ALMA Observations of the Frontier Fields

Franz Bauer, **Jorge Gonzalez, Rodrigo Carvajal, Sam Kim (PUC),**
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ALMA FF Team: T. Anguita, M. Aravena, F. Barrientos, R. Bouwens, L. Bradley, G. Brammer, M. Carrasco, D. Coe, R. Demarco, H. Ford, H. Francke, X. Huang, E. Ibar, L. Infante, A. Koekemoer, H. Messias, N. Nagar, N. Padilla, M. Postman, E. Treister, P. Troncoso, W. Zheng, A. Zitrin

Pontificia Universidad de Católica de Chile

Instituto de Astrofísica

Centro de Astro-Ingeniería

Obs Santa Martina

- active institute -

16 Faculty + ~5 Engineering/CompSci faculty
~49 Postdocs (~1/2 international)
~32 Graduate students (50/50 Master/PhD)

many visitors
many talks
daily astro-ph

If you find yourself in Chile (Santiago) => please visit us!

ALMA Observations of the Frontier Fields

ALMA can probe obscured star formation (LIRGs) out to high-z.
Complementary to optical/near-IR constraints that HST and Spitzer provide.

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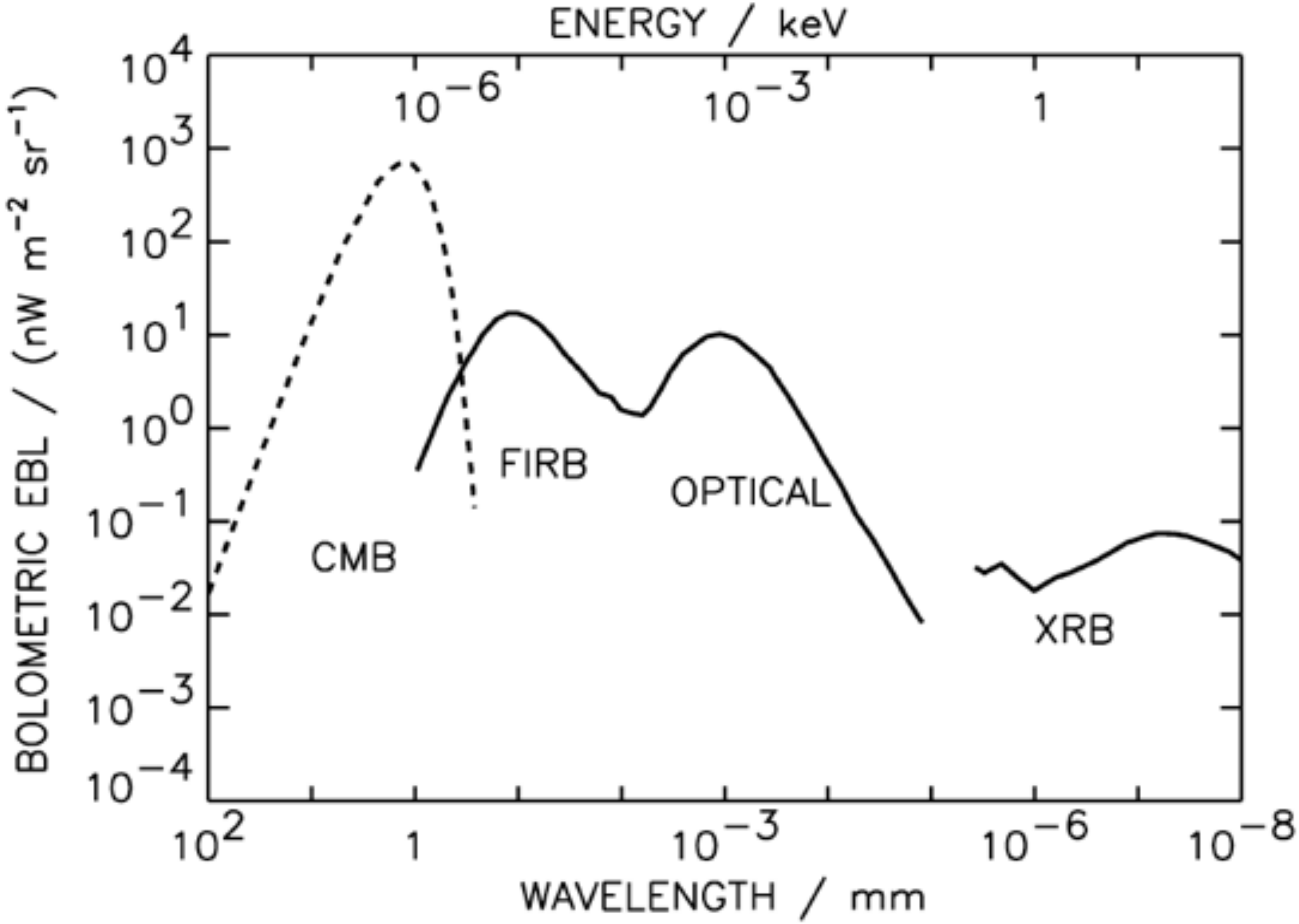
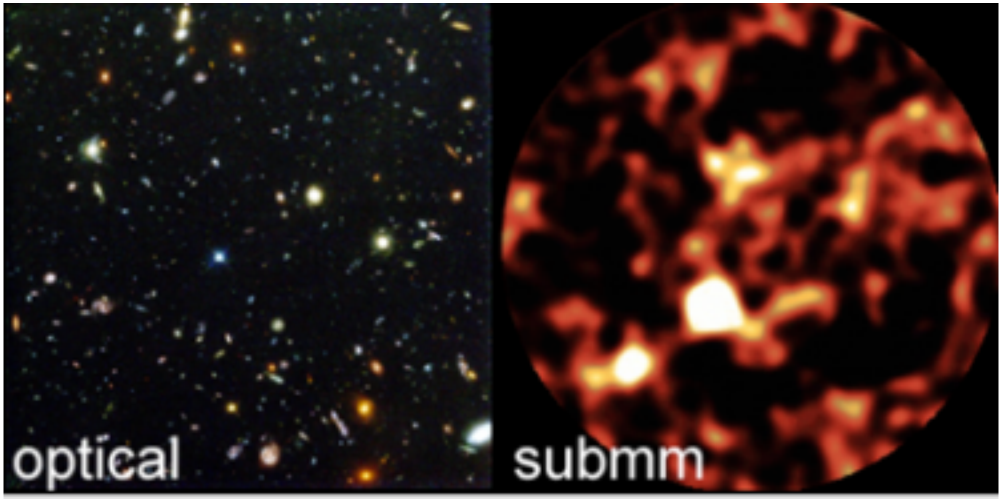
COBE/FIRAS background light measurements in the early 1990s, coupled with IRAS nearby galaxy constraints from the 1980s, demonstrated that the Universe emits a comparable energy density in IR and submm as in optical and UV.

=> optical and UV alone miss ≳ 50% of star formation activity in Universe. Moreover, extrapolation of FIRB from optical surveys implies dusty SF galaxy (DSFG) population.

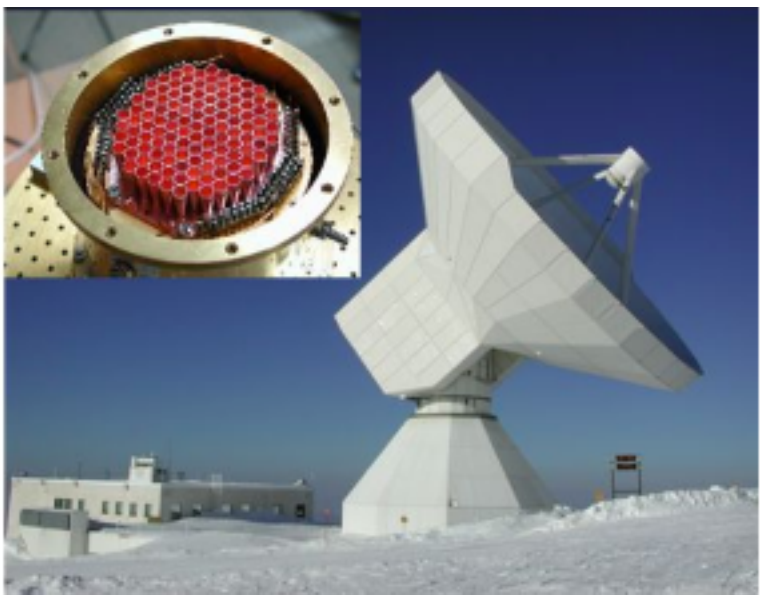


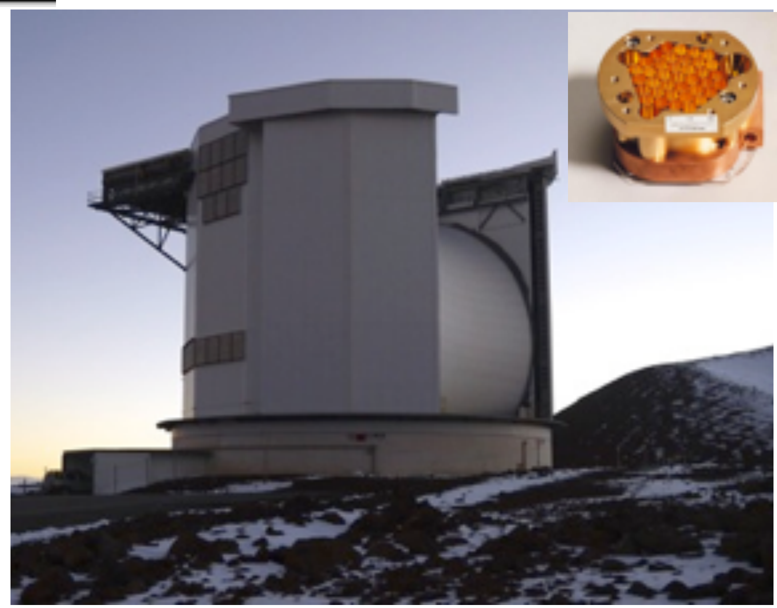
Ideally want to resolve FIRB into constitute components.

Deep blank field surveys with the SCUBA/JCMT (850 μm) and MAMBO/IRAM (1.2mm) in late 1990s and early 2000s detected populations of high-z galaxies that are extremely bright at far-IR/submm wavelengths yet nearly invisible at optical ones.



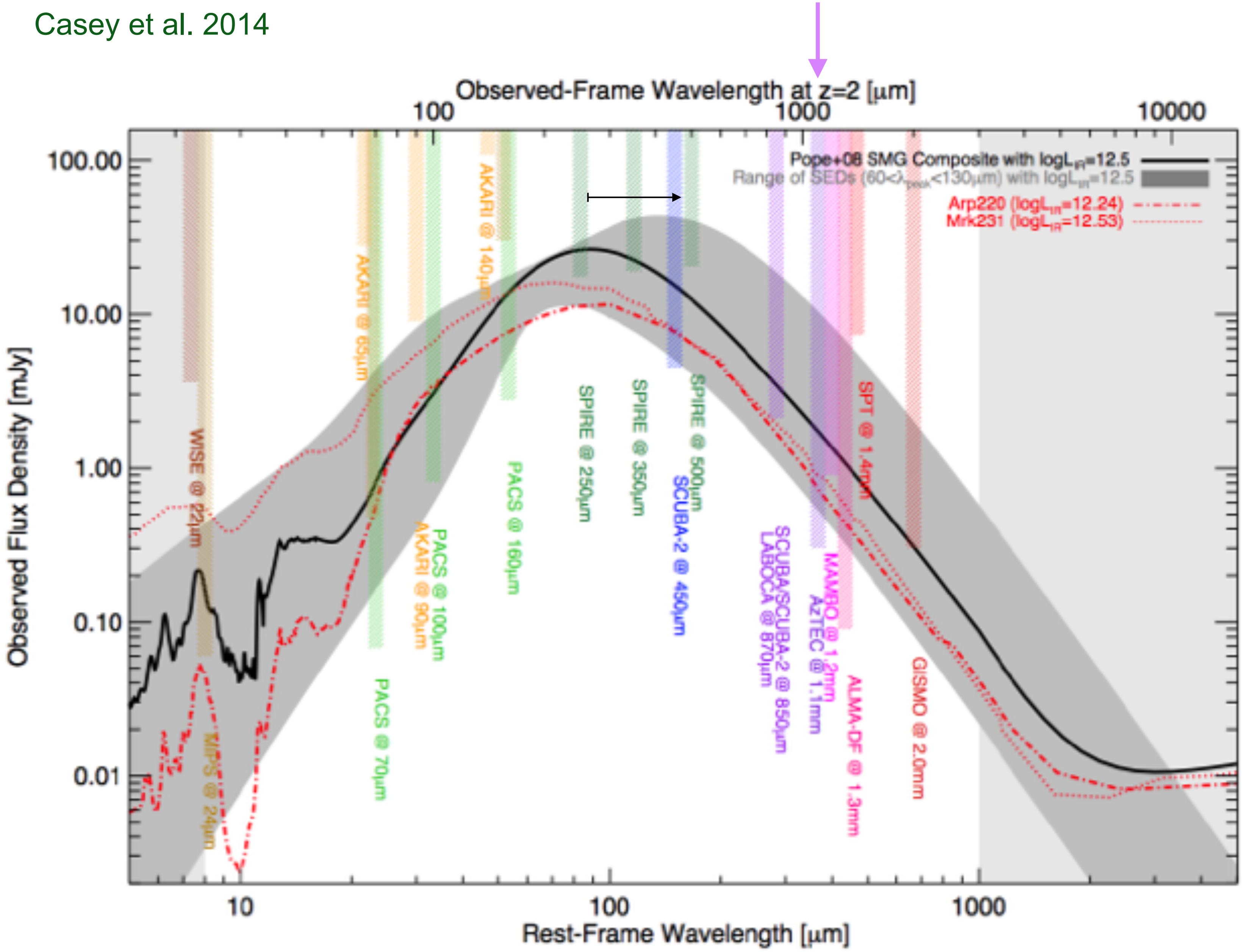
Hughes+98, Omont+01, etc.





“typical” SEDs of ULIRGs (local vs SMGs)

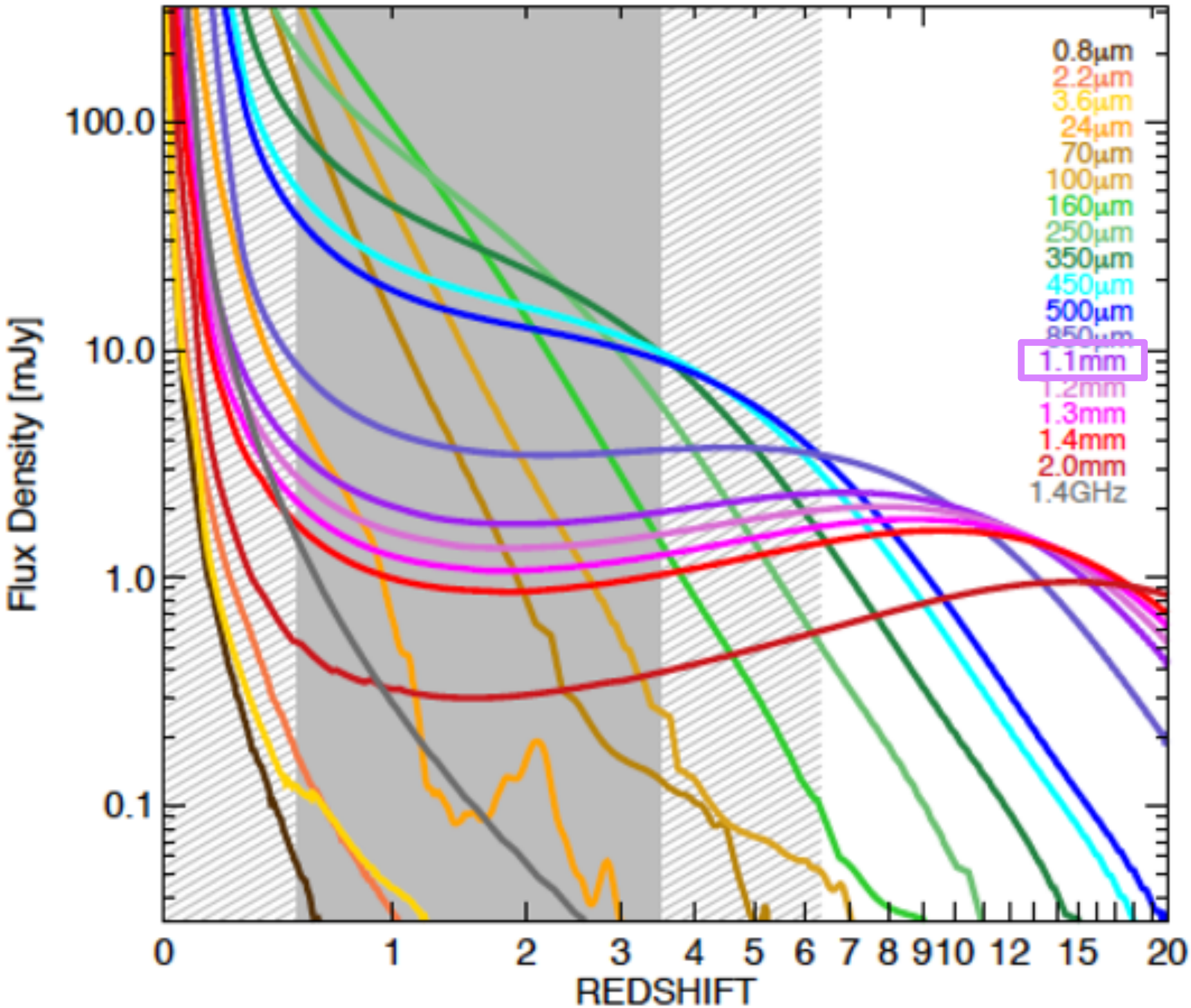
Casey et al. 2014



SED + redshift => negative K-correction

Casey et al. 2014

for constant L_{IR} source



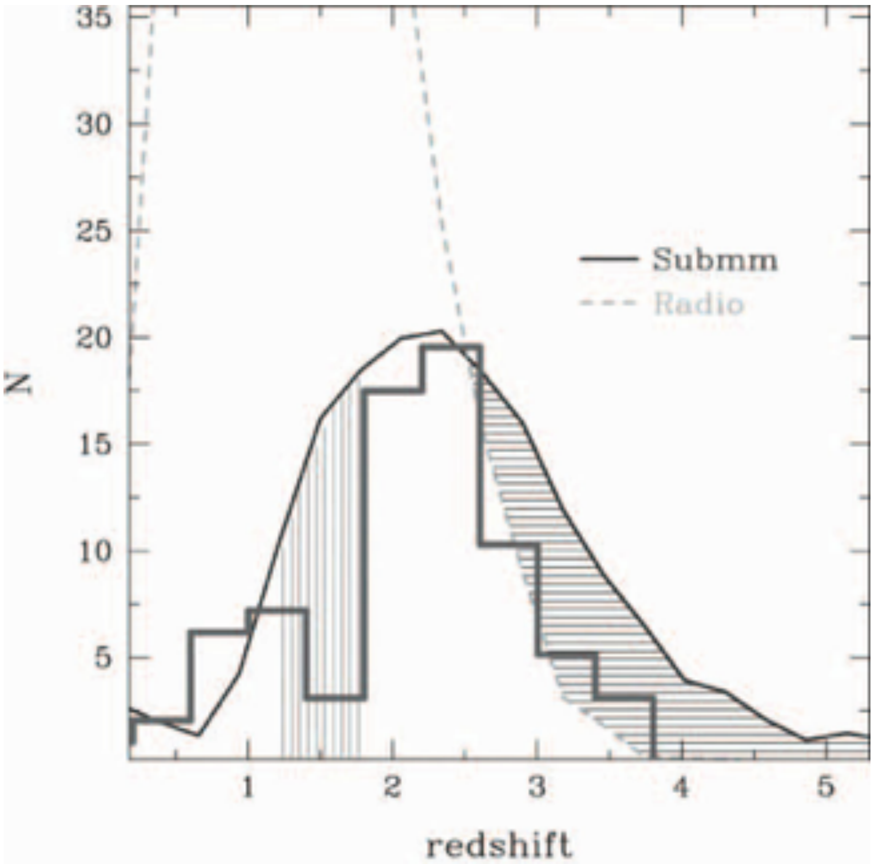
Counterpart Identification

Submm population found to be ~80% between z=2-4,

while midIR and farIR found to be ~80% z<1.7.

