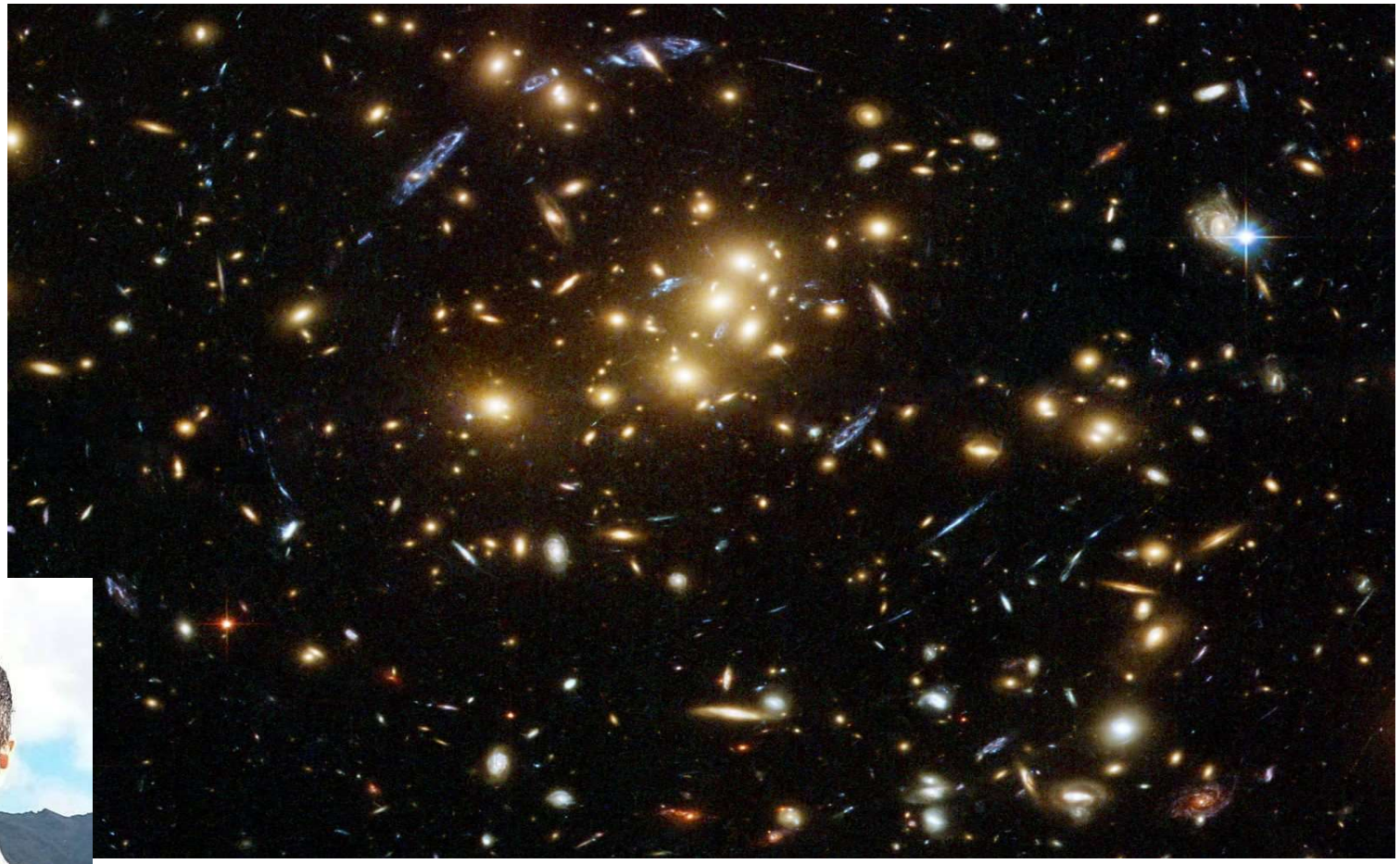
Multi-Wavelength Observations of Candidate Starbursting Protoclusters Selected by *Planck* and *Herschel*



A1689 (Local cluster, with red galaxies, ellipticals) Credit: http://www.wolaver.org/space/CL0024+17.jpg

Imperial College London

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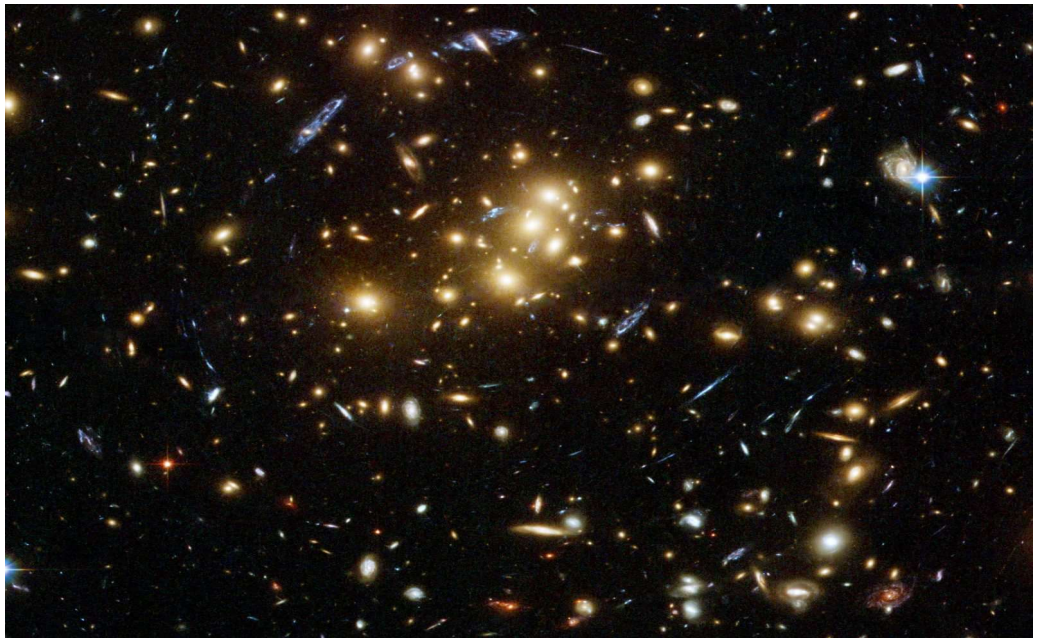
Outline

- Introduction & background:
- Cluster detection methods
- Protoclusters
- Submillimeter galaxies (SMGs), dusty star-forming galaxies (DSFGs)
- Protoclusters with DSFGs
- *Planck* + *Herschel* selected protocluster candidates

- Follow-up observations:
- Submm: SCUBA-2
- Radio: ATCA
- Radio: VLA
- Optical/Near-Infrared: WHT

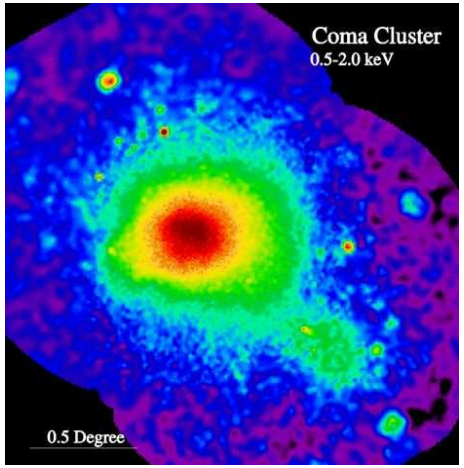
Local galaxy clusters are…



Credit: http://www.wolaver.org/space/CL0024+17.jpg

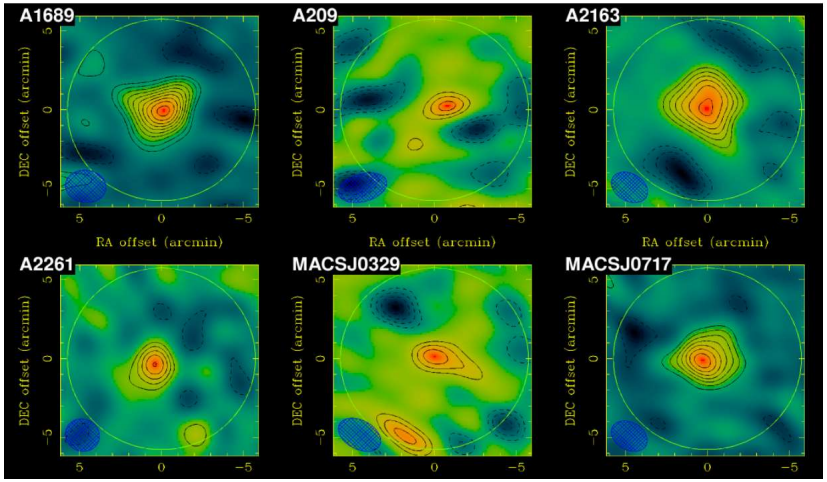
- Virialized
- Massive
- Having elliptical galaxies in the centers

X-ray



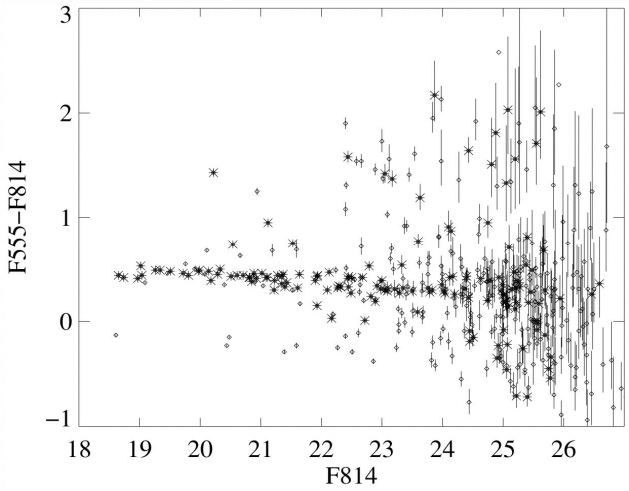
Credit: http://www.solstation.com/x-objects/coma-sc.htm

SZ Effect



Credit: Lin et al. (2016)

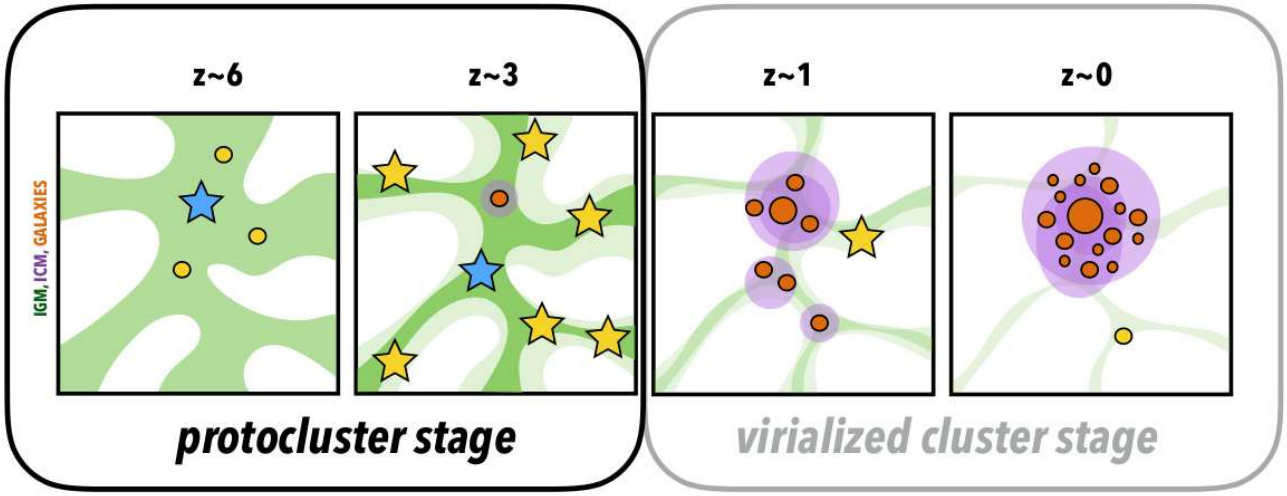
Red Sequence



Credit: Gladders & Yee (2000)

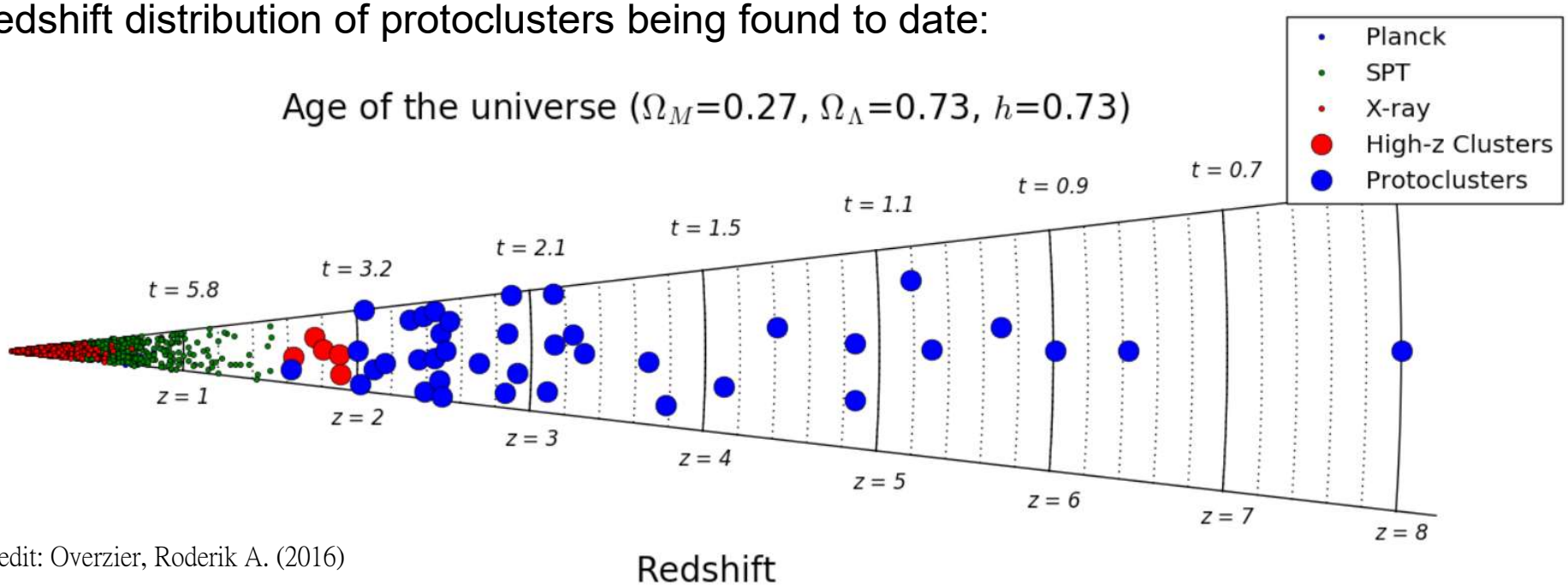
If we go to z>1.5 galaxy clusters…

- Hot gas not virialized
- Not collapsed
- Distributed in larger physical scales
- "Protoclusters"



