A MASSIVE, DISTANT PROTO-CLUSTER AT Z = 2.47 CAUGHT IN A PHASE OF RAPID FORMATION?

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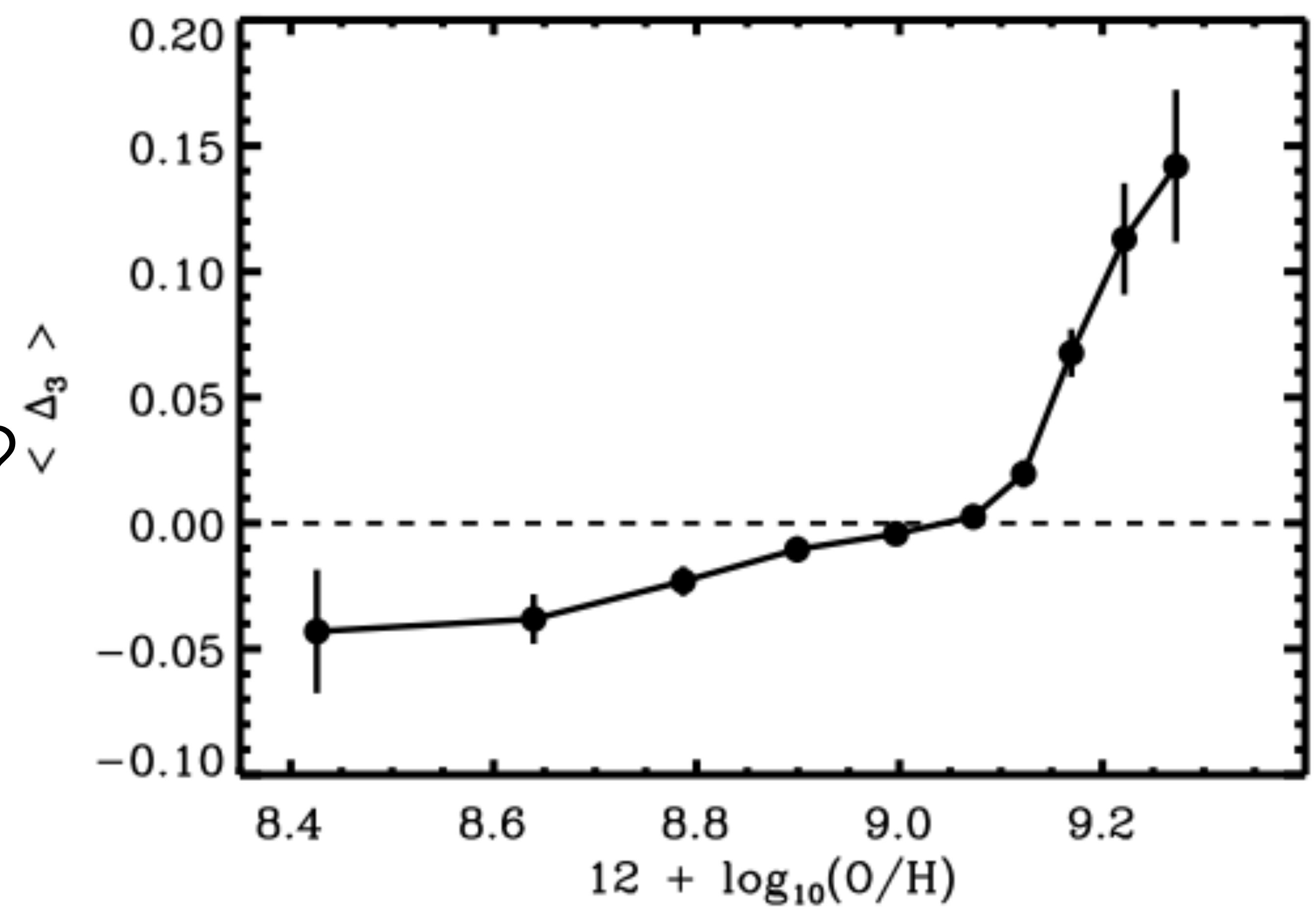
ABSTRACT

Numerical simulations of cosmological structure formation show that the Universe's most massive clusters, and the galaxies living in those clusters, assemble rapidly at early times ($2.5 < z < 4$). While more than twenty proto-clusters have been observed at $z \gtrsim 2$ based on associations of 5–40 galaxies around rare sources, the observational evidence for rapid cluster formation is weak. Here we report observations of an asymmetric, filamentary structure at $z = 2.47$ containing seven starbursting, submillimeter-luminous galaxies and five additional AGN within a volume of $4000\,\mathrm{Mpc}^3$. As the expected lifetime of both the luminous AGN and starburst phase of a galaxy is $\sim$100 Myr, we conclude that these sources were likely triggered in rapid succession by environmental factors or, alternatively, the duration of these cosmologically rare phenomena is much longer than prior direct measurements suggest. The stellar mass already built up in the structure is $\sim 10^{12}\,\mathrm{M}_\odot$ and we estimate that the cluster mass will exceed that of the Coma supercluster at $z \sim 0$. The filamentary structure is in line with hierarchical growth simulations which predict that the peak of cluster activity occurs rapidly at $z > 2$.

