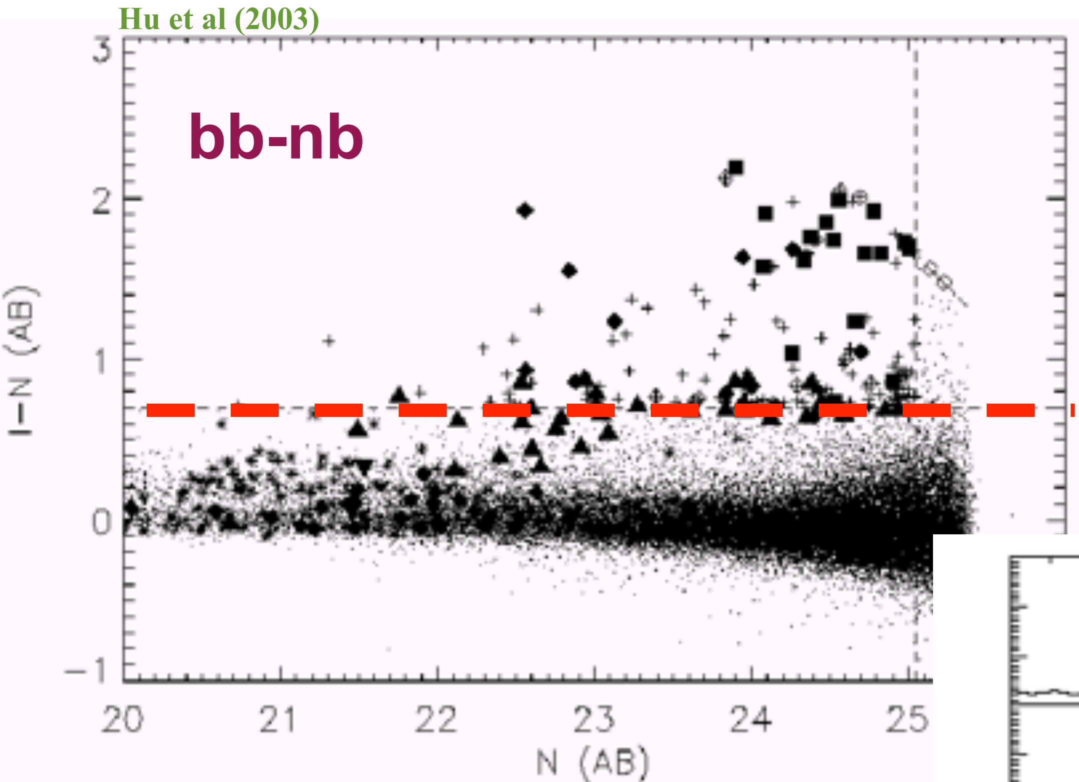
HAWK-I

FourSTAR

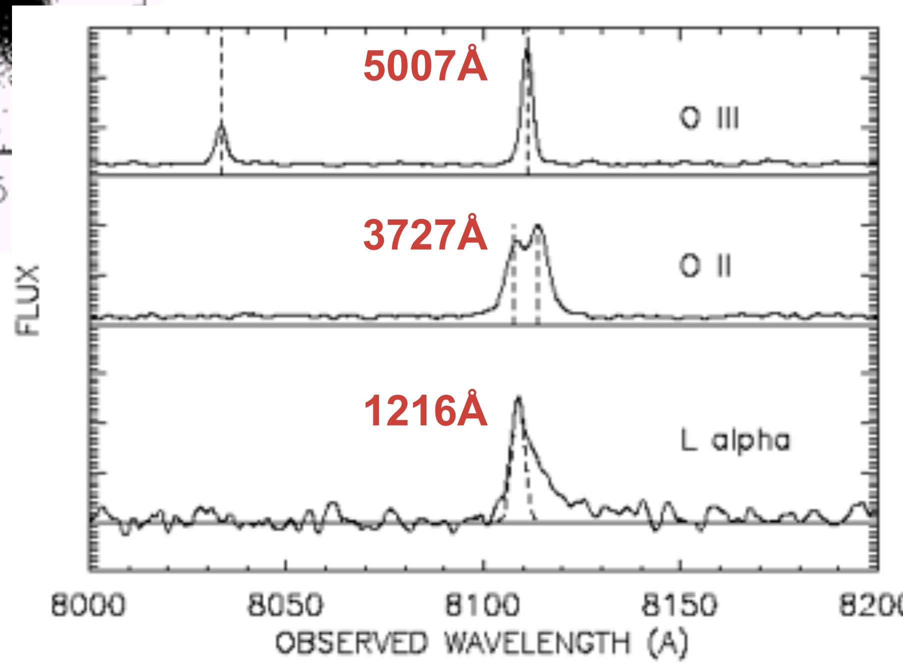
Requires large FOV imaging to compensate for small Δz range

Subaru SuprimeCAM (~30' FOV), eventually HyperSuprimeCAM (1.5dg FOV)

selection + spectroscopic verification



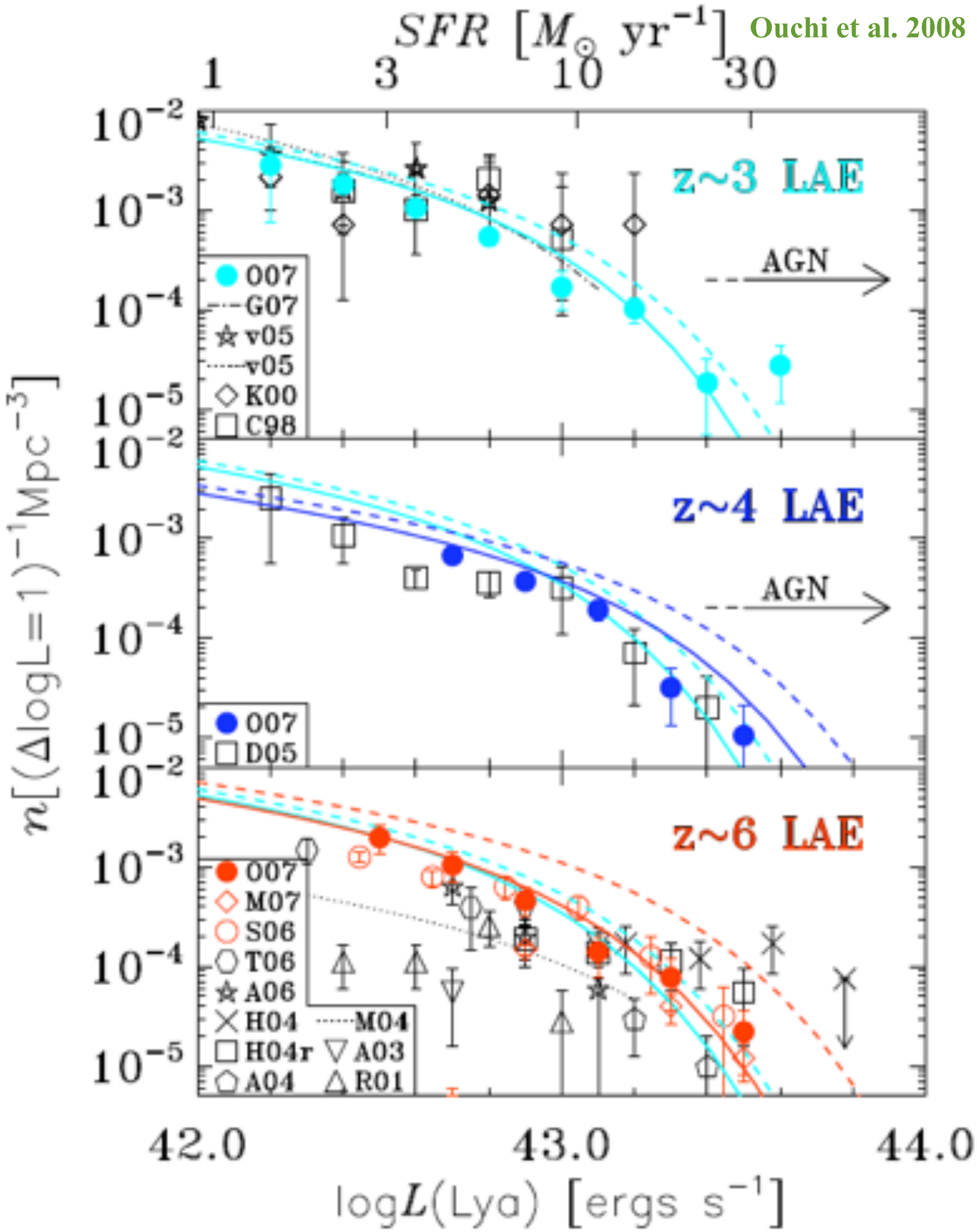
Compare signal in nb filter with bb signal using, e.g., Subaru



Some spectroscopic follow-up of candidates still required to determine contamination %

UV luminosity density in decline?

- 858 LAEs over 1 deg^2
- 84 spectroscopically-confirmed
- No evolution in L* or α
- Contrasts with LBG dropout evolution, implying that LAEs are a more dominant population at early epochs.
- In weaker systems (i.e. via strong lensing) Lyα may be a sensitive probe of reionization
- Might expect to see abrupt change in LF at the stage when reionization ends



What about at z > 7-12 (aka reionization epoch)?

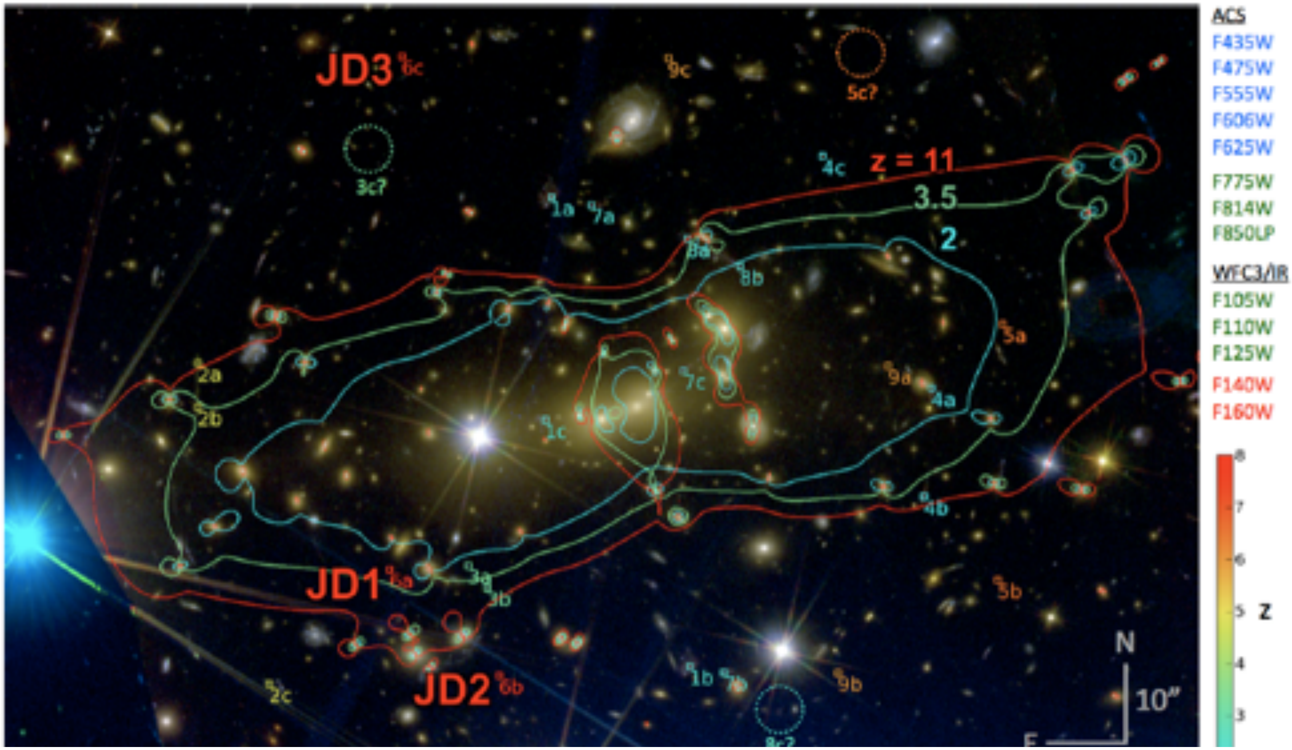
Isolated primarily to the CANDELS/Ultra Deep Field and Cluster lenses (e.g., CLASH, Abell 1689).

- ~10 dropout candidates in early 2014.
- extremely difficult to confirm.

•LAEs are found to be younger, smaller, less massive, less clustered than LBGs and comprise an increasing fraction of the total SFR density with increasing z.

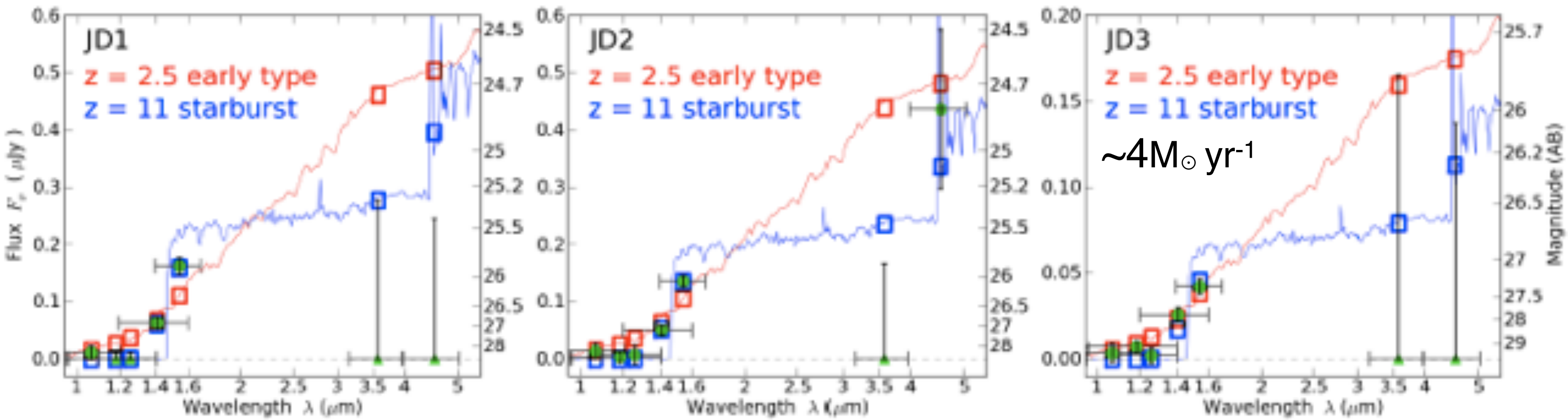
- Unclear whether LAE's contain `pristene' Pop III stars?
- Are claims for `anomalously high' (100-1000s) equivalent widths real?
- As yet, no evidence for He II emission (high ionization line expected in populations with steep IMF)

z=11 object from 3 lensed images



Coe et al. 2013

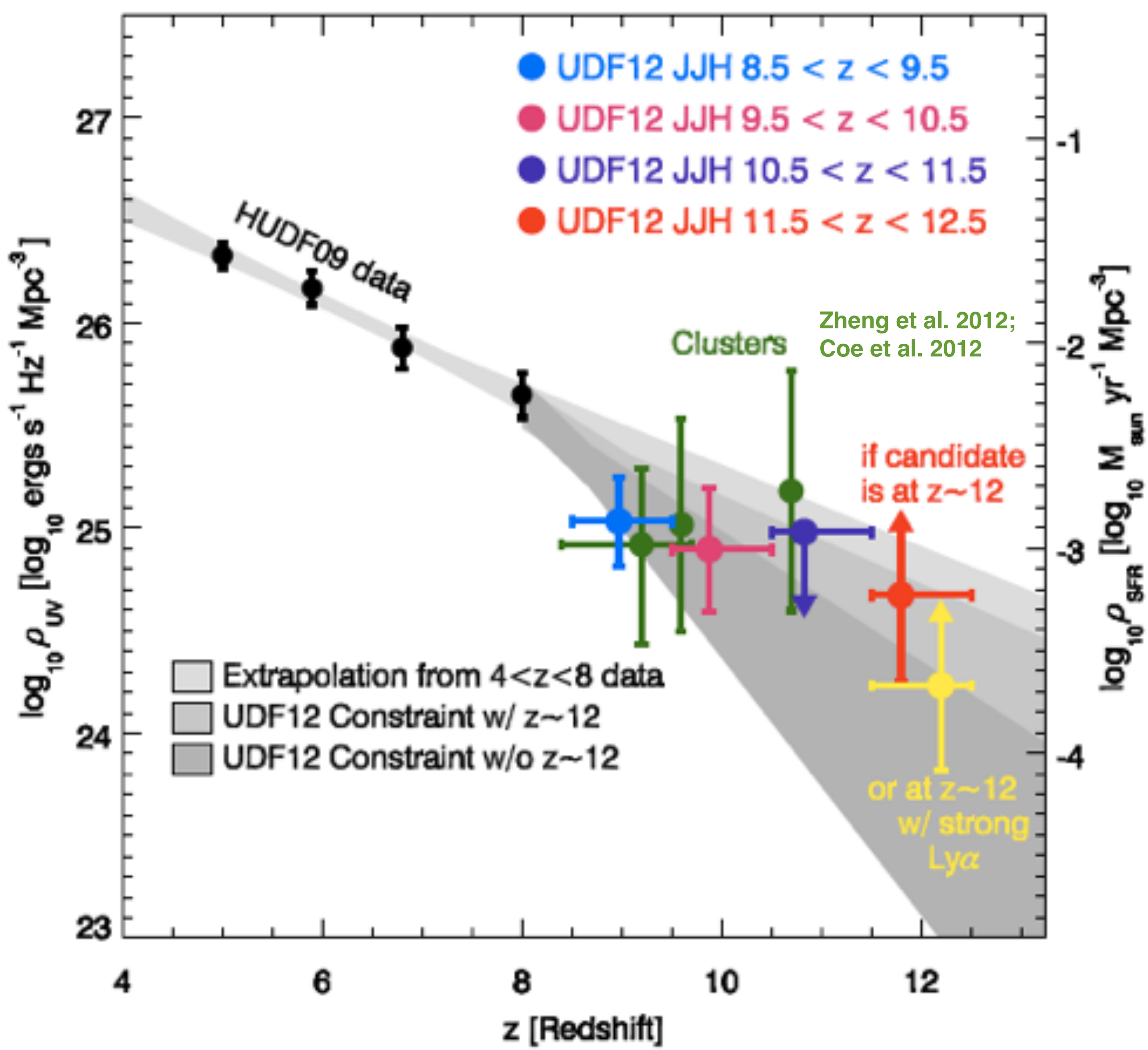
Pirzkal et al. 2015



mass model consistent with z=11.0 and 11.6, but z=3.5 solution acceptable / no grism lines