Given poor spatial resolution of early instruments, identifications were made using radio and midIR counterparts

=> problematic, since missed high-z fraction of population!



Smail+97,00,02;

Barger+99,00,03;

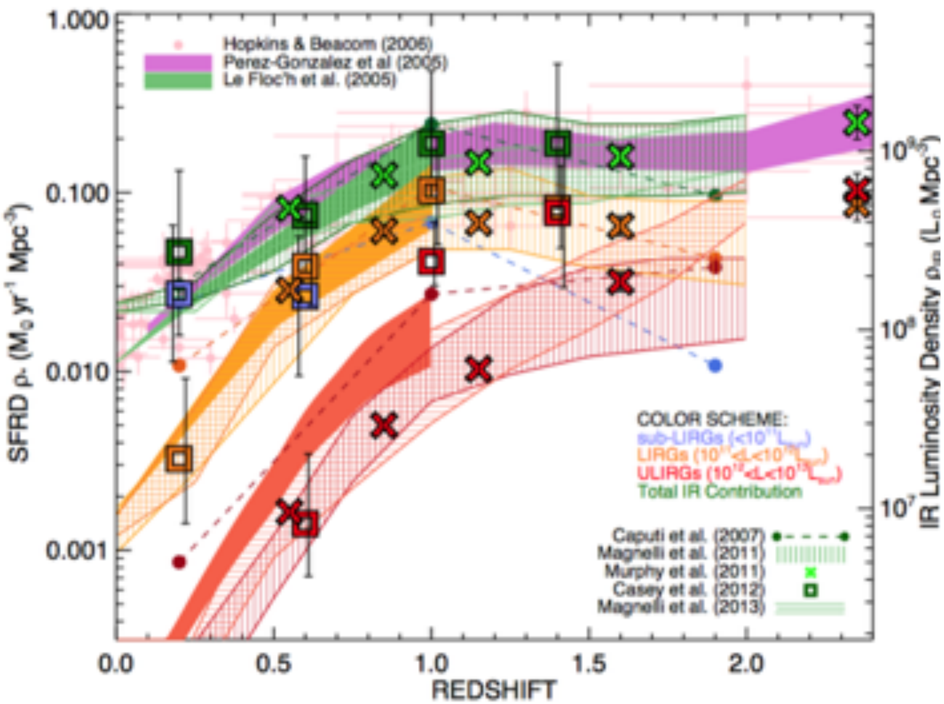
Chapman+03, 05;

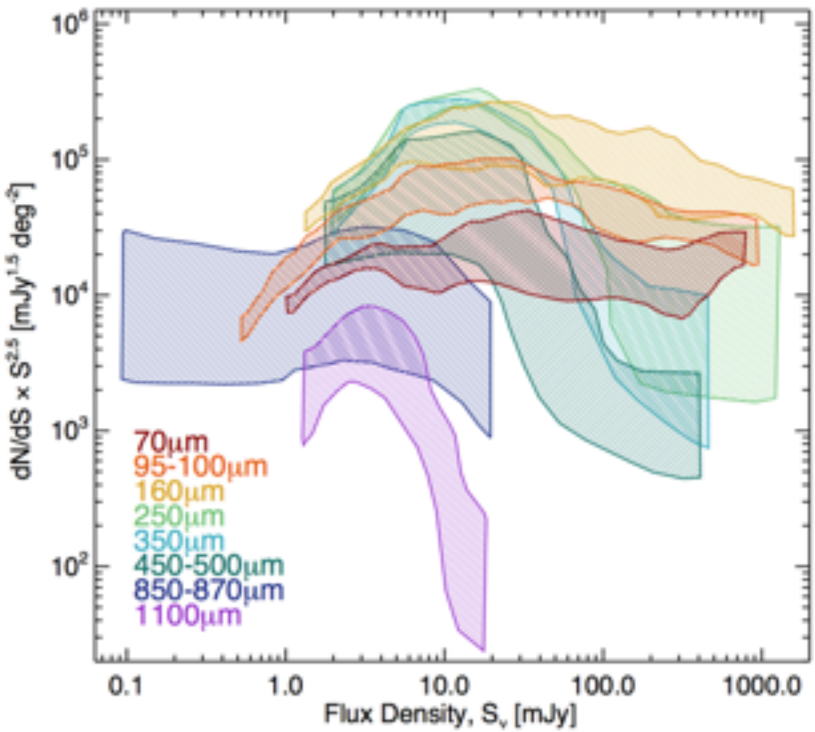
etc.

Spitzer, Herschel, and ground-based surveys began covering large areas (1000 deg^2), detecting DSFGs over wider range of inferred star formation rates, stellar masses, and black hole luminosities.

LIRGs dominate by z~1, ULIRGs at z > 2

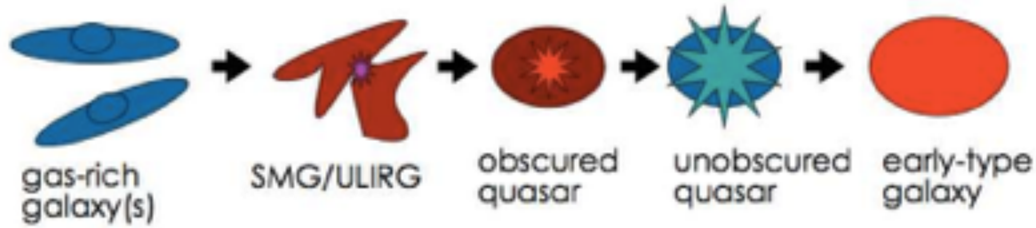
Longer wavelength DSFGs (higher z?) dominate at fainter fluxes?



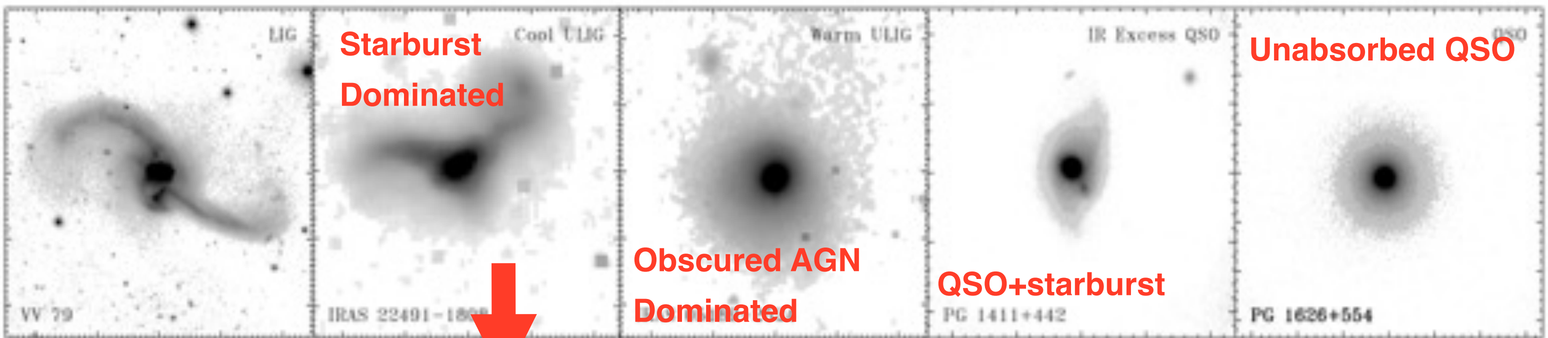


Casey et al. 2014

Major-merger driven growth paradigm?



The (hypothetical) major-merger evolutionary picture



e.g., Alexander & Hickox 2011

match to elliptical and QSO densities

Rapid black-hole growth during obscured phase

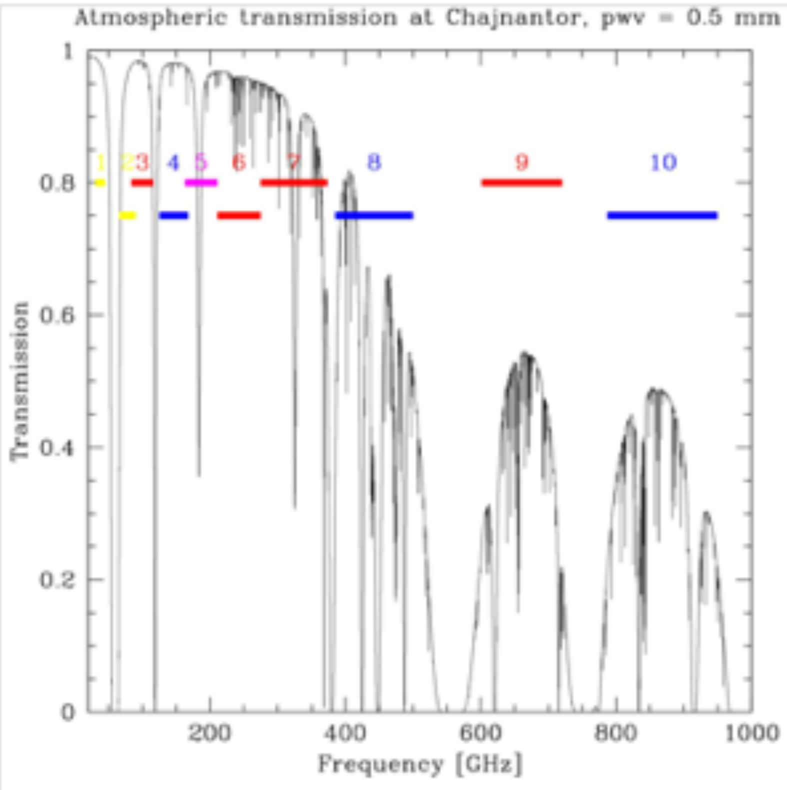
“QSO/wind-mode” feedback in obscured/ unobscured phase

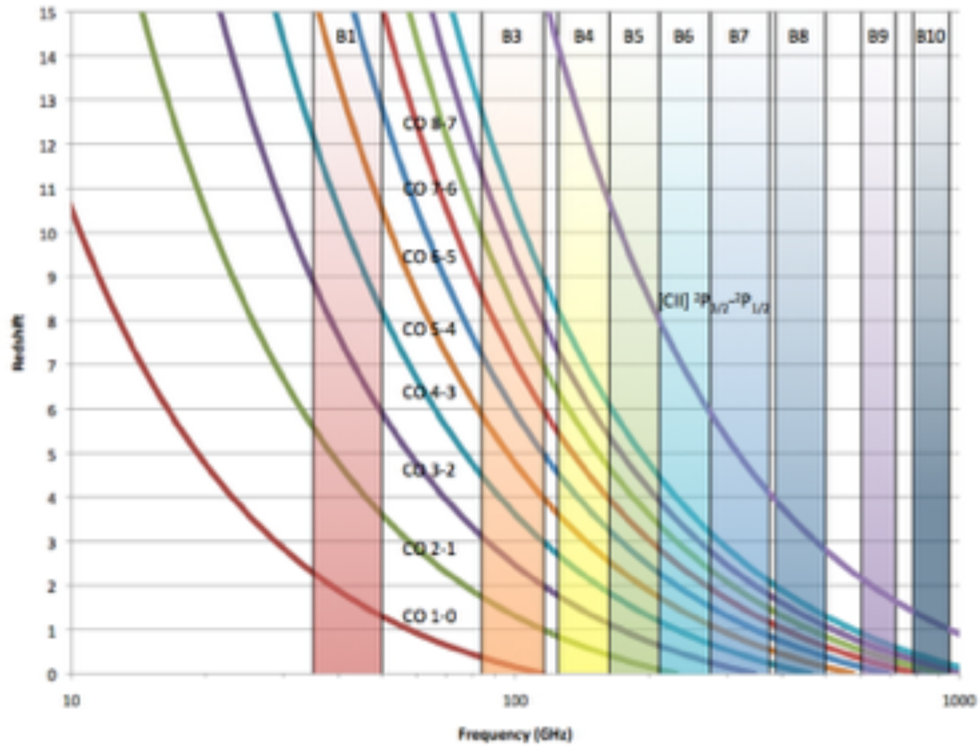
Sporadic “radio/jet-mode” feedback in early-type phase

Sanders+88; Hopkins+2008; Alexander+Hickox12

As we enter the ALMA era…

Our understanding of galaxy formation, evolution, and star formation remains incomplete without a window onto the dusty Universe (particularly one at high spatial and spectral resolution).





As we enter the ALMA era...

Our understanding of galaxy formation, evolution, and star formation remains incomplete without a window onto the dusty Universe (particularly one at high spatial and spectral resolution).

Outstanding questions:

- Is star formation fueled by secular processes or major mergers?
- Can we obtain detailed constraints on the cosmic star formation history?
- When did massive galaxies form?
- What is the total bolometric power radiated by the first galaxies?
- How do star formation and black hole accretion processes begin, fuel, and shut off?
- How did the ISM evolve over cosmic time?
- How, when, and where was cosmic dust created?
- What is link b/t different star forming populations (LBGs, LAEs, SMGs, DSFGs, …)

….

Summary of Early ALMA Results (Cycles 0-3)

BRIGHT sources:

- SPT+PLANCK (lensed; 2500+ deg^2, > 20-50 mJy @1.4mm)
- HERSCHEL (blended; 0.5-550 deg^2, > ~7-36mJy @500um)
- SCUBA+APEX (blended; 0.2-1 deg^2, > ~4mJy @850um)

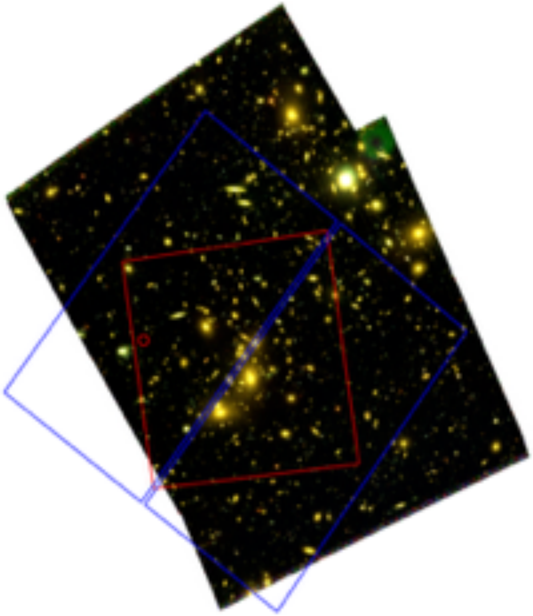
Blank-Field Surveys with ALMA:

- SXDF (Kohno+; 2 $arcmin^2$, > 0.25mJy)
- SSA22 (Umehata+; 4.5 $arcmin^2$, > 0.7mJy)
- UDF (Dunlop+; 4 $arcmin^2$, > 0.18mJy)
- ASPECS (Walter+Aravena+; 1 $arcmin^2$, > 0.07mJy)
- <u>FFs (Bauer+; 20 $arcmin^2$, > 0.3mJy => but smaller/fainter in src plane</u>)

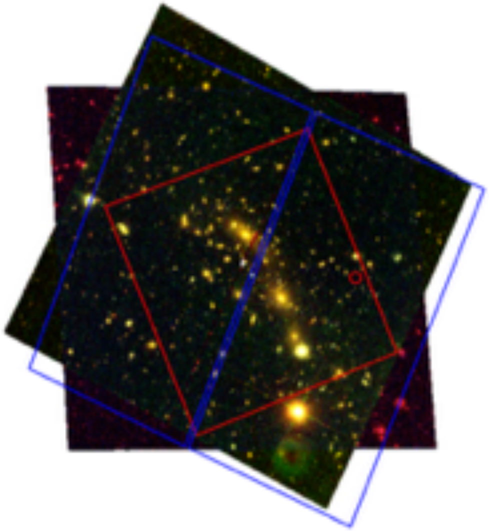
Archival studies (e.g., Ouchi+; 0.01-8 $arcmin^2$, > 0.01-0.4mJy)

HST + Spitzer Frontier Fields =>

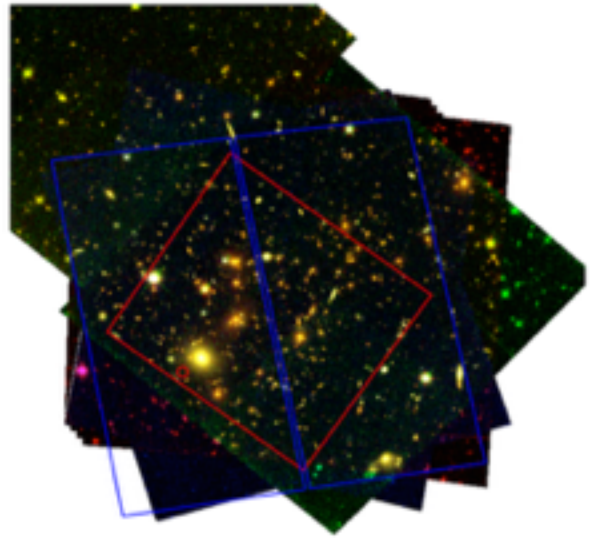
ACS ($F435W$=$F606W$=$F814W$≈**28.4– 29.0** ABmag),
WFC3 ($F105W$=$F125W$=$F140W$=$F160$≈**29.1– 29.4** ABmag)
IRAC1/IRAC2 (≈**25.0** ABmag)