Subject headings: galaxies: clusters: general – galaxies: starburst – galaxies: quasars: general – cosmology: large-scale structure of universe

Introduction : questioning the formation of massive galaxy cluster

- "cluster quenching"; morphology (color)-density relation
- When and how or reversal?
- Does it follow the hierarchical growth formation? thus, massive structure have more enhanced SFRs?



Cooper+08

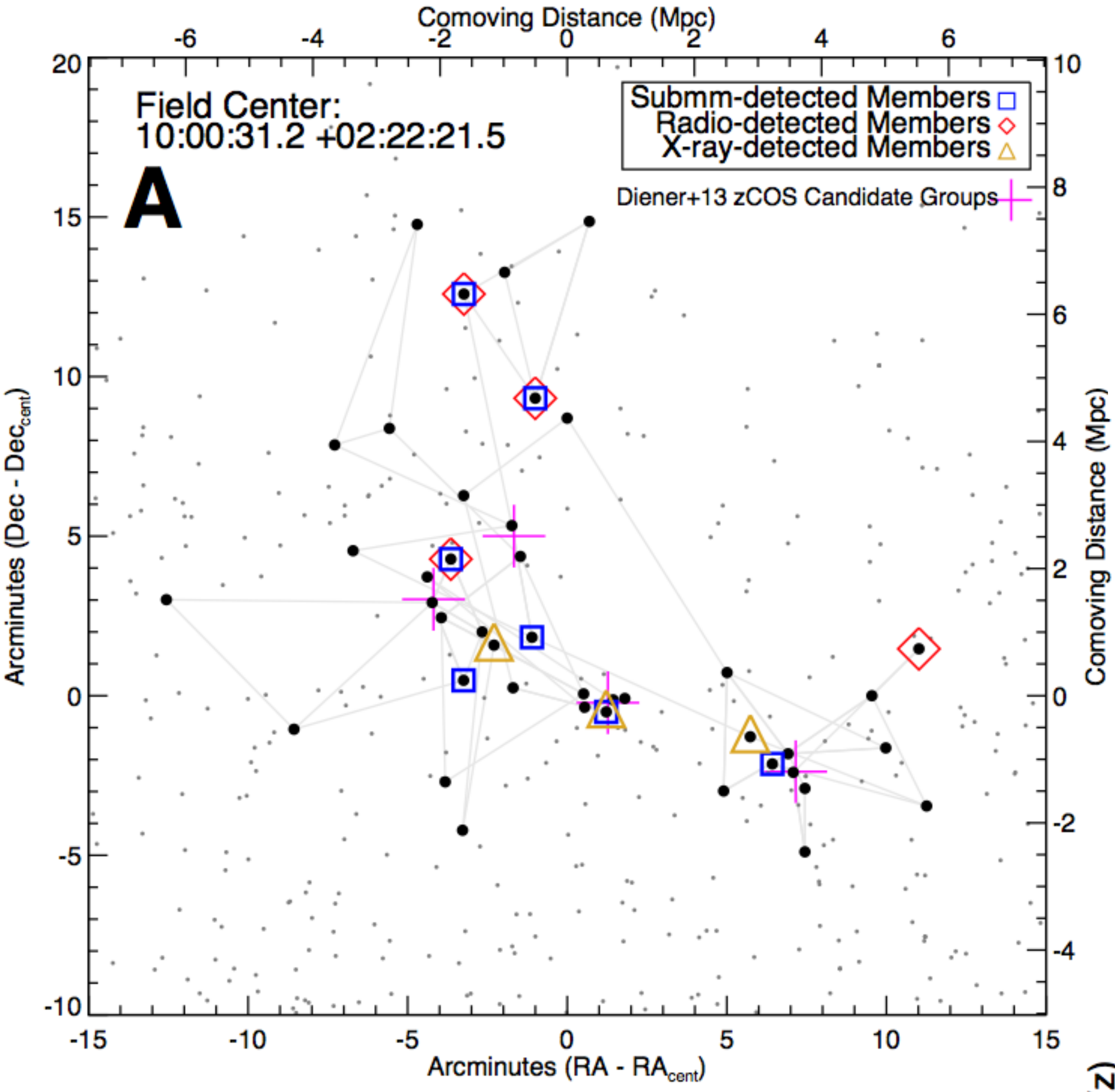
Data and observations

- $z = 2.47$ protocluster (PCL1002) in COSMOS field
  - 6 DSFGs from SCUBA-2 survey
    - spectroscopically confirmed with Hα redshifts $z = 2.472 \pm 0.007$
    - 4/6 have secured NIR counterpart
    - one DSFG may be a major-merger w/ multiple knots
    - one 24μm/radio/IRAC have position consistency
  - 1 DSFG from Herschel-SPIRE
    - CO(1-0) detection at $z = 2.4790$
  - from zCOSMOS survey 35 spectroscopically-confirmed sources within $2.463<z<2.487$ (via Lyα emission, FeII, SiII, CII absorption) (Lilly+09)