UDF z~12 candidate

Ellis et al. 2013



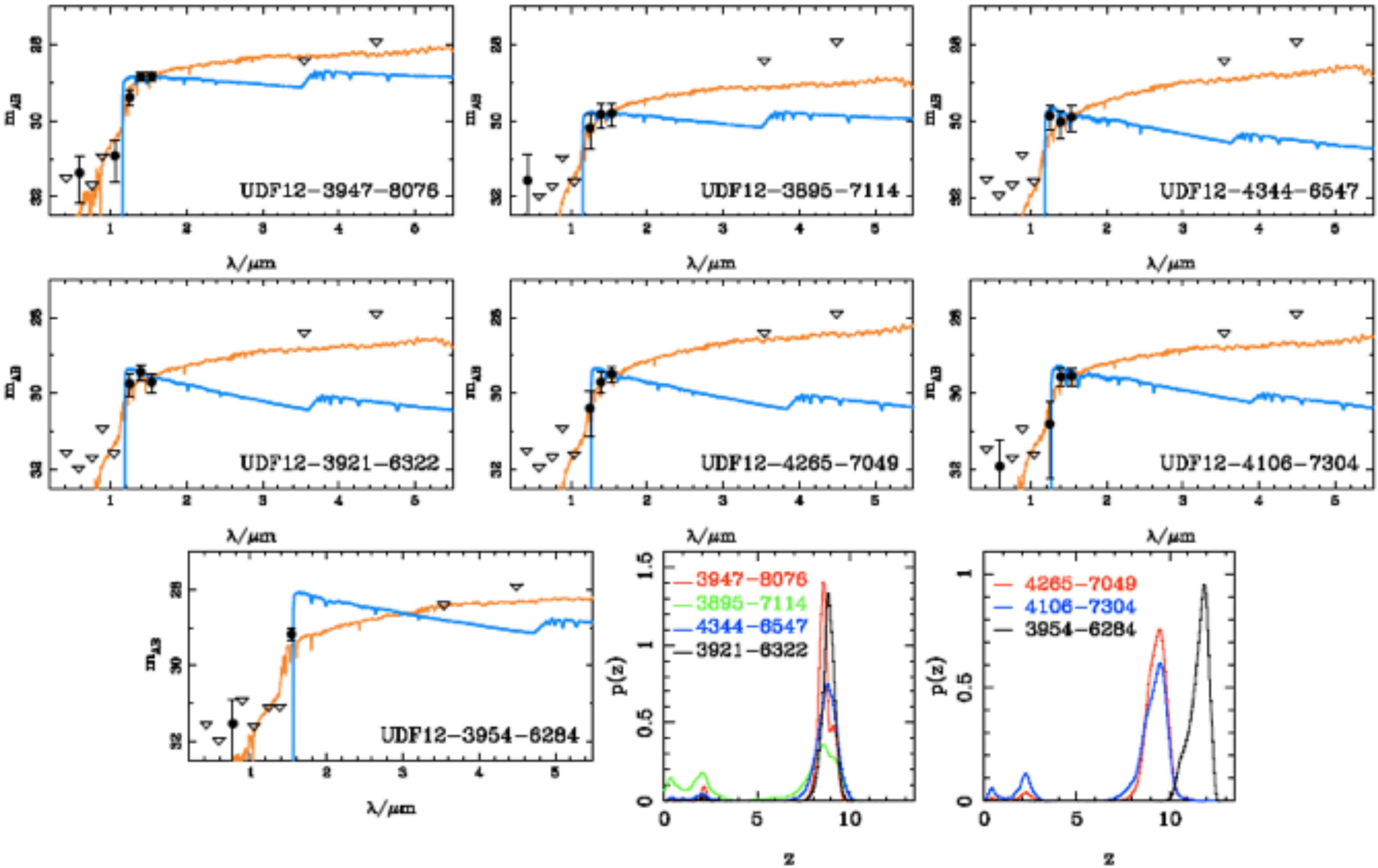
z~10 drop not so sharp with new sources

ramifications for reionization

z ~ 7-12 galaxies are extremely small: 0.3-0.4 kpc (Ono et al. 2013)

UDF z~12 candidate

Ellis et al. 2013



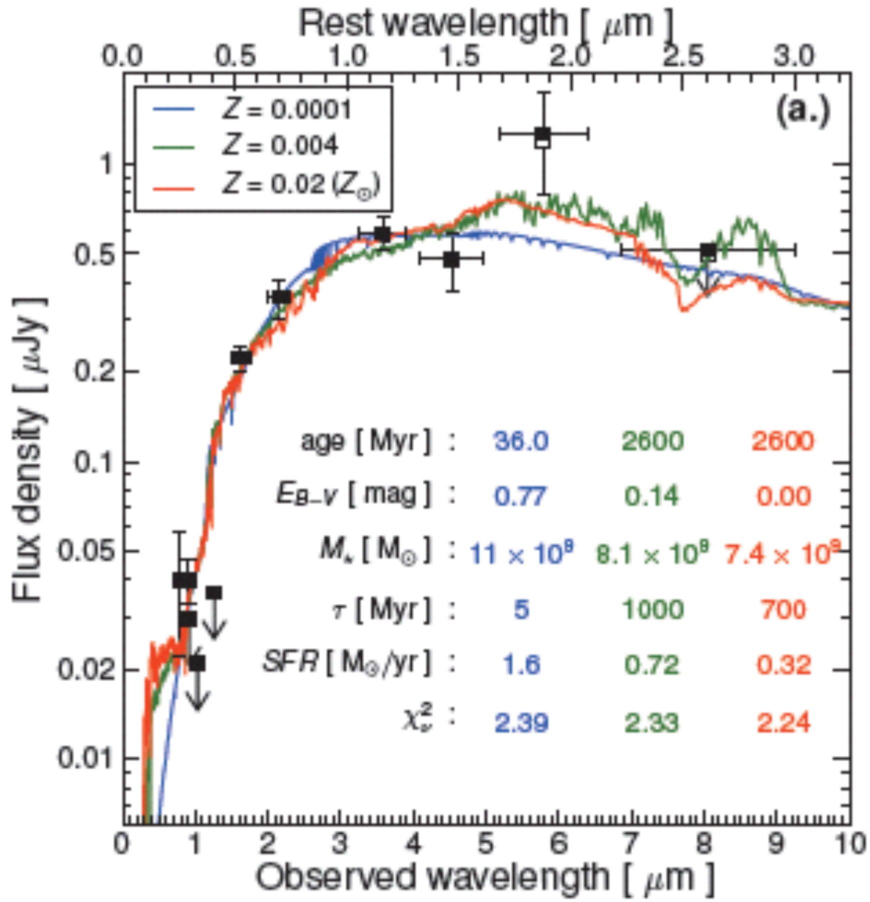
See also Brammer et al. 2013 => 2.8 line consistent with z=12.12 (EW=7300A! all of H-band flux), but could be [OIII] at z=2.19 too.

Some caveats...

Hayes et al. 2012 found their z=11.9 object to be an extremely metal-poor interloper at z=2.082

Schenker et al. 2013 found that high EW lines can skew SED fitting and distort mass, SFR, age.

Several z>7 candidates appear to lack Ly α (e.g., Capak et al. 2013, Caruana et al. 2012)



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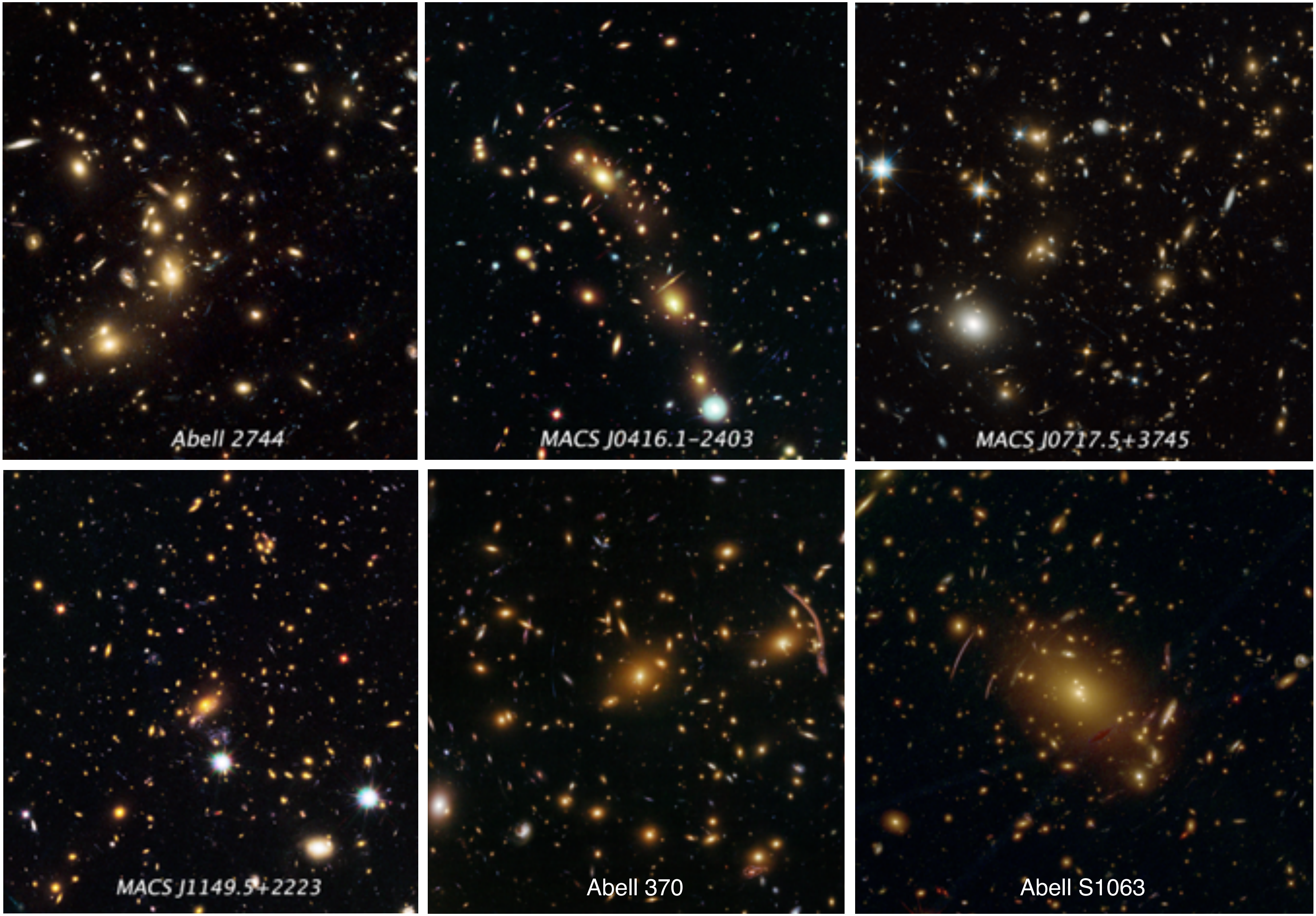
To delve deeper into the high-z population, we must combine the two previous strategies (deep and lensing), thus performing deep lensing observations.

=> reveal even fainter sources that would otherwise be inaccessible to current telescopes.

Enter the Hubble+Spitzer Frontier Fields



Enter the Hubble+Spitzer Frontier Fields

Cluster Name	z	Cluster		Parallel Field	
		RA	Dec	RA	Dec
Year 1:					
Abell 2744	0.308	00:14:21.2	-30:23:50.1	00:13:53.6	-30:22:54.3
MACSJ0416.1-2403	0.396	04:16:08.9	-24:04:28.7	04:16:33.1	-24:06:48.7
Year 2:					
MACSJ0717.5+3745	0.545	07:17:34.0	+37:44:49.0	07:17:17.0	+37:49:47.3
MACSJ1149.5+2223	0.543	11:49:36.3	+22:23:58.1	11:49:40.5	+22:18:02.3
Year 3:					
Abell S1063 (RXCJ2248.7-4431)	0.348	22:48:44.4	-44:31:48.5	22:49:17.7	-44:32:43.8
Abell 370	0.375	02:39:52.9	-01:34:36.5	02:40:13.4	-01:37:32.8

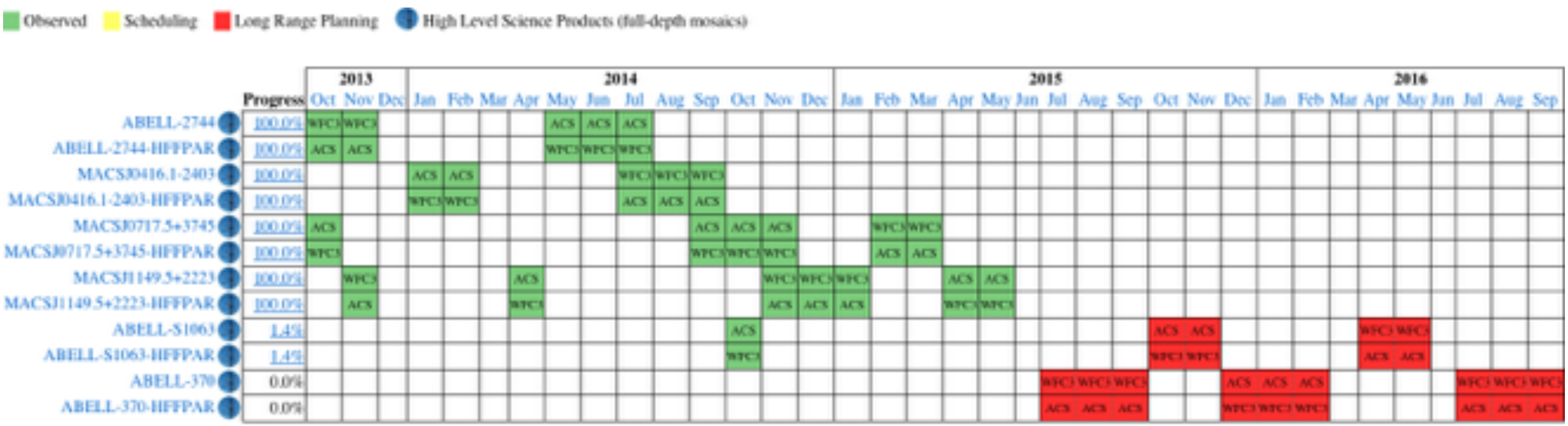
6 strong-lensing clusters + 6 adjacent parallel fields

140 HST DD orbits per cluster: ACS/ WFC3-IR in parallel ~29th ABmag in 7 bands

1000 hours warm Spitzer DD time: IRAC 3.6, 4.5 μm ~25.0-25.5 ABmag

All have strong and growing supporting data => deep VLT HAWK-I K, Herschel, Chandra, VLA,100s of z_{sp} per field, 1000s of z_{ph}, MUSE IFU obs, etc.

The cluster lenses have been well modeled by multiple groups, and these models are improving further with the deeper data.