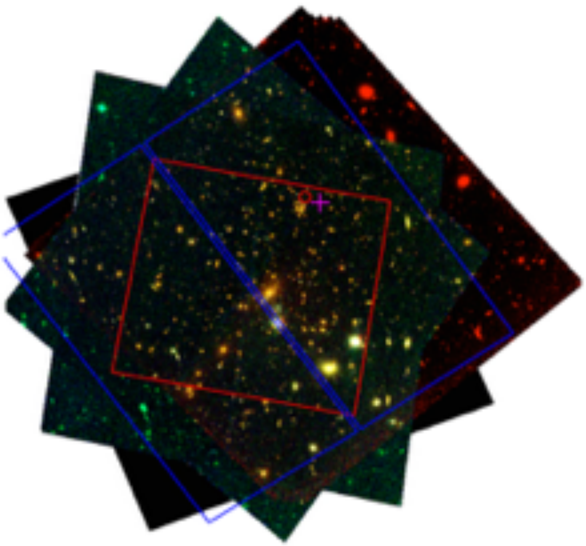
Abell 2744 (z=0.308)



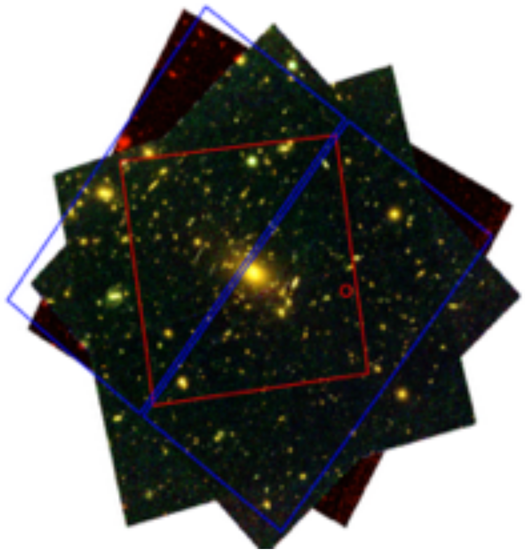
MACS J0416.1–2403 (z=0.396)



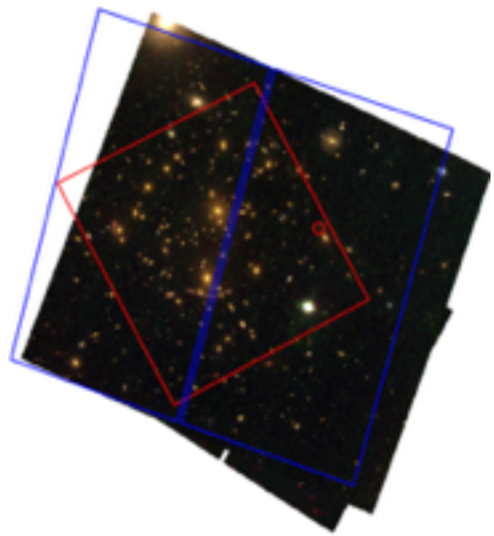
MACS J0717.5+3745 (z=0.545)



MACS J1149.5+2223 (z=0.544)



Abell S1063 (z=0.348)



Abell 370 (z=0.375)

Approved Cycle 2 ALMA Observations of FFs

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
~~[illegible]~~	~~[illegible]~~	~~[illegible]~~	~~[illegible]~~	~~[illegible]~~	~~[illegible]~~
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 first 4 FFs to depth of 70 uJy rms (126 pts)

(1σ depth equates to $L_\odot \sim$ (1-2)e11 erg/s or SFR ~ 8 $M_\odot$/yr between z=1-7)

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

Approved Cycle 3 ALMA Observations of FFs

Proposed to observe 3 remaining FFs to depth/coverage as above

Goal: complete coverage of FFs and sources therein

REPRESENTATIVE SCIENCE GOALS (UP TO FIRST 30)						
SCIENCE GOAL	POSITION	FREQUENCY	BAND	ANG.RES.(")	ACA?	NON-STANDARD MODE
Band 6 imaging of Abell 370	J2000: 02:39:52.6500, -01:34:37.900	254.75000 GHz	6	1.000	N	N
Band 6 imaging of Abell 1063S	J2000: 22:48:44.0000, -44:31:48.500	254.75000 GHz	6	1.000	N	N
~~[illegible]~~	~~[illegible]~~	~~[illegible]~~	~~[illegible]~~	~~[illegible]~~	~~[illegible]~~	~~[illegible]~~
Total # Science Goals : 3						

SCHEDULING TIME CONSTRAINTS	NONE	TIME ESTIMATES OVERRIDDEN ?	No

ALMA Observations of FFs

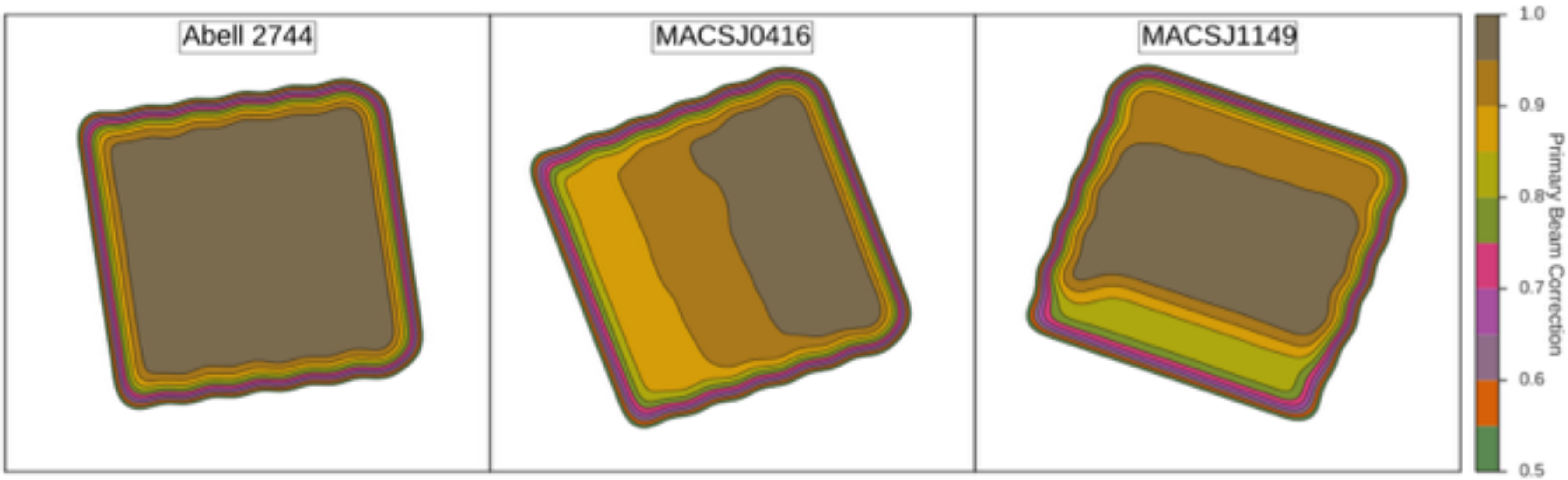
Status:

Abell 2744 => 6.5 executions between 06/14 to 01/15 (data received 06/15).
observed in many array configs, so has well-sampled UV coverage (0.5-1.5”)
with natural-weighted beam of ~0.7” resolution, **rms ~ 55 uJy (69)**

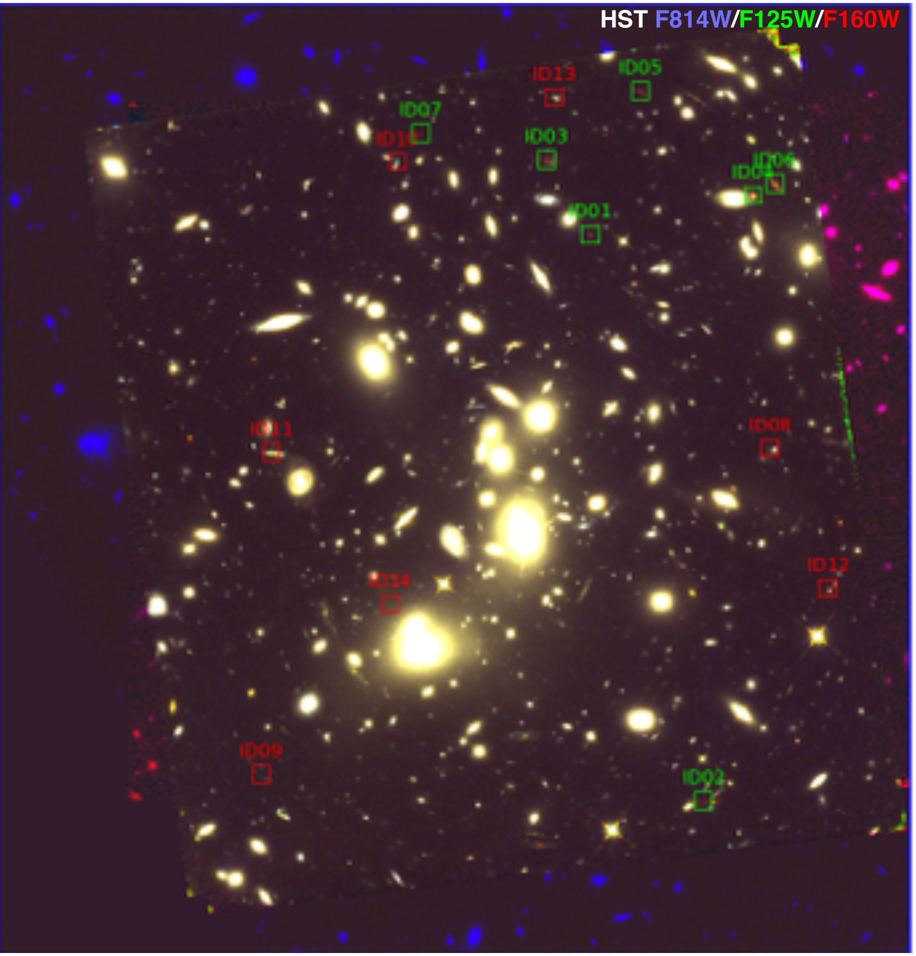
MACSJ0416-2403 => 4 executions between 12/14 to 05/15 (data received 06/15)
observed in 2 configs, with natural-weighted beam of 1.1”, **rms ~ 58-65 uJy (69)**

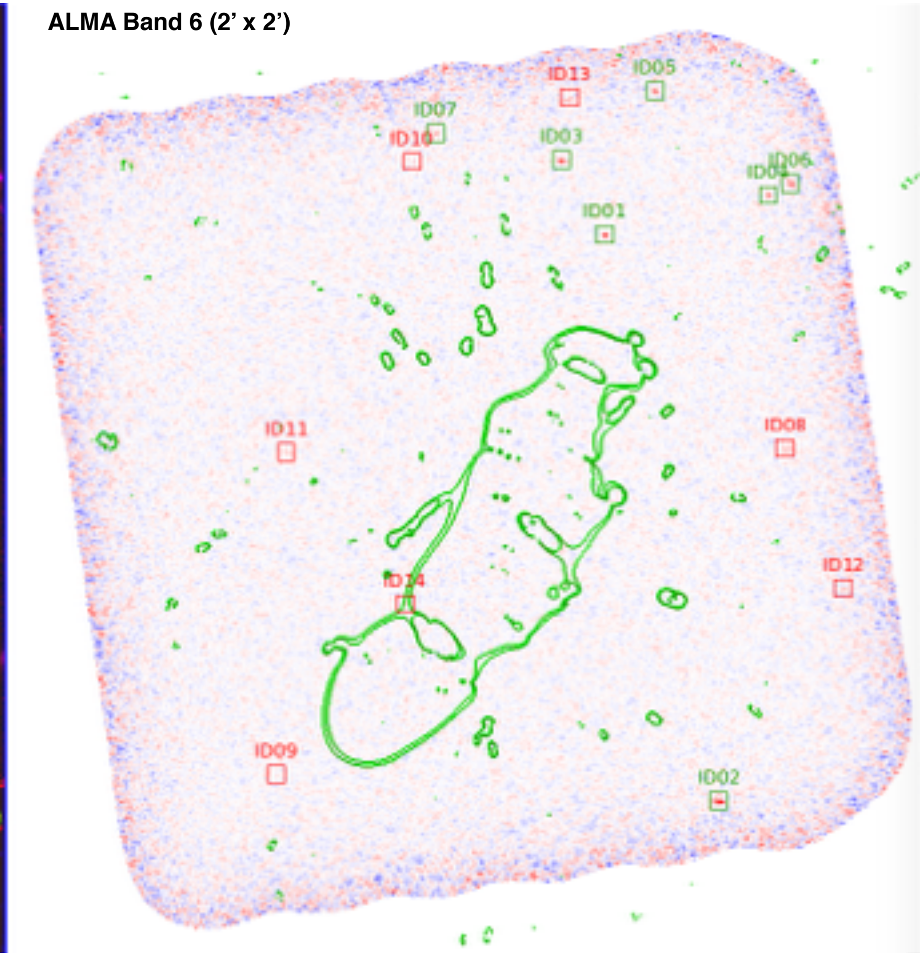
MACSJ1149+2223 => 4 executions between 12/14 to 05/15 (<u>data received 07/15</u>)
observed in 2 configs, with natural-weighted beam of 1.1”, **rms ~ 71-90 uJy (71)**

Published as Gonzalez-Lopez+16, Laporte+16 (in prep), …



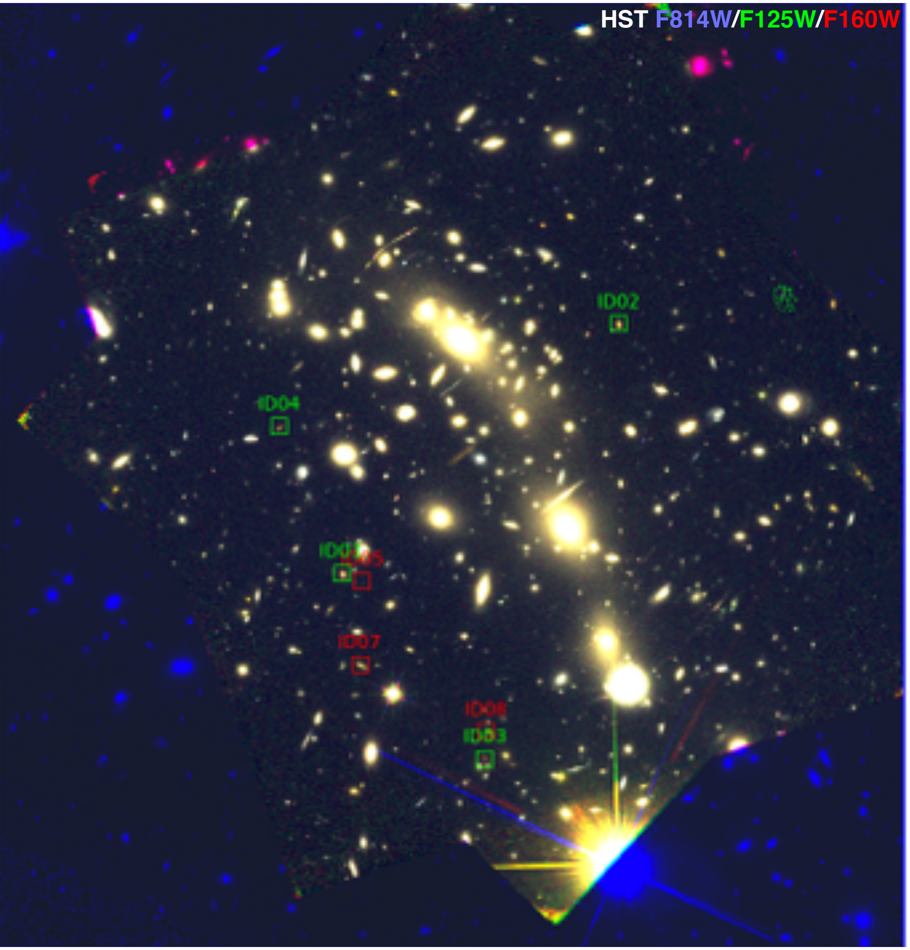
A2744

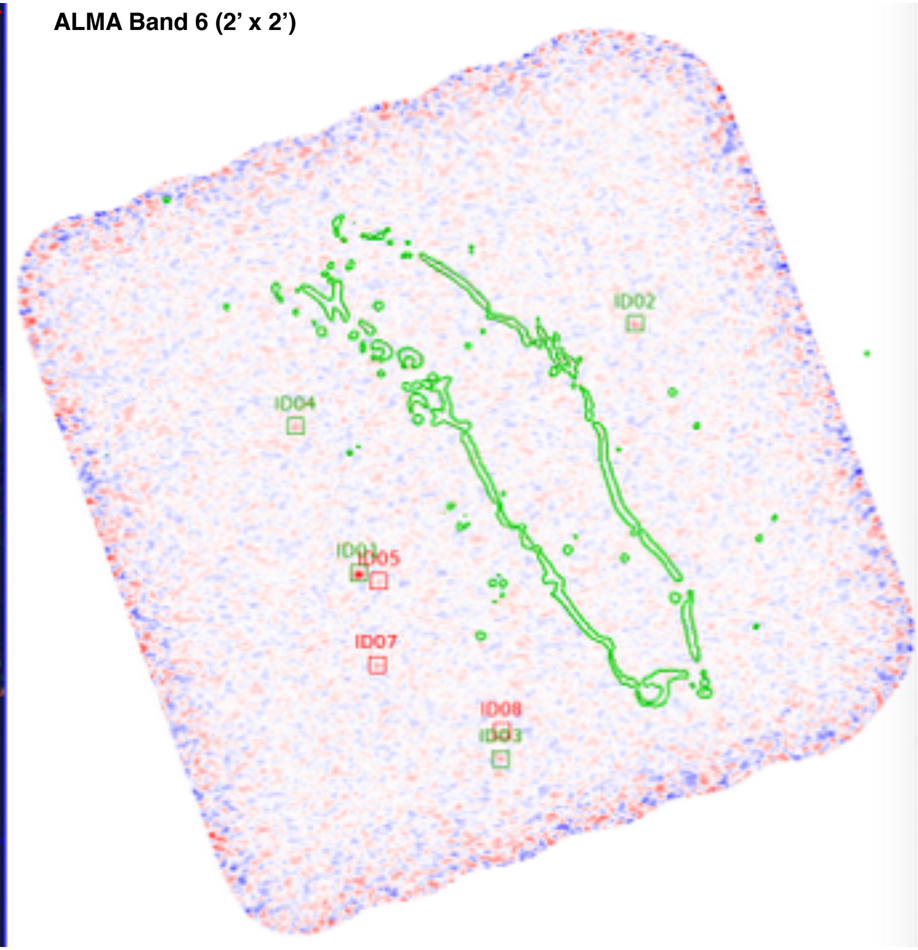




=> **7** detections above **5σ** + **7** more above **~4σ** with NIR counterparts