From slide of Casey et al. (2017): http://www.astro.dur.ac.uk/SMG20/

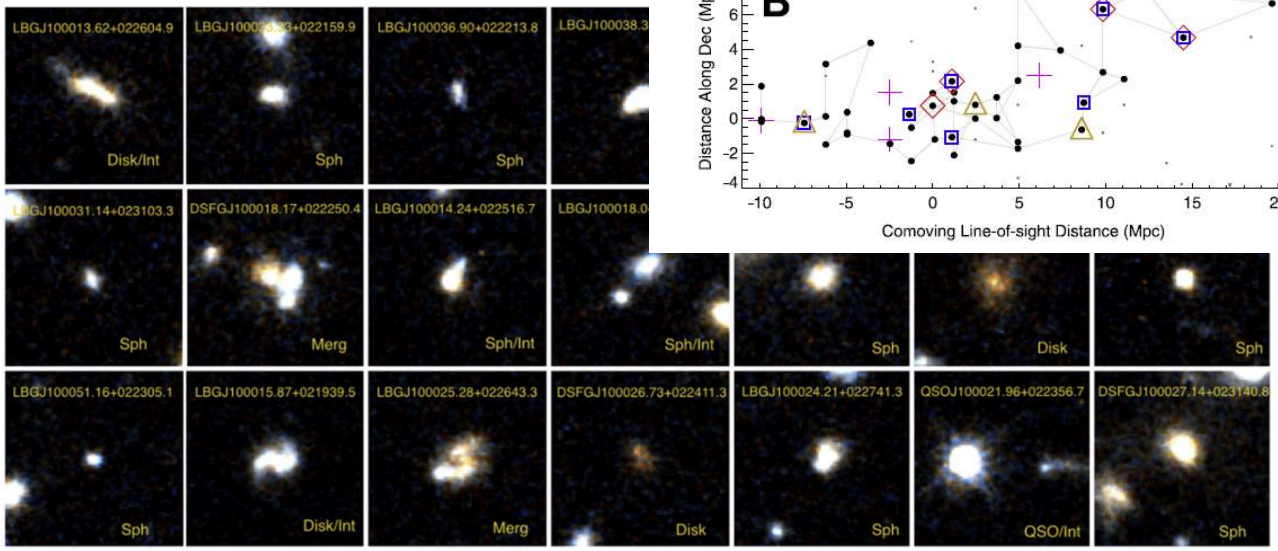
Redshift distribution of protoclusters being found to date:

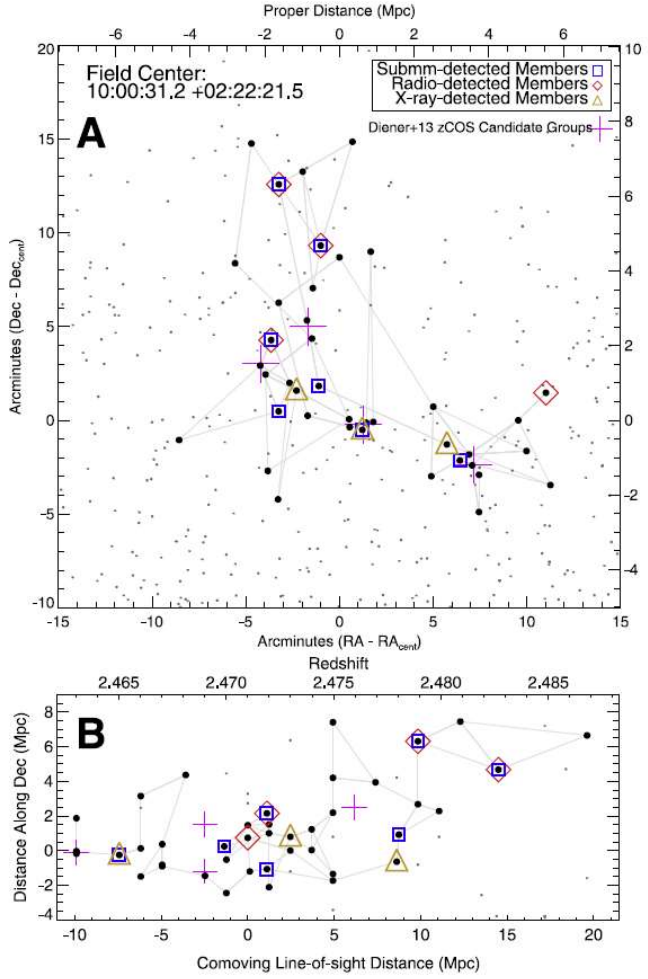


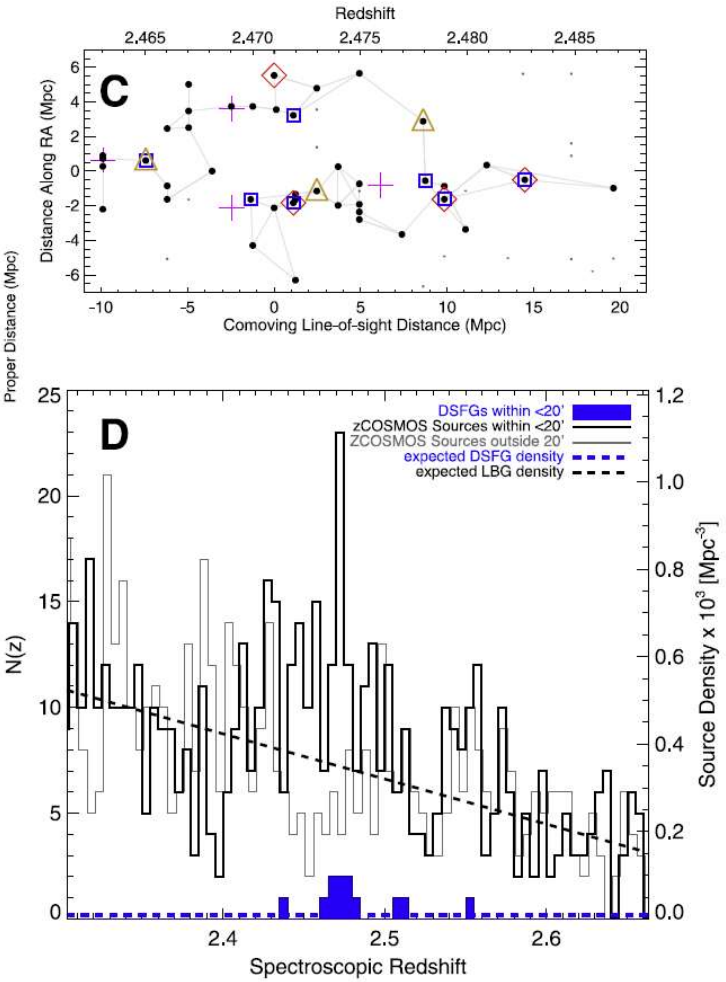
Credit: Overzier, Roderik A. (2016)

Protocluster detection methods

- Overdensities of....
- Lyman-alpha emitters (LAEs)
- Lyman-break galaxies (LBGs)
- H-alpha emitters (HAEs)
- Optical/NIR surveys (HSC-SSP)



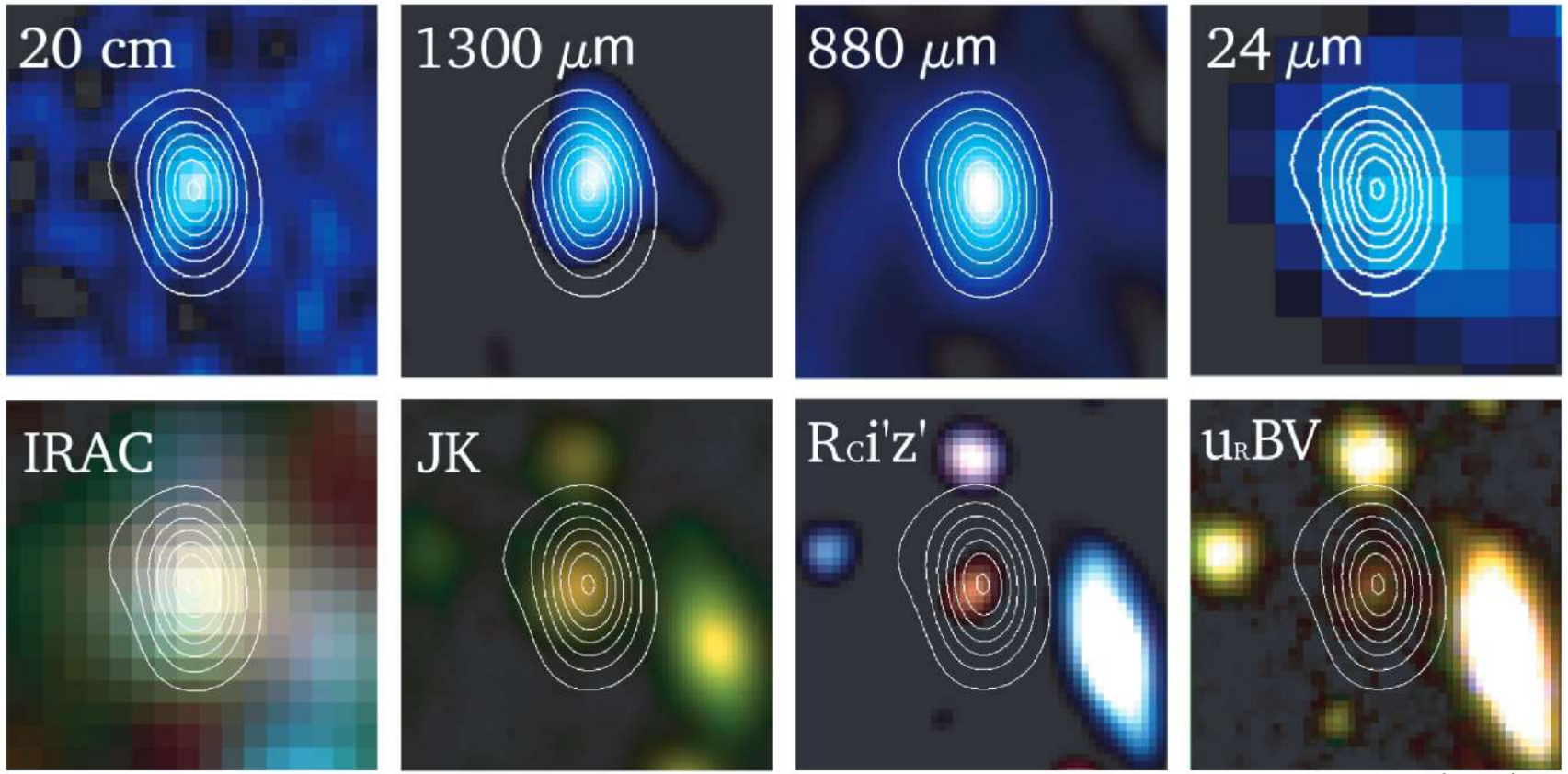




Casey et al. (2015): PCL1002, z=2.47

Submillimeter Galaxies (SMGs)

- Found by submm surveys, z>2
- Bright in submm/FIR
- Dusty, obscured
- Starbursting, forming majority of stellar mass
- "Dusty star-forming galaxies" (DSFGs)