Enter the Hubble+Spitzer Frontier Fields

Filter	Abell 2744 $m_{5\sigma}$ [AB]	MACS0416-2403 $m_{5\sigma}$ [AB]
B_{435}	28.5	28.4
V_{606}	28.7	29.0
I_{814}	28.7	28.7
Y_{105}	29.1	29.4
J_{125}	28.7	29.2
JH_{140}	28.8	29.1
H_{160}	28.8	29.1
K_s	26.0	26.0
3.6	25.5	25.2
4.5	25.0	24.9

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Observed | Scheduling | Long Range Planning | High Level Science Products (full-depth mosaics)

		2013			2014												2015												2016								
	Progress	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
ABELL-2744	100.0%	WFC3	WFC3						ACS	ACS	ACS																										
ABELL-2744-HFFPAR	100.0%	ACS	ACS						WFC3	WFC3	WFC3																										
MACSJ0416.1-2403	100.0%				ACS	ACS					WFC3	WFC3	WFC3																								
MACSJ0416.1-2403-HFFPAR	100.0%				WFC3	WFC3					ACS	ACS	ACS																								
MACSJ0717.5+3745	100.0%	ACS											ACS	ACS	ACS			WFC3	WFC3																		
MACSJ0717.5+3745-HFFPAR	100.0%	WFC3											WFC3	WFC3	WFC3			ACS	ACS																		
MACSJ1149.5+2223	100.0%		WFC3					ACS							WFC3	WFC3	WFC3			ACS	ACS																
MACSJ1149.5+2223-HFFPAR	100.0%		ACS					WFC3							ACS	ACS	ACS			WFC3	WFC3																
ABELL-S1063	1.4%													ACS												ACS	ACS					WFC3	WFC3				
ABELL-S1063-HFFPAR	1.4%													WFC3												WFC3	WFC3					ACS	ACS				
ABELL-370	0.0%																						WFC3	WFC3	WFC3			ACS	ACS	ACS					WFC3	WFC3	WFC3
ABELL-370-HFFPAR	0.0%																						ACS	ACS	ACS			WFC3	WFC3	WFC3					ACS	ACS	ACS

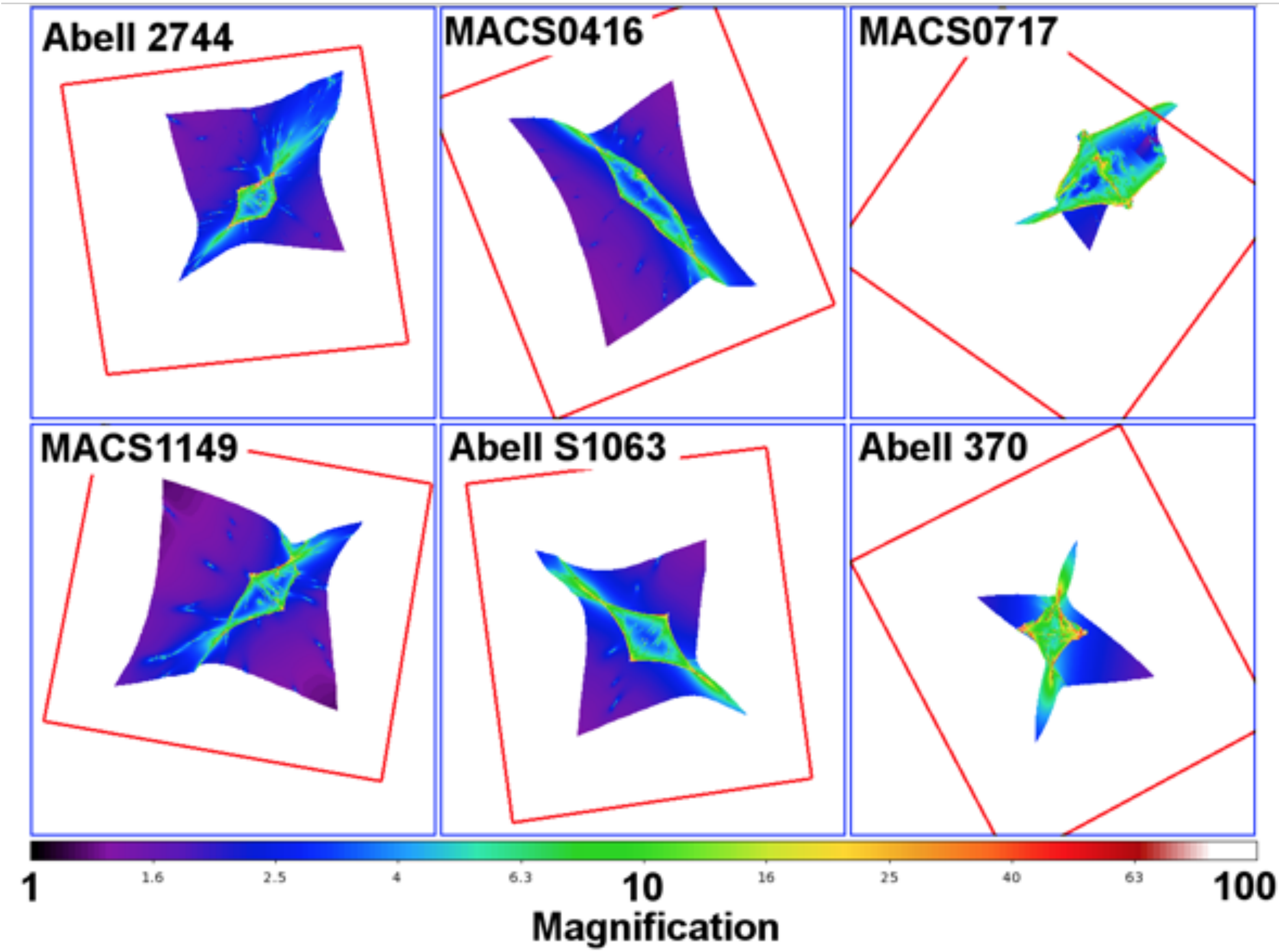
Enter the Hubble+Spitzer Frontier Fields

Deep observations of the Frontier Fields will:

- probe galaxies 10-50x intrinsically fainter than any seen before, particularly those before and during reionization
- study the early formation histories of galaxies intrinsically faint enough to be the early progenitors of the Milky Way
- study highly-magnified z~1-4 galaxies in detail: structures, colors, sizes and provide targets for spectroscopic followup
- provide statistical picture of galaxy formation at early times (3-5x more faint galaxies + 2x more z~8-10 galaxies vs UDF) => UV escape fraction, sub-kpc structures and star-formation
- map out dark matter and substructure in clusters
- study cluster galaxies, dwarfs, intracluster light in clusters
- search for (lensed) SN, transients in distant universe
- use 100s of multiple images as probe of distance, DE
- give proper motions of Milky Way stars + search for asteroids

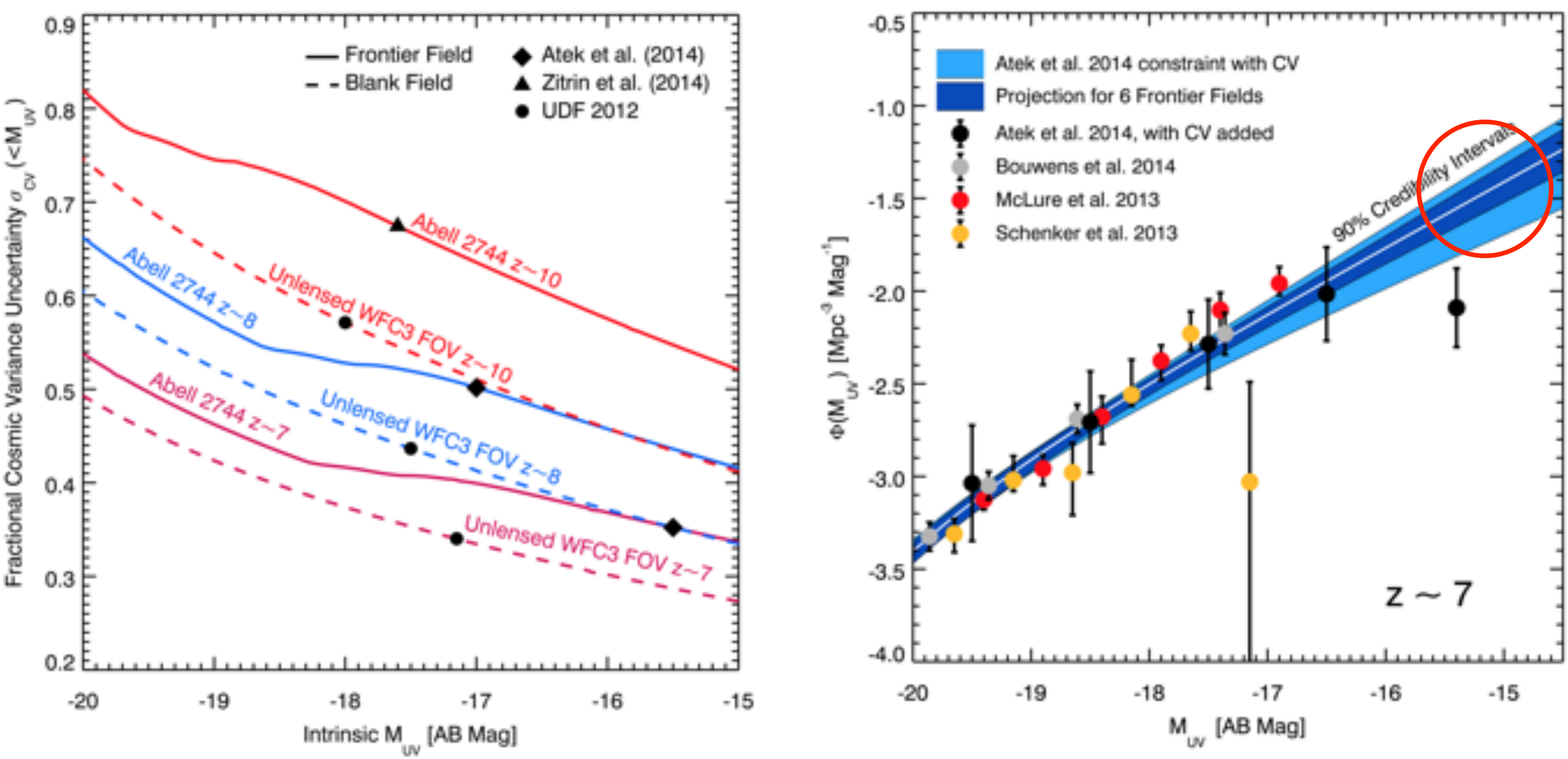
Enter the Hubble+Spitzer Frontier Fields

z~9 delensed volumes (Coe+14) => small high-z volumes probed by strong lensing



Enter the Hubble+Spitzer Frontier Fields

cosmic variance 10-30% higher due to smaller FOVs, but combining all 6 improves constraints on faint galaxy slope to probe UV ionization fraction (Robertson+14)

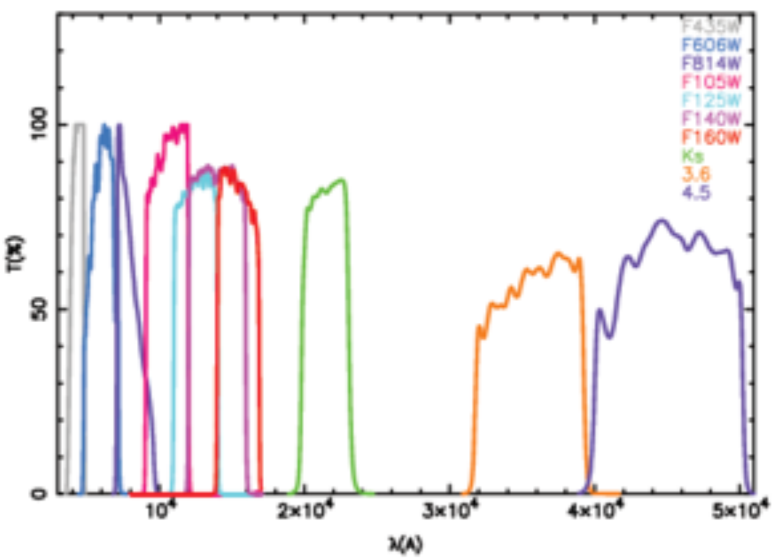


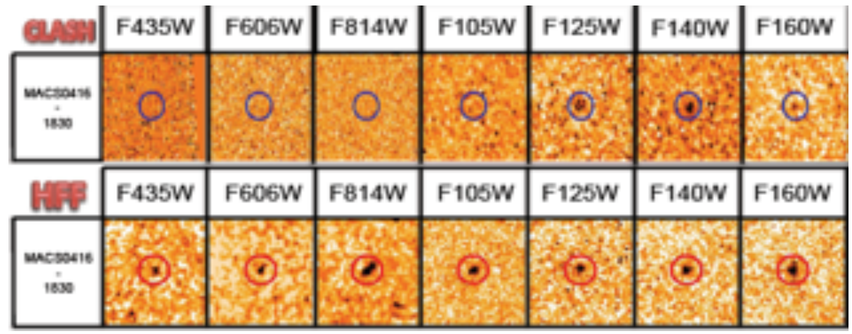
HFF Imaging studies: LBG Dropout Selection

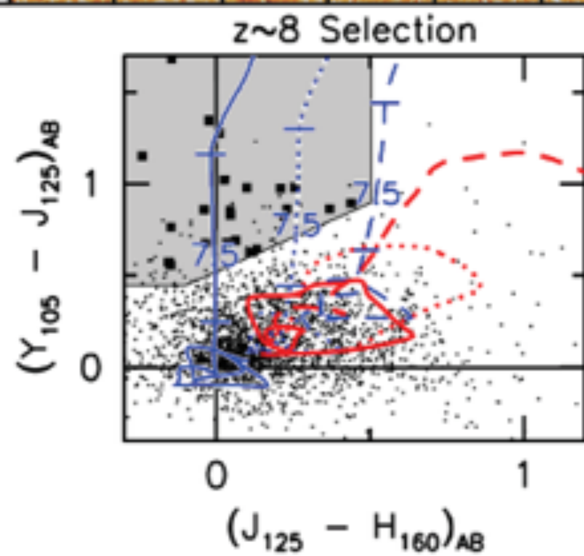
Abell 2744 + par: ~30 z=7-10 dropouts found (3 with μ>10)

MACS 0416 + par: ~25 z=7-10 dropouts found (1 with μ>20)

(Ishigaki+14; Atek+14; Zheng+14; Coe+14; Laporte+14; Zitrin+14; Oesch+14, Infante+15)







Bouwens+14

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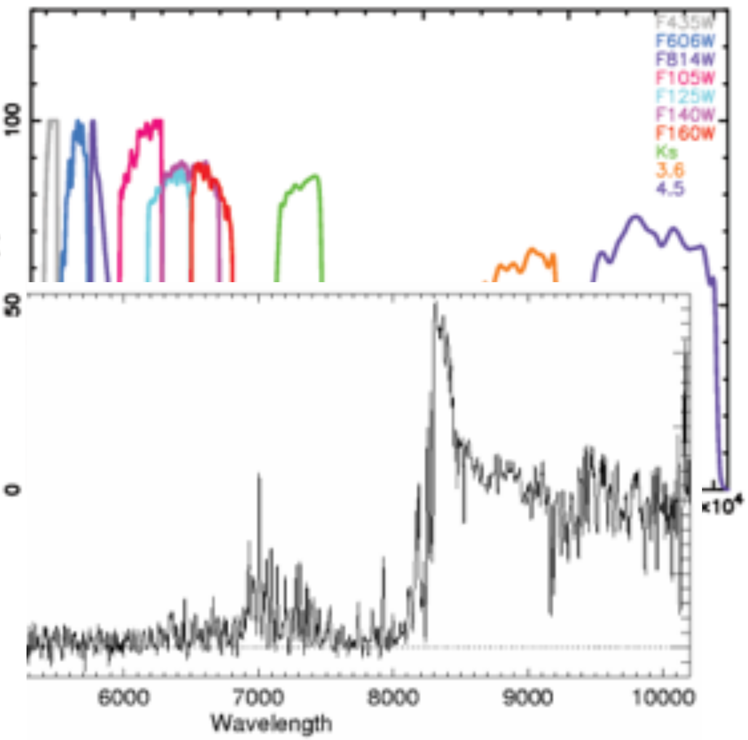

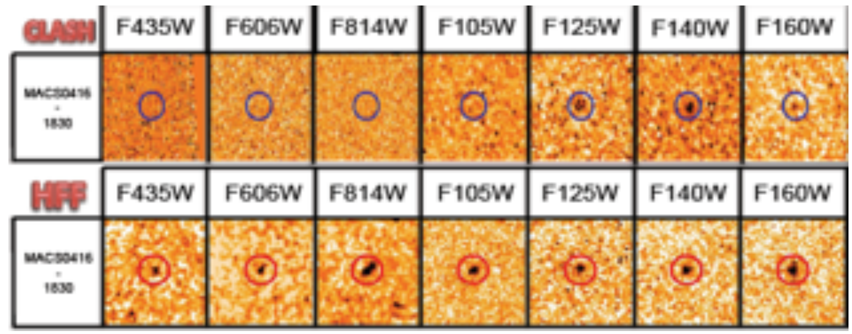

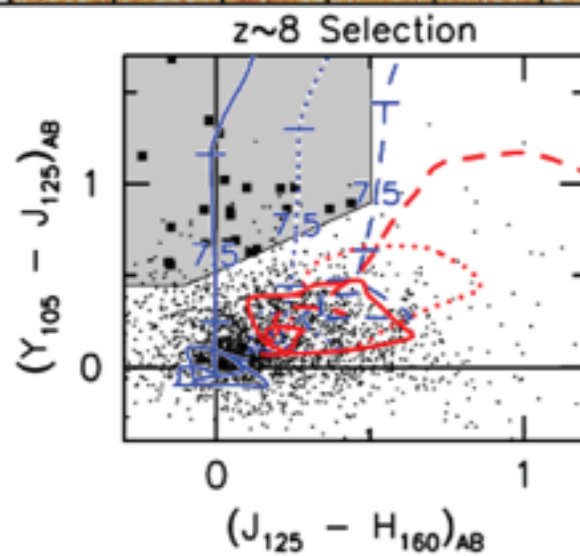

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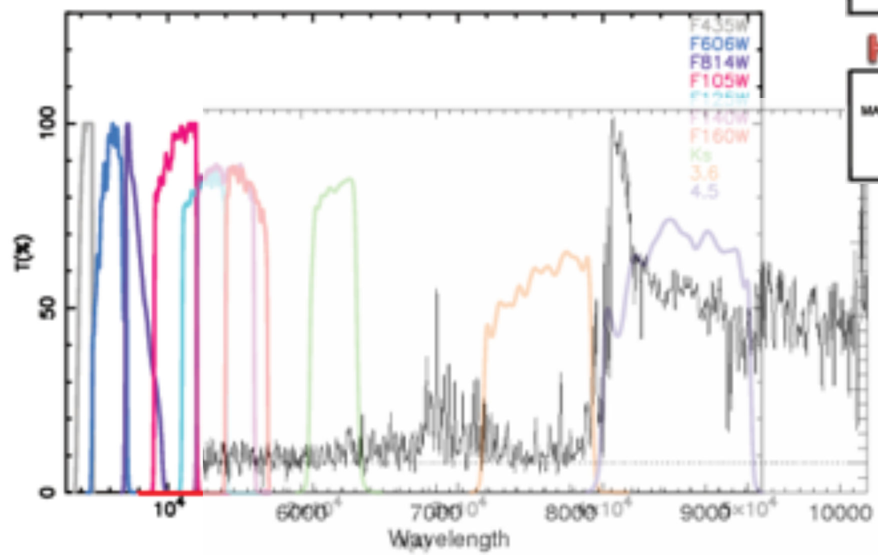
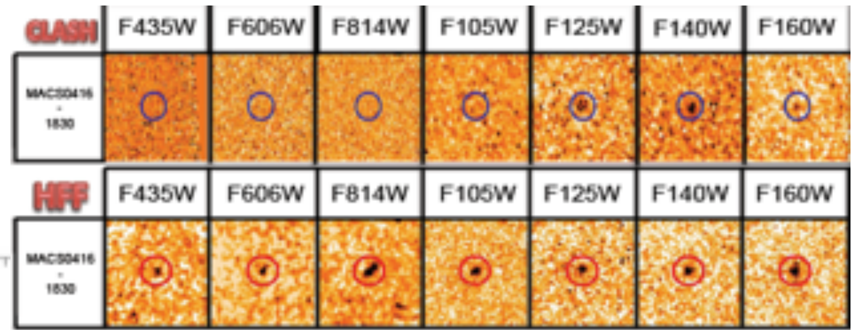
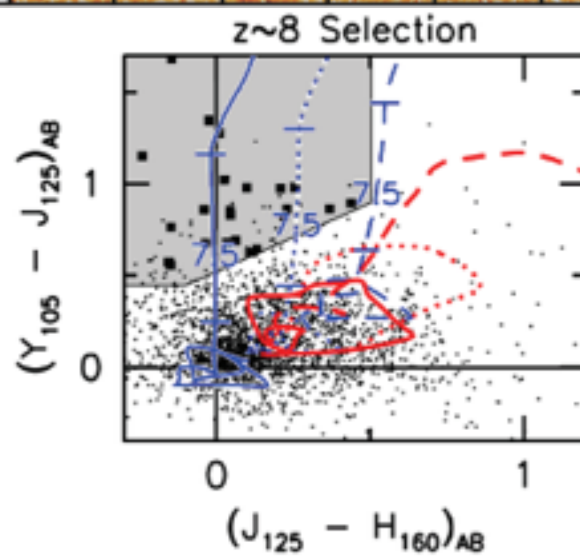