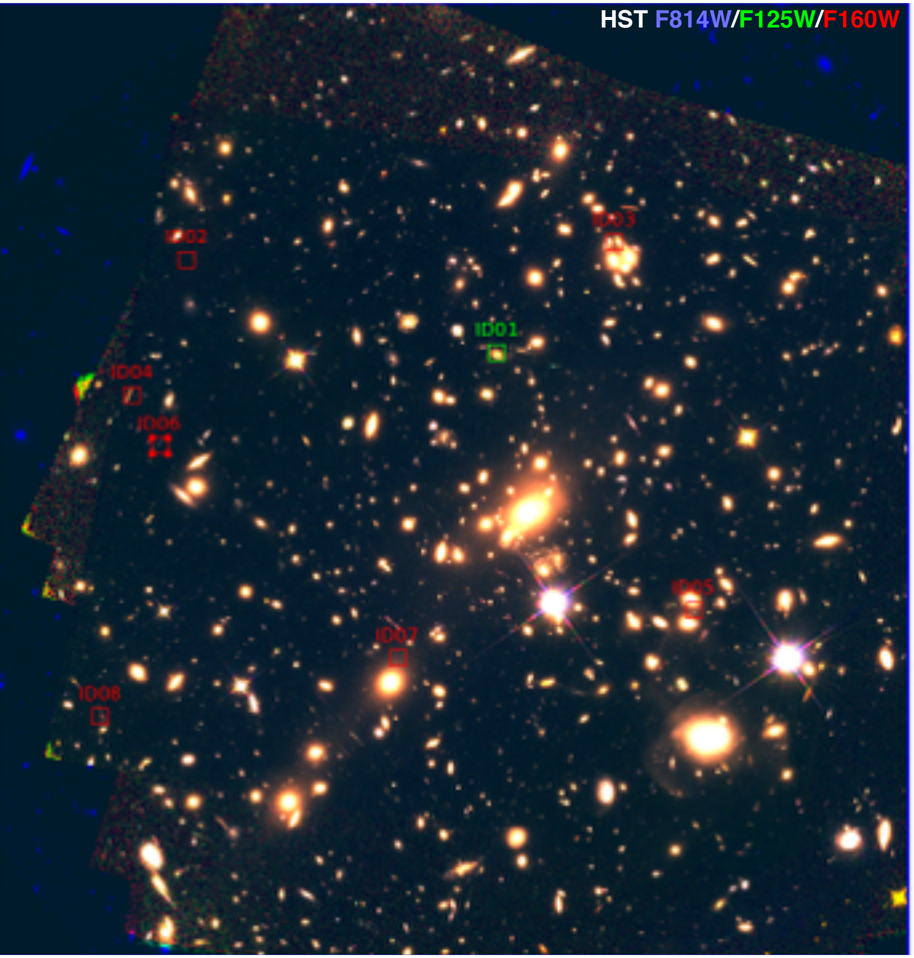
MACS0416

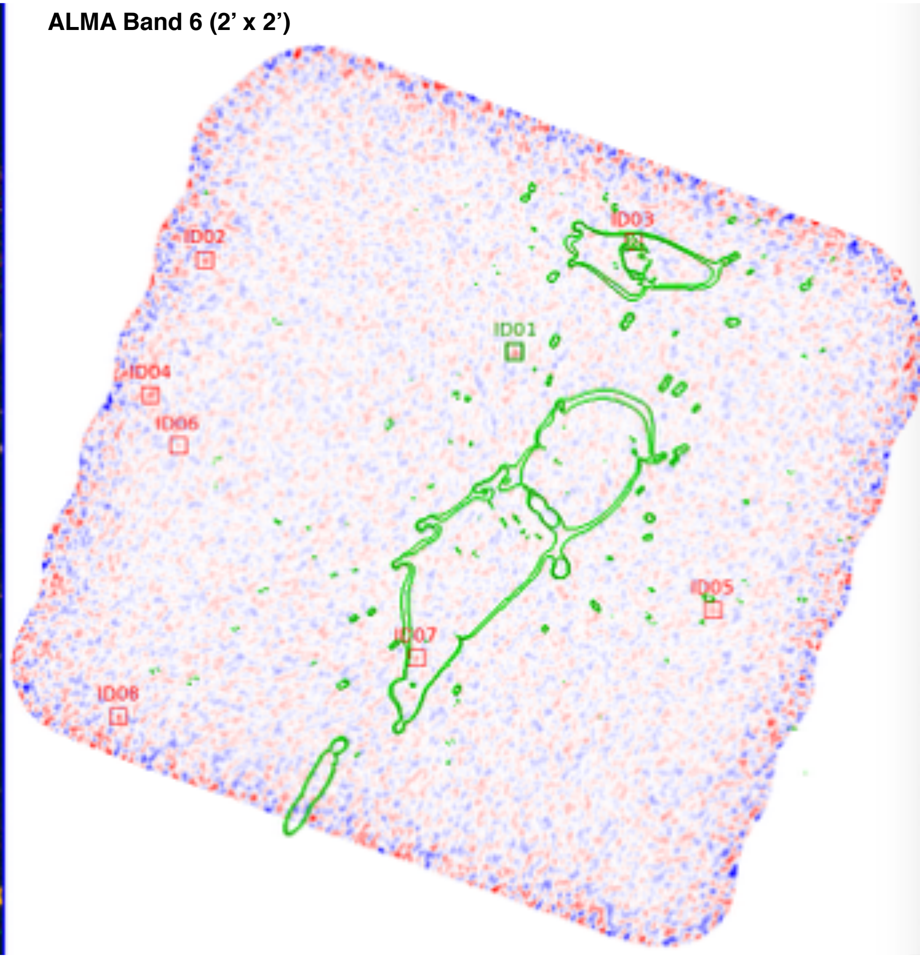




=> **4** detections above **5σ** + **3** more above **~4σ** with NIR counterparts

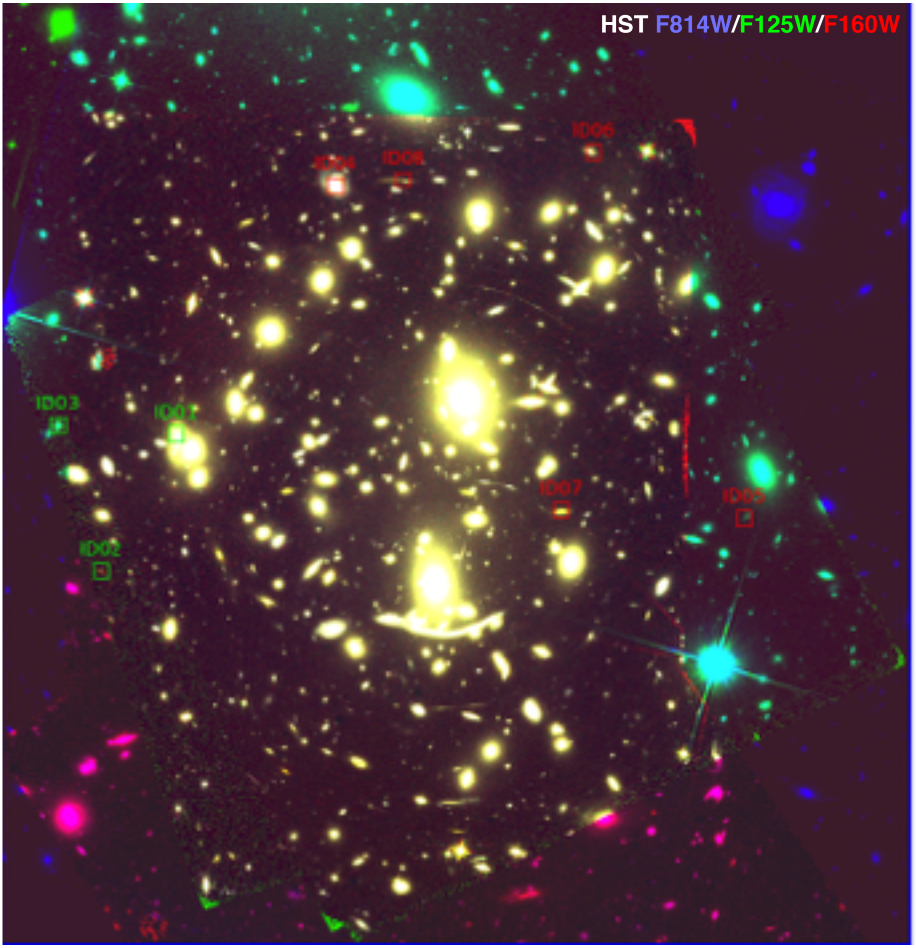
MACS1149

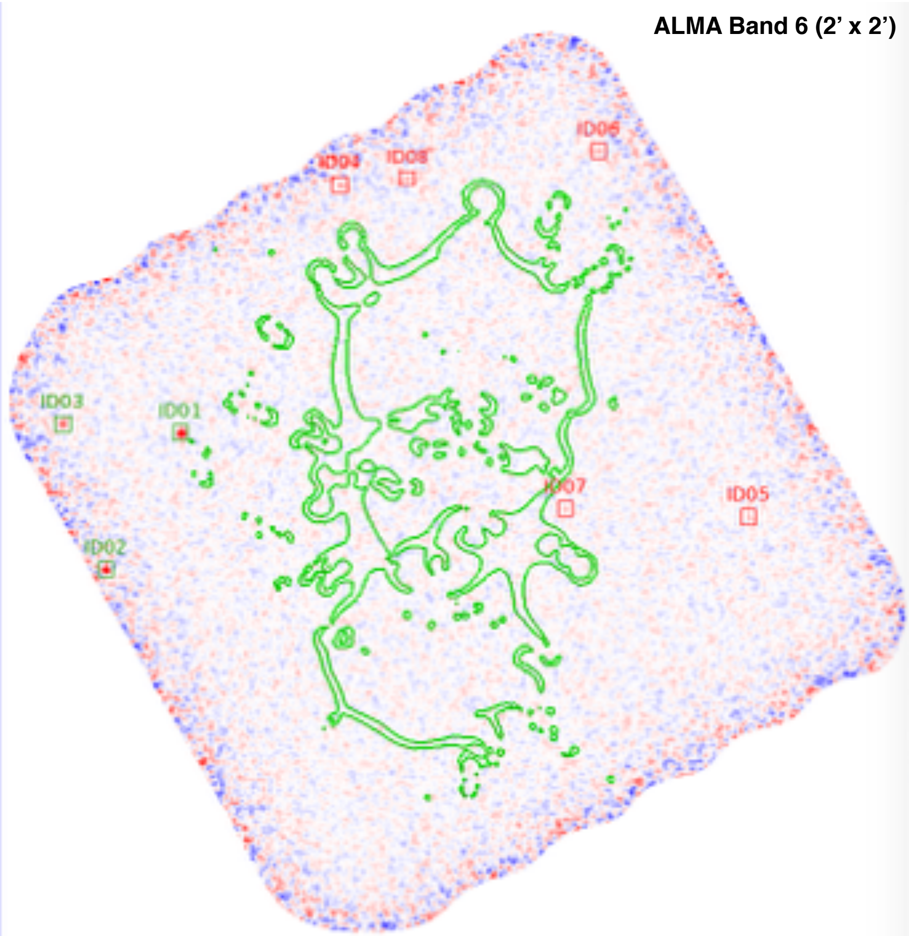




=> **1** detection above **5σ** + **6** more above **~4σ** with NIR counterparts

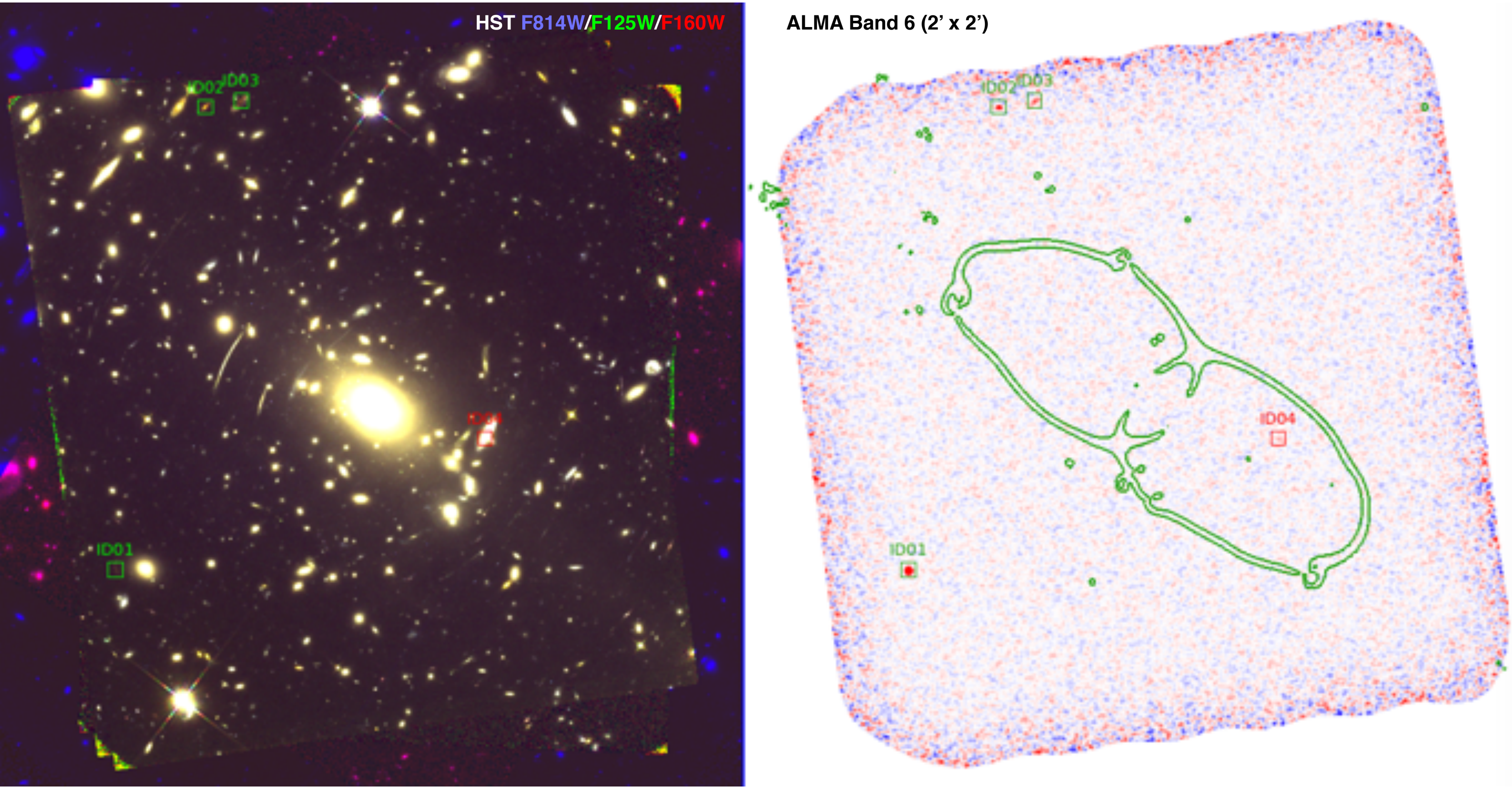
A370





=> **3** detections above **5σ** + **5** more above **~4σ** with NIR counterparts

AS1063



=> **3** detections above **5σ** + **1** more above **~4σ** with NIR counterparts

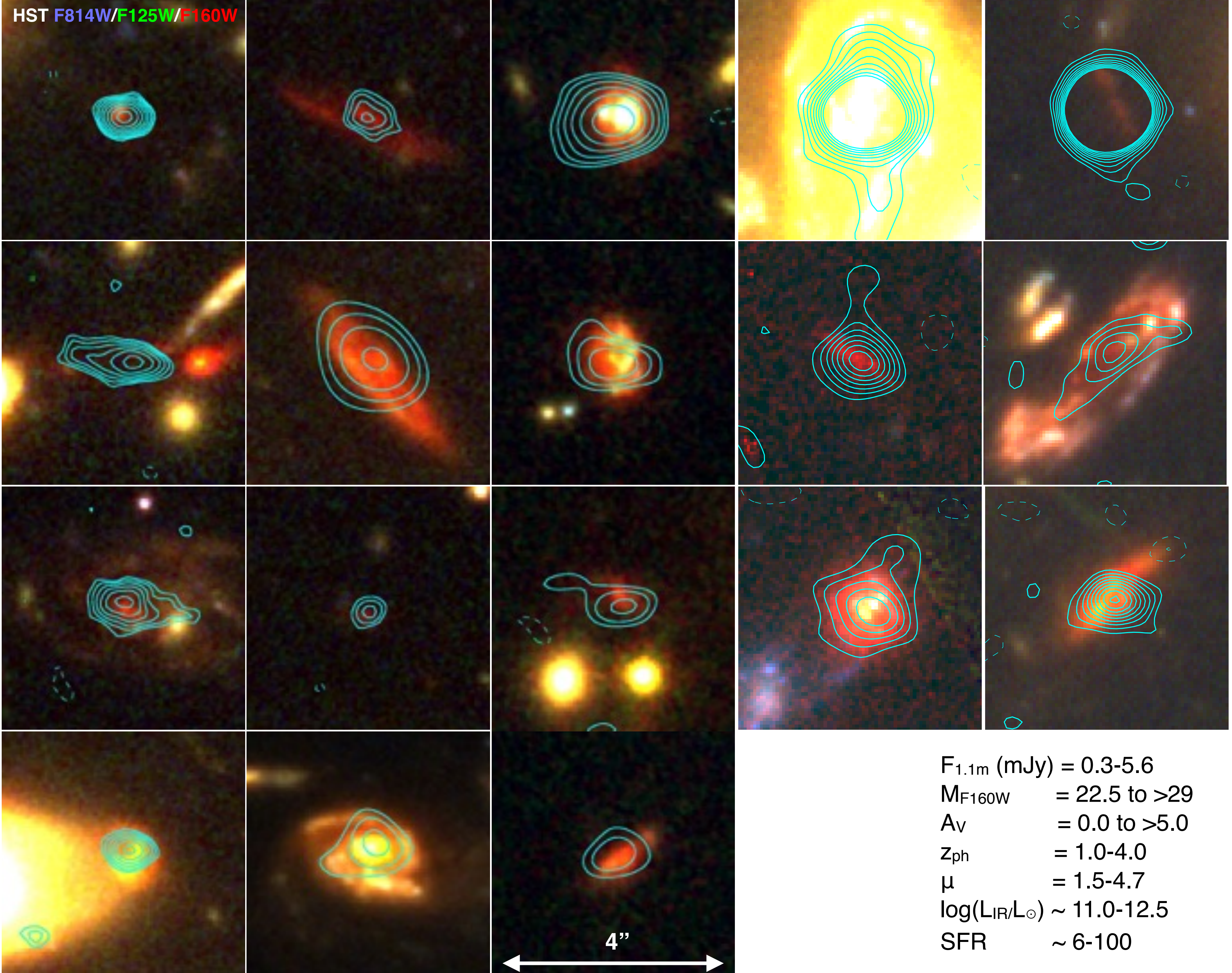
=> probing population down to observed ~0.3 mJy at 5σ