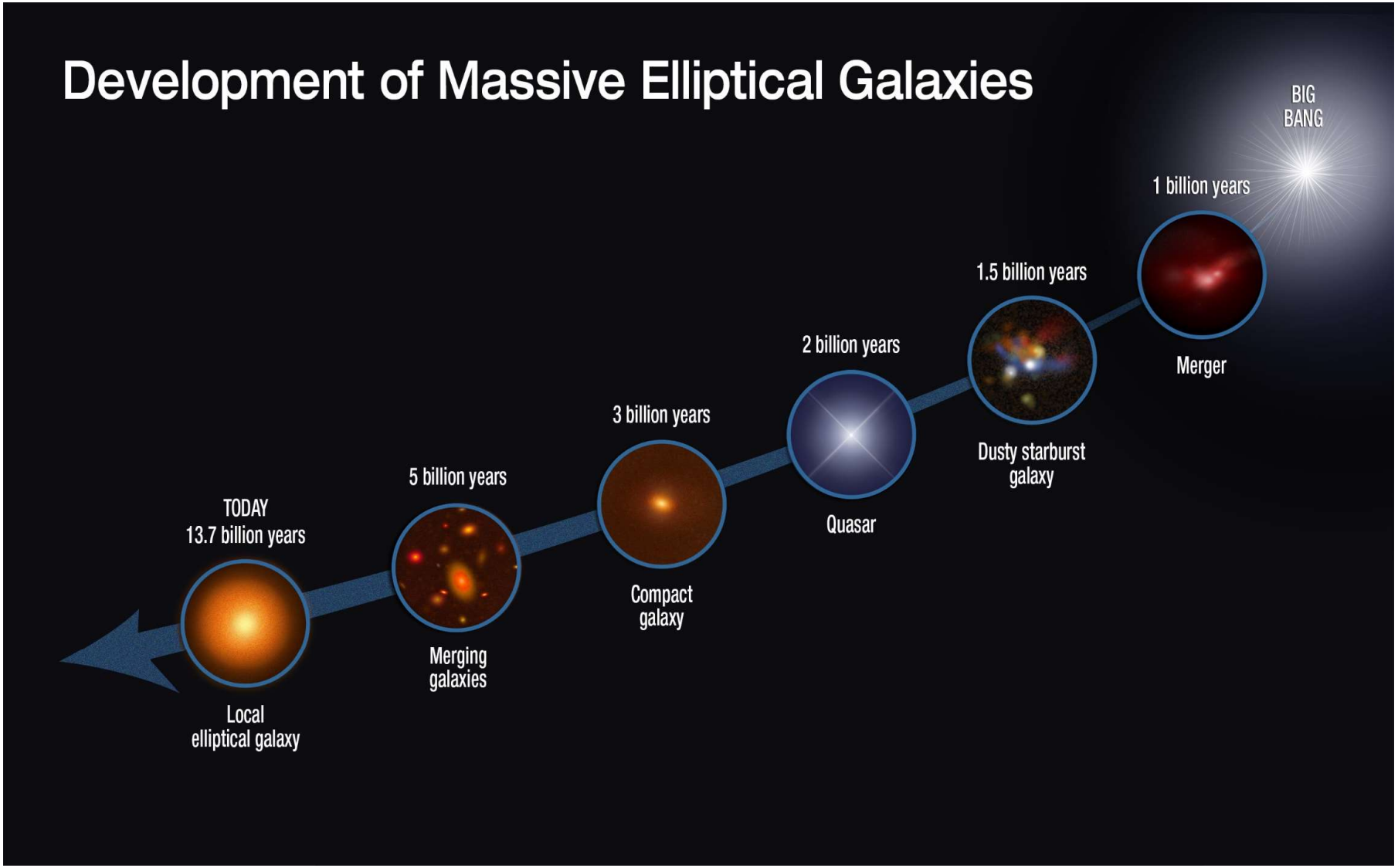


SXDF1100.001, or Orochi

Ikarashi et al. (2011)

Progenitors of massive elliptical galaxies?

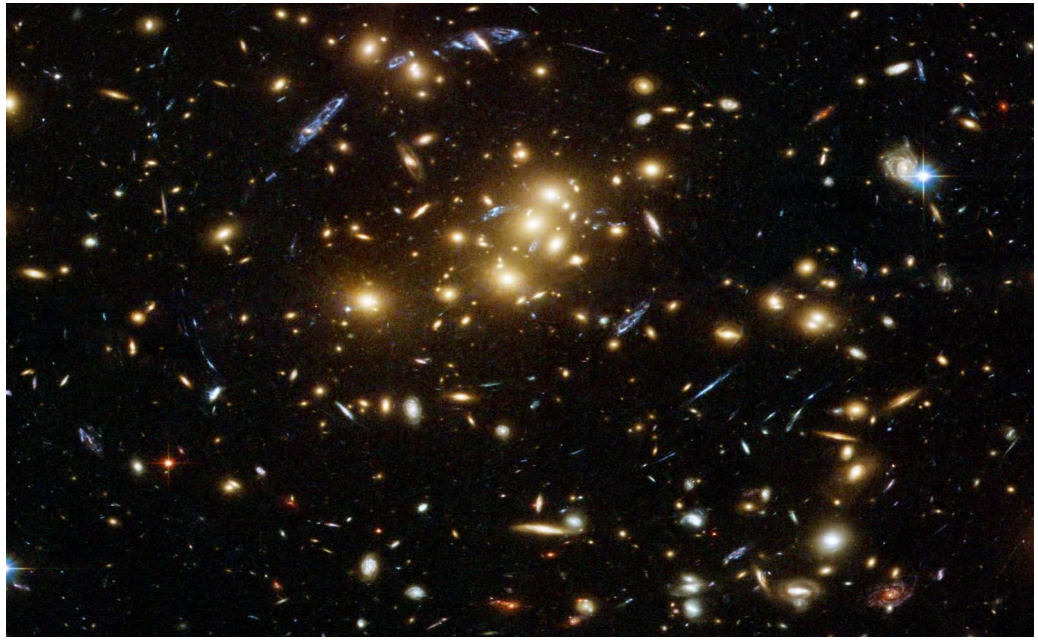
- Galaxy formation models



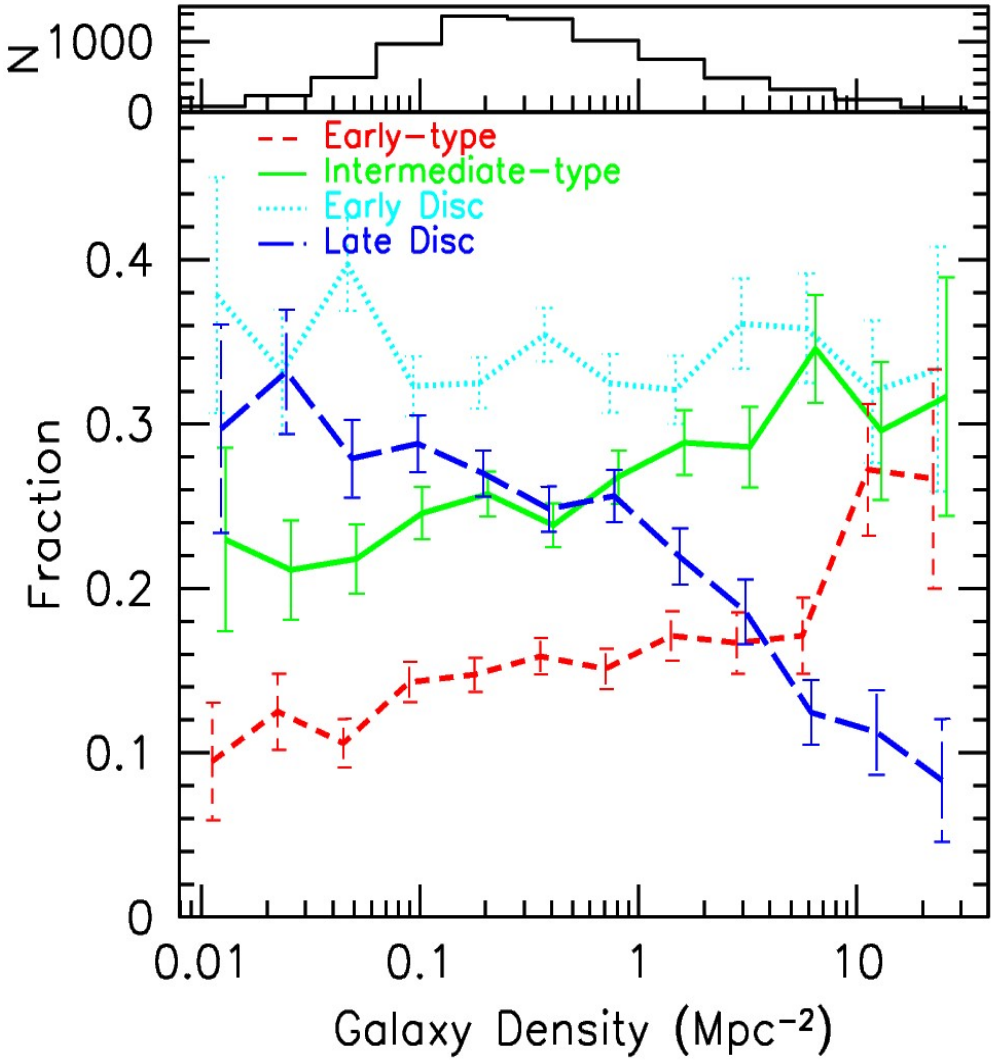
Credit: https://www.jpl.nasa.gov/news/news.php?feature=4028

Progenitors of massive elliptical galaxies in local cluster cores?

Morphology-Density relation



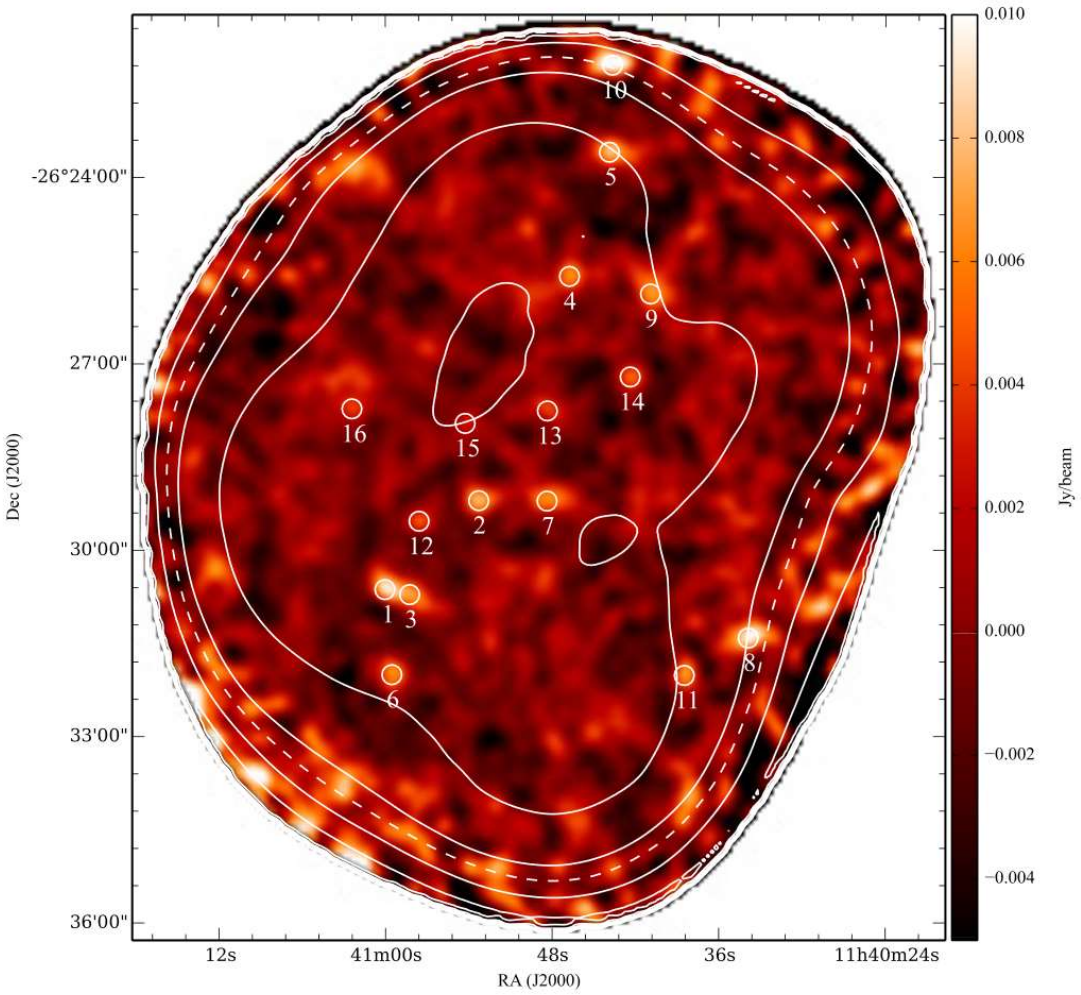
Credit: http://www.wolaver.org/space/CL0024+17.jpg



Credit: Goto et al. (2003)