TABLE 1
DEBOOSTED FIR-PHOTOMETRIC DATA FOR PCL1002'S DUSTY STARBURSTS

NAME	S_{24} [mJy]	S_{100} [μJy]	S_{160} [mJy]	S_{250} [mJy]	S_{350} [mJy]	S_{450} [mJy]	S_{500} [mJy]	S_{850} [mJy]	$S_{1.4GHz}$ [μJy]	L_{IR} [$L_\odot$]
DSFG J100036.03+022151.1...	194±17	–	–	11.3±2.2	15.6±2.7	11.3±4.9	14.5±3.1	4.6±1.1	–	$(3.12^{+1.39}_{-0.96})\times10^{12}$
DSFG J100018.17+022250.4...	128±16	–	–	11.3±2.2	–	3.9±4.1	–	3.3±1.0	–	$(3.84^{+2.35}_{-1.46})\times10^{12}$
DSFG J100016.57+022638.4...	890±17	6.7±1.9	19.2±3.6	24.5±2.2	21.5±2.7	17.3±4.7	11.6±3.0	3.7±1.0	5716±73	$(7.52^{+2.21}_{-1.71})\times10^{12}$
DSFG J100056.83+022013.3...	90±27	–	–	–	9.1±12.9	18.3±6.0	–	10.9±1.1	–	$(2.06^{+0.93}_{-0.64})\times10^{12}$
DSFG J100026.73+022411.3...	84±14	–	–	11.4±2.2	14.8±2.7	10.3±5.0	17.8±3.0	0.4±0.8	–	$(2.99^{+1.85}_{-1.16})\times10^{12}$
DSFG J100018.21+023456.7...	153±11	–	–	16.6±2.0	19.5±3.4	12.0±8.8	11.2±4.2	2.57±1.74	46±10	$(4.23^{+4.51}_{-2.18})\times10^{12}$
DSFG J100027.14+023140.8...	421±152	13.6±1.8	24.4±3.6	36.9±2.2	30.8±2.8	3.9±5.0	17.0±3.4	5.8±1.4	67±12	$(1.15^{+0.19}_{-0.16})\times10^{13}$

- > 30 photometric bands (Ilbert+13)
- Chandra X-ray catalog (Civano+12)
- radio 1.4 catalog (Schinnerer+07))
- Herschel PEP/PACS and HerMES/SPIRE (Lee+13)



grey : galaxies
2.30<z< 2.66
(control field)
black : confirmed
PCL member
(from FOF)

Overdensity of DSFGs

Number of DSFG $\Delta z = 0.02$ within a 150 arcmin^2 box $\lambda = 0.58$ (in a volume ~ 9000 Mpc^3)

→ probability of observing seven DSFGs in this interval is 0.002 %

$\delta_{DSFG} = (7-0.58)/0.58 = 11$

c.f. HDF at $z = 1.99$: $\delta_{DSFG} = 10$,

SSA22 at $z = 3.09$: 5-6 DSFGs (δ_{DSFG} =?)

MRC1138-256 at $z = 2.16$: ~ 5 DSFGs w/ more compact distribution ($\delta_{DSFG} \gtrsim 100$)

0.0001 % of occurring by chance (not an artefact of incompleteness or survey bias)