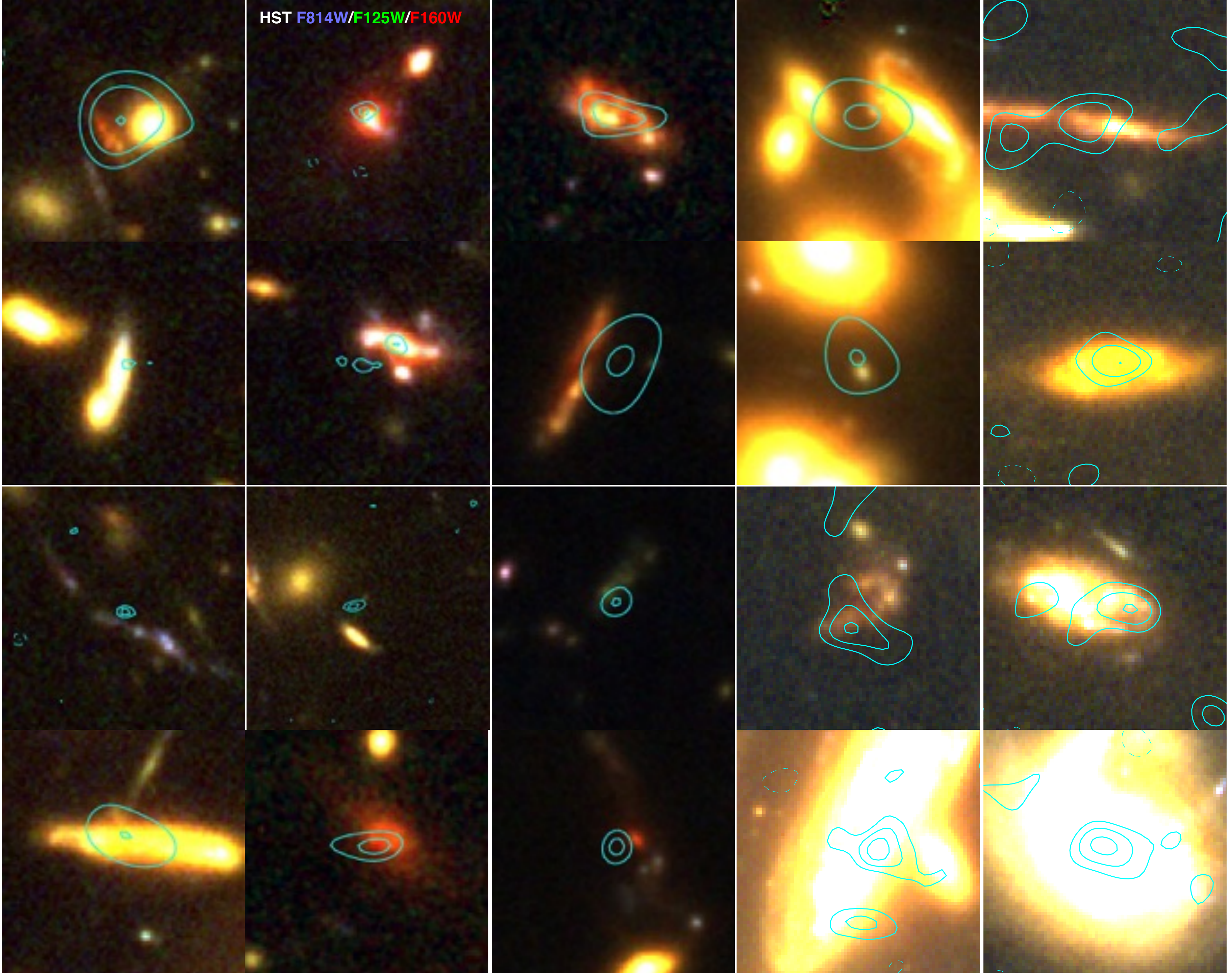
=> **18** detections above **5σ**, **22** more above **~4σ** with NIR counterparts

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

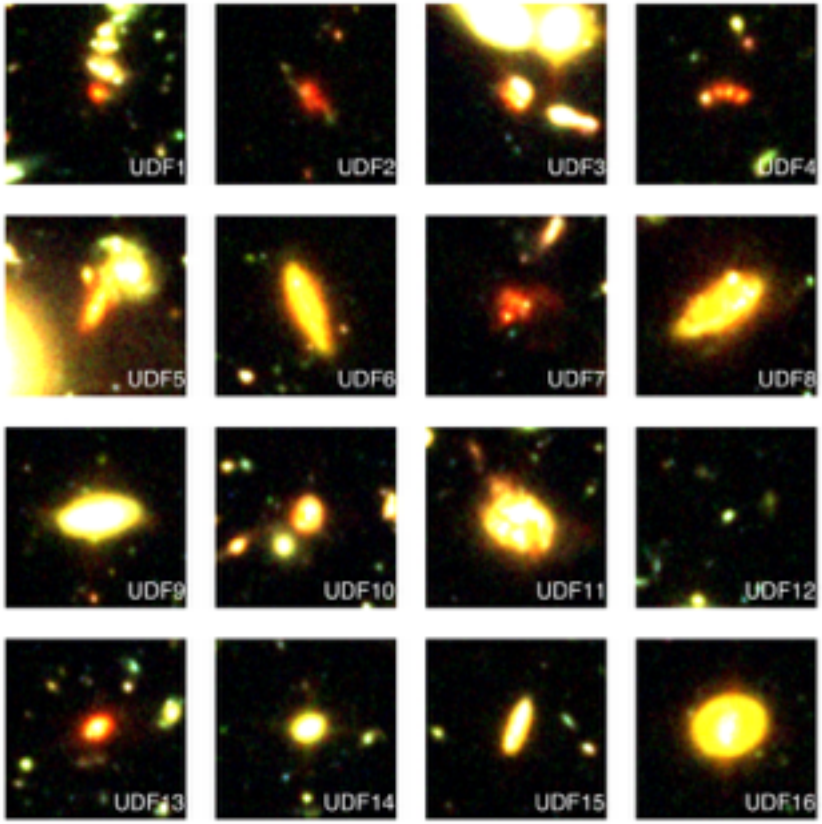
=> no clear strongly lensed or multiple sources (sources avoid center)

=> bulk of candidates are red (high-z and/or dusty).

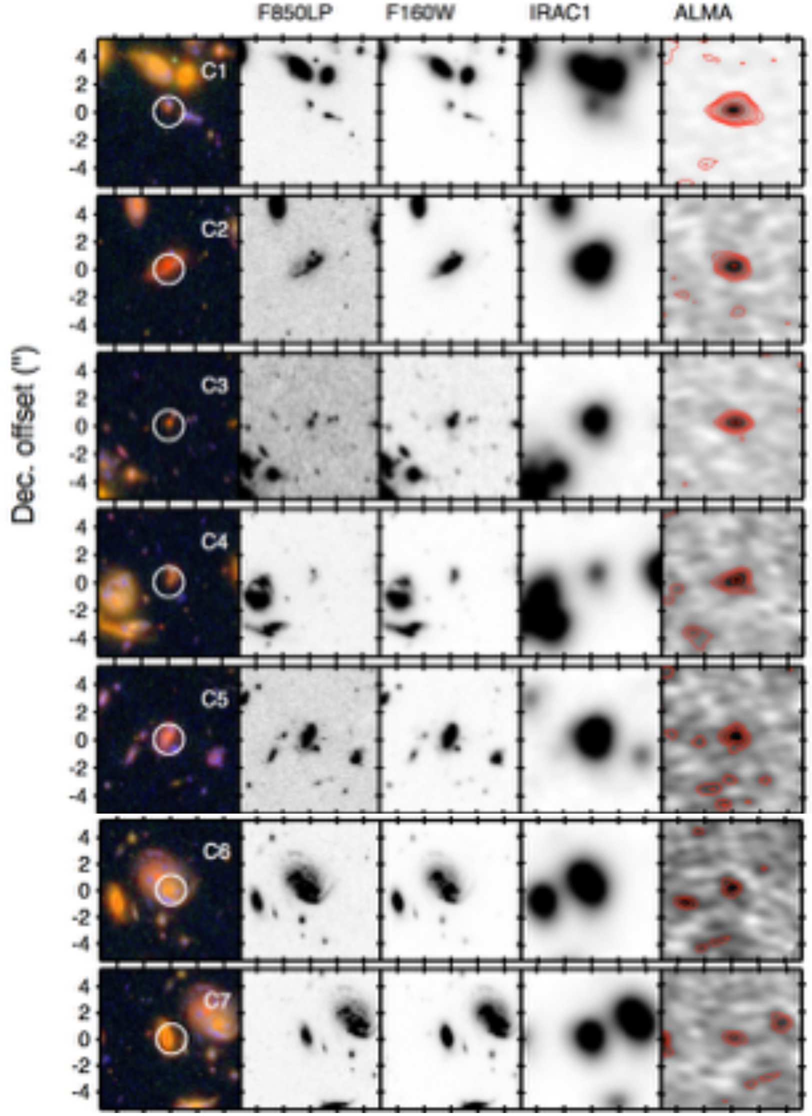

HST F814W/F125W/F160W
4”
$F_{1.1m}$ (mJy) = 0.3-5.6
M_{F160W} = 22.5 to >29
A_V = 0.0 to >5.0
z_{ph} = 1.0-4.0
μ = 1.5-4.7
$\log(L_{IR}/L_{\odot})$ ~ 11.0-12.5
SFR ~ 6-100


HST F814W/F125W/F160W

UDF (Dunlop+16)



ASPECS (Aravena+16)

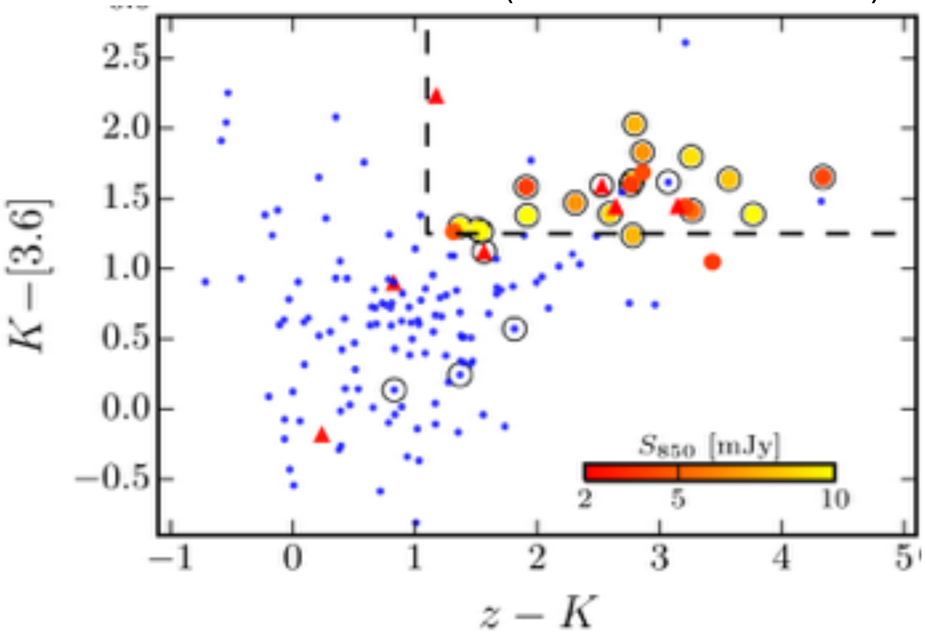


Going roughly 1-2 dex deeper with ALMA compared to bolometers…

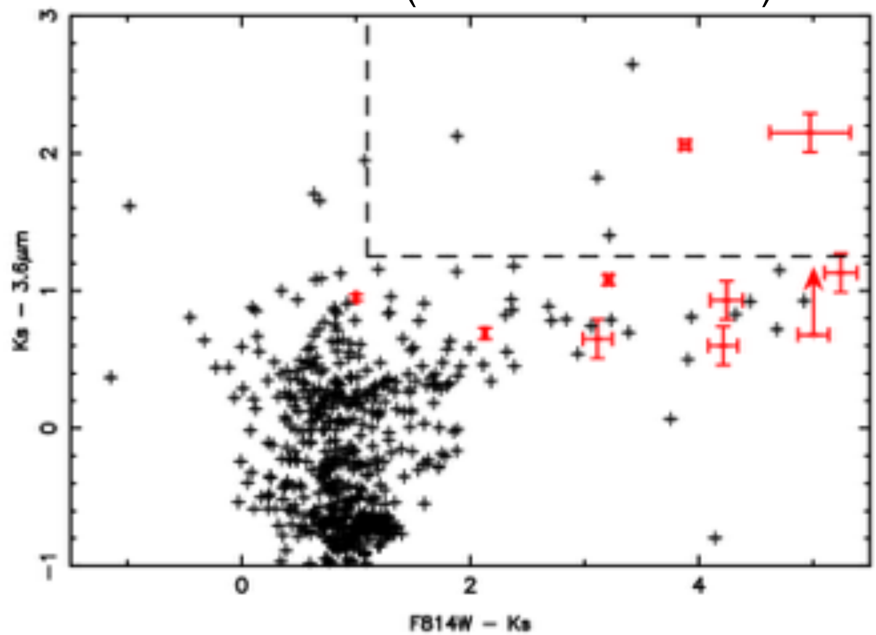
large fraction of counterparts remain quite red (high-z and/or dusty).

Counterpart Color Distribution (N. Laporte+, in prep)

Chen et al. 2016 (S2CL UKIDSS-UDS)



ALMA-FFs (A2744+MACS0416)

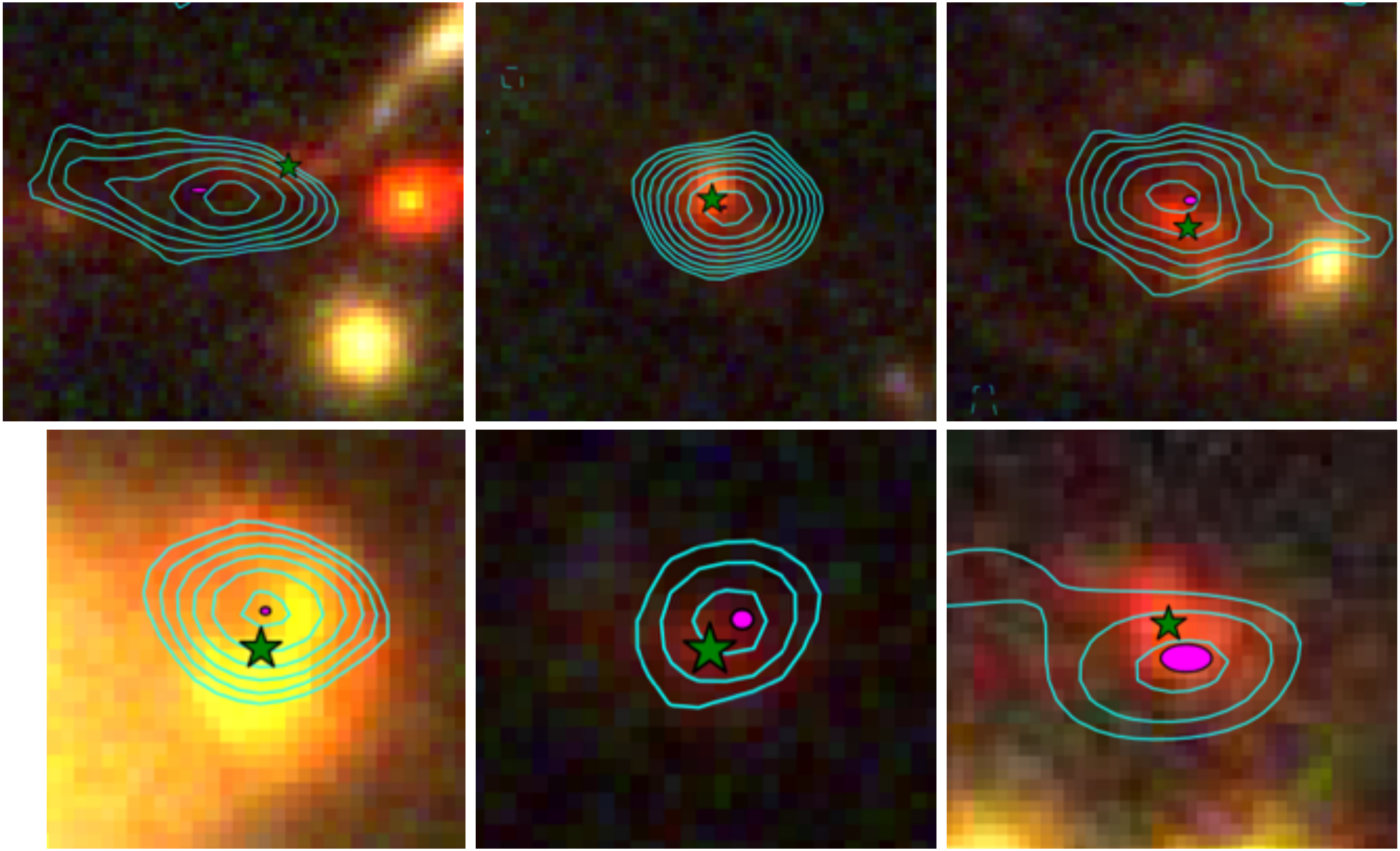


Double color cut of *F*814*W*-*K*S vs. *K*S-[3.6] (dashed lines) may provide very powerful selection of ALMA detections (large circled symbols) => 87% selected!

DSFGs (**red**) and field population (**black**) from *AstroDeep* catalog.