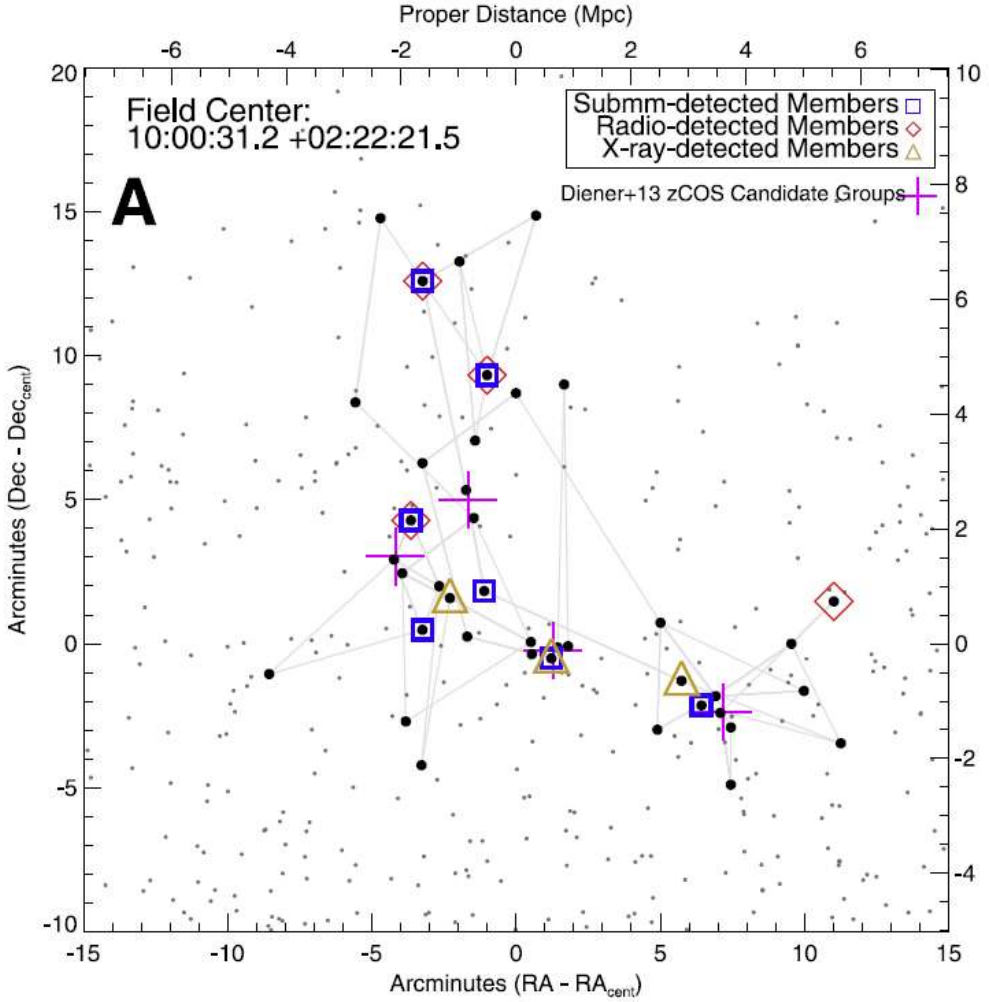
Protoclusters with dusty star-forming galaxies (DSFGs)

MRC1138-262, or Spiderweb Galaxy, z=2.16



Dannerbauer et al. (2014)

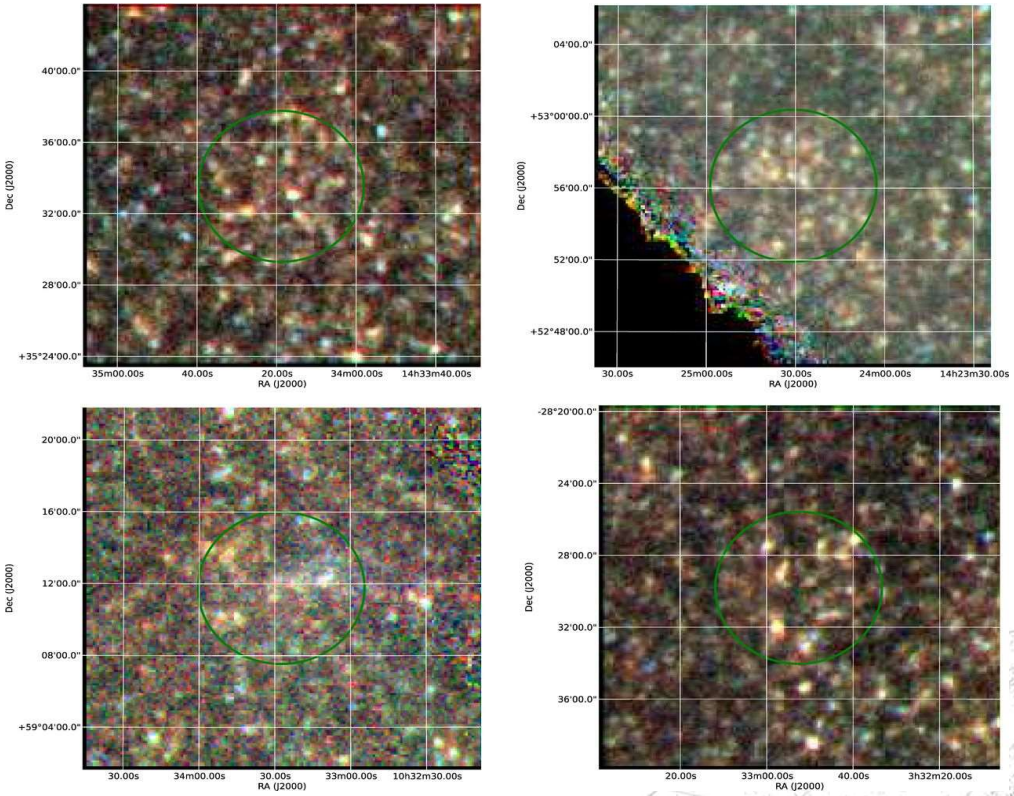
PCL1002, z=2.47



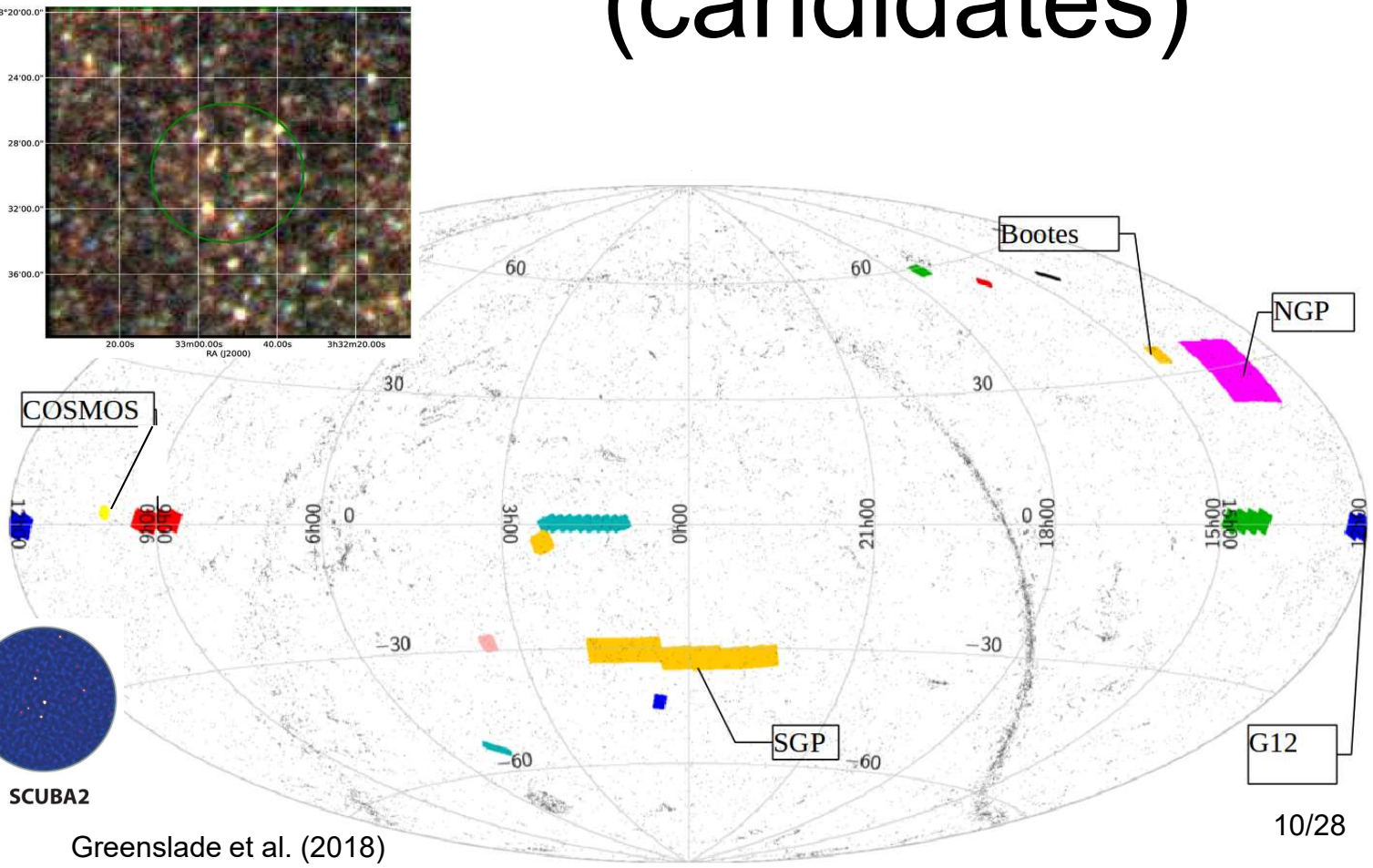
Casey et al. (2015)

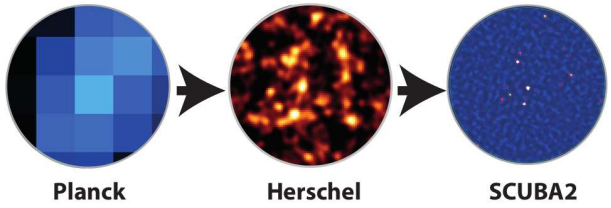
~30 candidates to confirm

Planck + *Herschel* selected protoclusters (candidates)



Clements et al. (2014)

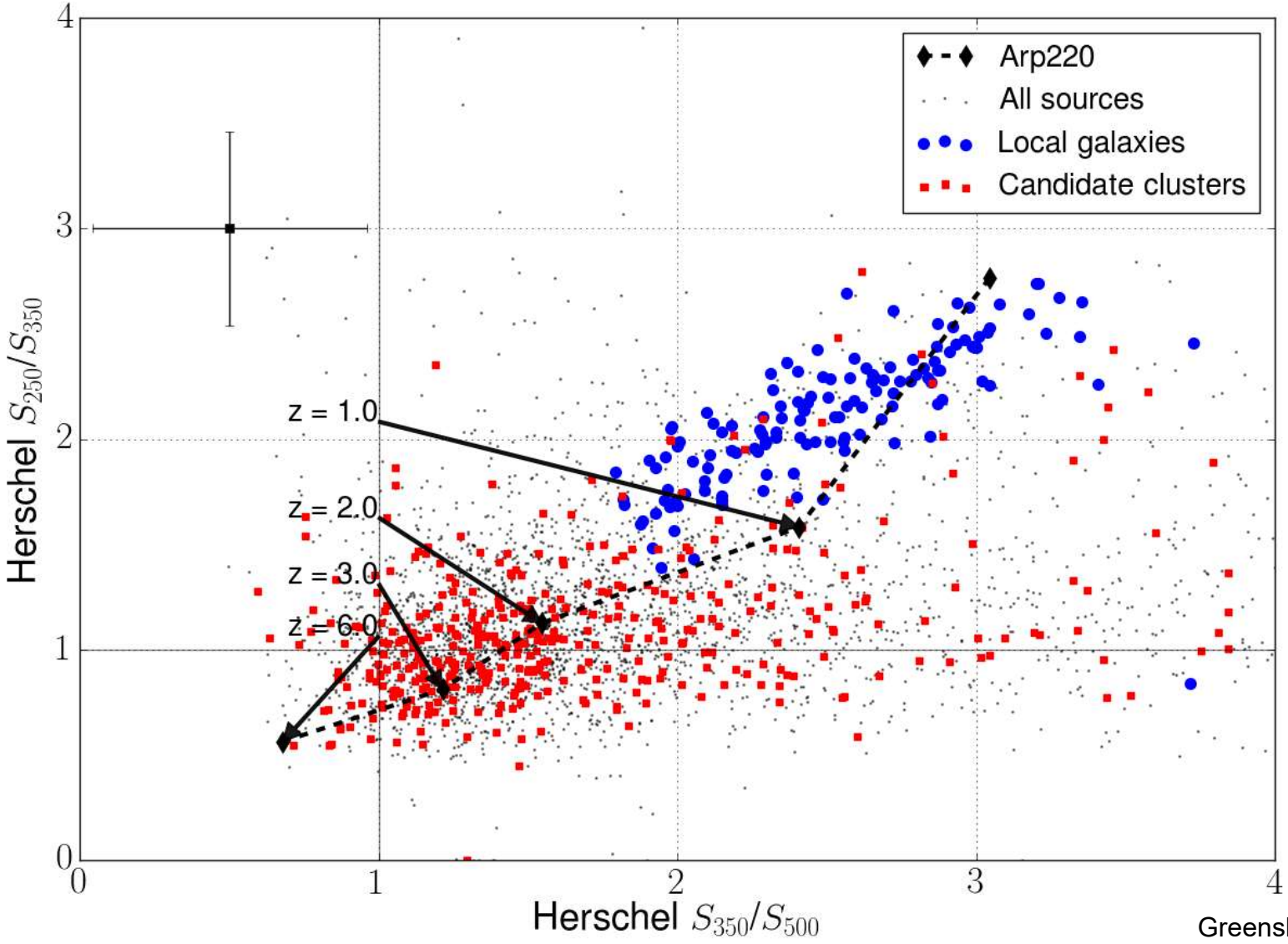




Greenslade et al. (2018)

Planck + *Herschel* selected protoclusters (candidates)