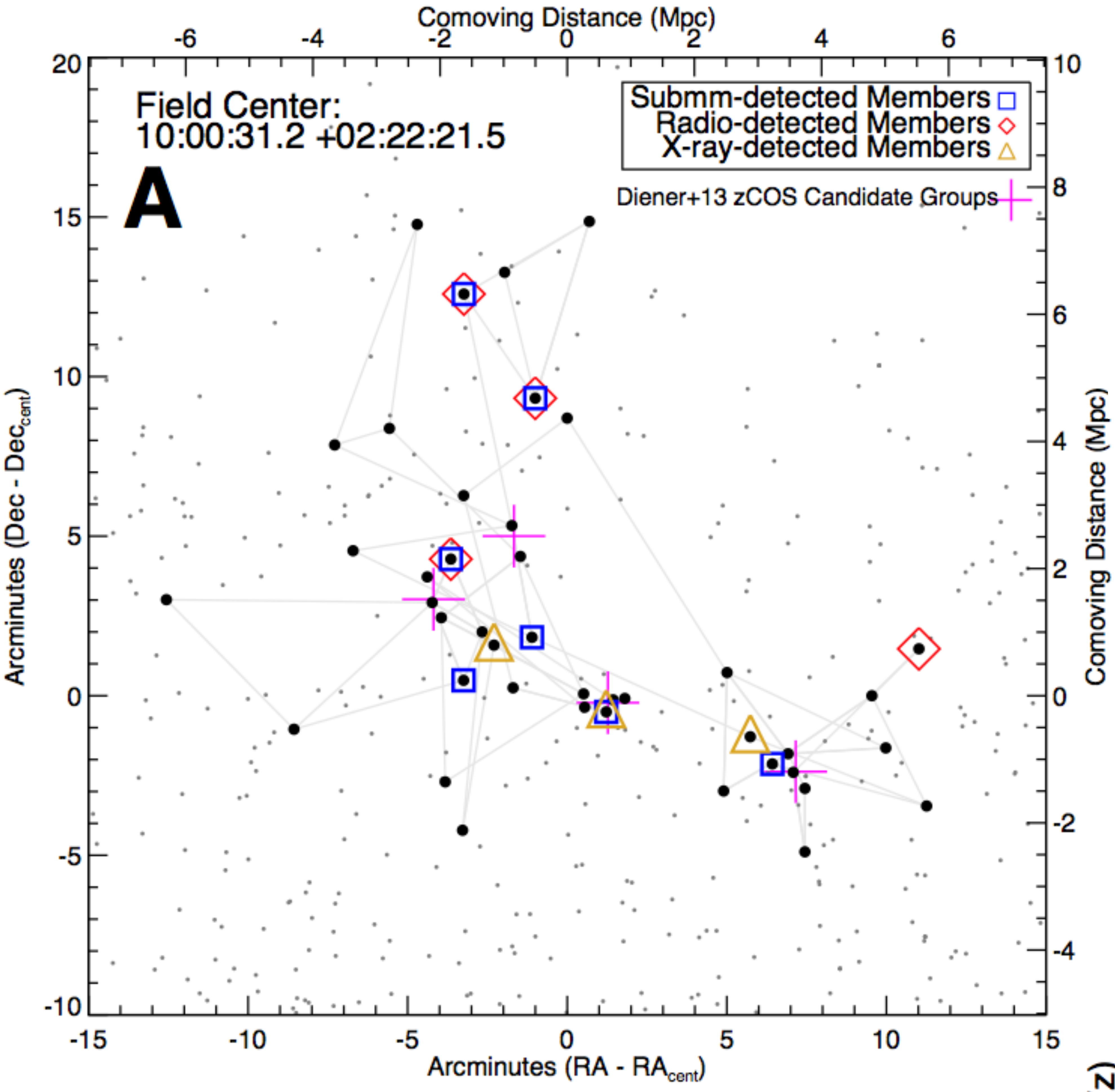
Overdensity of LBGs

$\delta_g = 3.3$
← used FOF algorithm which LBGs are in fact members of the DSFG over density : selecting sources within 2 Mpc-comoving of the DSFGs or their immediate neighbours, or within 5 Mpc comoving of the DSFGs
(この値は high-zのnon-virialized structureをトレースするために選ばれたもの Chiang+13)

Control field

- limiting sources within ±200 Myr of observed structure (2.30 $<z<$2.66)
  - from zCOSMOS, 1072 galaxies are identified
  - remove within 20 Mpc of PCL1002 (x2 in comoving distance beyond the boundary of a proto-cluster)