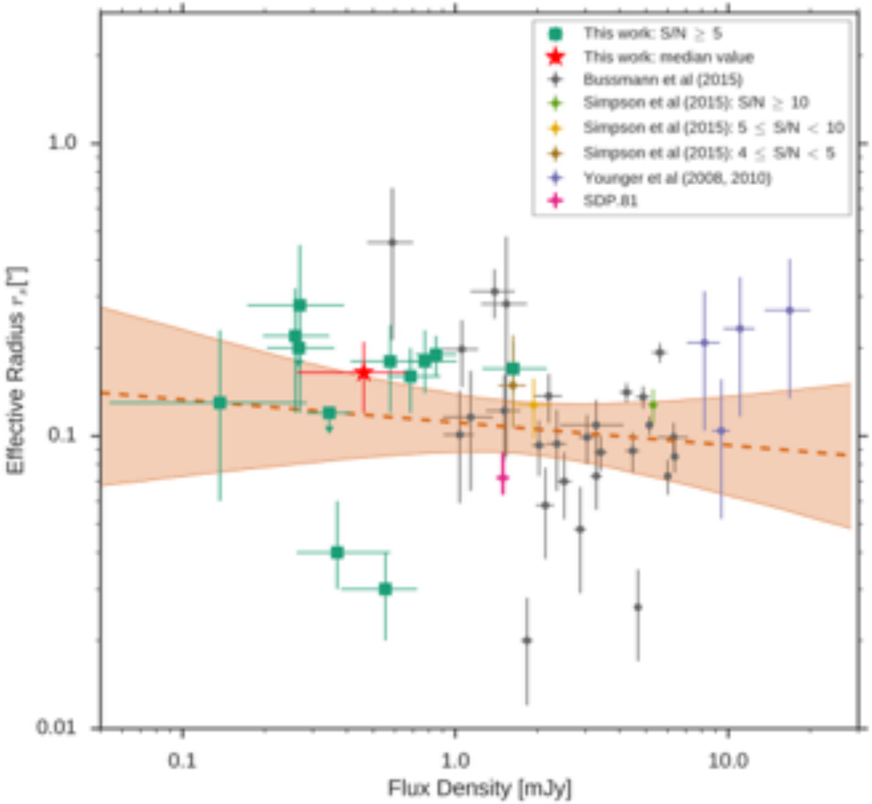
K-[3.6] does not seem to be as effective. Possible z-dependence

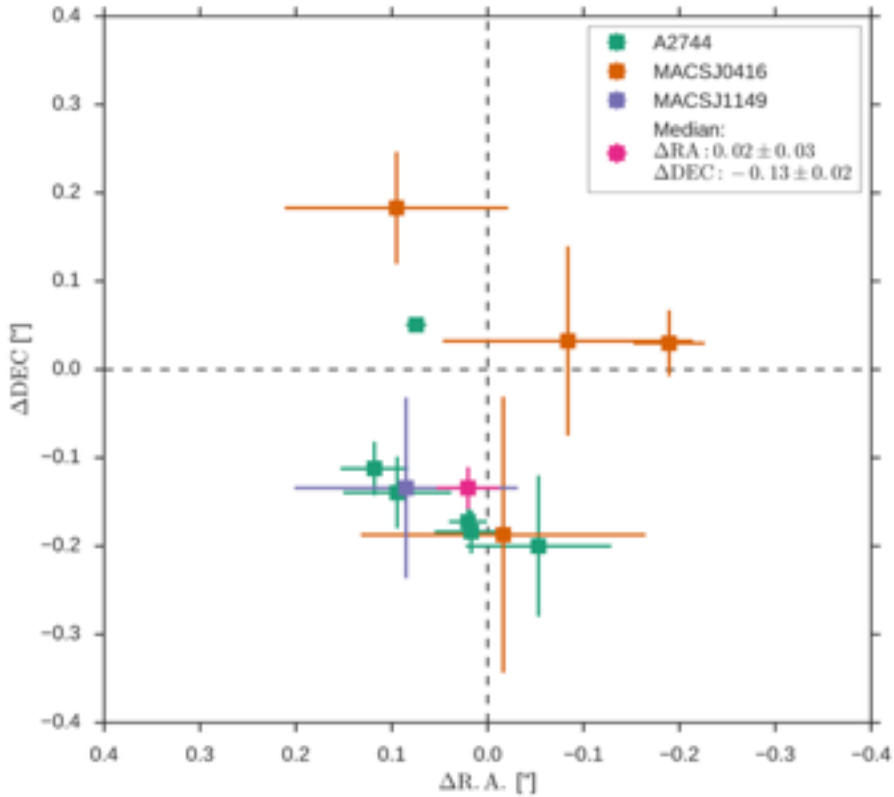
1.1mm Sizes and Offsets (Gonzalez-Lopez+16)



Hosts are globally dusty, but ALMA emission strongest in dustiest regions.

1.1mm Sizes and Offsets (Gonzalez-Lopez+16)



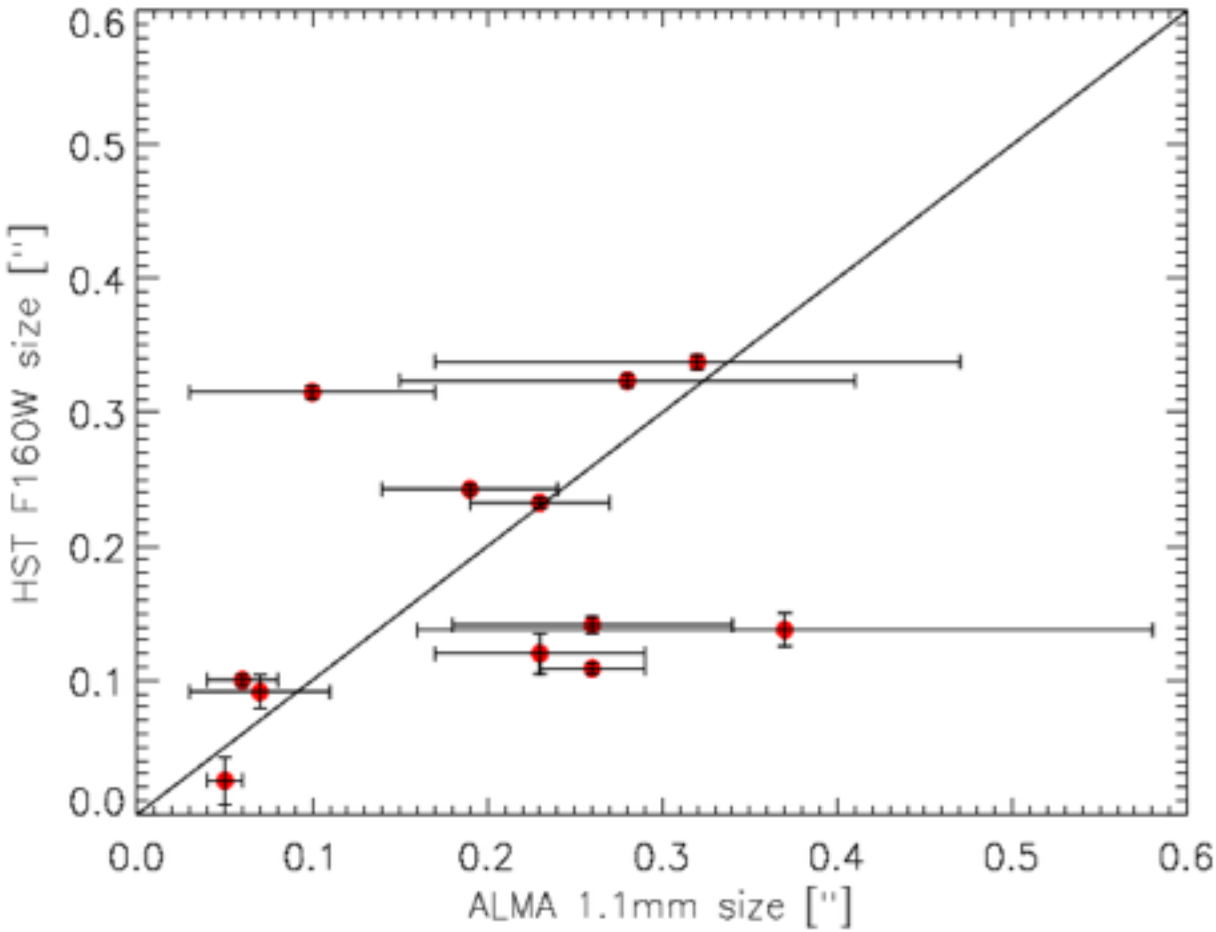


Observed effective radii range between 0.05” to 0.37”±0.21.

Offsets of 0.1-0.2” seen. If ALMA+HST alignment perfect, represent real offsets of ~1 kpc on average and ~4 kpc in extreme.

Both results consistent with brighter samples
(e.g., Wiklind+14; Simpson+15; Dunlop+16; Hodge+16)

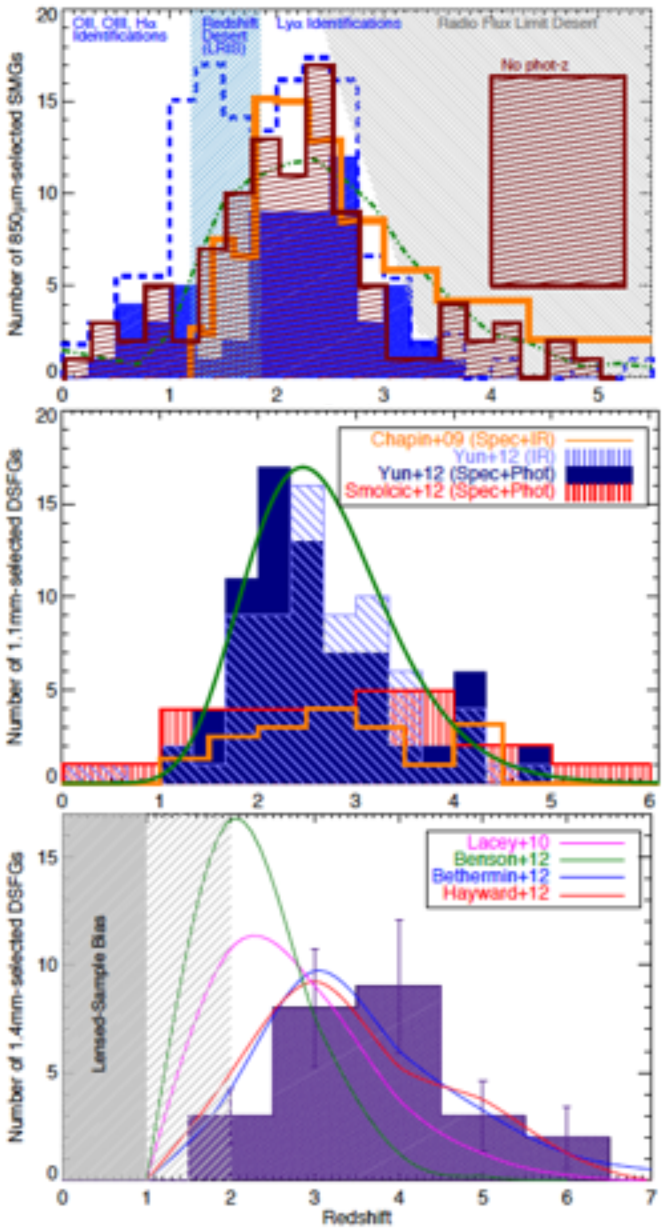
Apparent 1.1mm vs NIR Sizes (Laporte+16)



Dust generally follows stellar size…but with significant scatter.

Estimating opt-NIR redshifts (N. Laporte+, in prep)

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

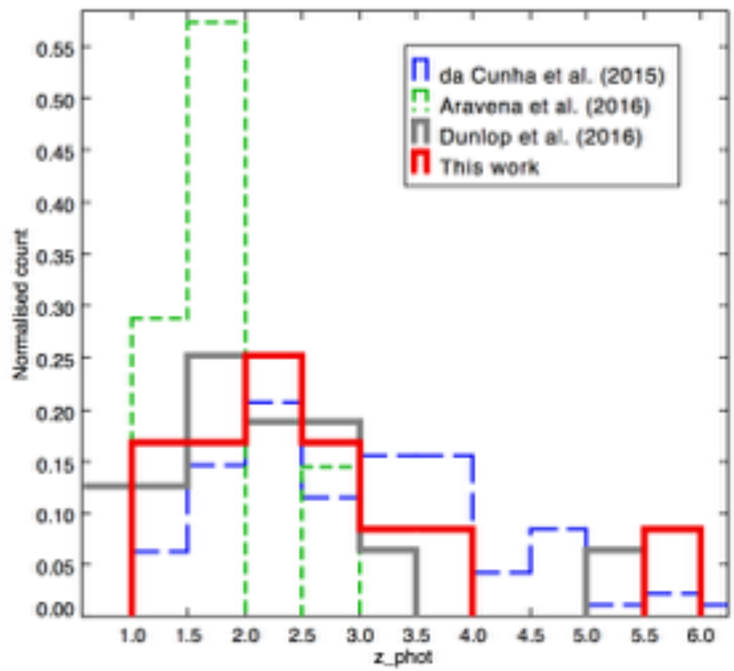


Radio-matched SCUBA

AzTEC

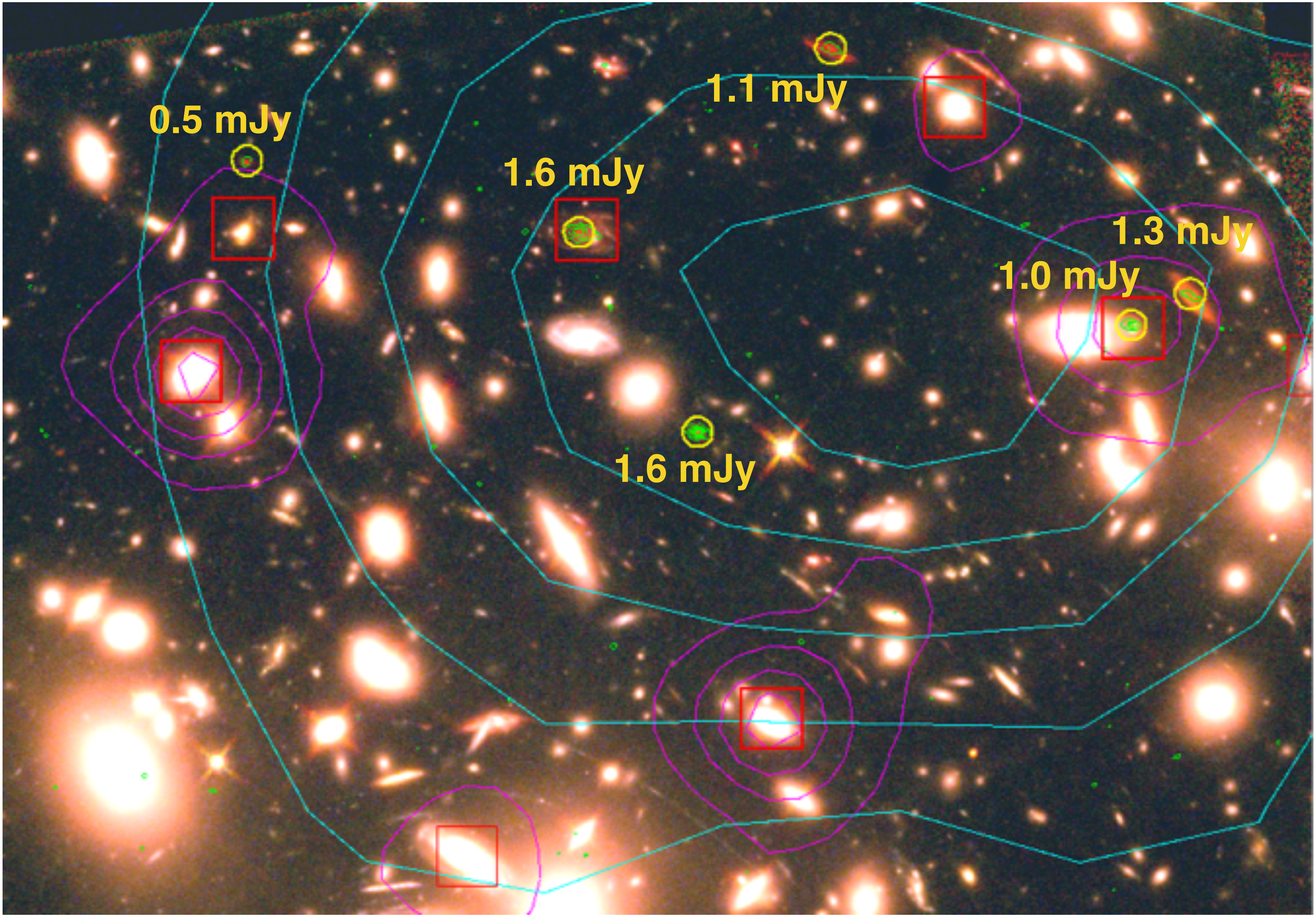
SPT

ALESS vs blank fields

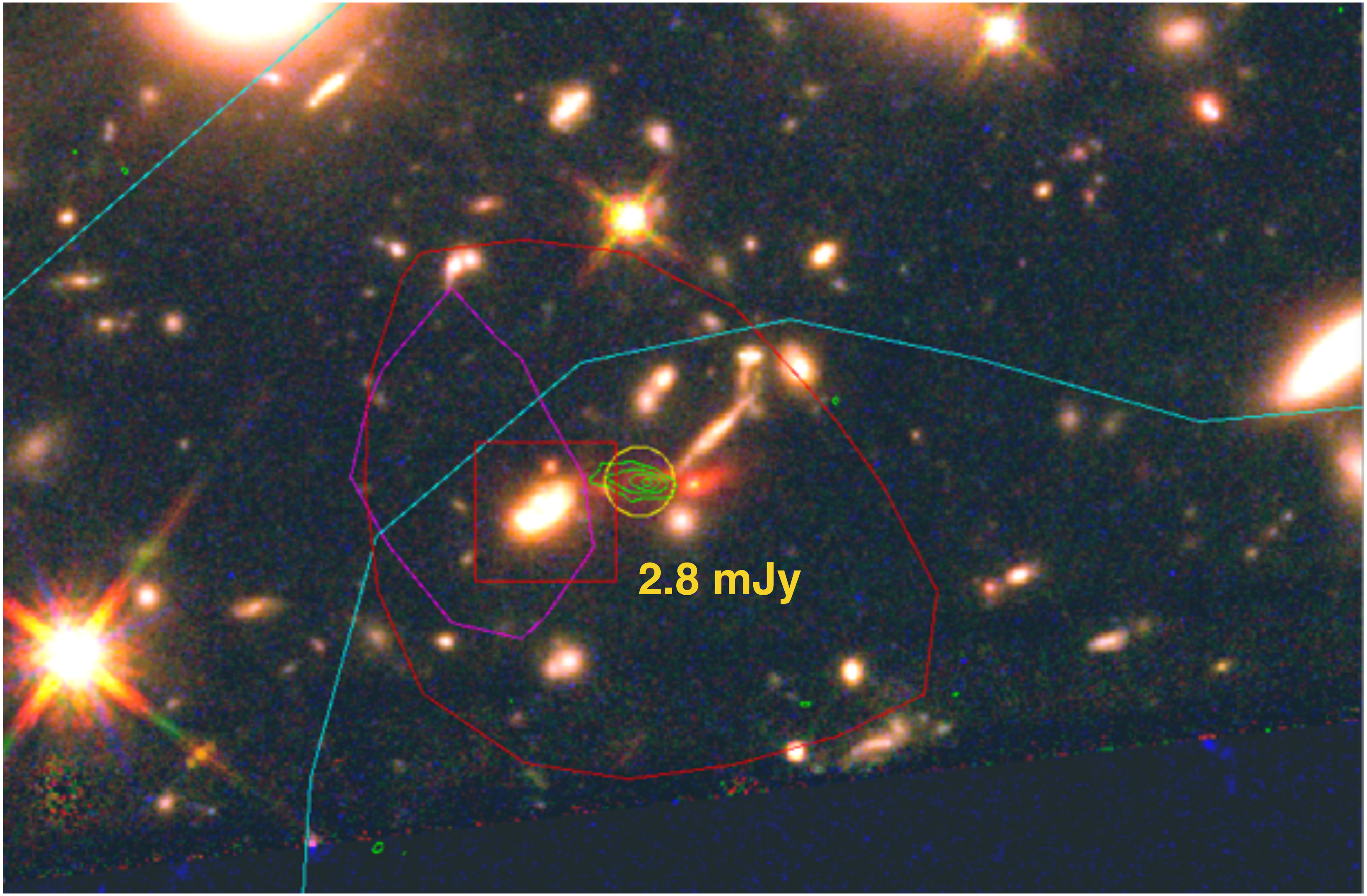


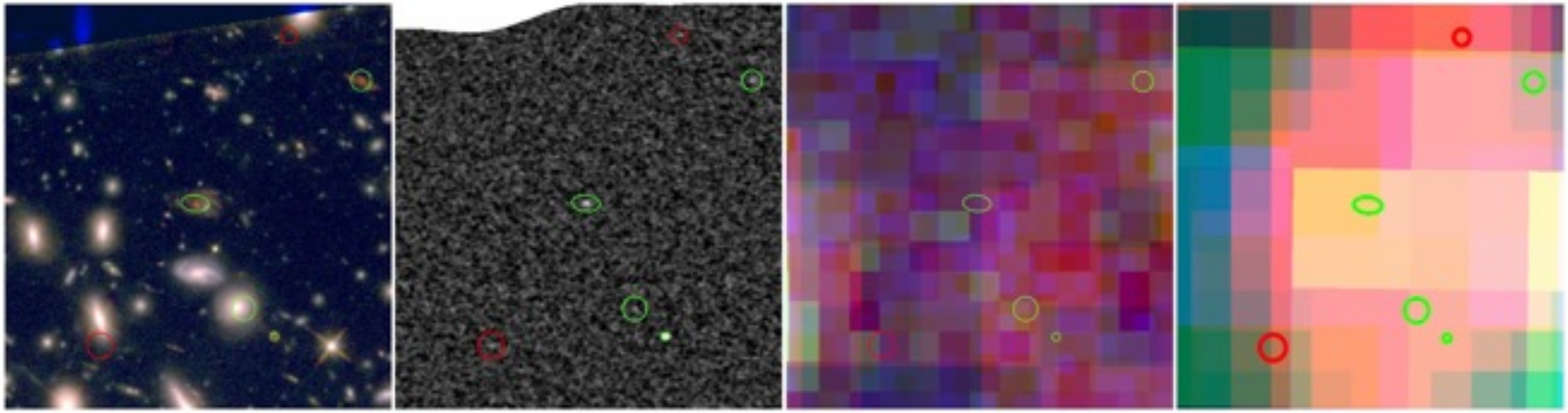
FFs are probing factors of several fainter flux densities than ALESS, and slightly lower average redshifts (consistent with other studies).