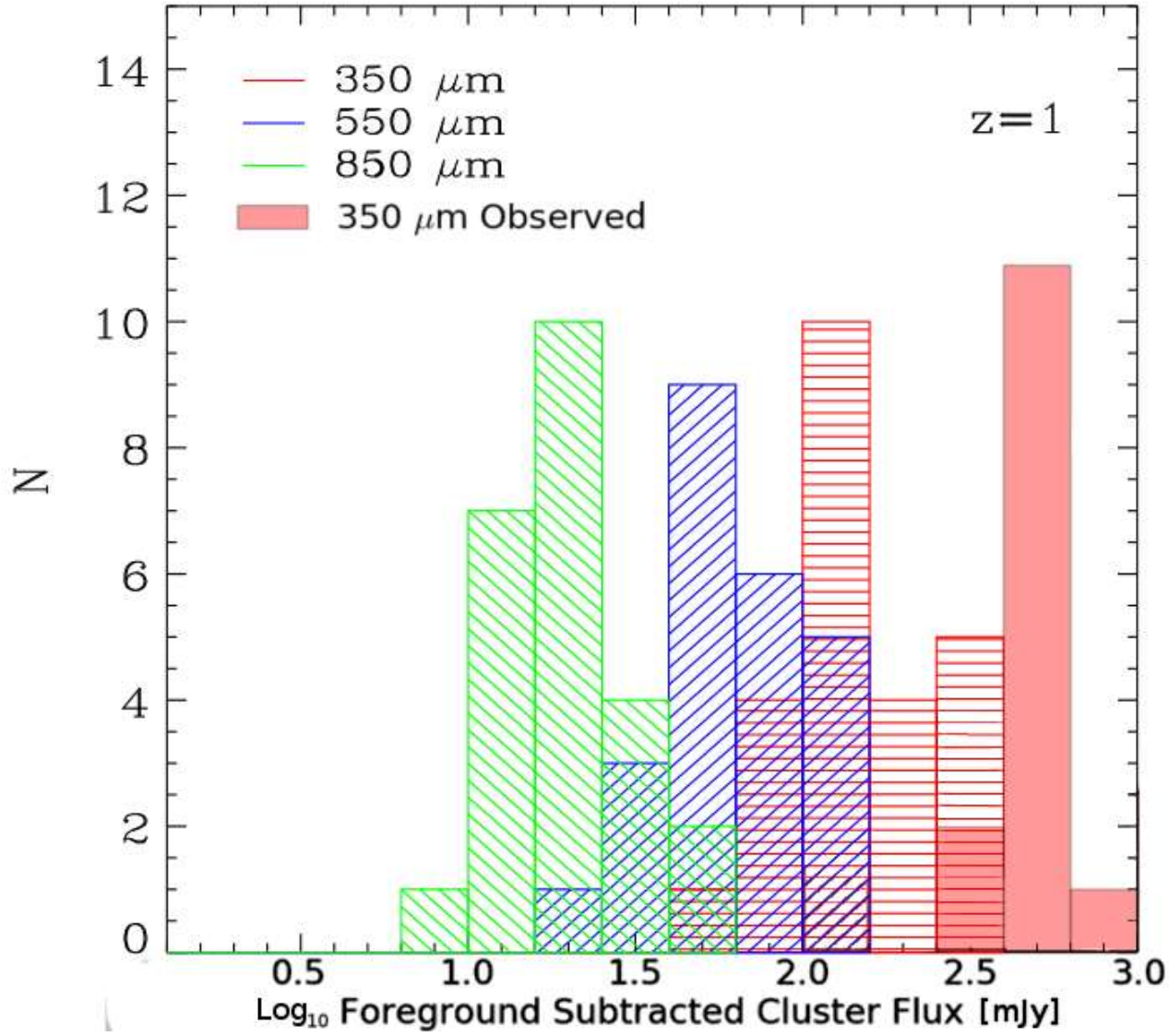
Herschel colors



Greenslade et al. (2018)

Planck + *Herschel* selected protoclusters (candidates)

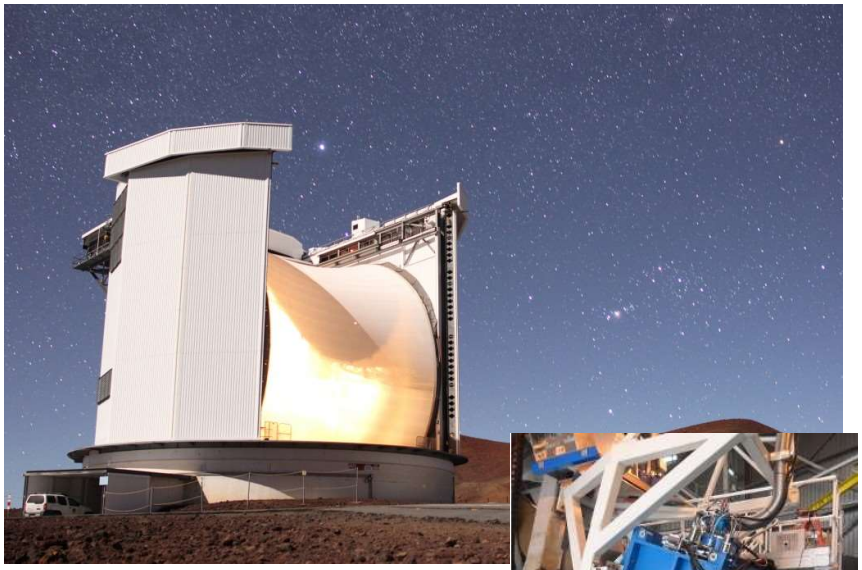
Discrepancies between models!?



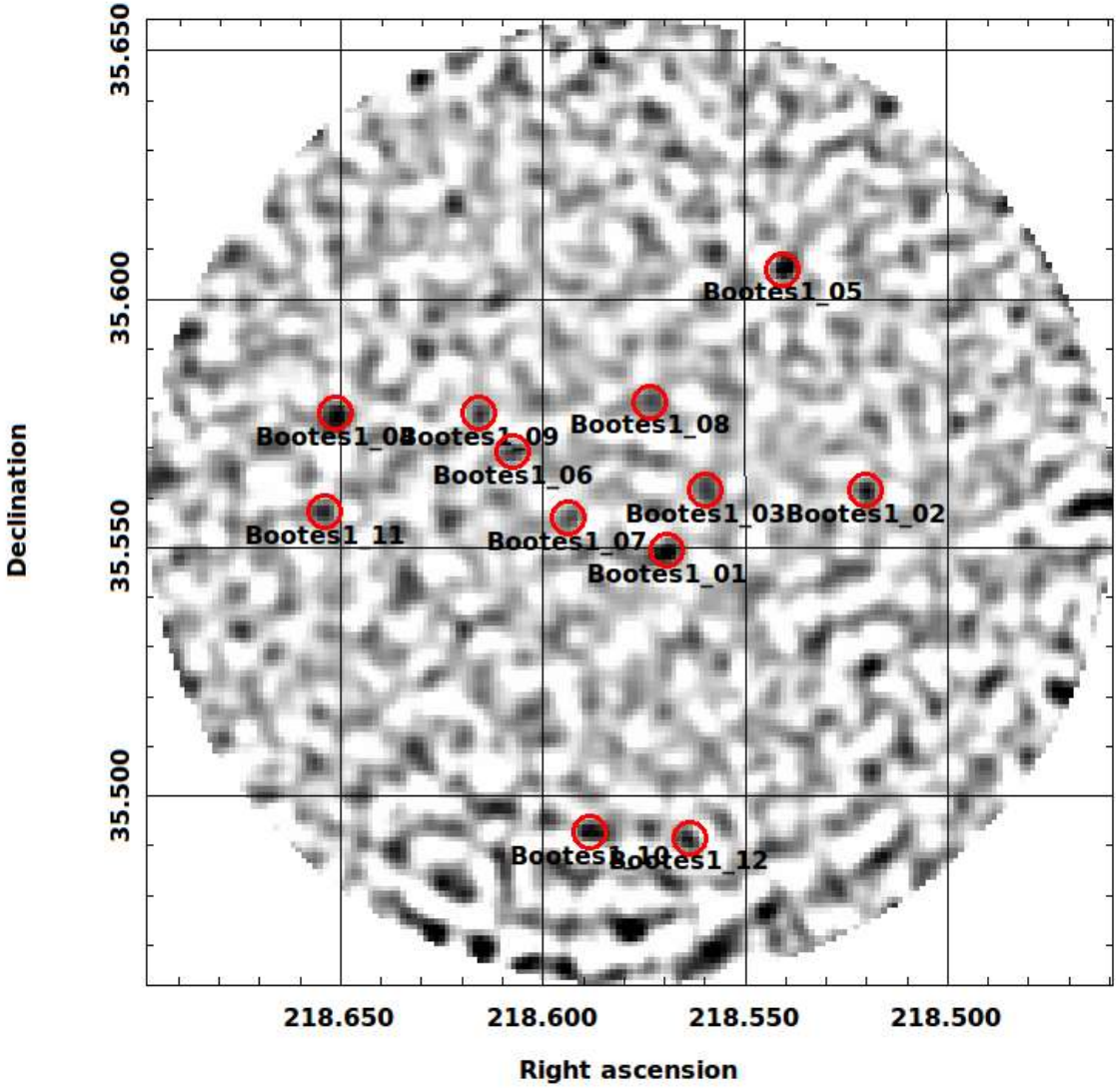
Greenslade et al. (2018)

SCUBA-2 Follow-up

- 13 candidate protoclusters
- 850 micron



JCMT & SCUBA-2:
http://www.eaobservatory.org/jcmt/

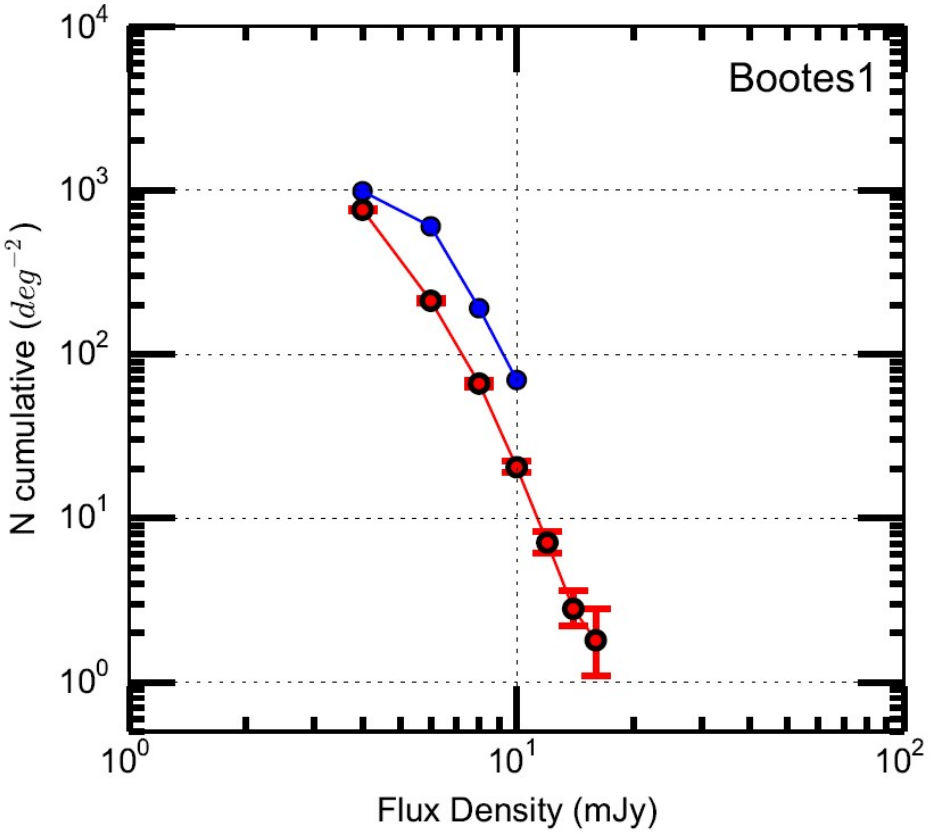


Bootes1

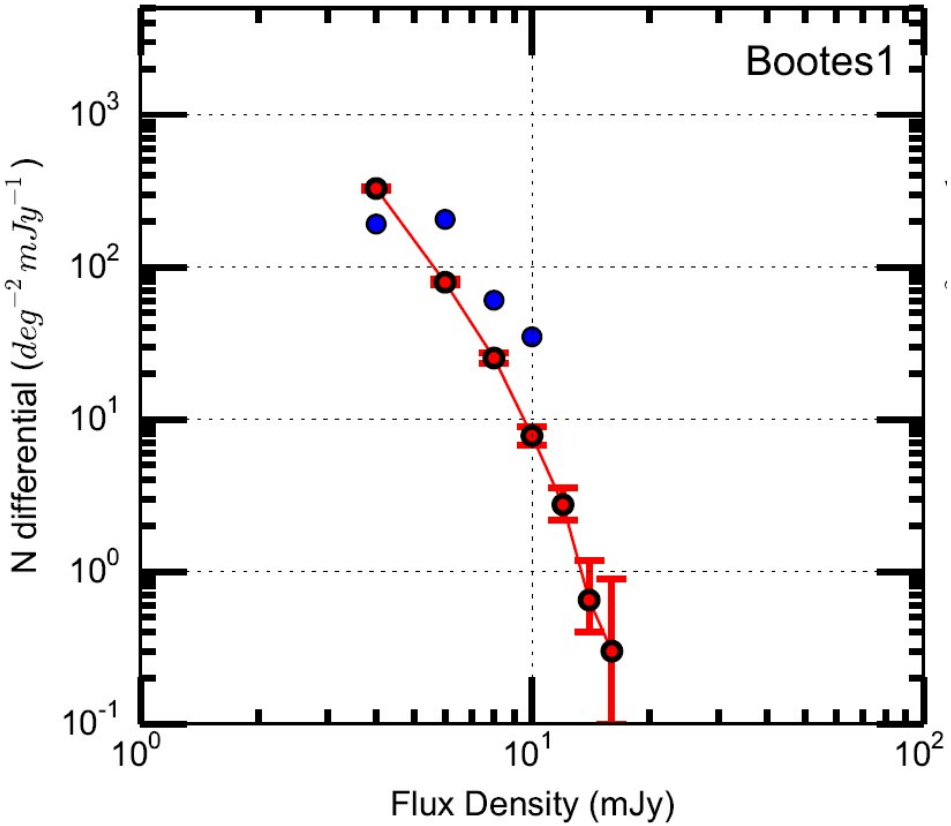
Cheng et al. (in prep)