→ 401 samples



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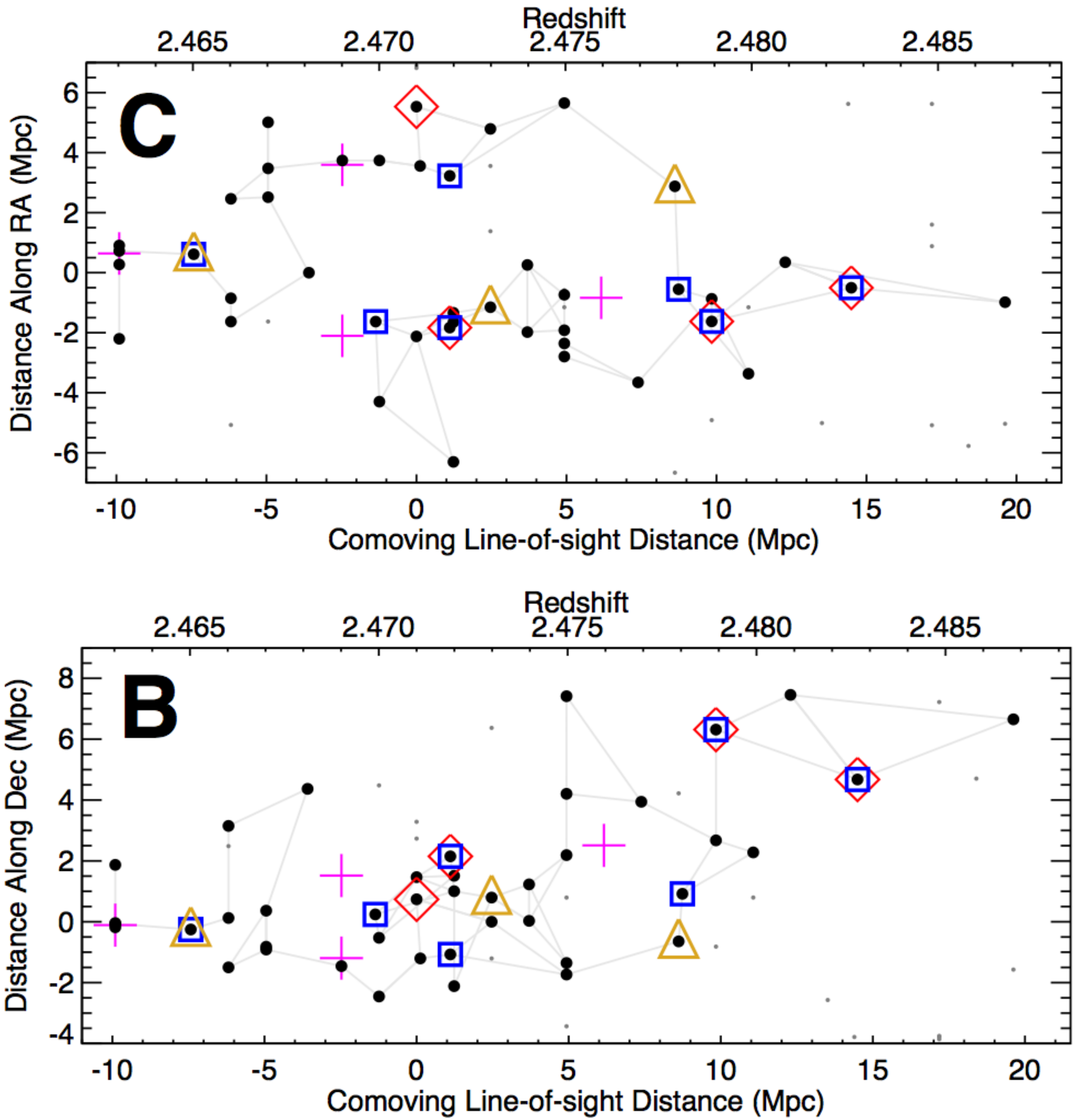
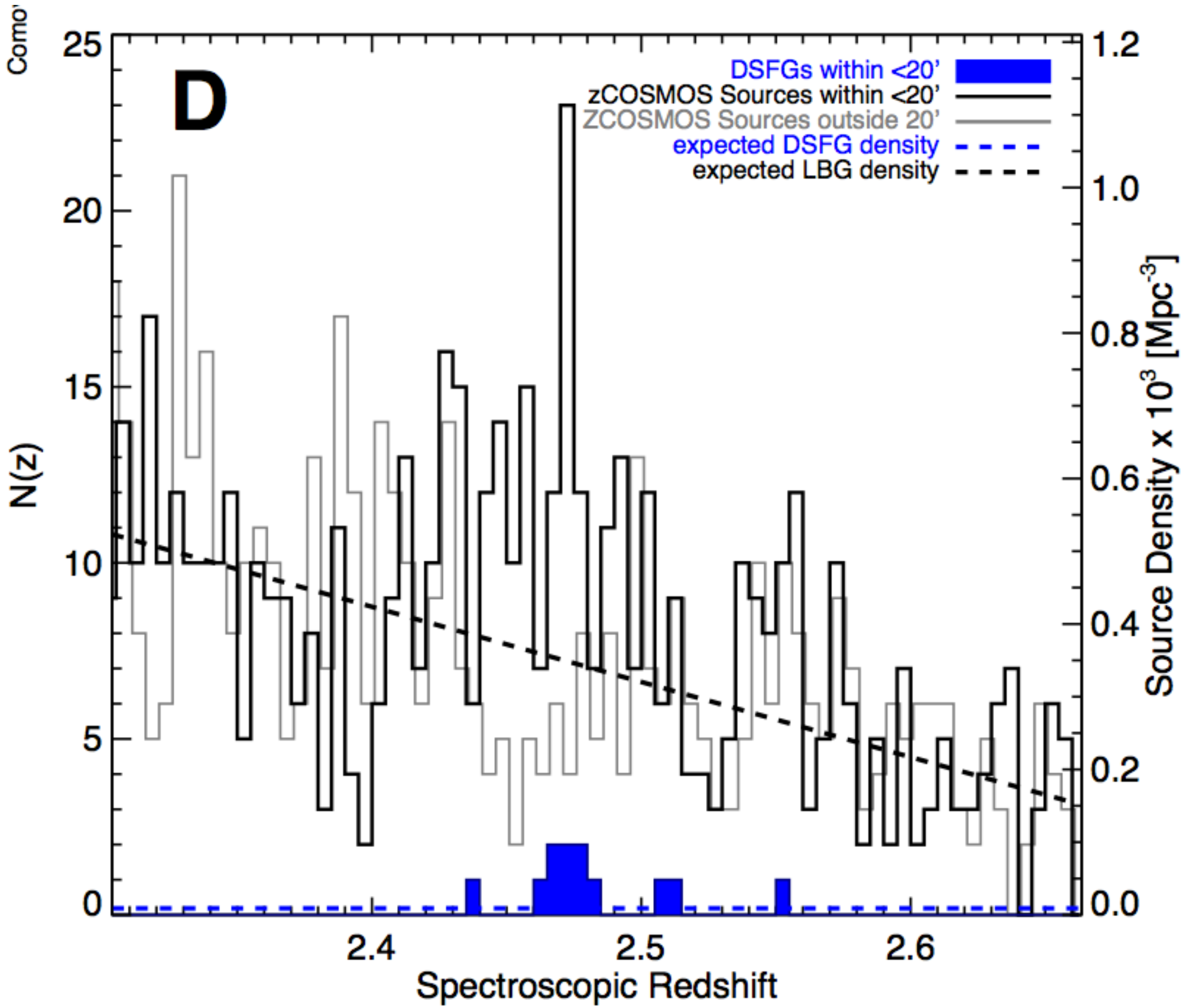