Difficulty to assign Herschel flux



Difficulty to assign Herschel flux



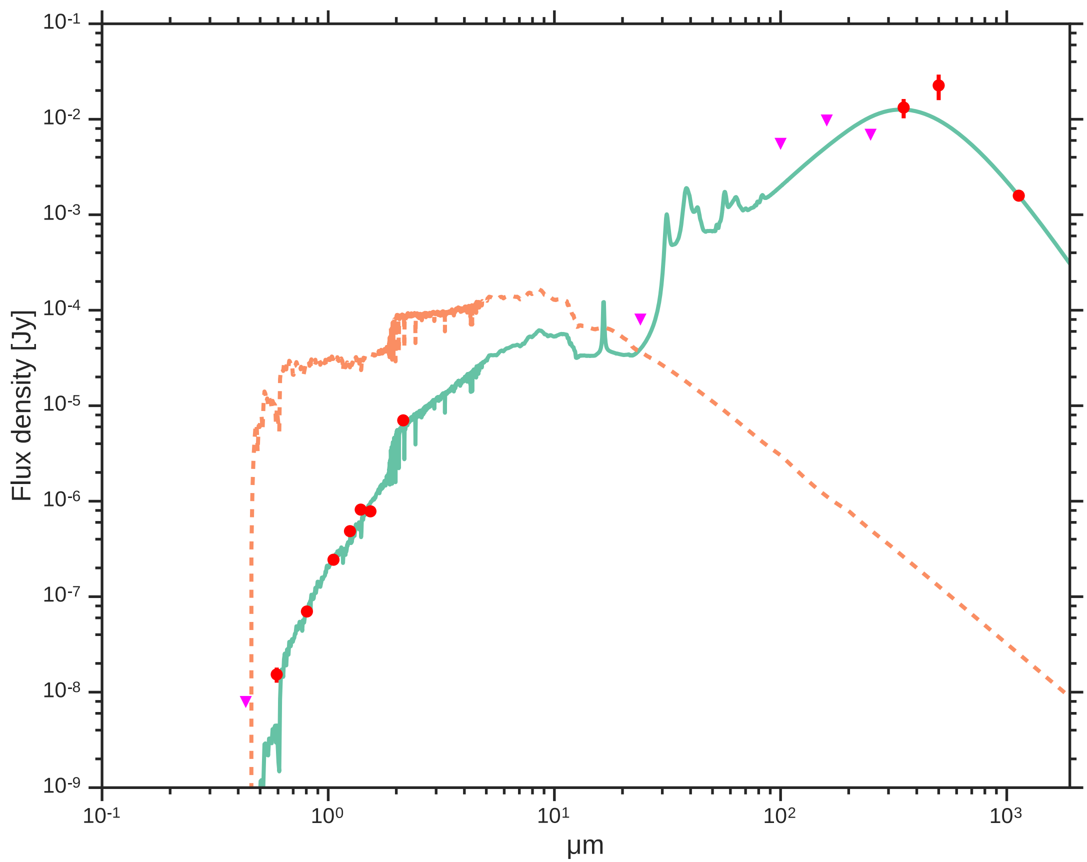


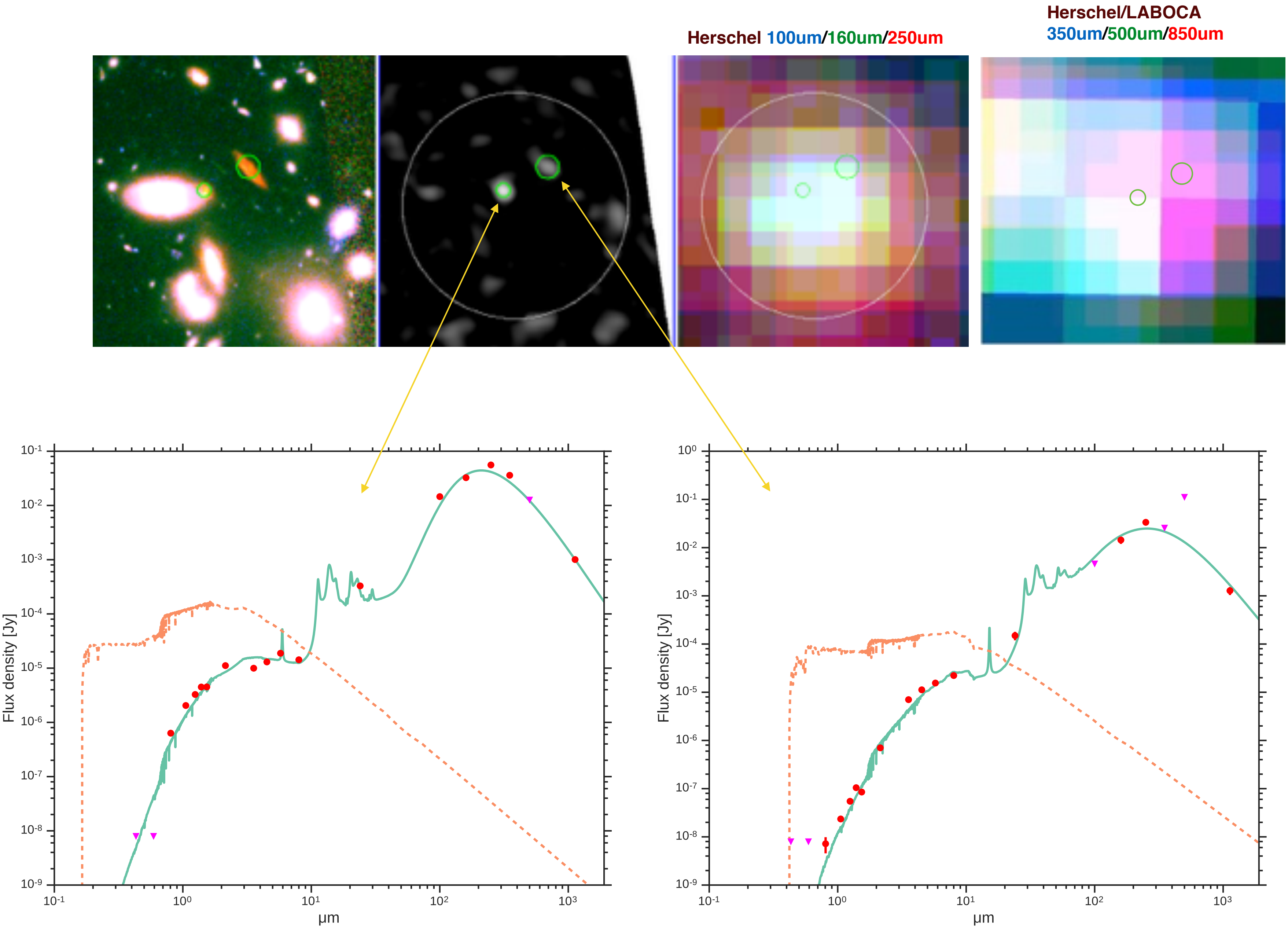
Herschel 100um 160um 250um

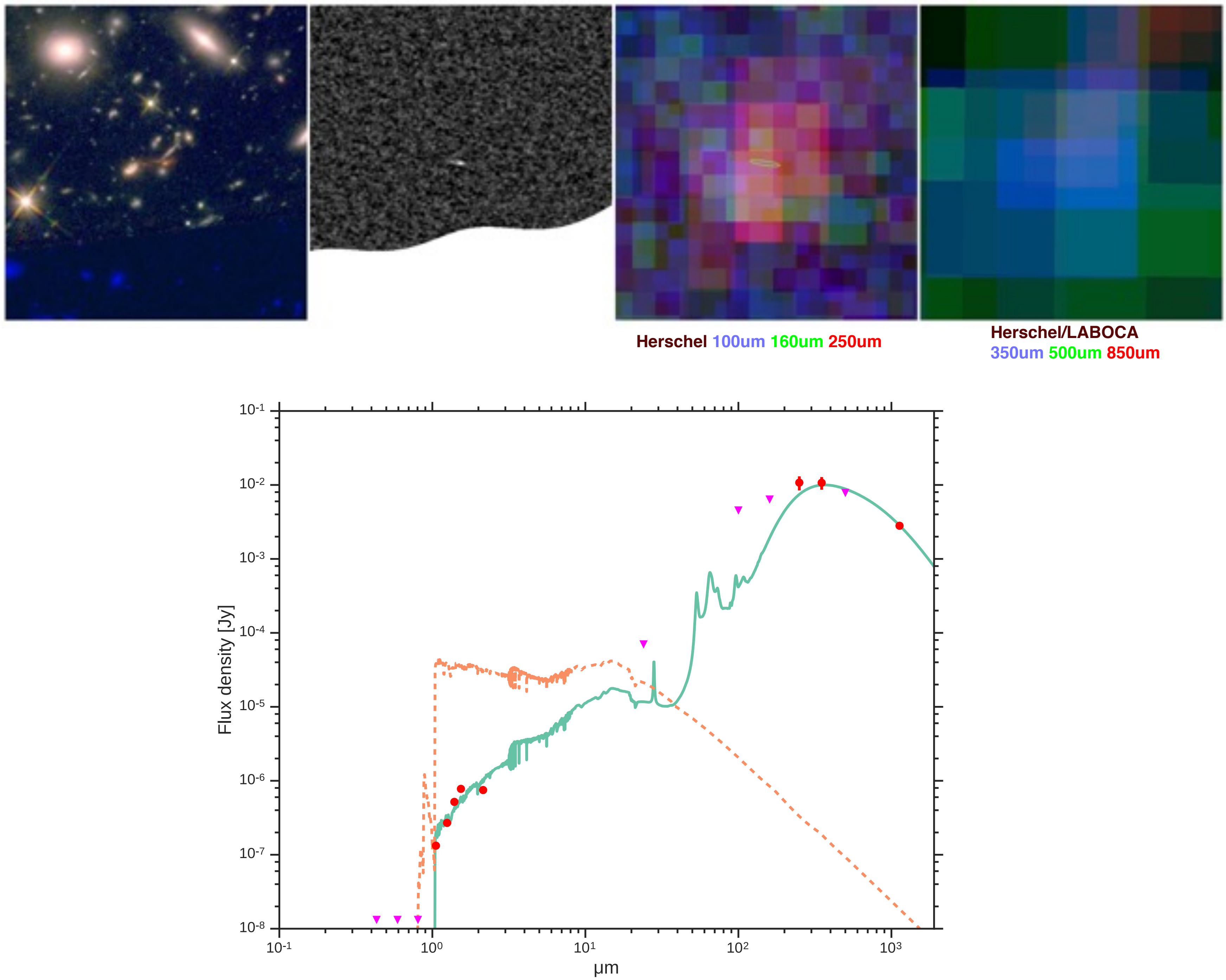
Herschel/LABOCA
350um 500um 850um

Fit SEDs using MAGPHYS (da Cunha +08,15) to derive basic physical parameters

(Gonzalez-Lopez+16, in prep.)

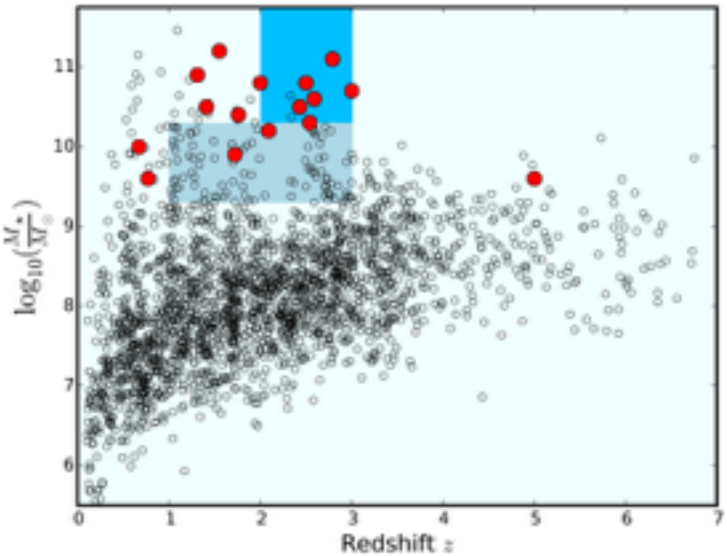



Herschel 100um/160um/250um
Herschel/LABOCA
350um/500um/850um
Flux density [Jy]
µm
Flux density [Jy]
µm

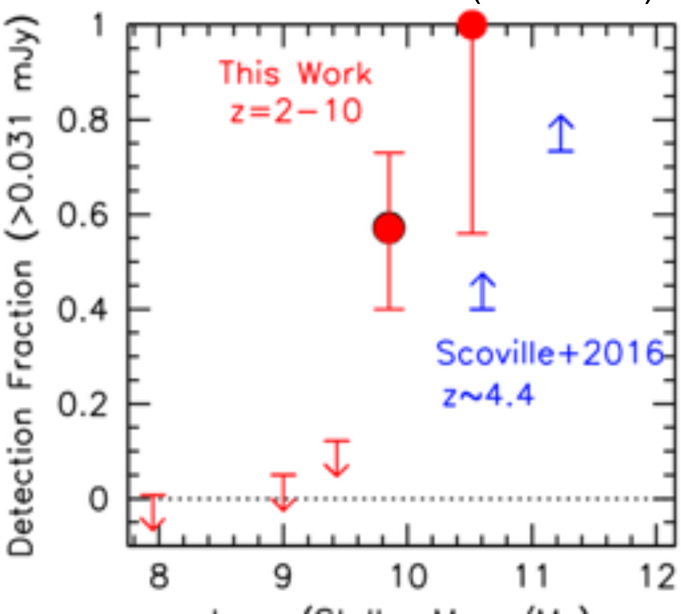

Herschel 100um 160um 250um
Herschel/LABOCA
350um 500um 850um
Flux density [Jy]
μm
10-1
10-2
10-3
10-4
10-5
10-6
10-7
10-8
10-1
10^0
10^1
10^2
10^3

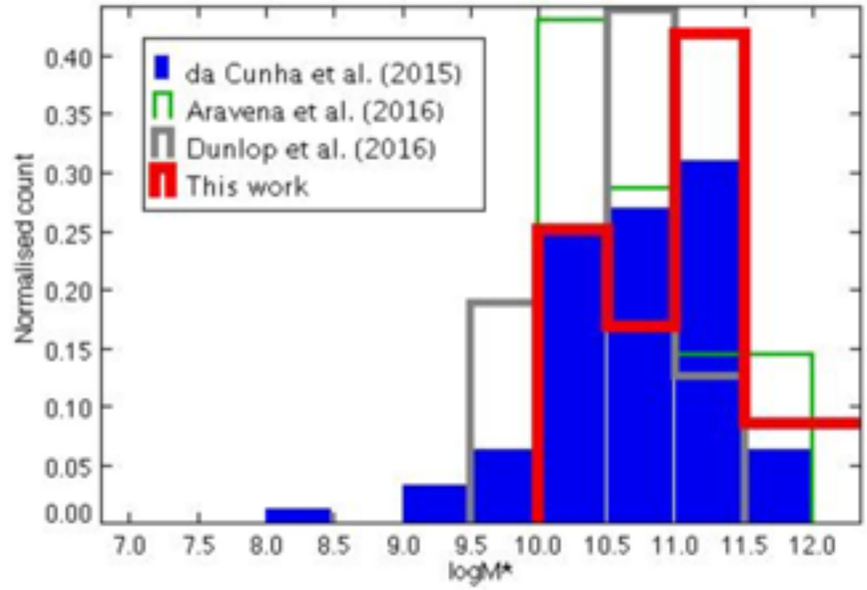
Counterpart Stellar Mass Distribution (N. Laporte+, in prep)

Dunlop et al. 2016 (UDF)



Bouwens et al. 2016 (ASPECS)

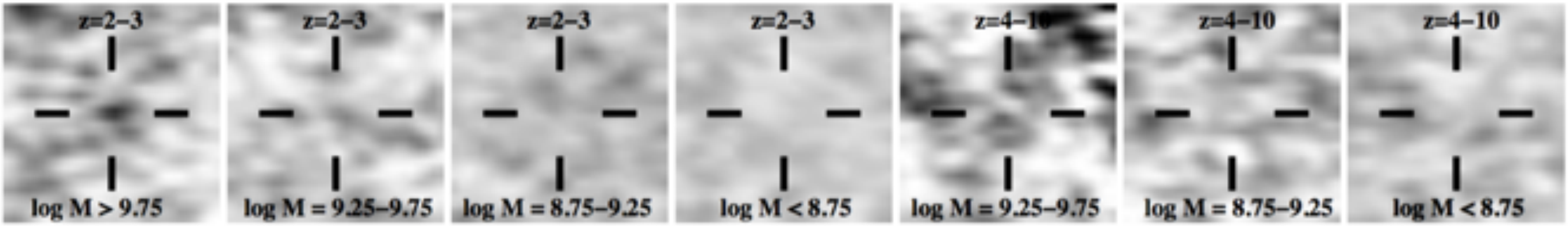




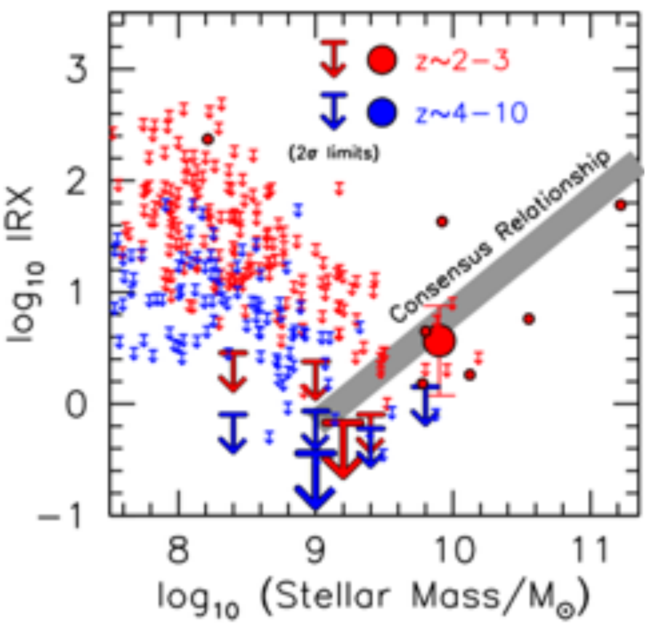
There appears to be a relatively universal stellar mass cutoff for DSFGs below ~10^{10} $M_\star$.