SCUBA-2 Follow-up

Cumulative number counts



Differential number counts

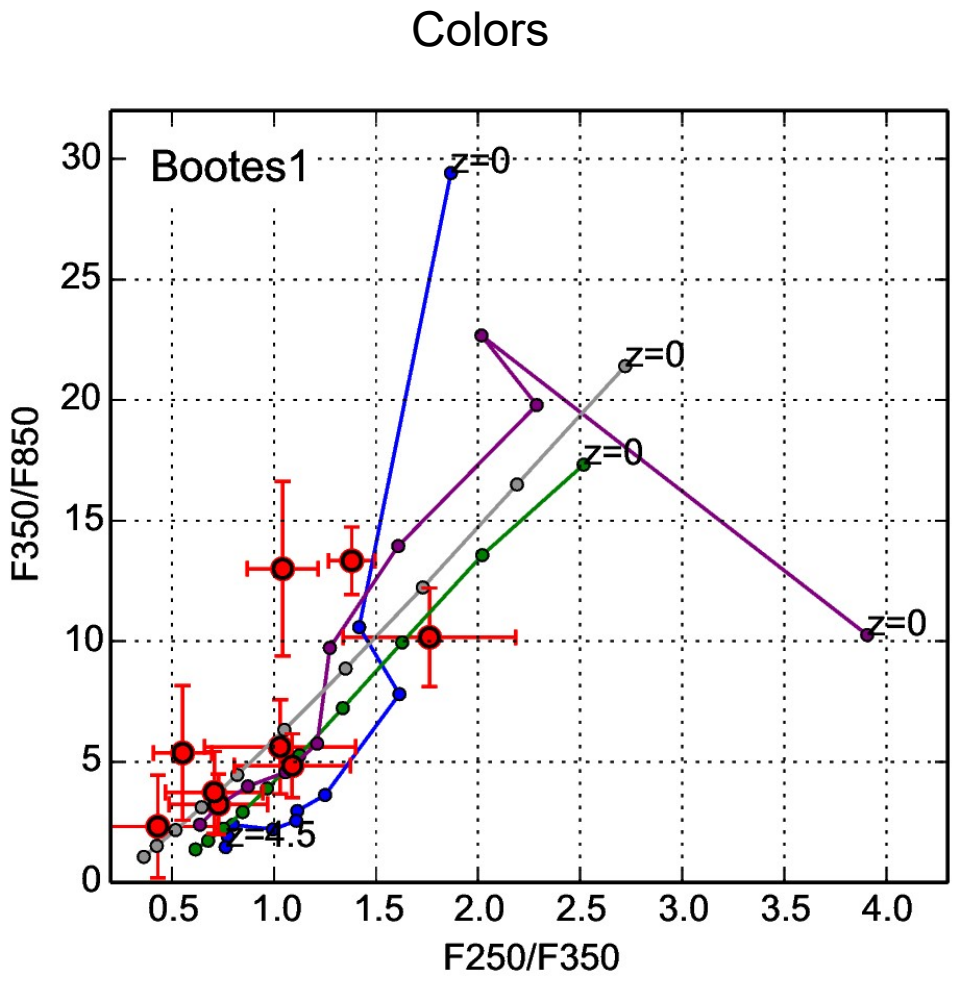


Cheng et al. (in prep)

- Blue: Planck-Herschel protoclusters
- Red: Geach et al. (2017) (field)

SCUBA-2 Follow-up

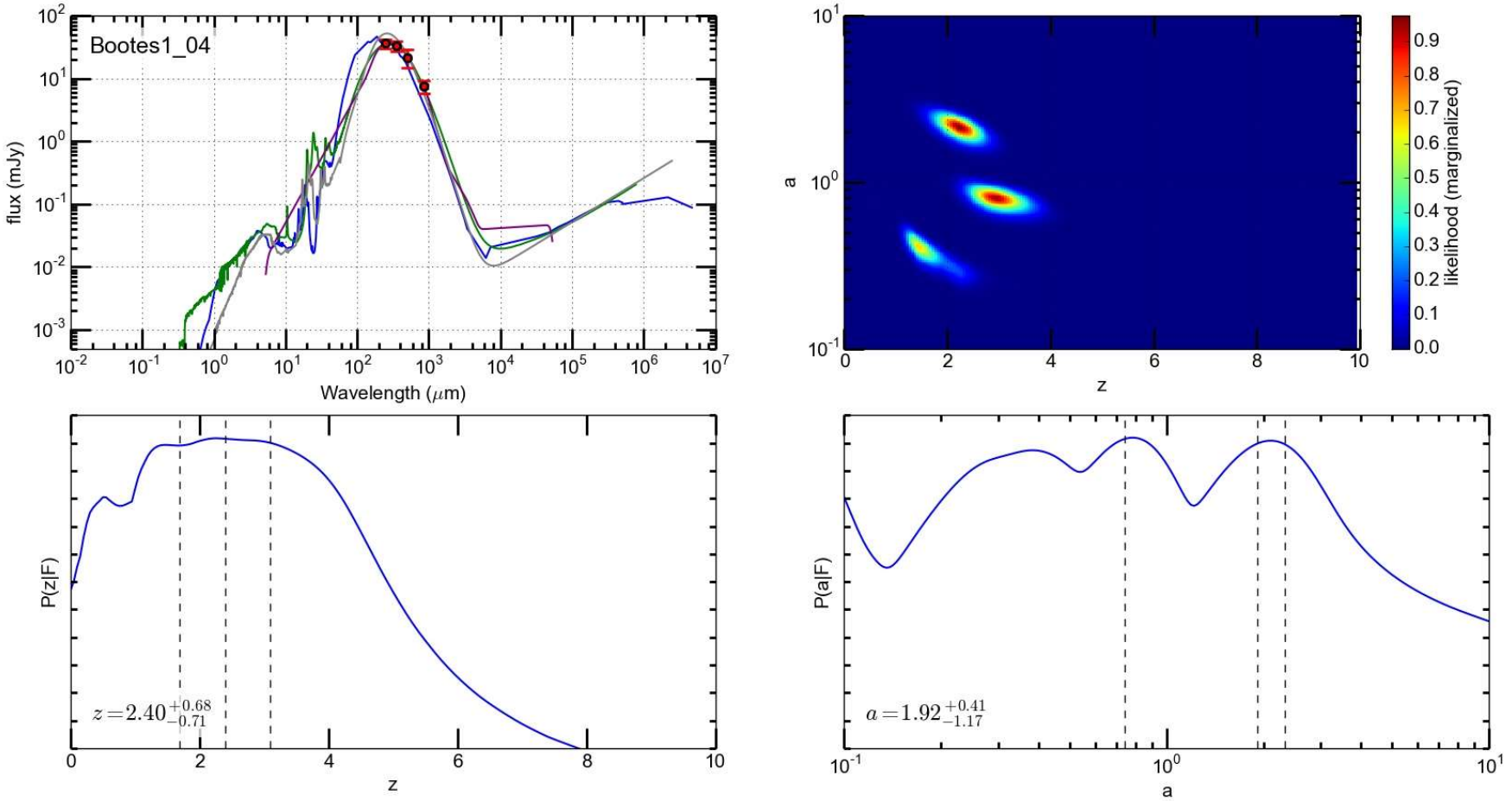
•Cross-match with *Herschel* catalogues/maps



Cheng et al. (in prep)

SCUBA-2 Follow-up

Photometric redshits

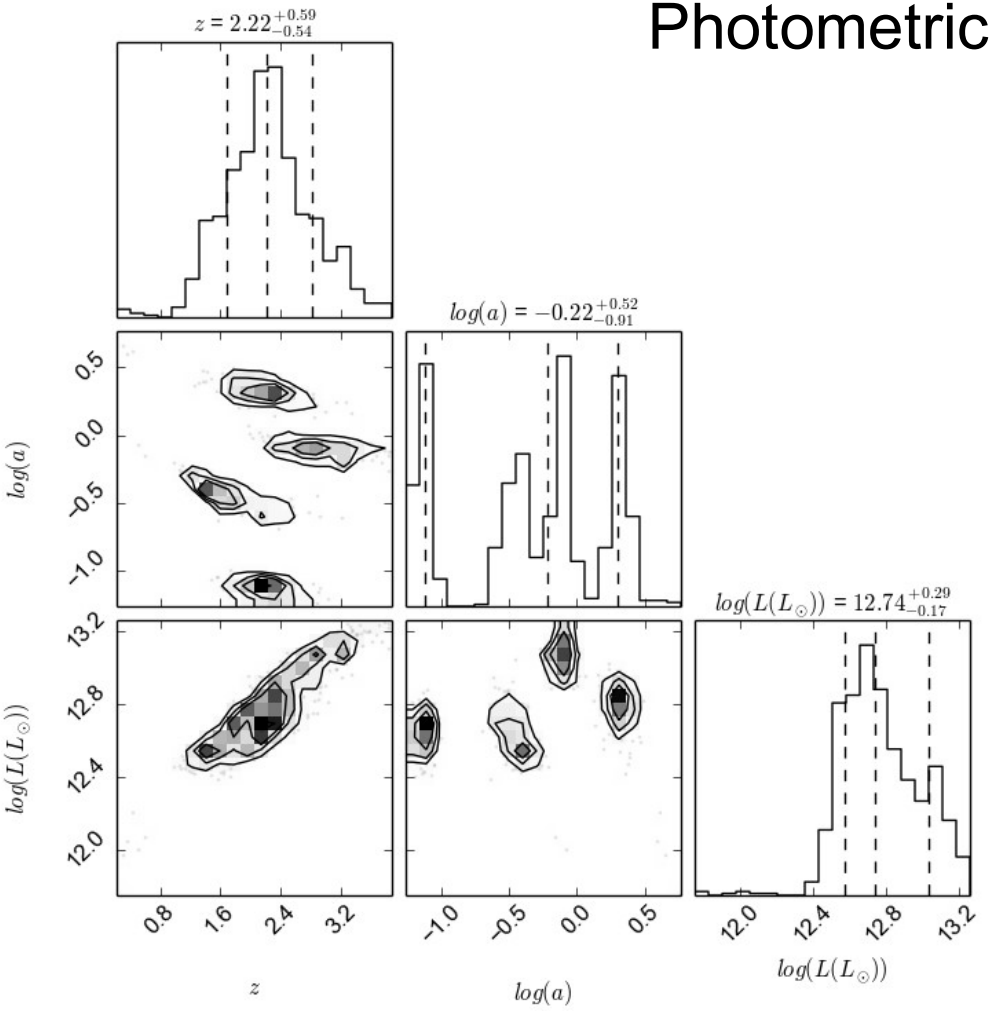


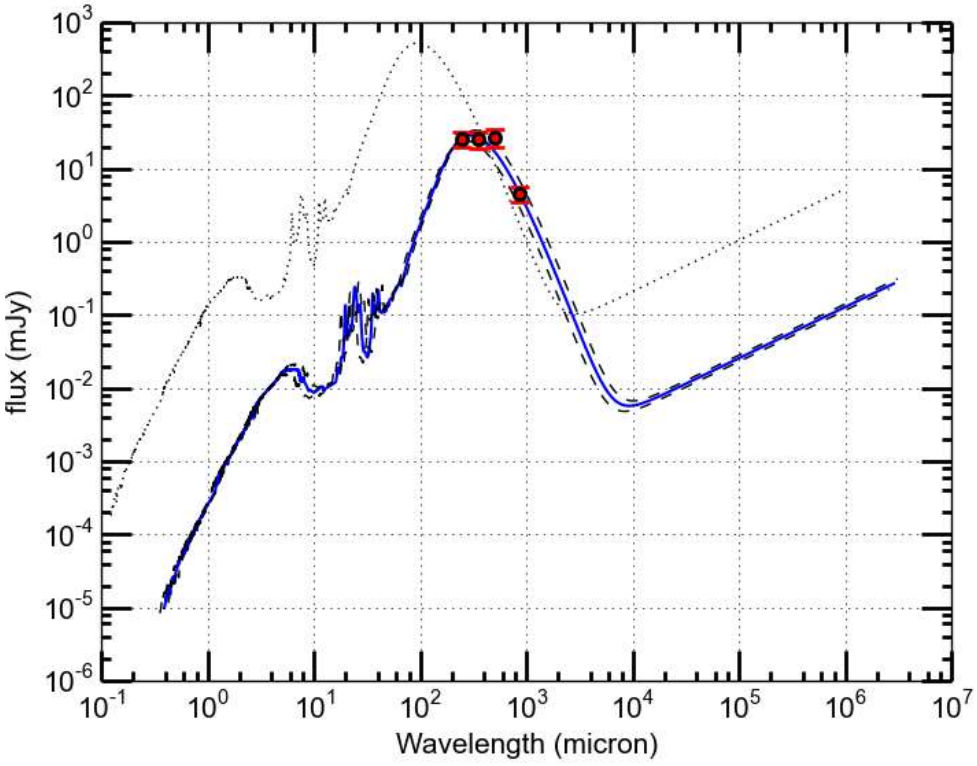
Cheng et al. (in prep)

- 250, 350, 500, 850 micron flux densities
- Chi-squared minimization
- Four DSFG template SEDs with various dust temperatures
- Redshift-Temperature degeneracy