Bouwens+14

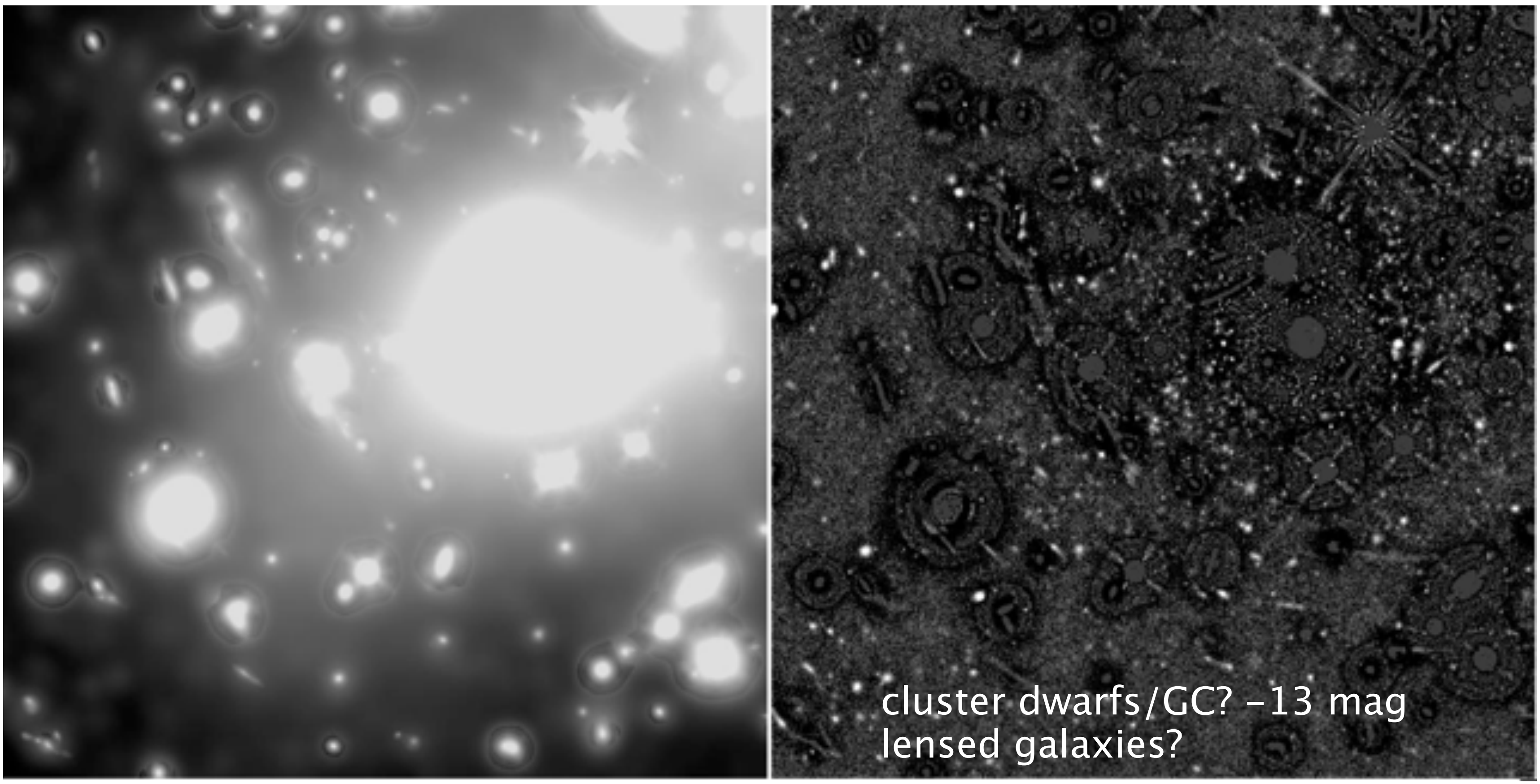
HFF Imaging studies: LBG Dropout Selection

Abell 2744 + par: ~30 z=7-10 dropouts found (3 with μ>10)

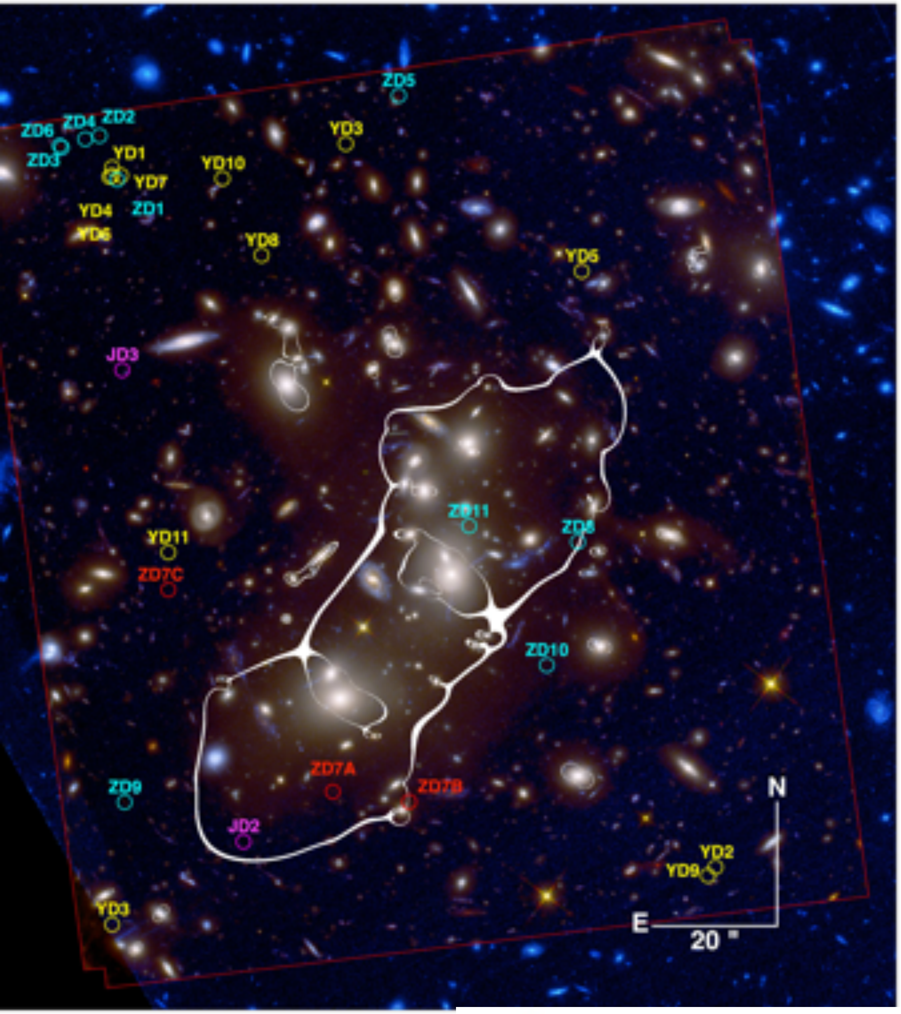
MACS 0416 + par: ~25 z=7-10 dropouts found (1 with μ>20)

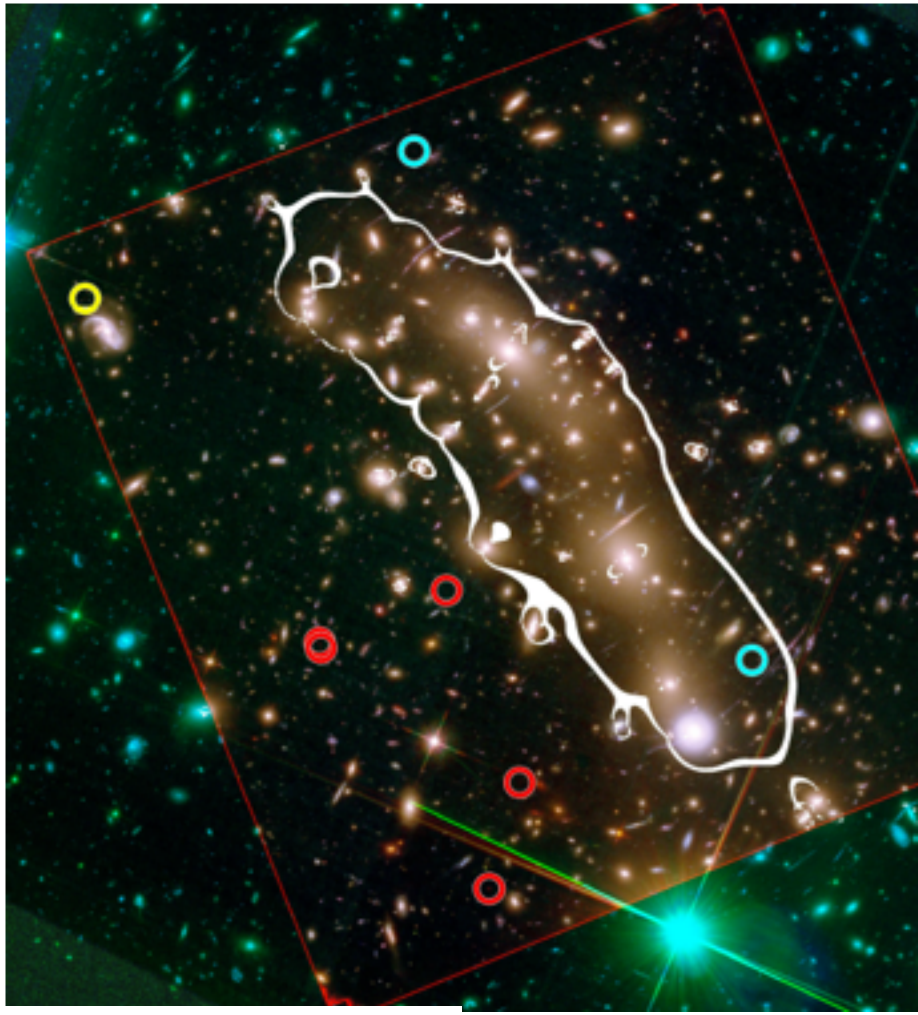
(Ishigaki+14; Atek+14; Zheng+14; Coe+14; Laporte+14; Zitrin+14; Oesch+14, Infante+15)

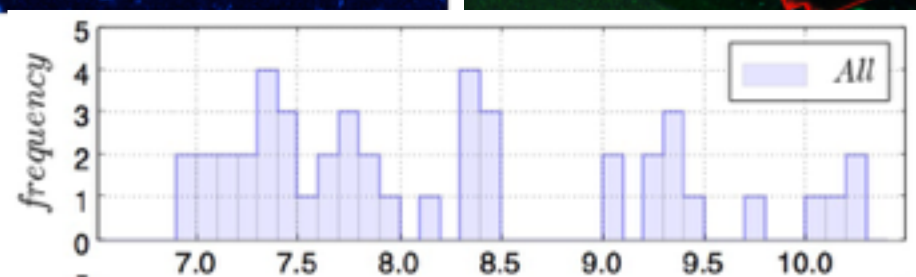
Standard source detection misses many. Need to subtract large-scale "foreground" (cluster + ICL) to probe behind cluster.



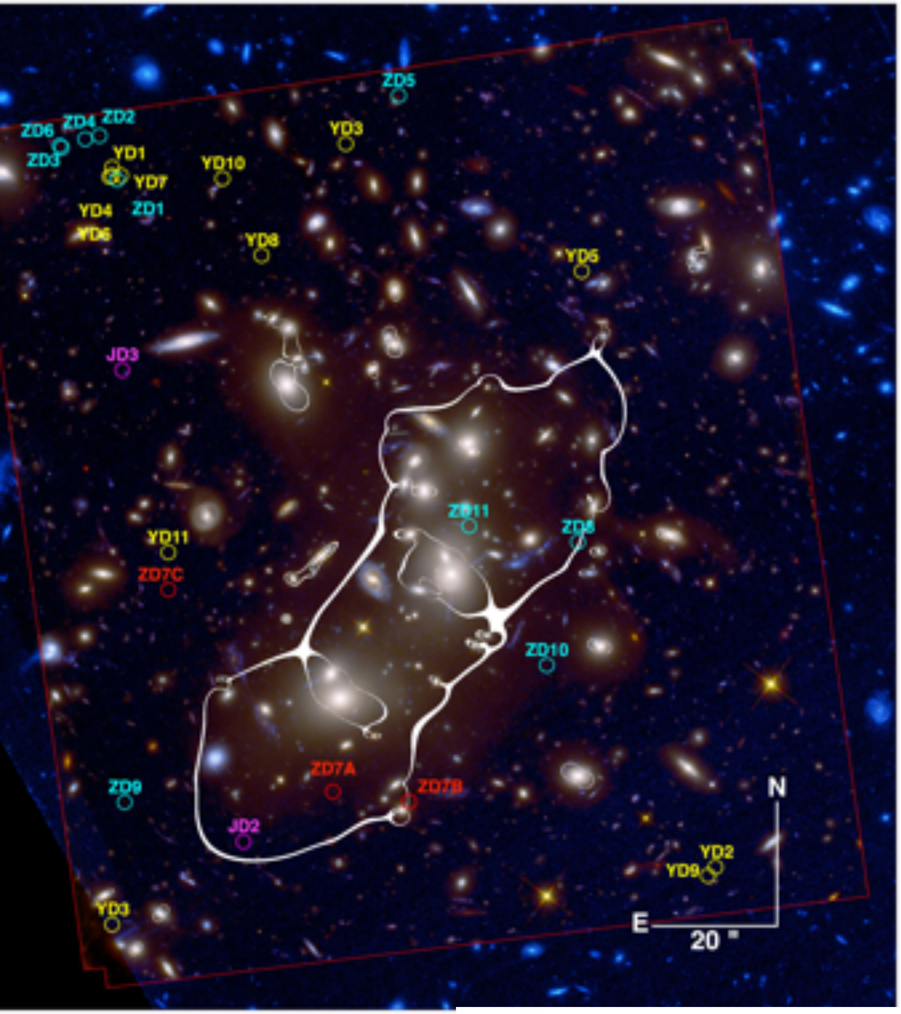
HFF Imaging studies: LBG Dropout Selection