C
Redshift
2.465
2.470
2.475
2.480
2.485
Distance Along RA (Mpc)
6
4
2
0
-2
-4
-6
-10
-5
0
5
10
15
20
Comoving Line-of-sight Distance (Mpc)
B
Redshift
2.465
2.470
2.475
2.480
2.485
Distance Along Dec (Mpc)
8
6
4
2
0
-2
-4
-10
-5
0
5
10
15
20
Comoving Line-of-sight Distance (Mpc)



D
DSFGs within <20'
zCOSMOS Sources within <20'
ZCOSMOS Sources outside 20'
expected DSFG density
expected LBG density
N(z)
Source Density x 10^3 [Mpc^{-3}]
Spectroscopic Redshift
25
20
15
10
5
0
1.2
1.0
0.8
0.6
0.4
0.2
0.0
2.4
2.5
2.6

AGN enhancement

- Four galaxies (9.5 %) are luminous X-ray sources (Lx > 1e43.7 erg/s; Civano+12) (x82 compared to expected volume density of AGN of similarly high luminosities; Siverman+08)
- 4/7 DSFG has AGN features in either X-ray, radio, optical or uv (57 %) (x2 than in non-clustered DSFGs; Alexander+05)
  - stacked Chandra but no X-ray emission
  - 1/7 and one LBG host radio-loud AGN
    - become BCG? — consistent with other high-z over densities that host single radio-loud quasars
  - three DSFG, one LBG have broad Hα lines or high [NII]/Hα ratio

Mstar and SFR

- MAGPHYS SED (da Cunha+08)
  - stellar synthesis template library as input, attenuation is determined from a mix of hot/cool/PAH dust grains
  - SFR not from only FIR
  - Mstar for all galaxies including DSFGs
  - compare field and member galaxies
- to derive SFR; fit the SED with modified blackbodies (β= 1.8, α = 2.0) from MIR to submm and integrated from 8-1000 μm (Chabrier IMF, Kennicutt+98 calibration)
- for stellar mass, compare with H-band-based Mstar
  - rest-frame H-band magnitude for each DSFG
  - removing any MIR dusty power-law (on average ~ 50% contribution)
  - converting to stellar mass using L_H/Mstar = 7.9 Lsun/mag (Hainline+11)

→ Mstar of LBGs are more higher than control LBGs

Submm stacking

- (PCL1002) LBGs versus (control LBGs)
- S850 = 0.25±0.16 mJy vs 0.11±0.13 mJy ; likelihood of greater 850 μm in PCL1002 is 76 %
- S450 = 0.42±0.85 mJy vs 1.66±0.69
- suggestive that mass of cold dust and interstellar medium (ISM) is potentially higher for galaxies in the dense structure, despite their comparable star-formation rates?; molecular gas reservoirs are deeper than galaxies living outside (follow-up molecular gas measurements is necessary)

Rest-frame optical morphologies

- HST H-band for 21/42 PCL members
- use CANDELS visual classification scheme (Kocevski+12; Kartaltepe+12)
  - morphology class : disk, spheriod, irregular, or unclassifiable
  - interaction class : merger, interacting pair or non-interacting