SCUBA-2 Follow-up

Photometric redshits: MCMC

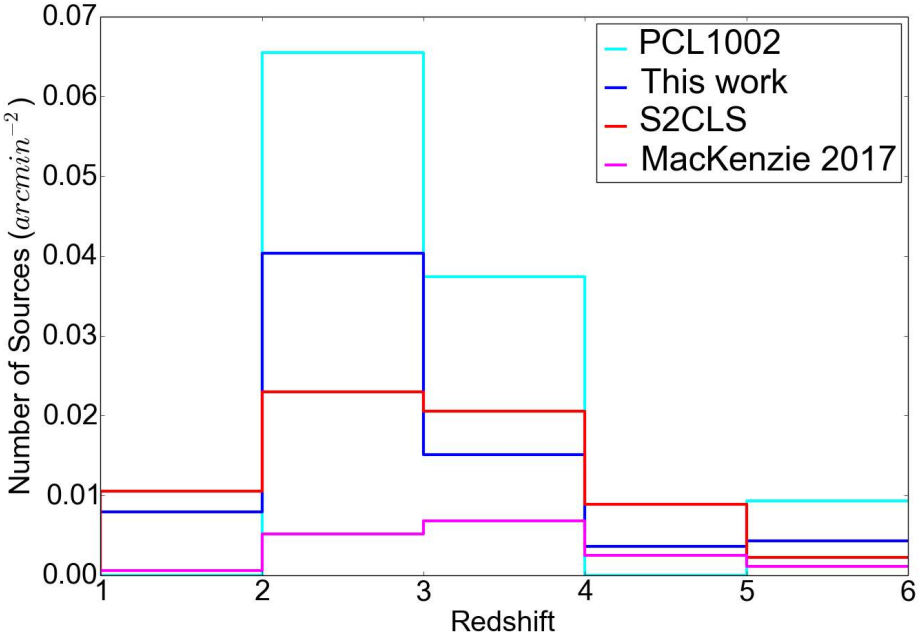


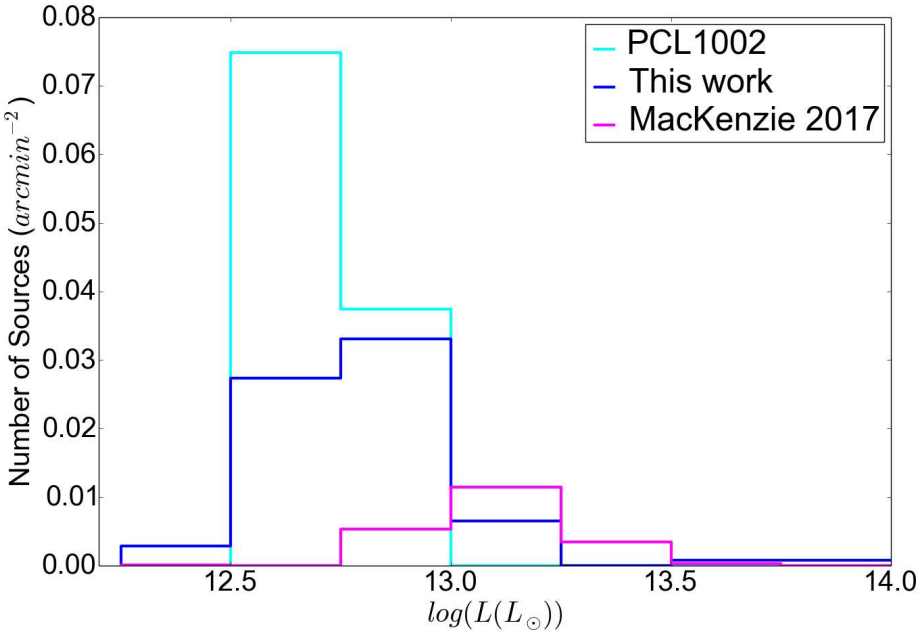


Cheng et al. (in prep)

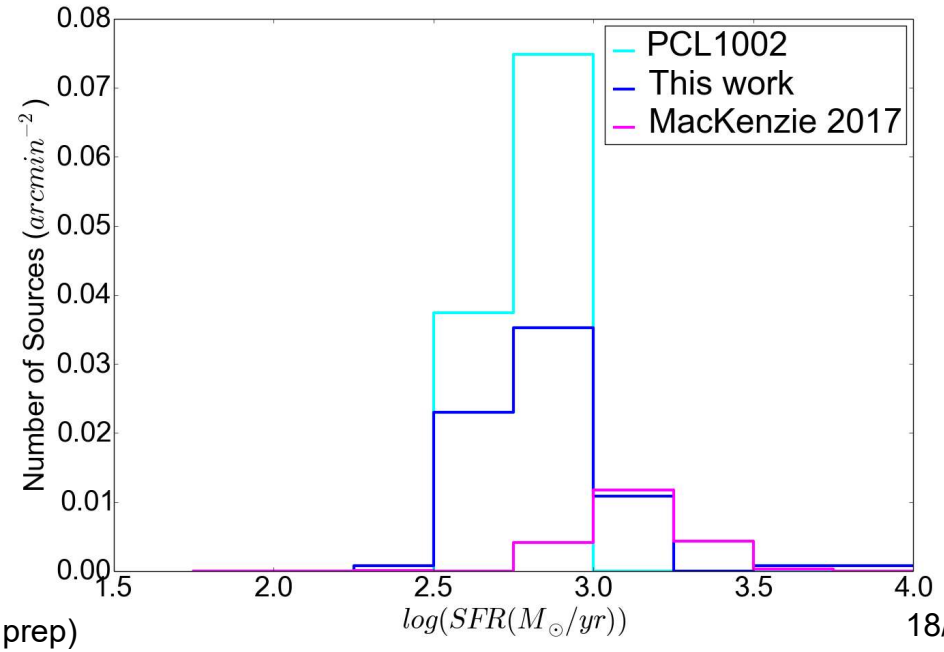
- Marginalized over the templates

SCUBA-2 Follow-up





- IR luminosity calculated from 8-1000 micron
- SFR calculated assuming linear relation with IR luminosity (Kennicutt 1998)



Cheng et al. (in prep)

SCUBA-2 Follow-up

•Compare with Greenslade et al. (2018), who studies Herschel-SPIRE overdensities (250-500 micron)

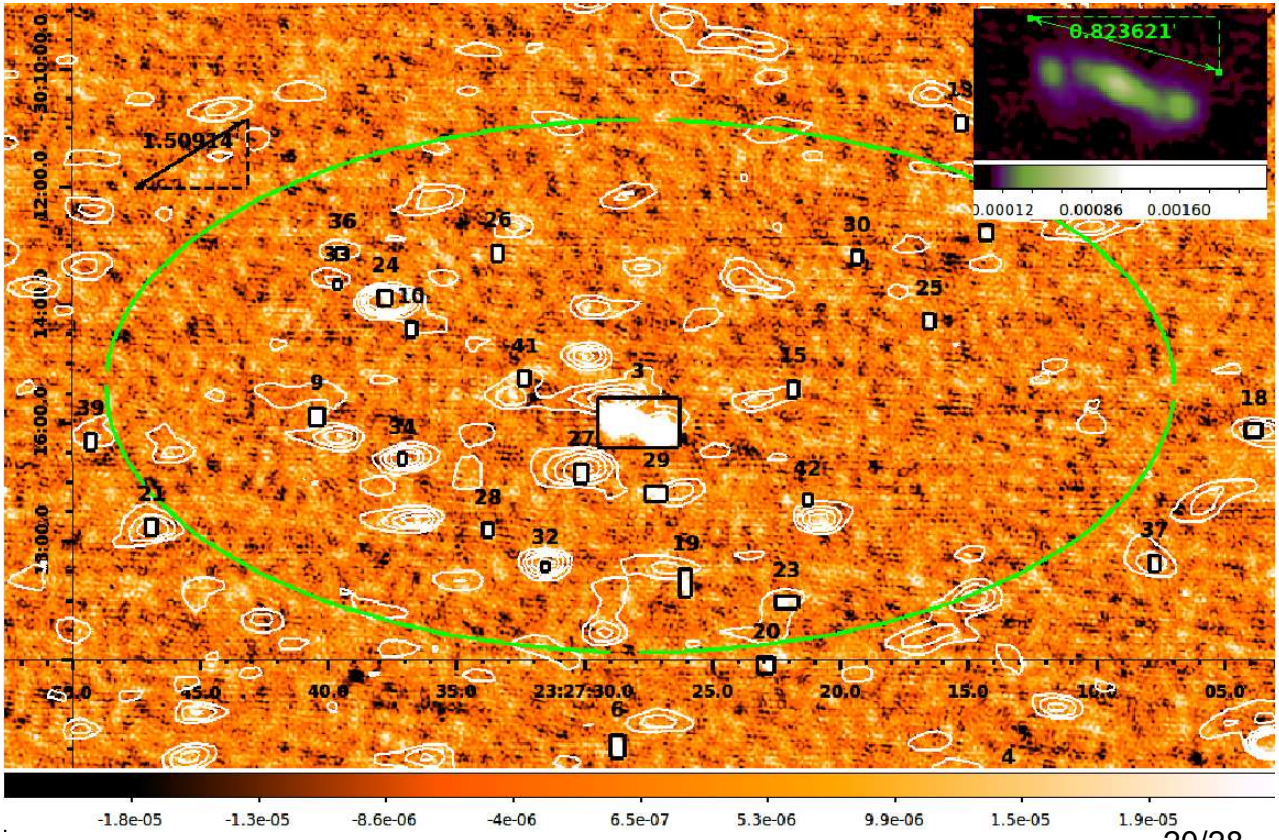
Number of candidate protoclusters	**Having overdensities at 250-500 micron (Greenslade et al. 2018)**	**Not having overdensities at 250-500 micron (Greenslade et al. 2018)**
Having overdensities at 850 micron	6 (High-z (z>2) protoclusters)	3 (high-z (z>2) protoclusters with lensed DSFGs or rich with 850-micron sources)
Not having overdensities at 850 micron	1 (low-z (z<2) cluster/prototcluster)	3 (not protoclusters, or are protoclusters but sources are not sensitive to *Herschel* or SCUBA-2)

ATCA Follow-up

- 4-cm, 2 candidate protoclusters
- Radio observations: localize the FIR source
- FIR-radio correlation
- Multiplicity & morphology
- Look for AGNs (in cluster environments)