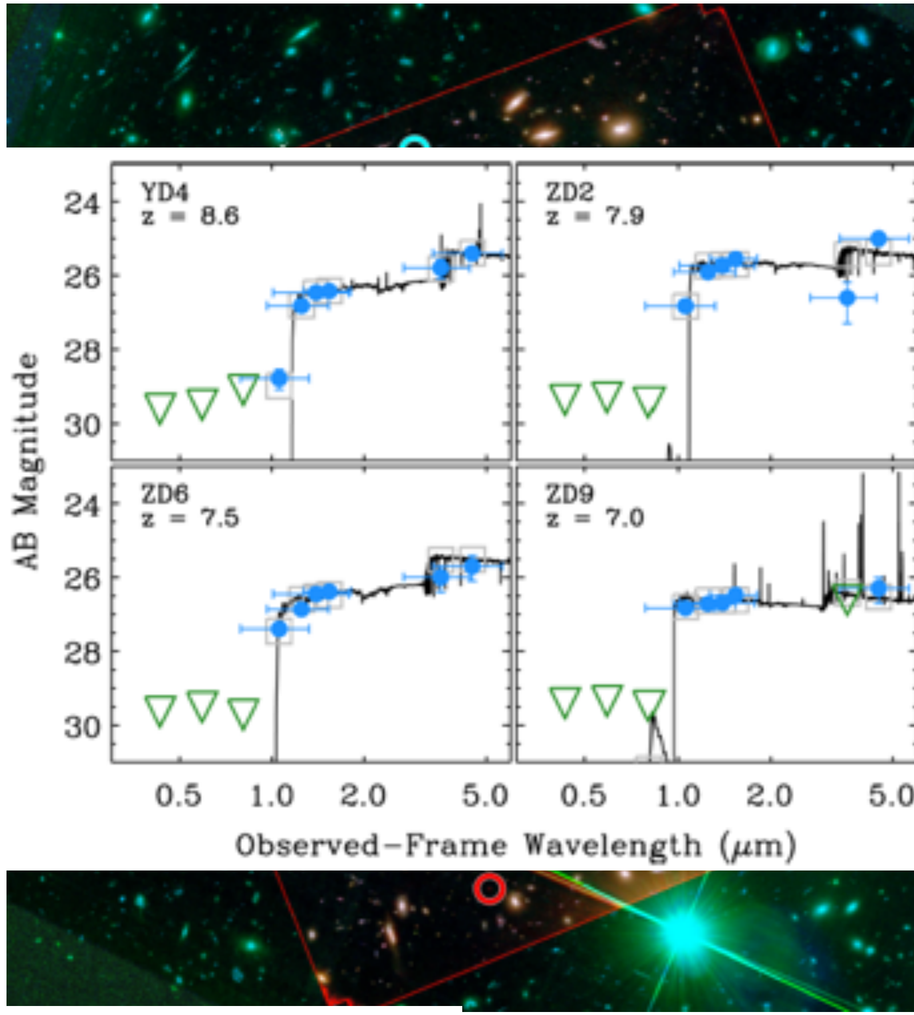


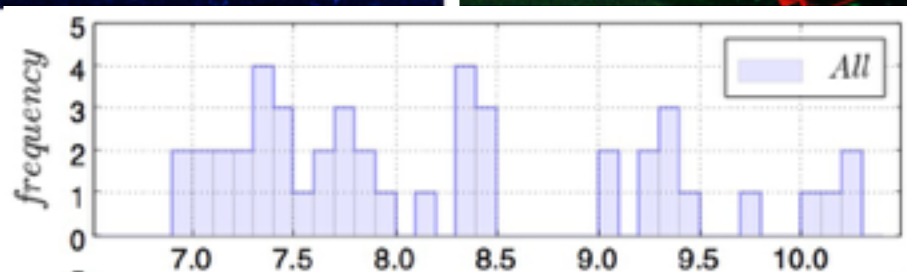




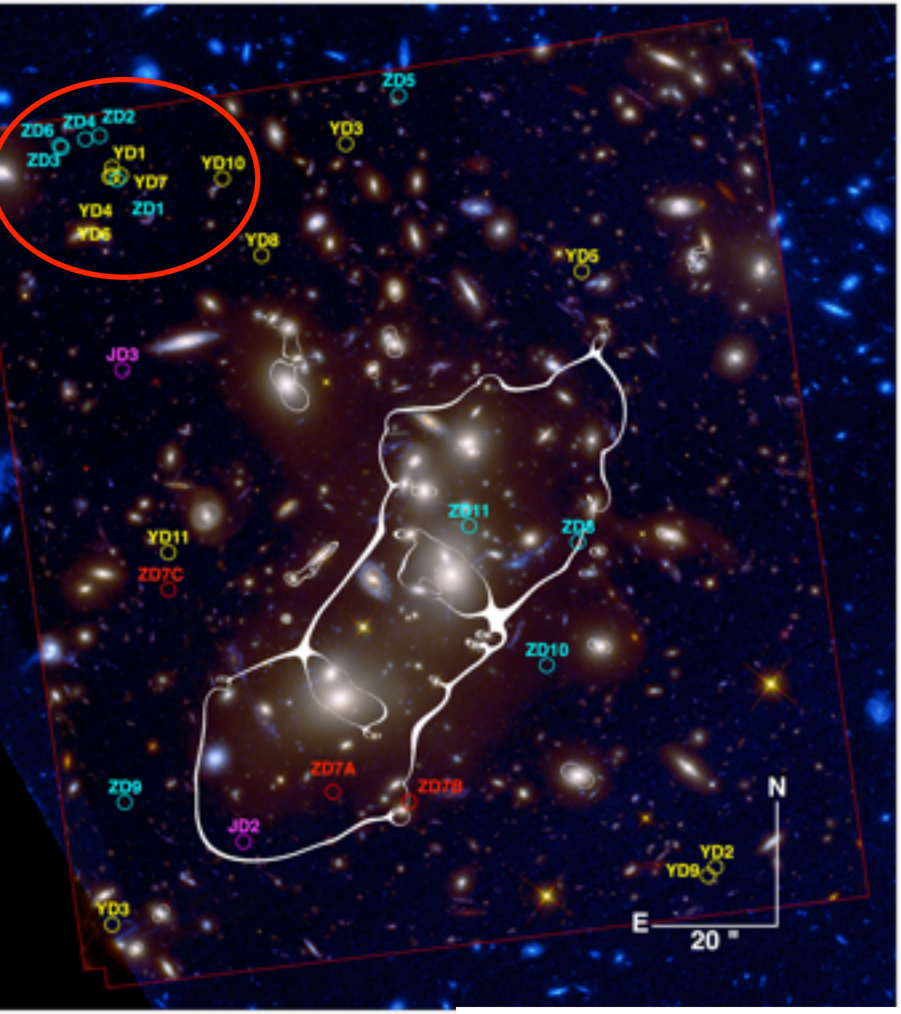
HFF Imaging studies: LBG Dropout Selection

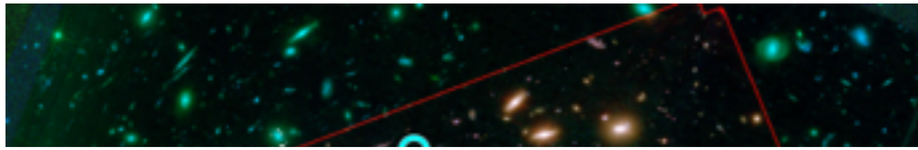


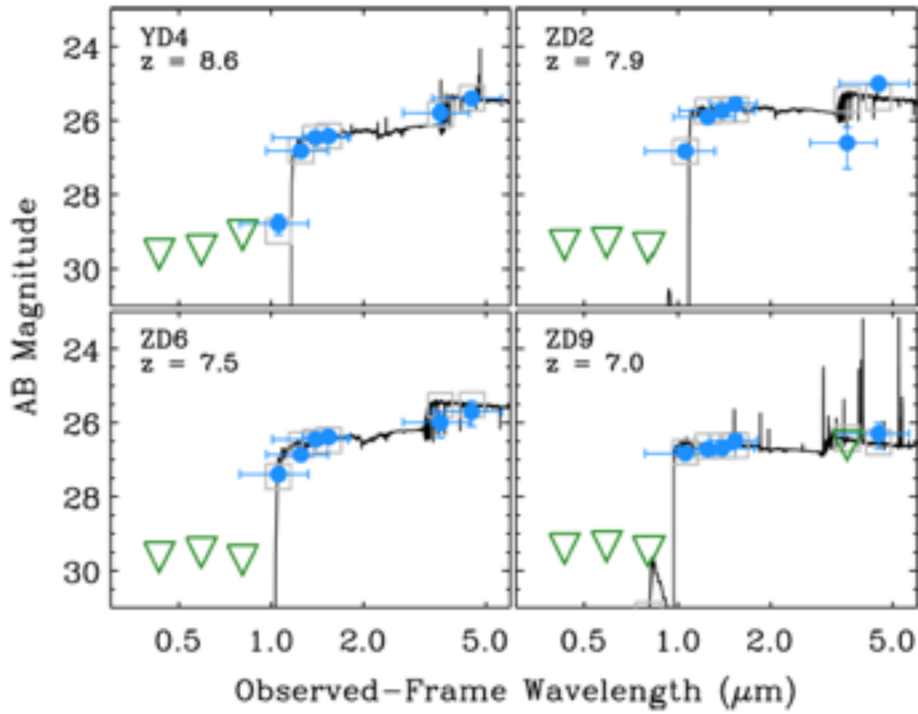


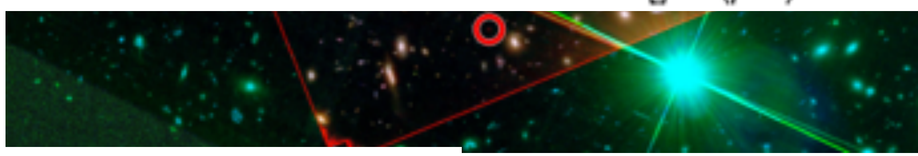


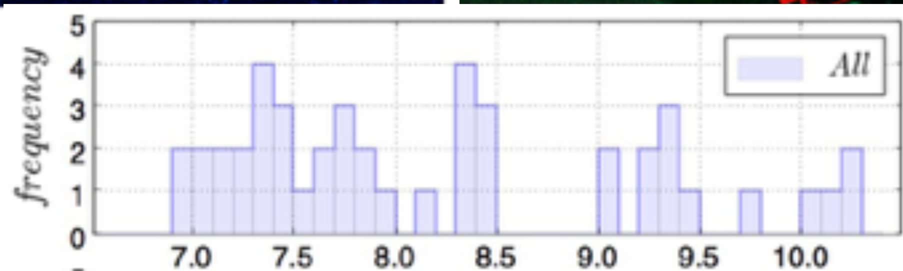
HFF Imaging studies: LBG Dropout Selection





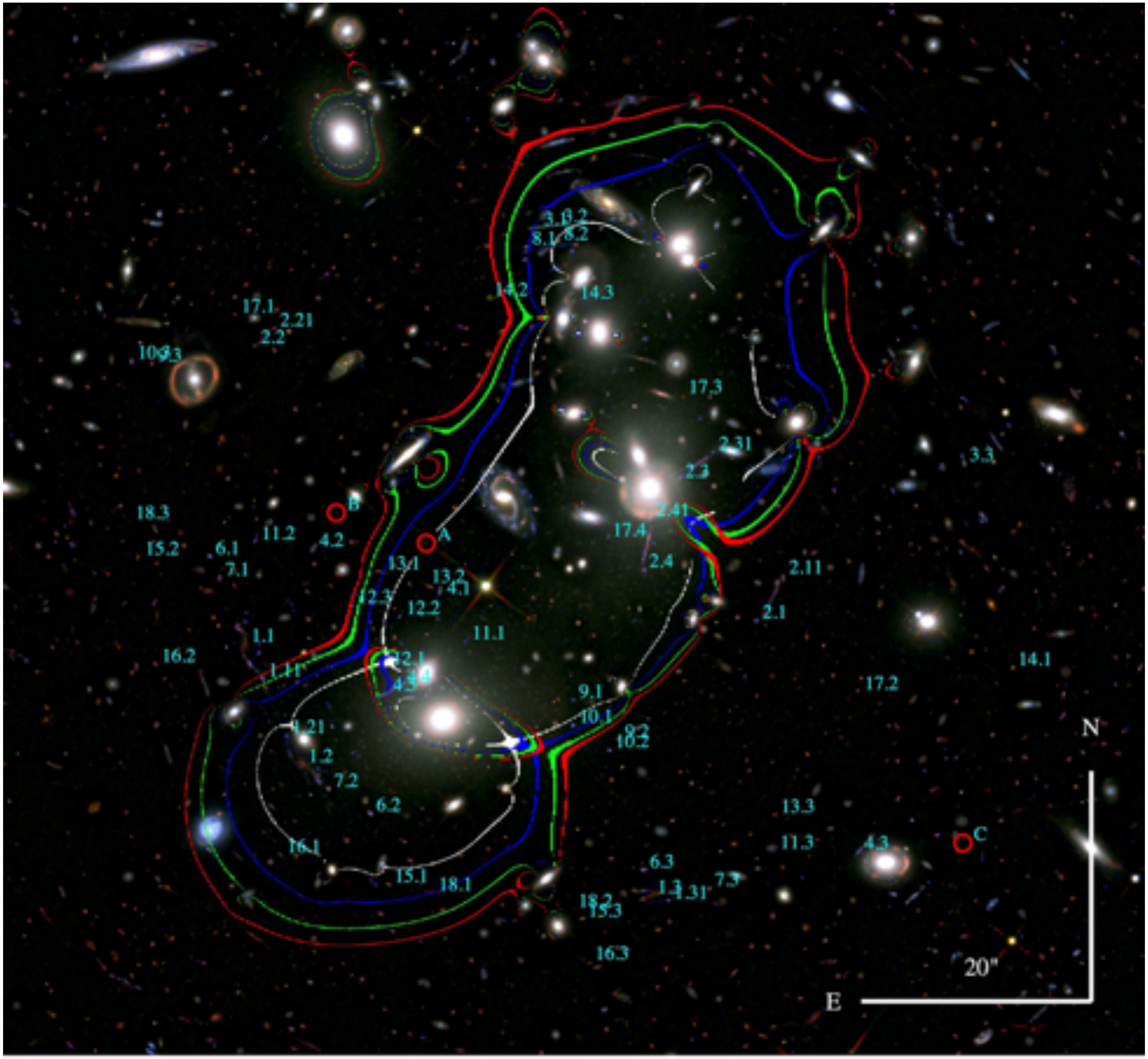






HFF Imaging studies: LBG Dropout Selection

Geometrically confirmed redshift! (Zitrin+14)



HFF Imaging studies: LBG Dropout Selection

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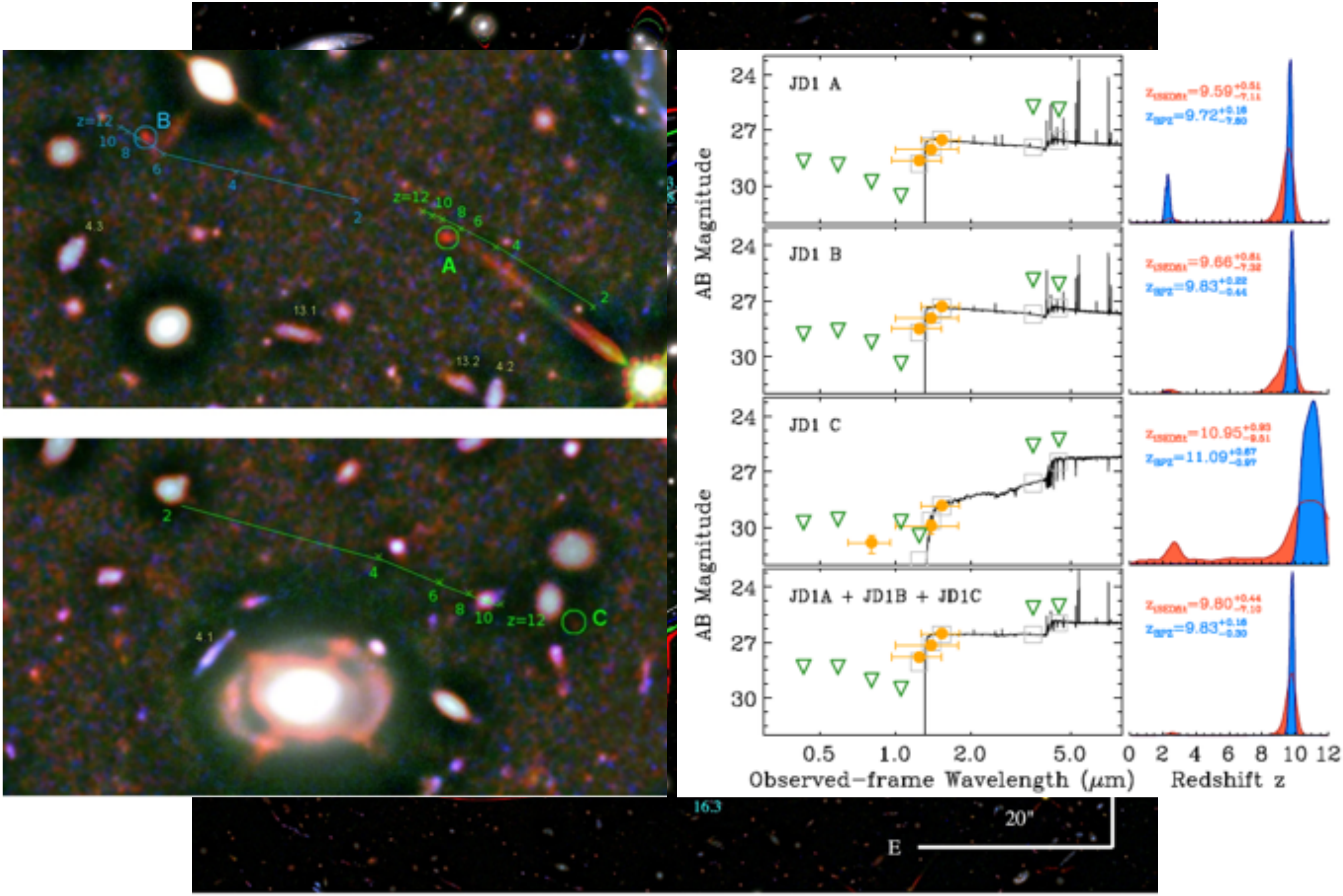
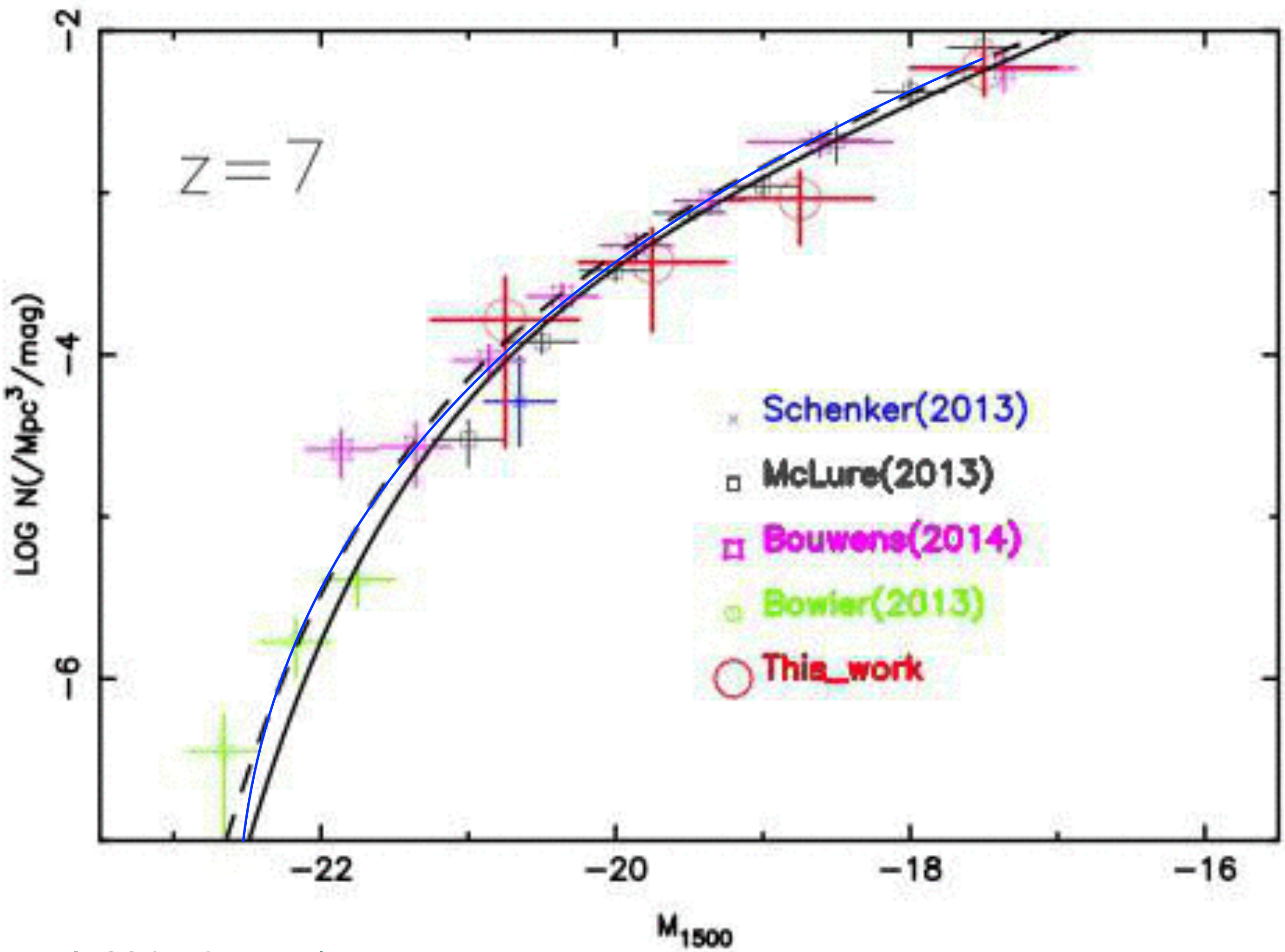