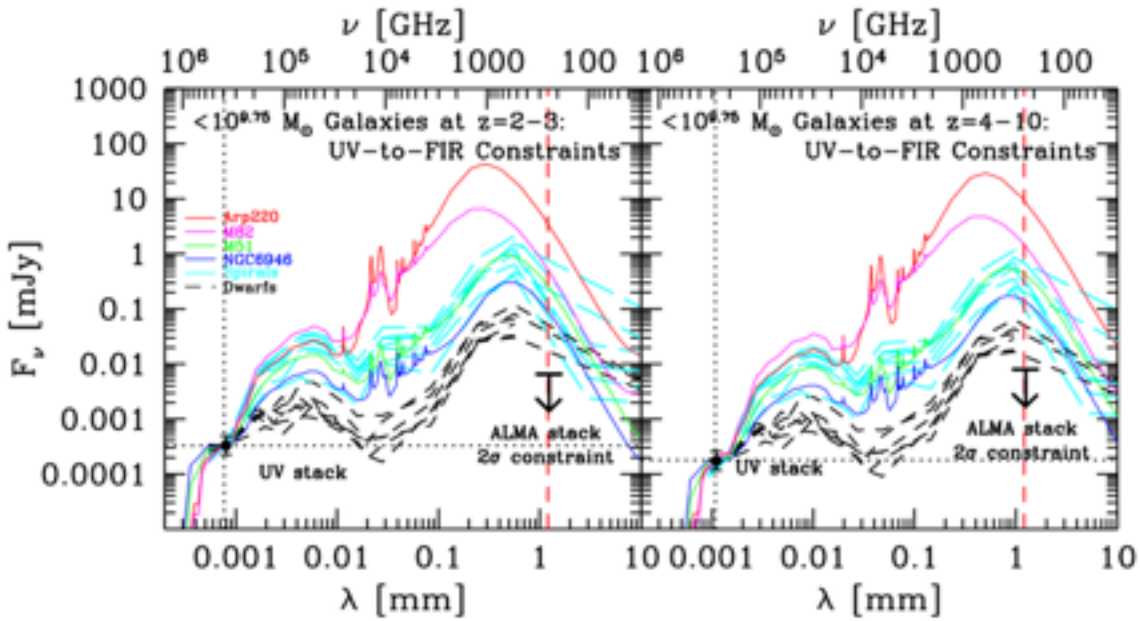
Given strong SFR-$M_\star$ correlation at high-z, remains unclear what is ultimately driving this cutoff.

ALMA Stacking in ASPECS (Bouwens et al. 2016)



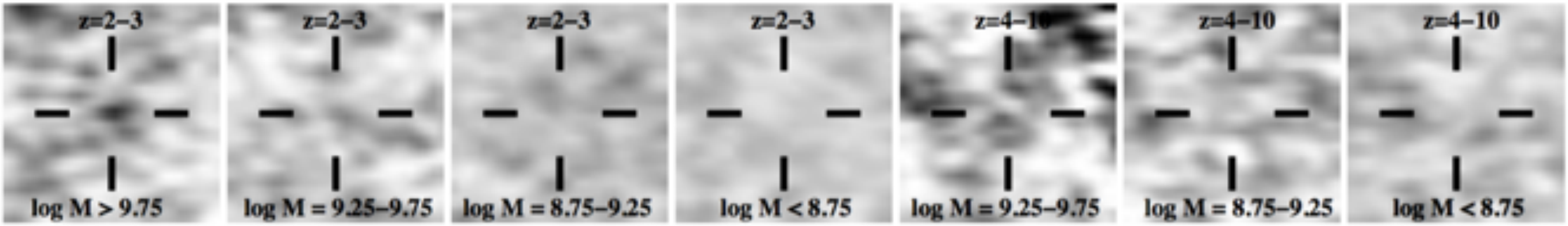
infrared excess IRX (= L_{IR}/L_{UV}) vs $M_{\star}$. vs UV slope ß



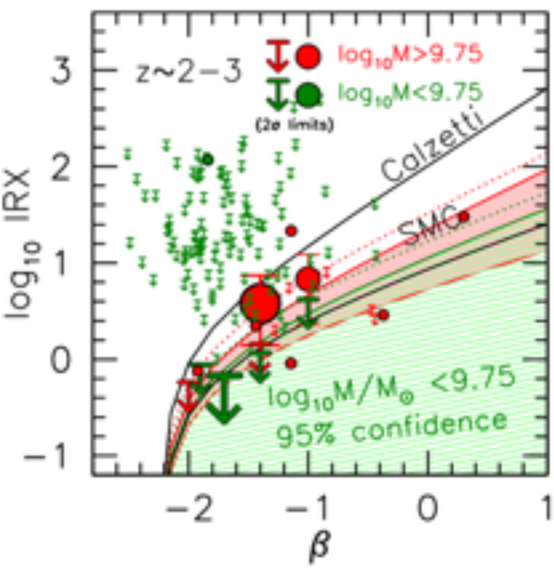


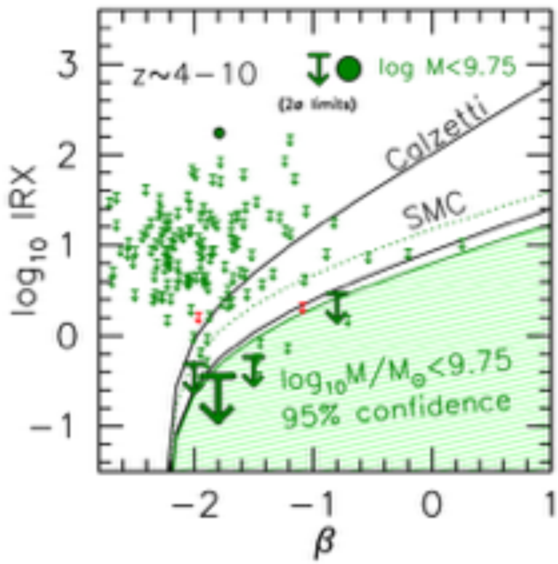
apparent deficit of dust in low-mass galaxies, ruling out consensus relation

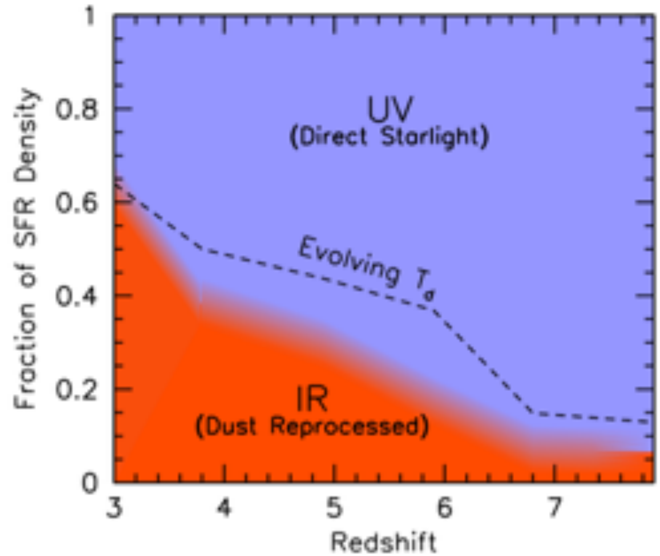
ALMA Stacking in ASPECS (Bouwens et al. 2016)



infrared excess IRX (= L_{IR}/L_{UV}) vs $M_{\star}$. vs UV slope ß







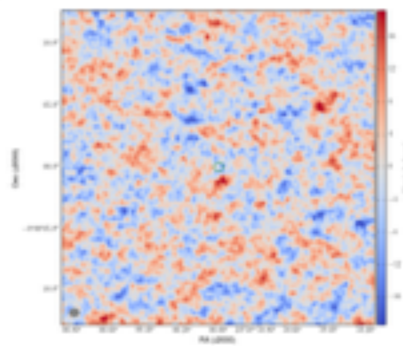
apparent z-evolution in IRX-ß, potentially excluding previous methods for making UV-corrections. Attributed to evolving dust temperature scenario.
=> implications for Lyman continuum production efficiencies

ALMA Stacking in FFs (R. Carvajal+, in prep)

LBG samples at z~2, 3, 4, 5, 6, 7, 8 => no detections

	Sample	N	mag F160W		CLEAN mode	imstack		uvstack	
			Min	Max		Central pixel [μJy]	SNR	Central pixel [μJy]	SNR
2	275	96	23.31 ± 0.07	28.35 ± 0.07	Natural	10.652 ± 6.798	1.57	14.402 ± 6.560	2.20
					Taper	23.963 ± 12.401	1.93	25.181 ± 11.560	2.18
3	336	240	22.90 ± 0.20	29.08 ± 0.20	Natural	0.507 ± 4.379	0.12	-0.706 ± 4.314	-0.16
					Taper	2.354 ± 8.597	0.27	2.797 ± 7.948	0.35
4	B	409	22.22 ± 0.03	30.23 ± 0.03	Natural	6.096 ± 3.190	1.91	5.675 ± 3.124	1.82
					Taper	-3.480 ± 6.008	-0.58	-3.405 ± 5.902	-0.58
5	V	95	25.87 ± 0.35	30.52 ± 0.35	Natural	0.934 ± 6.450	0.14	3.006 ± 6.412	0.47
					Taper	-9.853 ± 11.629	-0.85	-10.058 ± 11.643	-0.86
6	I	11	28.07 ± 0.25	29.70 ± 0.25	Natural	-2.826 ± 18.635	-0.15	1.154 ± 18.789	0.06
					Taper	-6.721 ± 32.140	-0.21	2.964 ± 30.912	0.10
7	Z	107	24.75 ± 0.21	30.30 ± 0.21	Natural	7.664 ± 6.325	1.21	7.618 ± 6.154	1.24
					Taper	7.548 ± 11.032	0.68	7.964 ± 10.637	0.75
8	Y	20	26.02 ± 0.18	29.00 ± 0.18	Natural	14.397 ± 15.886	0.91	19.334 ± 15.497	1.25
					Taper	23.605 ± 32.264	0.73	33.036 ± 28.299	1.17

Table 1: Abell2744 properties



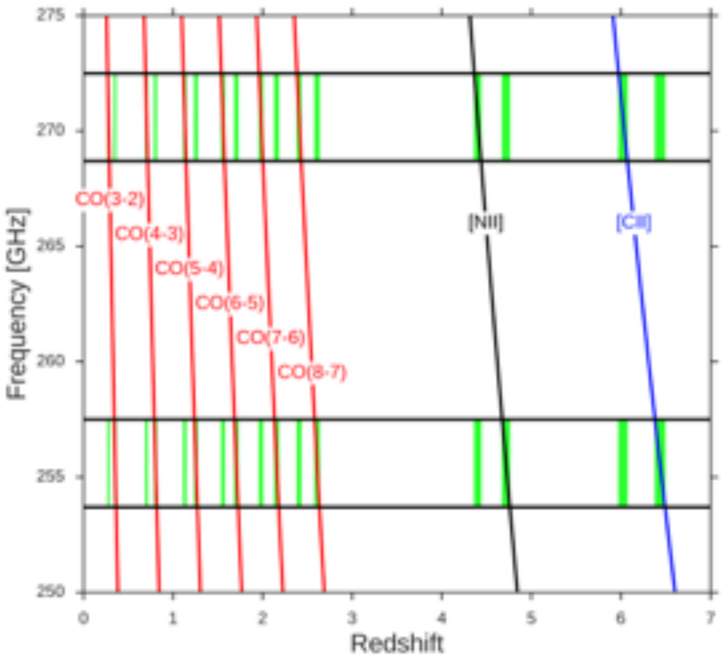
Sample	N	mag F160W		CLEAN mode	imstack		uvstack	
		Min	Max		Central pixel [μJy]	SNR	Central pixel [μJy]	SNR
275	11	23.31 ± 0.00	23.99 ± 0.00	Natural	29.794 ± 21.426	1.39	26.295 ± 21.512	1.22
				Taper	47.411 ± 42.113	1.13	36.372 ± 41.996	0.87
336	12	22.90 ± 0.01	23.99 ± 0.01	Natural	29.966 ± 22.748	1.32	27.802 ± 21.850	1.27
				Taper	24.394 ± 41.810	0.58	36.651 ± 39.926	0.92
B	20	22.22 ± 0.00	23.92 ± 0.00	Natural	3.646 ± 15.584	0.23	6.170 ± 15.829	0.39
				Taper	13.824 ± 29.115	0.47	17.783 ± 29.277	0.61

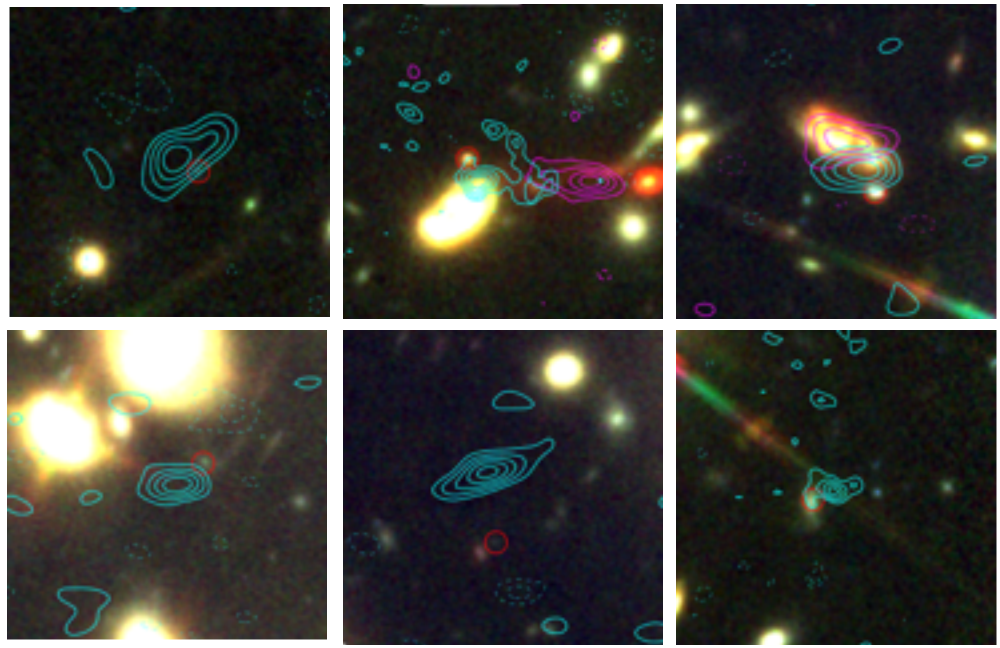
Table 1: Abell2744 properties. Brighter mag 24

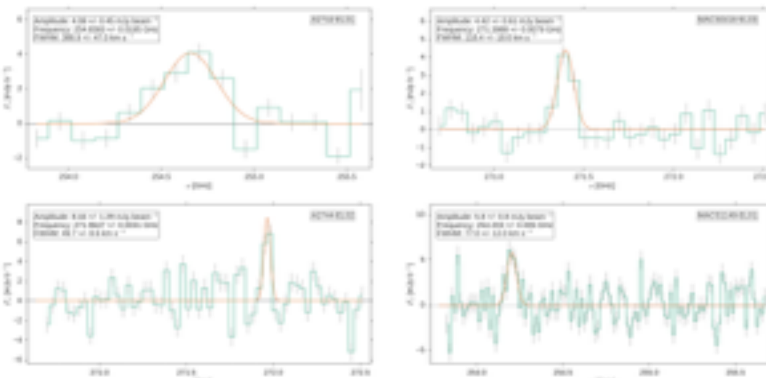
$F_{1.2mm}$ ~ 20 uJy ~ < 1 Msun/yr
SFR_{Bdrop} ~ >15 Msun/yr

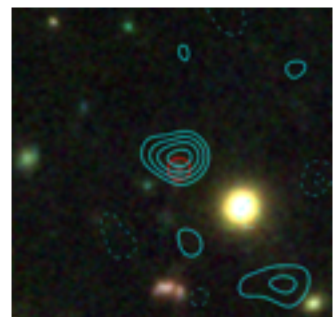
Look at individual and stacking constraints for u > 10 LBG samples, to see if we can improve upon Bouwens et al. ASPEC constraints at low mass end for individual sources

Serendipitous ALMA Line studies (Gonzalez-Lopez et al., in prep)









Allow redshift estimates and open up studies of the internal physics
=> aim to do more targeted searches for lines in Cycle 4
Complementary to ASPECS-LP and focused studies of bright targets

Conclusions:

ALMA analyses proceeding rapidly (in FFs and elsewhere).
Field-to-field variance (consistent with Poisson statistics + Cosmic var.), mostly detecting very modestly lensed z~1-4 (U)LIRGs.
~50% could be targeted for NIR spectroscopy (rest require ALMA spec)

We constrain sizes, morphologies, and multi-wavelength SEDs, etc.

Most of the properties are in line with smaller FOV studies done to date; we see broad consistency between brighter and fainter DSFG population. Combination points an intriguing mass cutoff and strong dust evolution at high-z.

Looking forward to follow-up studies of most interesting objects in cycle 4 and beyond. Would like to address underlying reasons for the observed trends and understand in better detail how gas is consumed and galaxy build up stellar mass.