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TABLE 2
PHYSICAL CHARACTERISTICS OF PCL1002 MEMBERS

NAME	z	TYPE	L_{UV} ($L_\odot$)	SFR ($M_\odot\ yr^{-1}$)	$M_\star$ ($M_\odot$)	MORPH CLASS	AGN INDICATOR
LBG J100013.62+022604.9	2.463	UV	$(4.26^{+0.66}_{-0.57})\times10^{10}$	$6.67^{+0.55}_{-1.41}$	$(1.14^{+0.06}_{-0.21})\times10^{10}$	Disk/Int	–
LBG J100033.33+022159.9	2.463	UV	$(4.36^{+0.69}_{-0.60})\times10^{10}$	$49.5^{+0.6}_{-21.1}$	$(4.65^{+0.52}_{-0.87})\times10^{10}$	Sph	–
LBG J100036.90+022213.8	2.463	Lyα/UV	$(2.24^{+0.07}_{-0.07})\times10^{10}$	$3.17^{+0.20}_{-1.02}$	$(5.74^{+0.90}_{-0.90})\times10^{8}$	Sph	–
LBG J100038.35+022216.4	2.463	UV	$(5.86^{+0.78}_{-0.69})\times10^{10}$	$25.9^{+29.1}_{-3.5}$	$(7.92^{+1.01}_{-2.09})\times10^{9}$	Sph/Int	–
DSFG J100036.03+022151.1	2.465	Hα	$<3.0\times10^{10}$	296^{+132}_{-91}	$(1.01^{+0.06}_{-0.18})\times10^{11}$	Disk/Int	X-ray
LBG J100018.18+022837.7	2.466	UV	$(4.28^{+0.69}_{-0.59})\times10^{10}$	$12.7^{+3.4}_{-2.7}$	$(2.37^{+0.30}_{-0.43})\times10^{9}$	Sph/Int	–
LBG J100024.36+022236.3	2.466	UV	$(4.88^{+0.70}_{-0.61})\times10^{10}$	$25.5^{+4.8}_{-9.8}$	$(8.79^{+0.08}_{-0.09})\times10^{9}$	Sph/Int	–
LBG J100050.73+021922.4	2.466	UV	$(6.61^{+0.81}_{-0.72})\times10^{10}$	$98.2^{+7.6}_{-17.4}$	$(1.44^{+0.06}_{-0.28})\times10^{10}$	–	–
LBG J100031.14+023103.3	2.467	Hα/Lyα	$(2.61^{+0.66}_{-0.59})\times10^{10}$	$8.21^{+1.96}_{-1.96}$	$(3.22^{+0.20}_{-0.31})\times10^{10}$	Sph	–
LBG J100051.16+022305.1	2.467	Lyα	$(2.86^{+0.63}_{-0.51})\times10^{10}$	$17.8^{+0.9}_{-7.3}$	$(2.01^{+0.15}_{-1.03})\times10^{9}$	–	–
LBG J100058.80+022032.4	2.467	UV	$(4.90^{+0.74}_{-0.64})\times10^{10}$	$63.1^{+1.2}_{-8.2}$	$(5.94^{+0.57}_{-1.31})\times10^{9}$	–	–
LBG J100111.03+022043.4	2.467	UV	$(5.69^{+0.77}_{-0.68})\times10^{10}$	$45.0^{+21.0}_{-17.0}$	$(1.65^{+0.03}_{-0.43})\times10^{10}$	–	–
LBG J100100.91+021927.3	2.469	UV	$(5.07^{+0.75}_{-0.65})\times10^{10}$	$32.3^{+2.4}_{-7.9}$	$(3.46^{+0.14}_{-1.19})\times10^{9}$	–	–
LBG J095956.93+022118.5	2.470	UV	$(2.48^{+0.65}_{-0.51})\times10^{10}$	$15.7^{+0.5}_{-7.8}$	$(1.77^{+0.01}_{-0.62})\times10^{9}$	–	–
LBG J100059.45+021957.4	2.470	Hα/Lyα	$(3.75^{+0.72}_{-0.60})\times10^{10}$	$16.9^{+1.7}_{-4.2}$	$(2.66^{+0.02}_{-0.64})\times10^{10}$	–	Opt/X-ray
LBG J100100.91+021728.1	2.470	Lyα	$(7.18^{+0.84}_{-0.75})\times10^{10}$	$30.7^{+0.1}_{-4.7}$	$(2.84^{+0.11}_{-0.51})\times10^{9}$	–	–
DSFG J100018.17+022250.4	2.470	Hα	$(1.01^{+0.09}_{-0.08})\times10^{11}$	365^{+223}_{-138}	$(1.91^{+0.15}_{-0.41})\times10^{10}$	Merg	–
LBG J100014.24+022516.7	2.471	UV	$(3.24^{+0.65}_{-0.54})\times10^{10}$	$46.7^{+1.8}_{-5.3}$	$(1.13^{+0.05}_{-0.20})\times10^{10}$	Sph/Int	–
LBG J100115.18+022349.7	2.471	Lyα/UV	$(3.48^{+0.70}_{-0.59})\times10^{10}$	$17.8^{+1.0}_{-6.7}$	$(5.54^{+1.05}_{-7.27})\times10^{10}$	–	Radio
DSFG J100016.57+022638.4	2.472	Hα	$(8.82^{+5.45}_{-3.37})\times10^{9}$	714^{+210}_{-162}	$(1.09^{+0.02}_{-0.34})\times10^{11}$	Disk	Radio
DSFG J100056.83+022013.3	2.472	Hα	$(3.71^{+0.69}_{-0.58})\times10^{10}$	196^{+88}_{-61}	$(8.13^{+0.76}_{-0.74})\times10^{10}$	–	–
LBG J095940.95+022522.1	2.472	UV	$(4.28^{+0.74}_{-0.63})\times10^{10}$	$21.5^{+15.5}_{-2.4}$	$(4.95^{+0.83}_{-2.21})\times10^{9}$	–	–