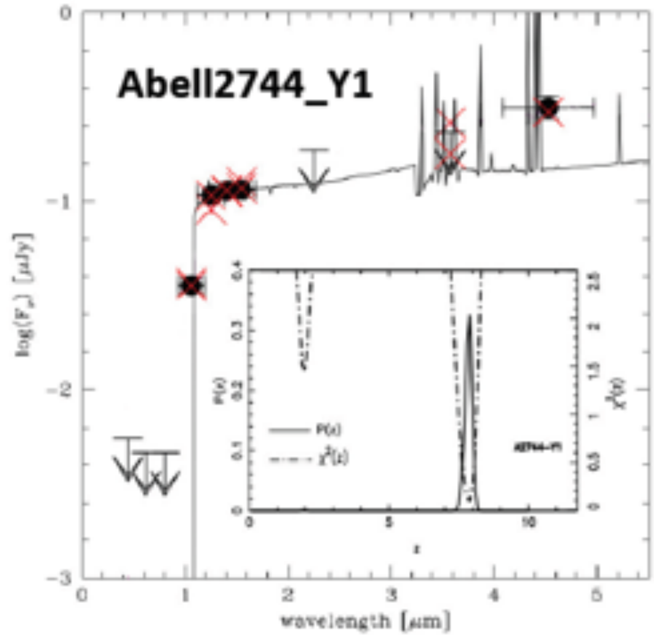
HFF Imaging studies: LBG Dropout Selection



(Laporte et al. 2015, in prep)

HFF Spectroscopy studies…(how secure are dropouts?)

Abell 2744: targeted 12 z>6.5 dropouts with 10 hrs of zJ spectroscopy with MMIRS in Oct 2014 (CNTAC2014B-101)

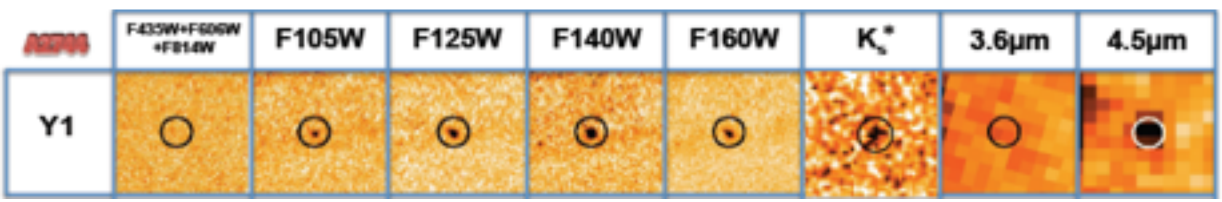


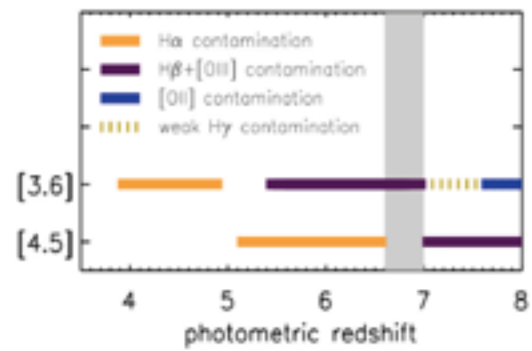
Laporte+14b

Object	z_{phot}	M_{1500}	SFR [$M_{\odot}$/yr]	μ	r [kpc]
Abell2744_Y1	$8.0^{+0.5}_{-0.2}$	-20.5	$8.0^{+1.2}_{-0.7}$	1.5	0.35 ± 0.15

*One of the most secure candidates is Y1, which has a **F814W-F125W > 3.5 mag***

(>2.5 mag suggested by Hayes et al. 2012)





HFF Spectroscopy studies…(how secure are dropouts?)

Below z~6.6, optical spectroscopy still quite viable. VLT MUSE will be super efficient and useful for the HFFs.

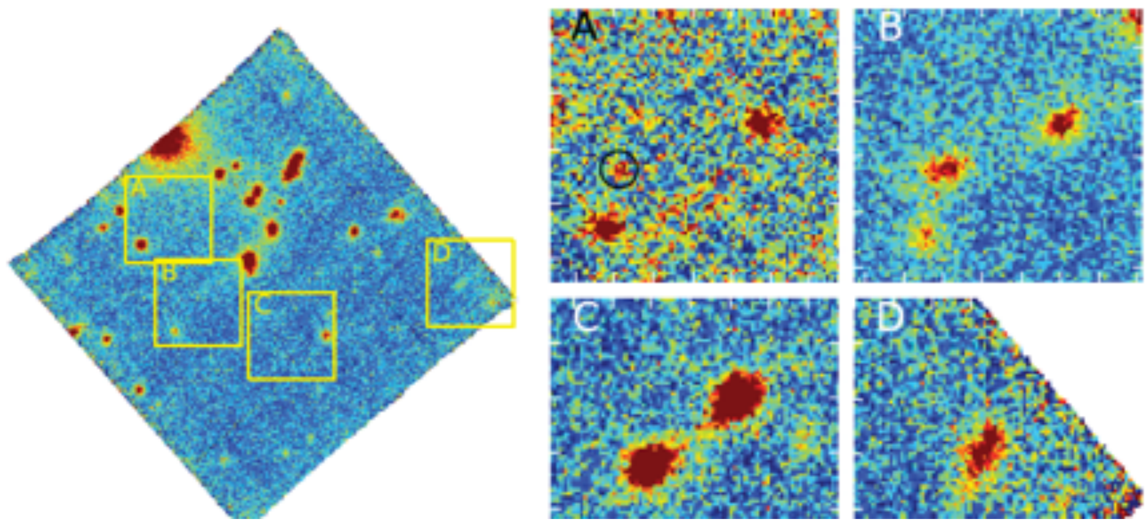
J. Richard has GTO program to map several of the HFFs.

Likewise, PUC group has 11 hrs of MUSE on MACS 0416 is currently being reduced….

2hr MUSE IFU data on Abell 2744 (Karmen et al. 2014)

confirm + discover ~100 multiple lensed objs. LAEs, etc.

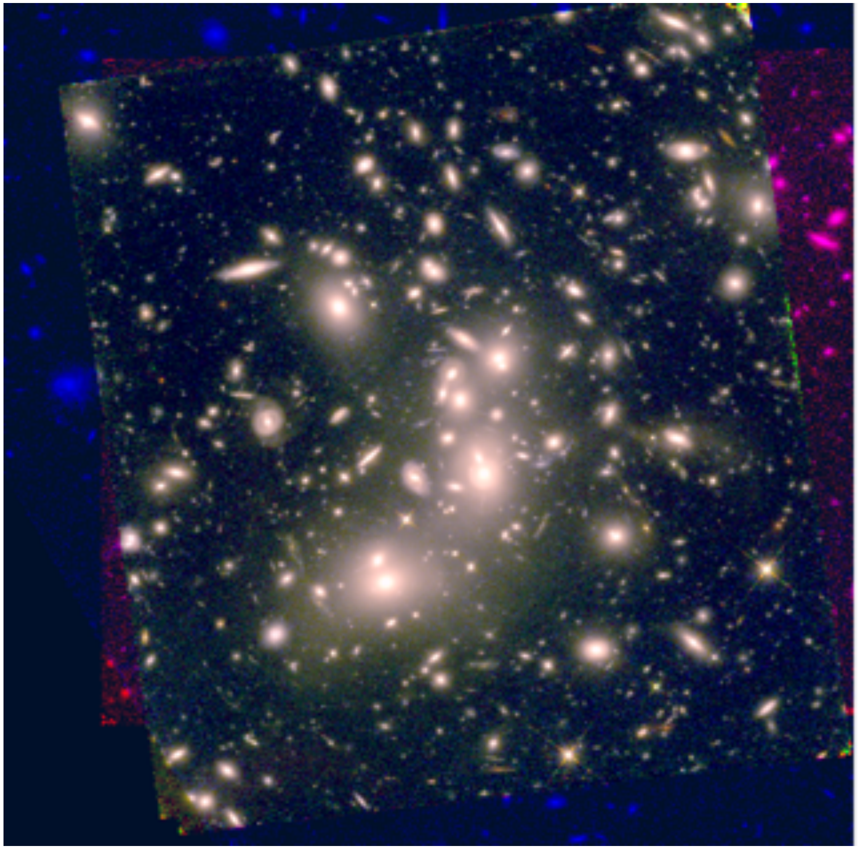
few without ANY optical counterparts!



HFF Spectroscopy studies…What about ALMA?

ALMA can probe obscured star formation (LIRGs) out to high-z
Complementary with optical/near-IR constraints

ALMA Observations of Hubble Frontier Fields:
First look at Abell 2744



Franz Bauer, Cristina Romero-Cañizales, Nicolas Laporte, Sam Kim (PUC)
Eric Villard, Ruediger Kneissl (JAO)

Timo Anguita, Manuel Aravena, Patricia Arévalo, Felipe Barrientos, Mauricio Carrasco, Ricardo Demarco, Harold Francke, Jorge Gonzalez, Edo Ibar, Leopoldo Infante, Hugo Messias, Alejandra Muñoz Arancibia, David Murphy, Neil Nagar, Julie Nantais, Nelson Padilla, Ezequiel Treister, Paulina Troncoso Italo Balestra, Rychard Bouwens, Larry Bradley, Dan Coe, Holland Ford, Marc Postman, Piero Rosati, Wei Zheng, Adi Zitrin

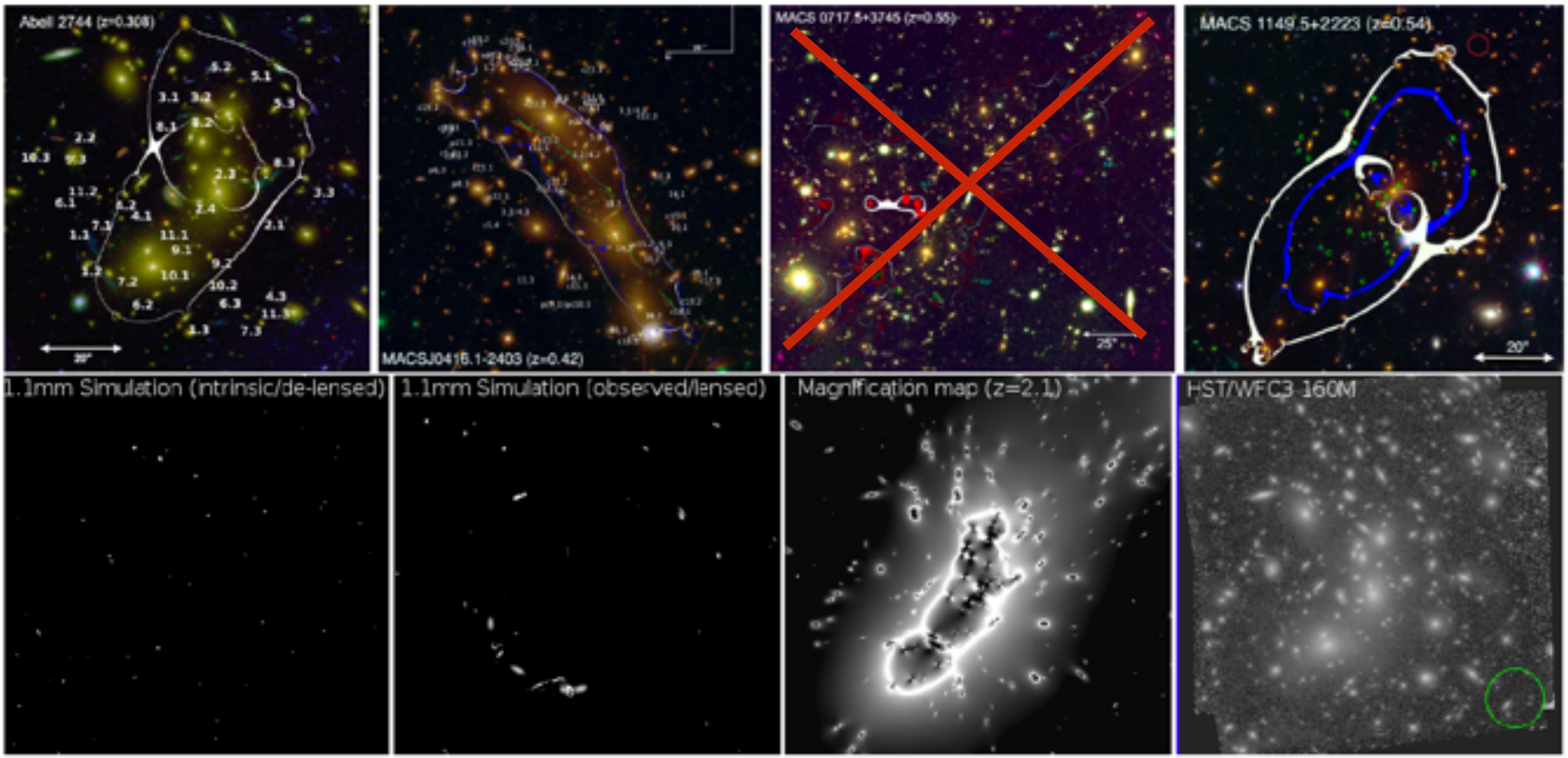
ALMA Observations of Hubble Frontier Fields

REPRESENTATIVE SCIENCE GOALS (UP TO FIRST 5)					
SCIENCE GOAL	POSITION	FREQUENCY	BAND	ANG.RES.(")	ACA?
Band 6 imaging of Abell 2744	J2000: 00:14:21.2000, -30:23:50.100	254.75000 GHz	6	1.4	N
~~Band 6 imaging of MACSJ0717.5+3745~~	~~[illegible]~~	~~254.75000 GHz~~	~~6~~	~~1.4~~	~~N~~
Band 6 imaging of MACSJ1149.5+2223	J2000: 11:49:36.3000, 22:23:58.100	254.75000 GHz	6	1.4	N
Band 6 imaging of MACSJ0416.1-2403	J2000: 04:16:08.9000, -24:04:28.700	254.75000 GHz	6	1.4	N
Total # Science Goals : 4					

Proposed to observe all 4 approved HFFs to depth of 70 uJy rms (126 pts)

(1σ depth equates to $L_\odot \sim$ (1-2)e11 erg/s between z=1-7)

Goals: nail down faint end of detected number cnts, z distribution, SF properties + stacking



ALMA Observations of Hubble Frontier Fields

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[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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Band 6 imaging of MACSJ0416.1-2403	J2000: 04:16:08.9000, -24:04:28.700	254.75000 GHz	6	1.4	N
Total # Science Goals : 4					

Status:

Abell 2744 had 4.5 passes in June 2014 (extended configuration).
received 2 further passes (late Dec 2014; compact configuration).
still awaiting data!

MACS J0416-2403 received 2 passes in Dec 2014 (compact configuration) awaiting 2 further passes in Jan 2014. Failed QA2, received 2 passes in Apr. 2015…still awaiting data!

MACS J1149.5+2223 received 4 passes in Jan 2015 (compact configuration). Failed QA2, received 2 passes in Apr. 2015…still awaiting data!

ALMA Observations of Hubble Frontier Fields

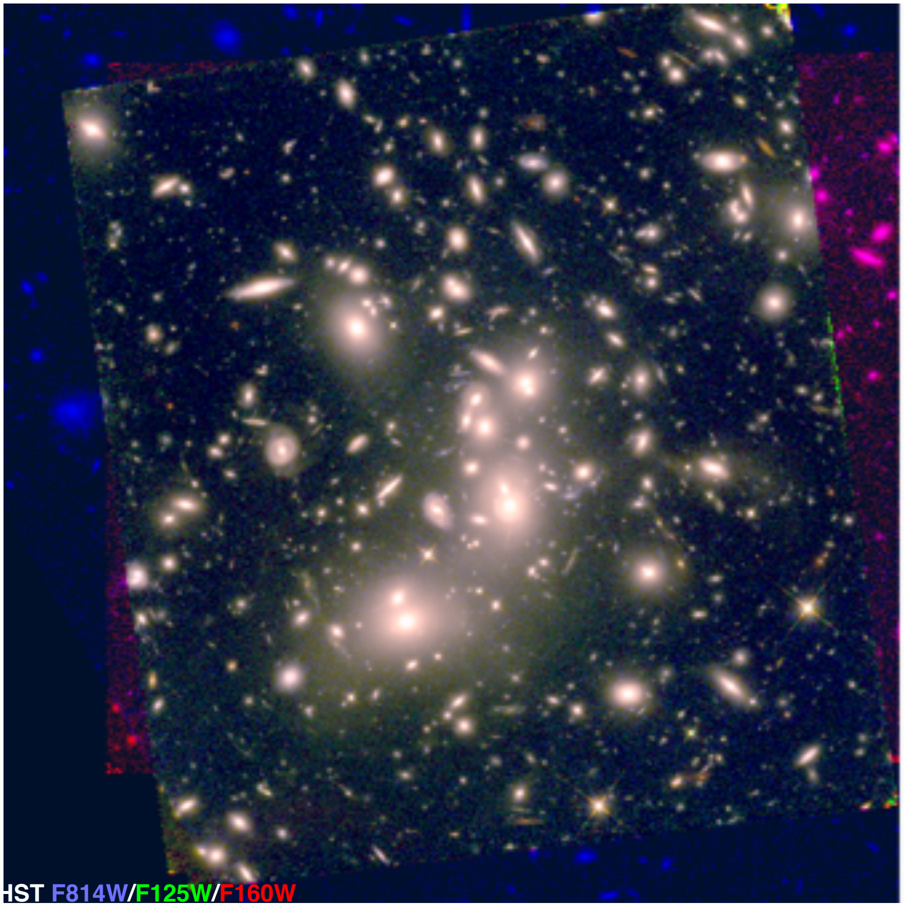
Late June: First Abell 2744 data taken (5.7h, band-6, 0.4” beam)

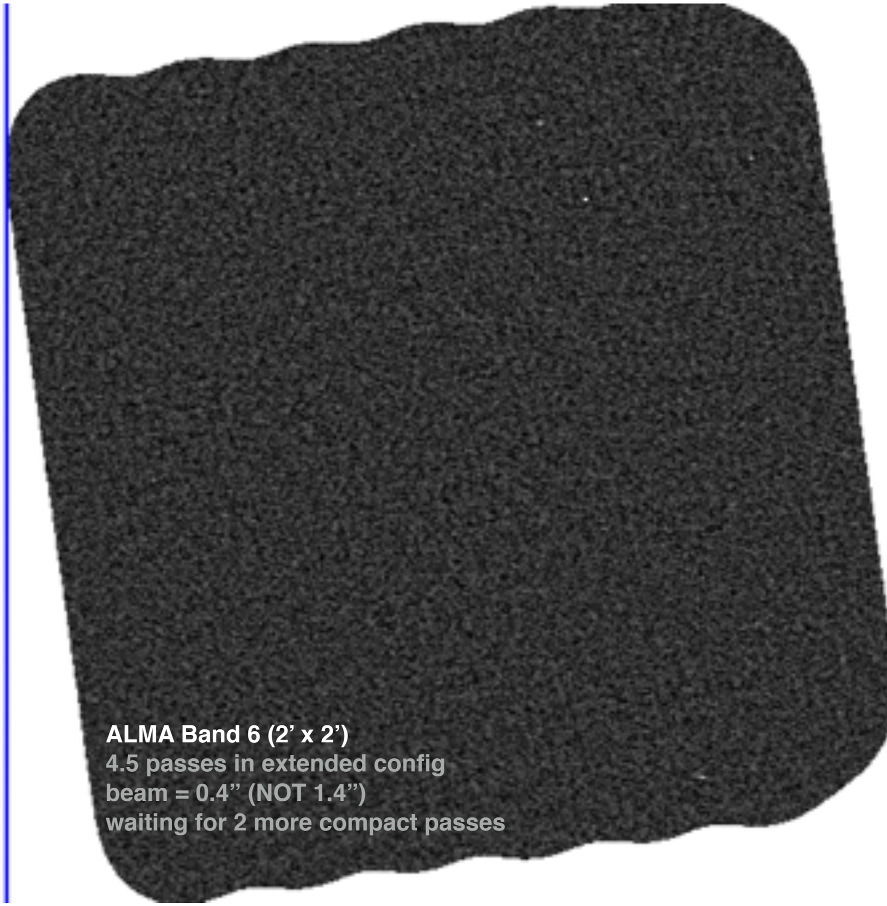
Mid Sept: Received access to first Abell 2744 data

Early Oct: Cristina R-C, Eric V. and Ruediger K. made improved ALMA map of Abell 2744

=> **7** detections above **5σ**, 10 more above 4.5σ

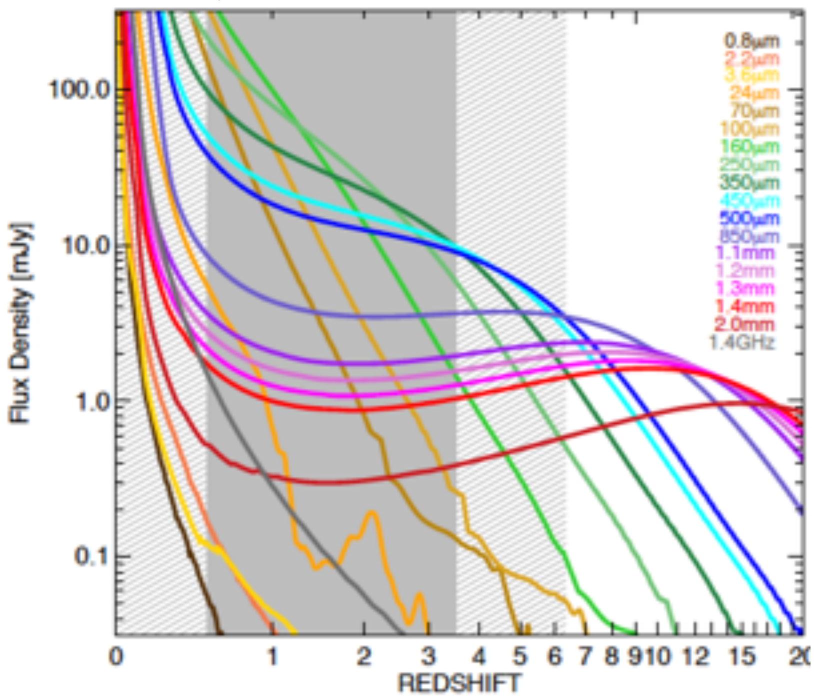
=> none of the z > 6 dropout candidates detected (< 30 $M_\odot$ / yr)

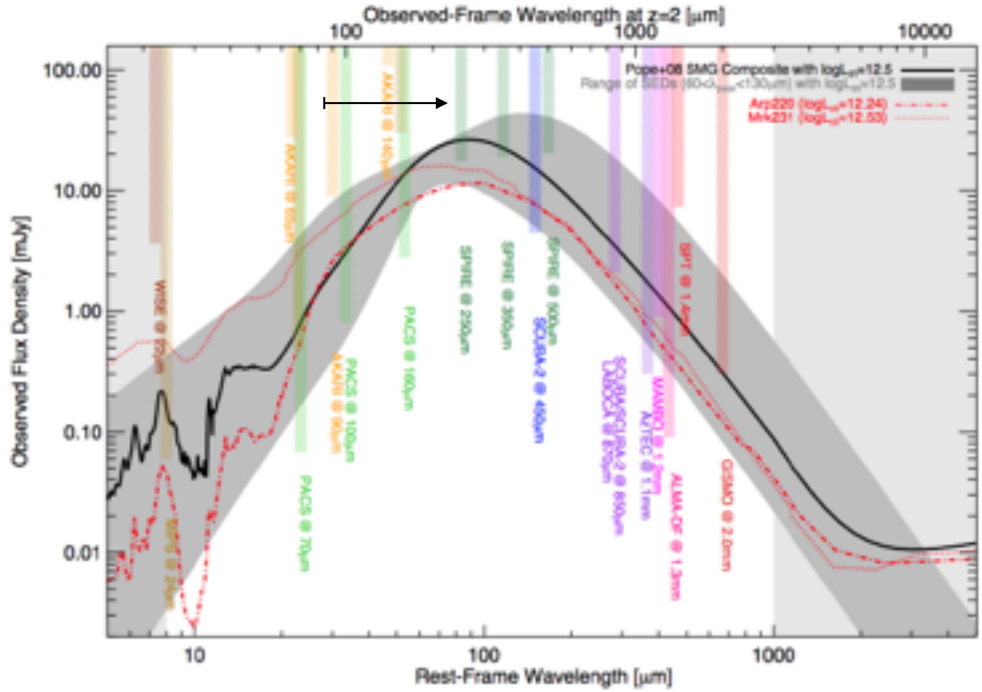




ALMA Observations of Hubble Frontier Fields

Casey et al. 2014





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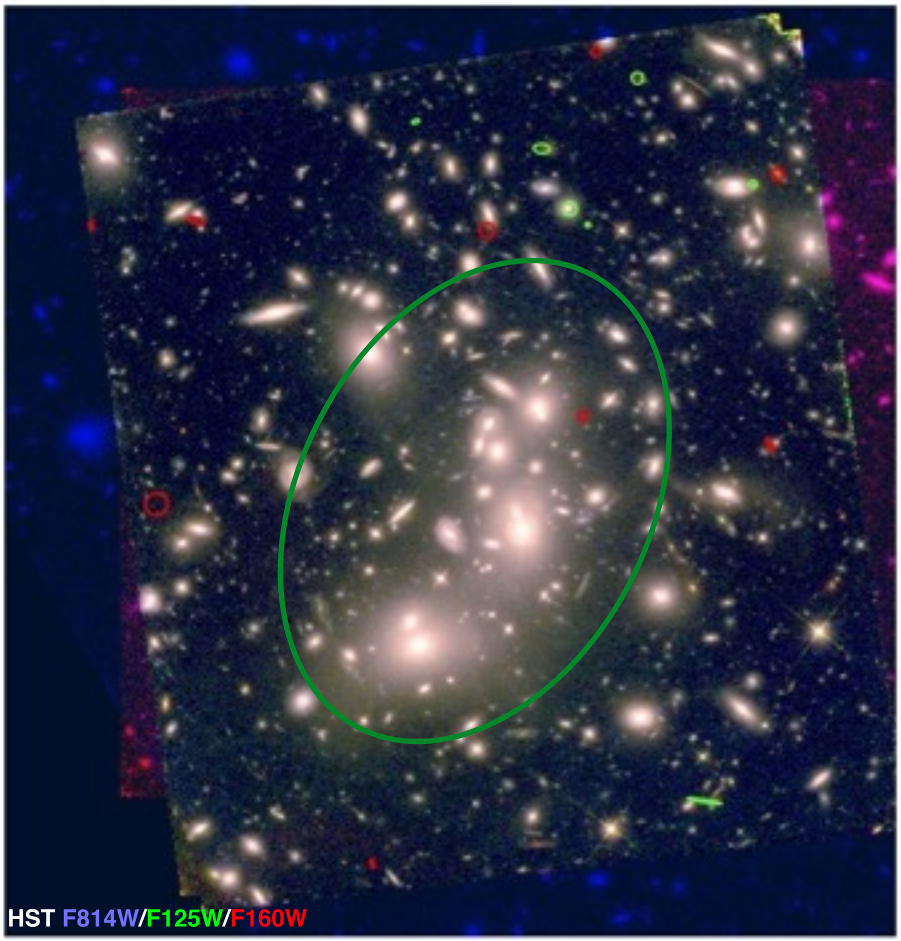

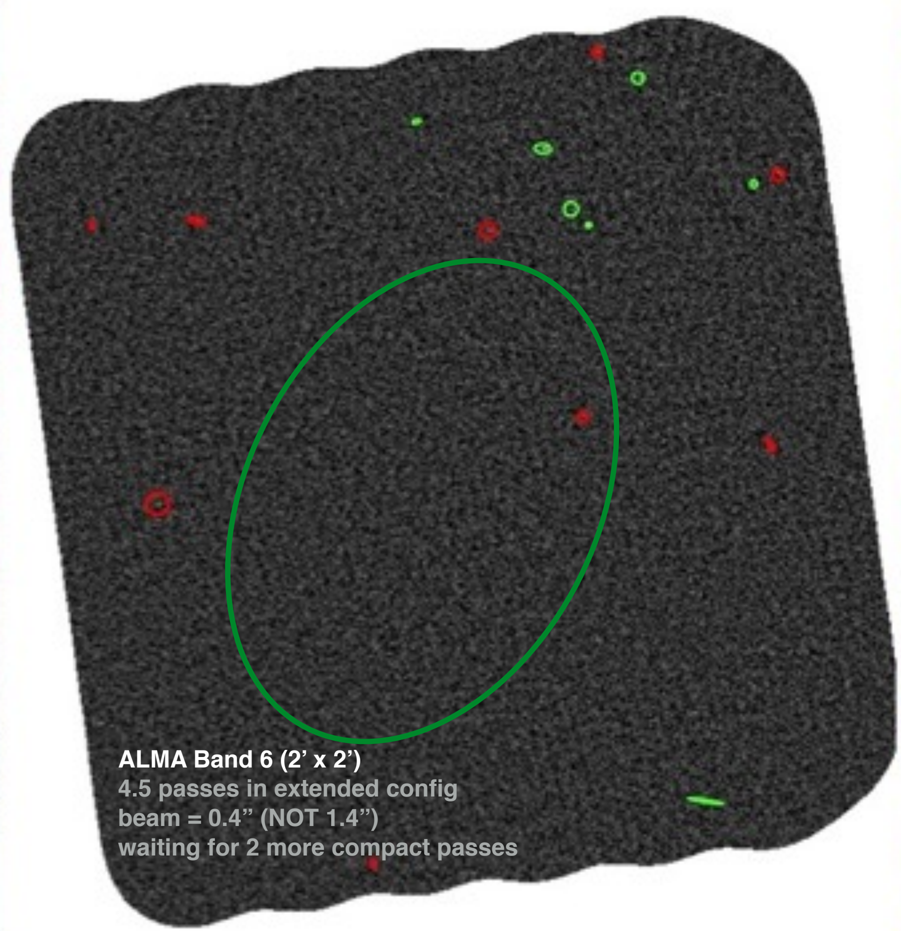

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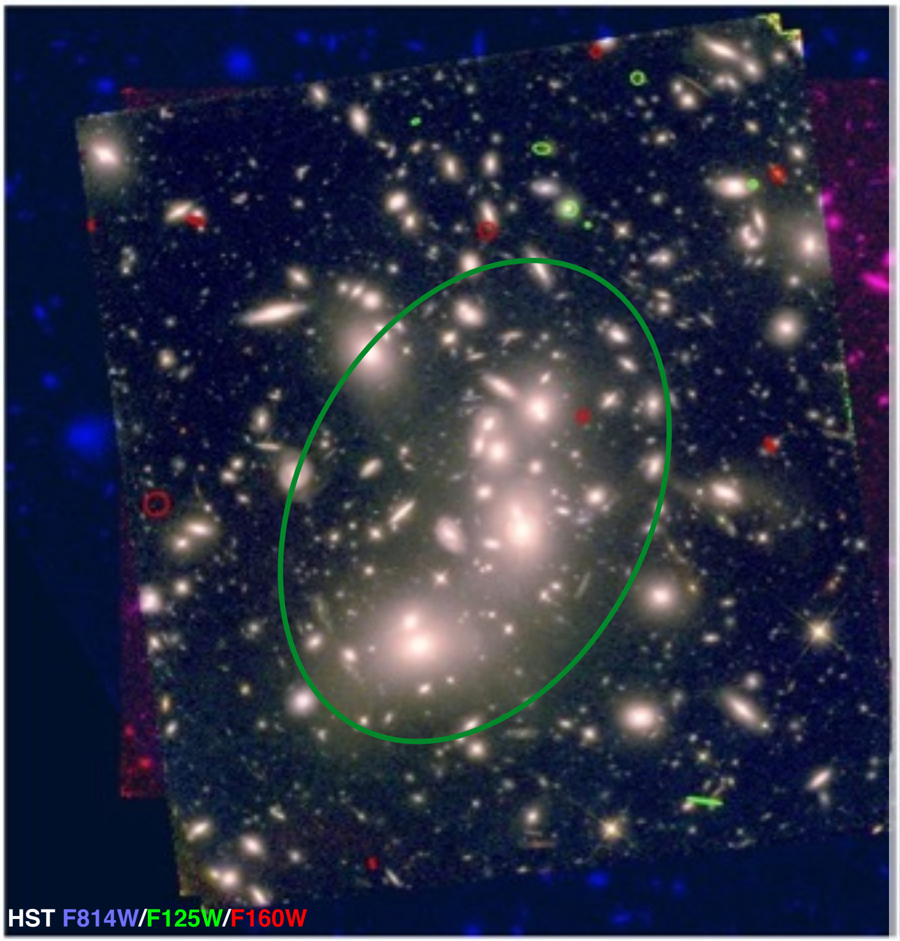