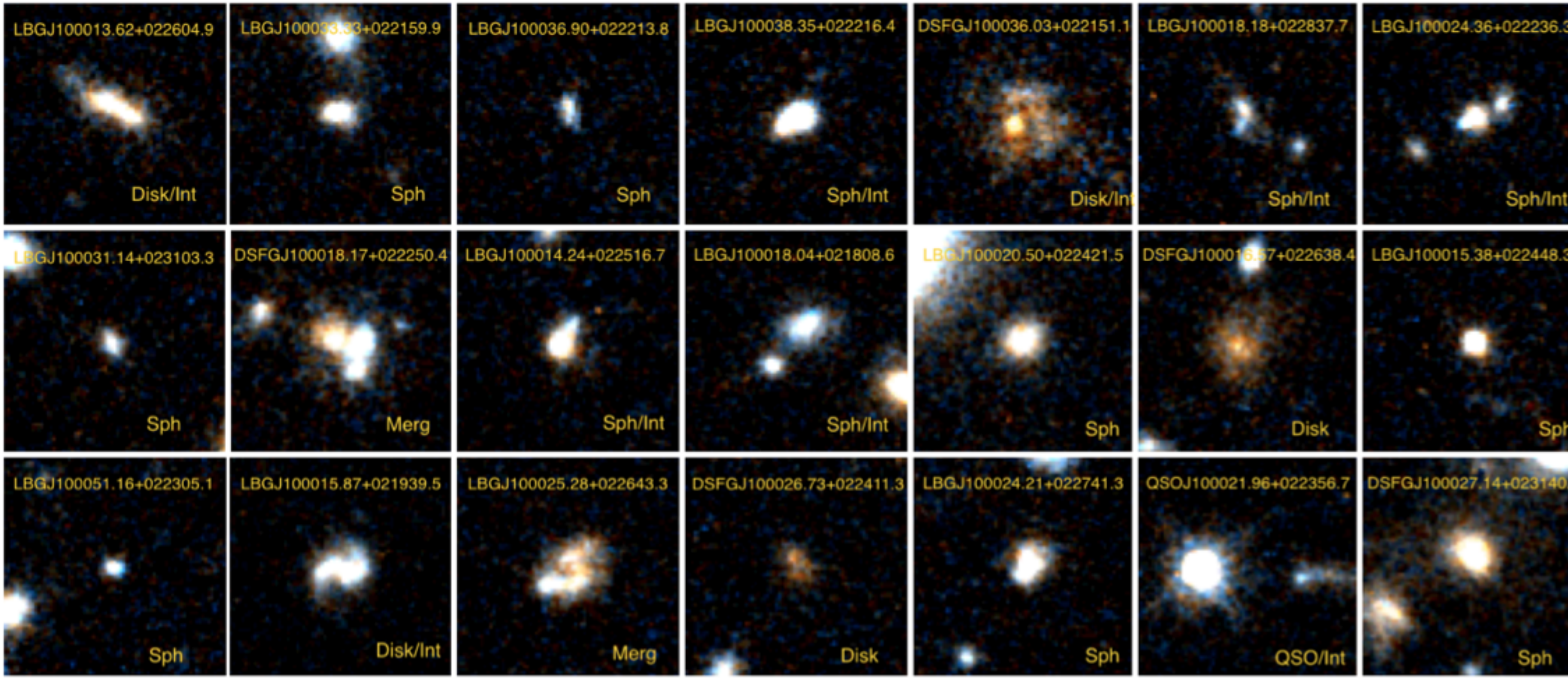

FIG. 3.— 4″×4″ rest-frame optical cutouts for PCL1002 members from *HST*-WFC3. Galaxy names are indicated along with morphological and interaction indicators (see Table 2).

- 10/21 of proto-cluster member galaxies are irregular or undergoing interaction (48±10 %)
- And 7/16 (except DSFG) (44 %)
    - c.f. 5/25 of control shows interaction (20±8 %)

Halo Mass

- Abundance matching techniques from large-volume simulations
- M_{halo} > (8±3)×1e13 Msun at z = 2.47
  - w/ mass-dependent exponential growth : z = 0 halo mass to be (2±1)×1e15 Msun
  - ~ x2 larger than Coma Supercluster (2e15 Msun)
- related notes on DSFG favouring the over dense region
  - Miller+15 argues DSFG are poor tracers of the most massive over-densities at high-redshift (because Poisson noise dominates for low numbers of DSFGs)
  - rather, it is simply due to insufficient number of spectroscopically confirmed DSFGs around SB-enriched and AGN-enriched protoclusters
  - one more thing is to investigate LBG in large scale is very challenging
  - anyhow, it is already found four protocluster with DSFG, it is promising

Discussion and conclusions

- Overdense with AGN and DSFG is a rare phenomenon, given their short duration ~100 Myr
- LBG is also over dense

- Reason?
  - hypothesis 1 : DSFG and AGN are short-lived and triggered simultaneously via a process related to the over-dense environment
  - hypothesis 2 : DSFGs and AGN must be longer lived than expected

- hypothesis 1 is more likely…because
  - increased interaction
  - larger ISM mass (albeit a marginal distinction)
  - lack of physical motivation for long QSO lifetimes

What we need for now

- large and deep > 100 deg2 SMG survey is crucial
- spectroscopic follow-up at z>2
- potential future large mm line searches targeting CO or [CII]

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- with ALMA (high resolution)
  - SFR and ISM mass will differ?

- SED fitting
- compare with simulation
- metallicity