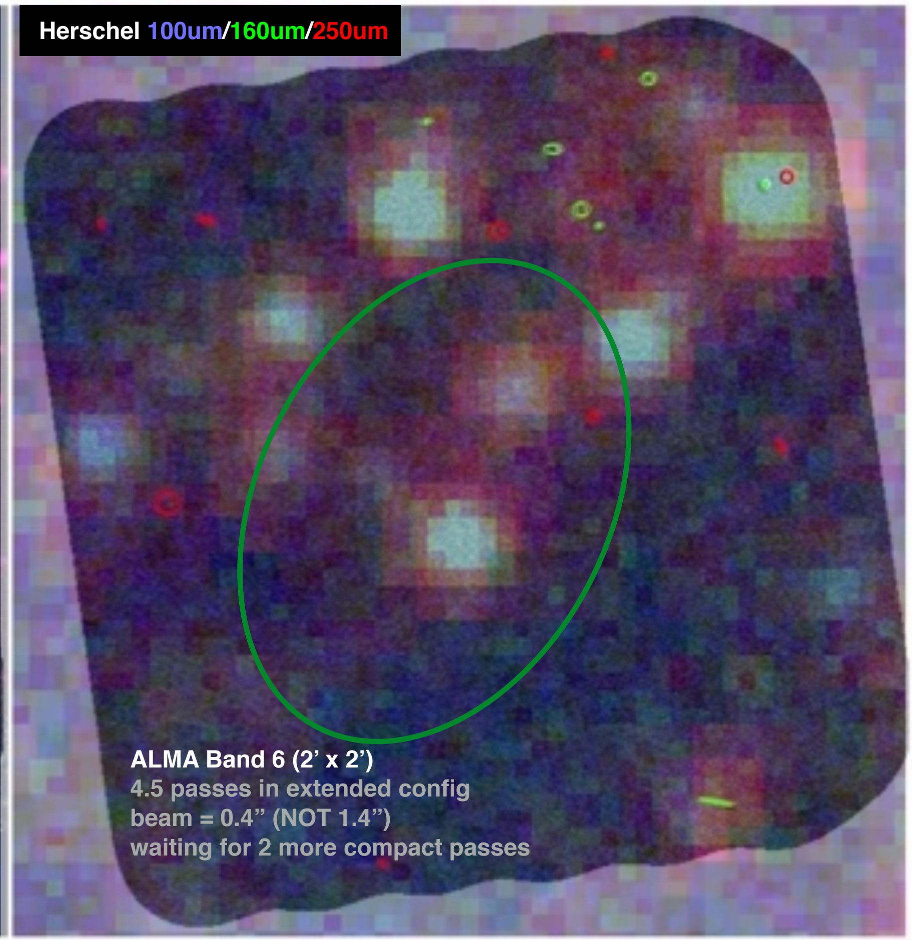

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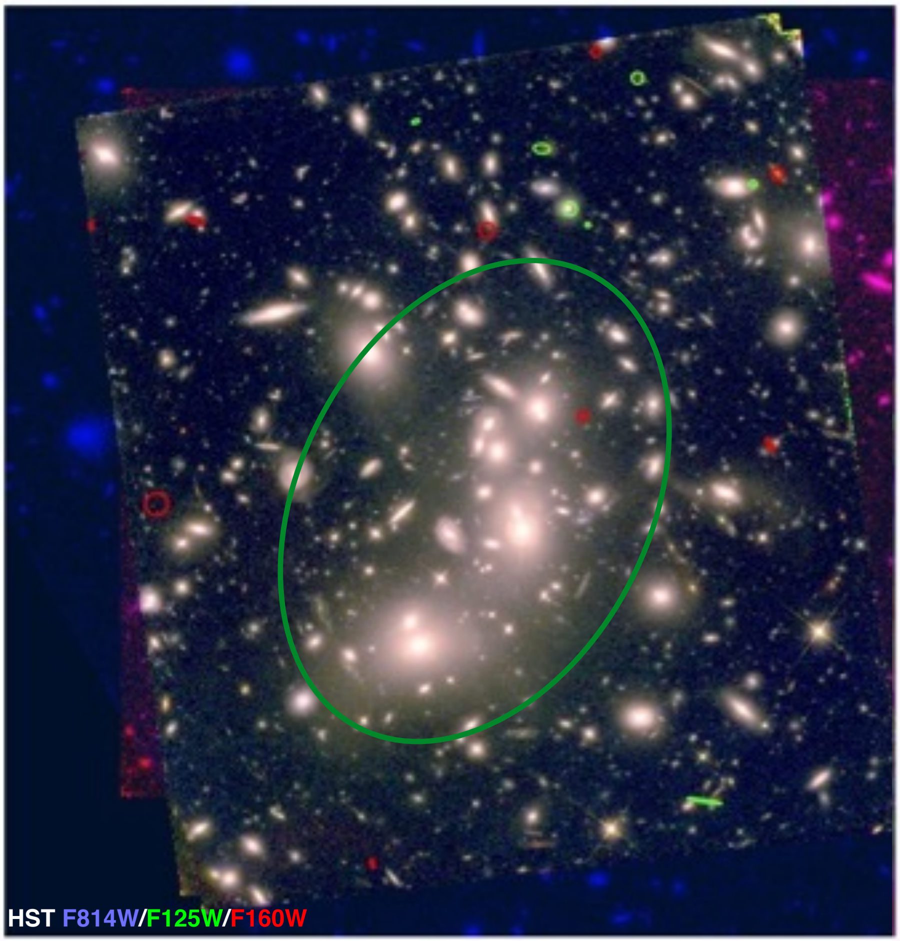
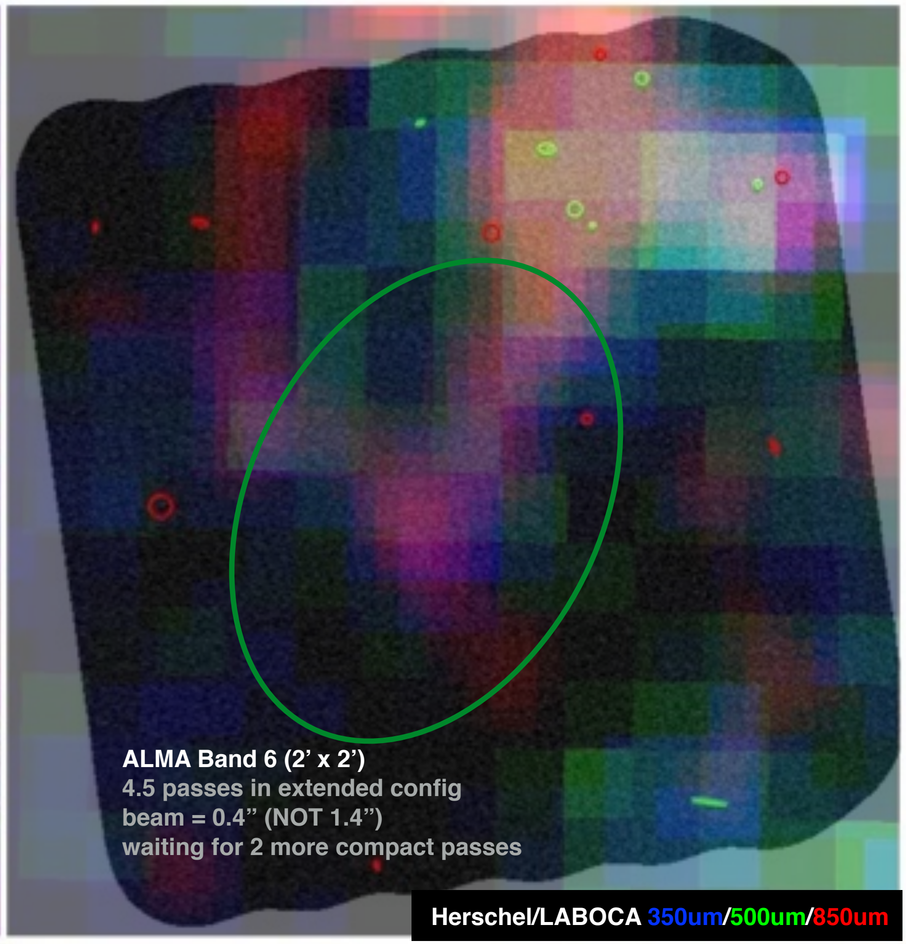
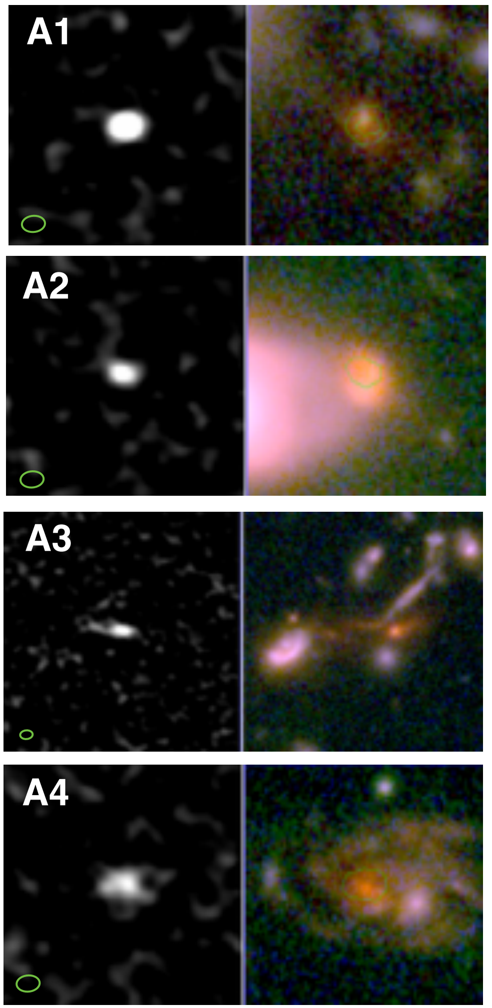
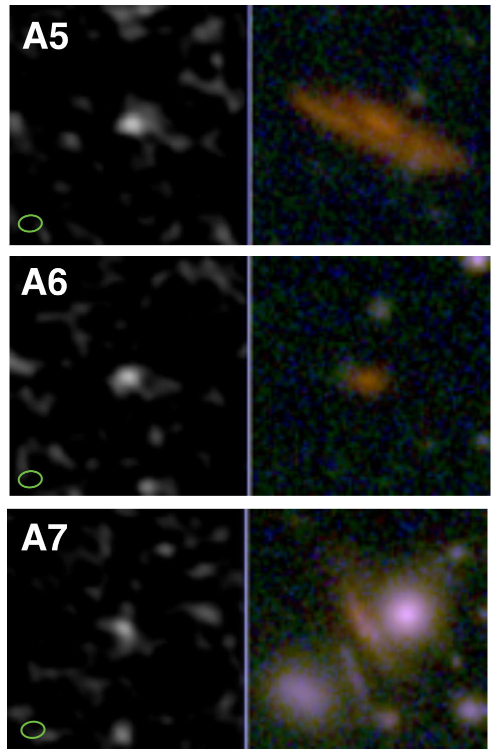




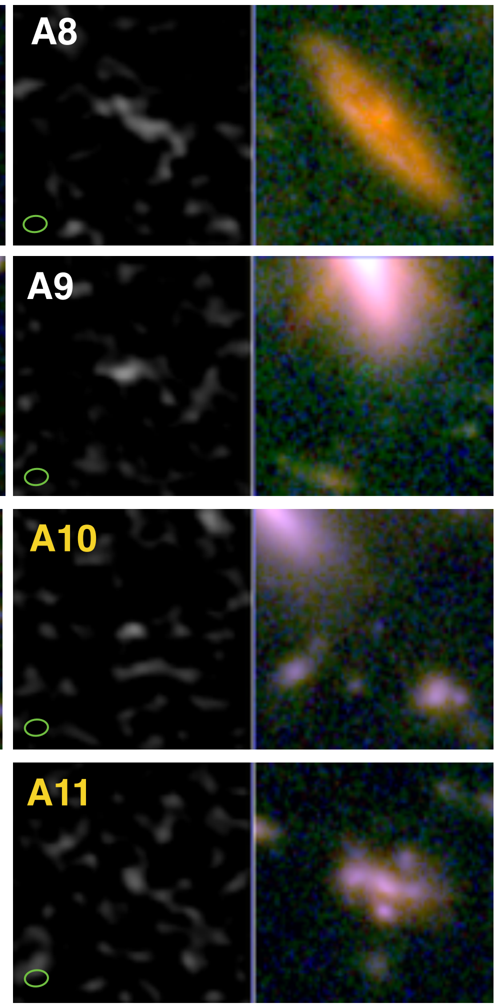
ALMA Observations of Hubble Frontier Fields

Compare to HST images (F160W+F125W+F814W)



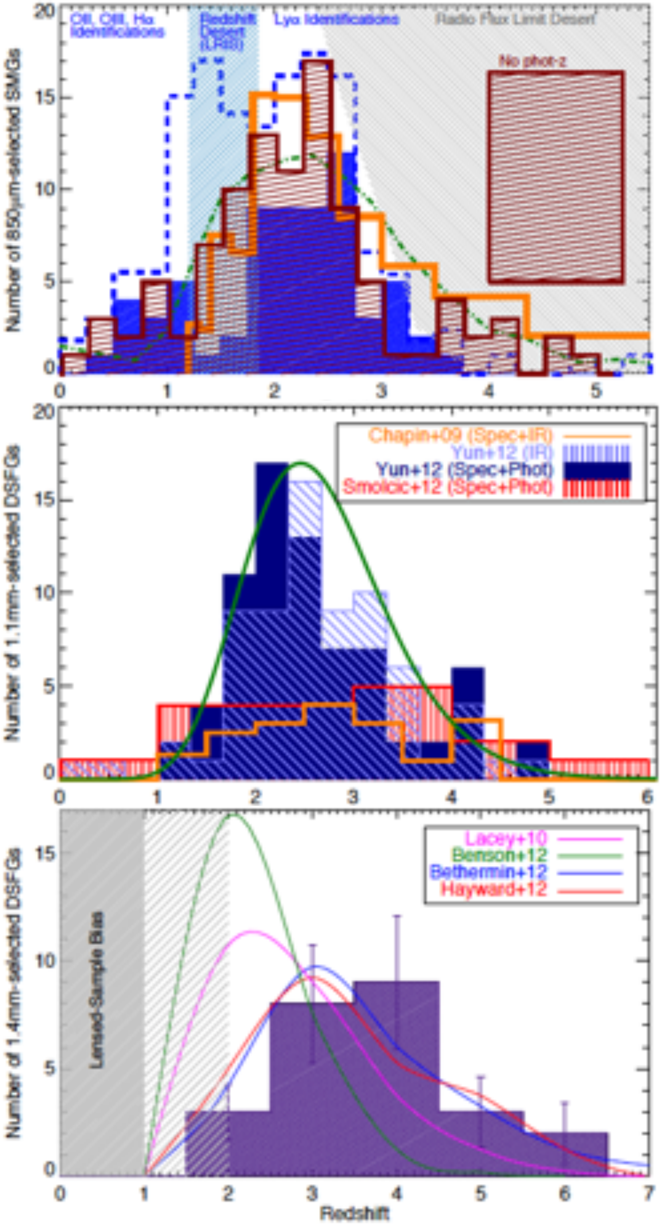


F160W => 21 - 26+
A_V => 1 - 5
z_{ph} => 1.5 - 6.0
μ => 1.9 - 6.7
L_{IR} => 1e11 - 1e13 $L_\odot$



ALMA Observations of Hubble Frontier Fields

Compare preliminary (z_{ph}) redshift distribution to a few others.

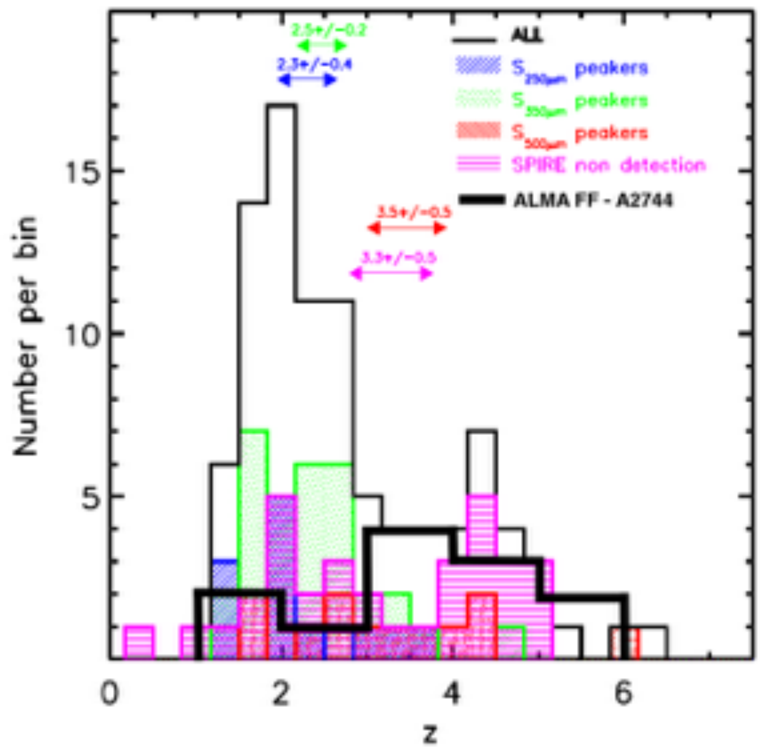


Radio-matched SCUBA

AzTEC

SPT

ALESS vs HFF



HFFs are probing factor of several fainter fluxes, and hence to higher redshifts.

Conclusions:

HFFs are still very much a work in progress.

Early optical results seem to confirm trends in UDF and CANDELS, and with 6 fields, will hopefully secure the $z > 7$ LFs. Unfortunate dearth of objs in high magnification area (hopefully will change with other fields).

Deep spectroscopy suggests that at $z > 7$, we are potentially finding a heterogeneous population with several potential interlopers (which will be interesting in their own right).

ALMA analysis will proceed rapidly in the next several months as we get final datasets with proper beam sizes (>1”). Ultimately, we hope to have constraints on the faint end number counts, detailed studies of individual interesting objects, and stacked constraints on number populations.

what does the future hold?

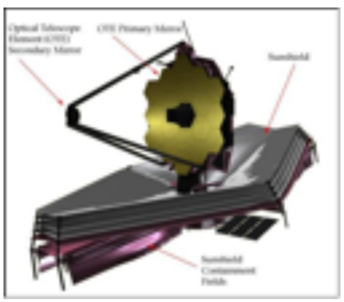
Pushing relations to beyond peak of SFR density (to z~5)

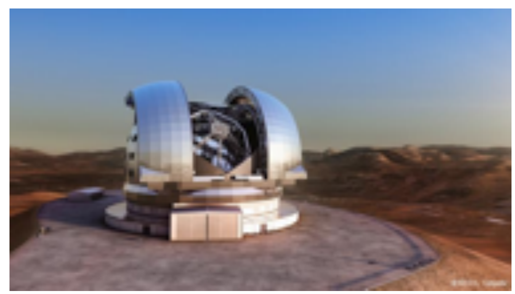
Probing the End of the Dark Ages…

In next few years:

- Improve constraints on z~5-8 dropouts+nb (HST/Spitzer + NIR AO-IFU + NIR MOS)
- Characterization and spectral identification of $8<z<12$ candidates (HST WF3, NIR nb)
- ALMA (CII) & perhaps 21cm (LOFAR) constraints

Eventually (~2018-2020): **JWST** + 25-40m ELTs



Reionization