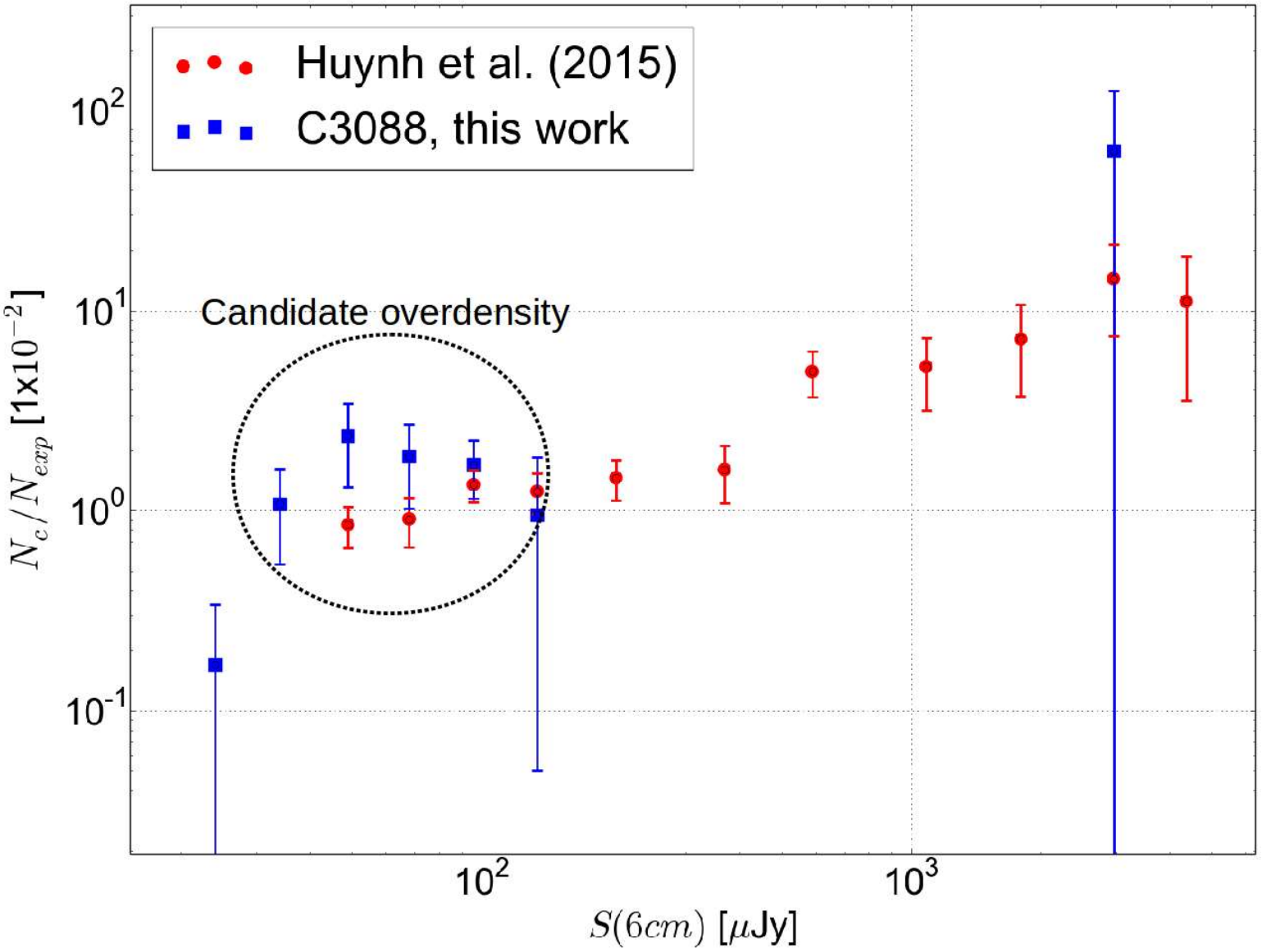
Australia Telecope Compact Array

Credit: http://www.narrabri.atnf.csiro.au/public/



ATCA Follow-up

Differential number counts



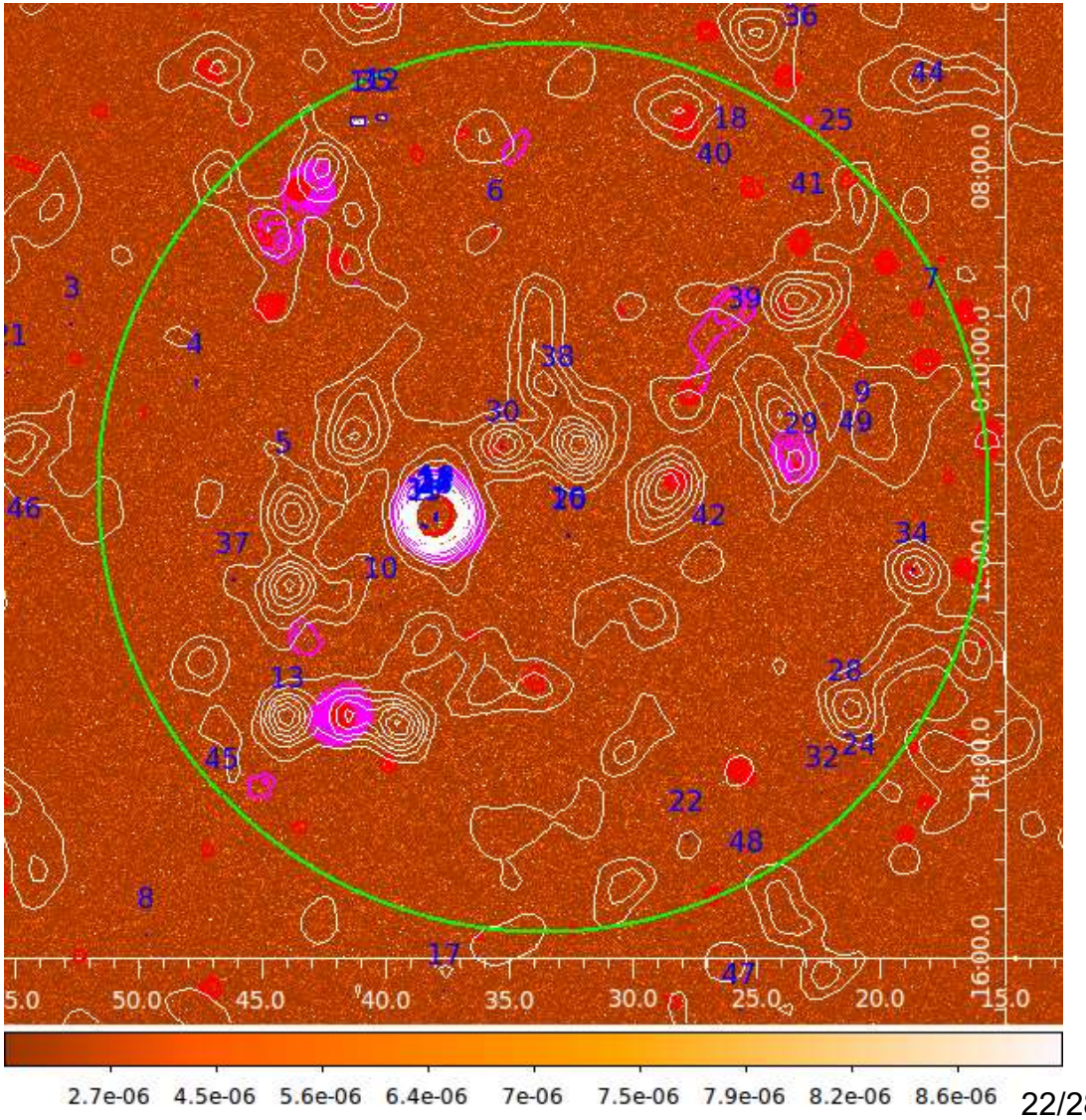
VLA Follow-up

- 4-cm, 9 candidate protoclusters

Very Large Array

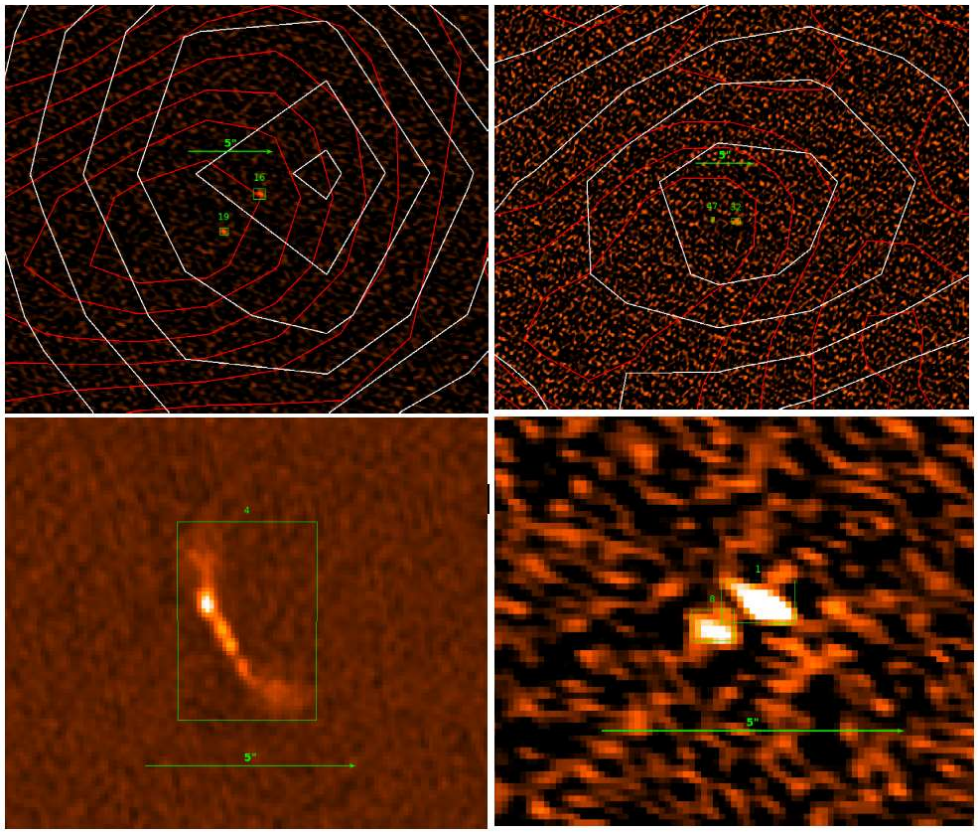
Credit: https://www.nrao.edu/pr/2000/vla20/background/vlafacts/

G12

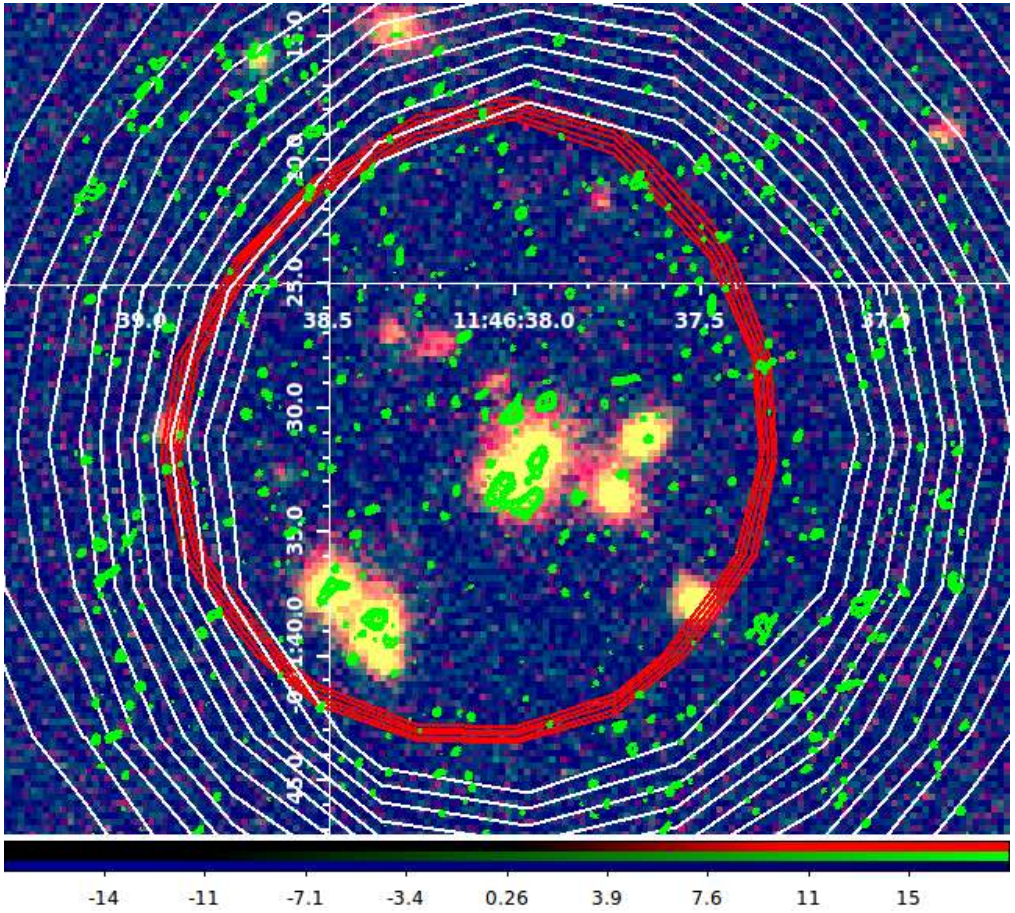


VLA Follow-up

- Left: Study multiplicities & morphologies
- Right: Cross-match with optical/NIR sources

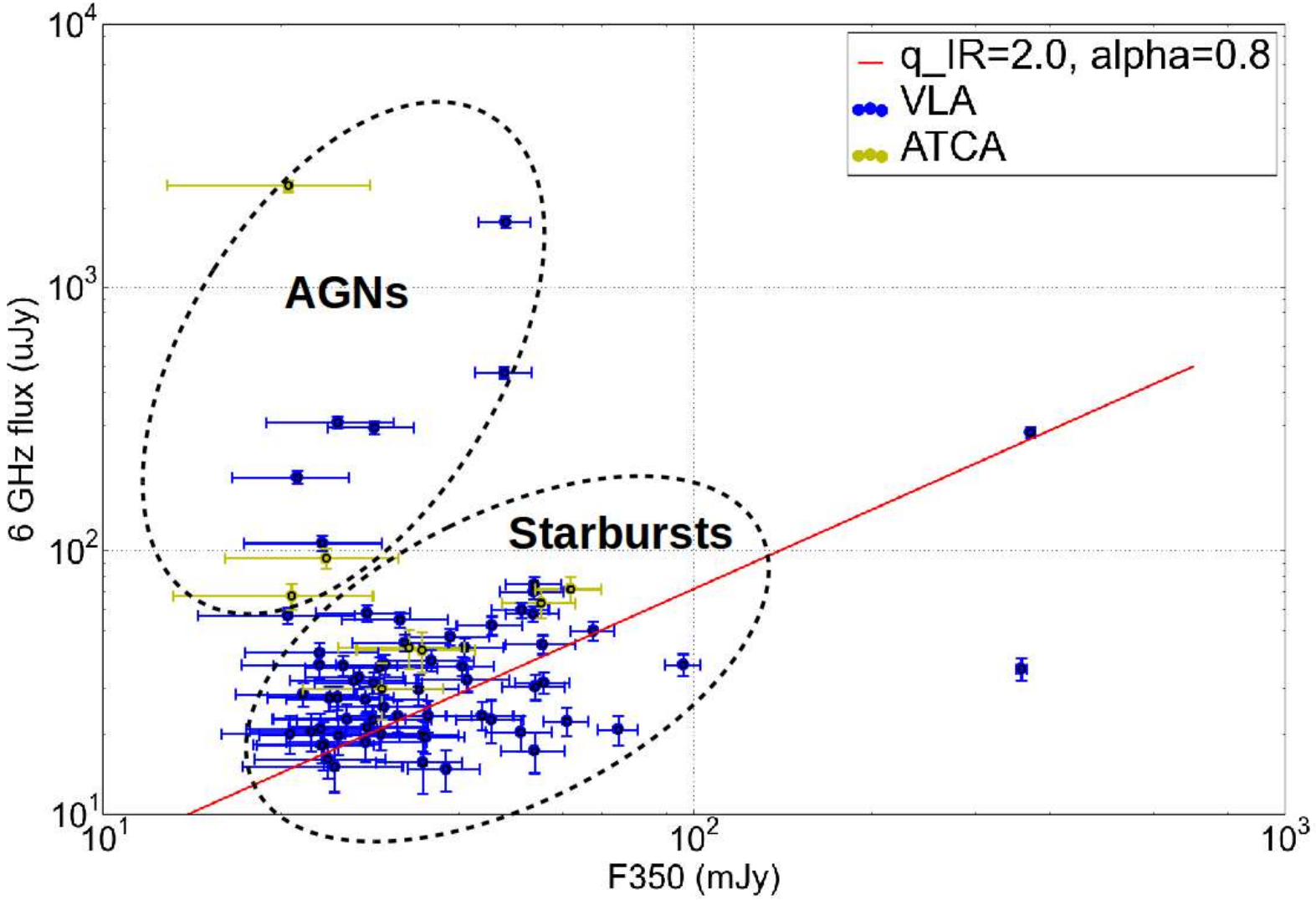


G12



VLA Follow-up

- Cross-match with *Herschel* sources
- FIR-radio correlation
- Look for AGNs

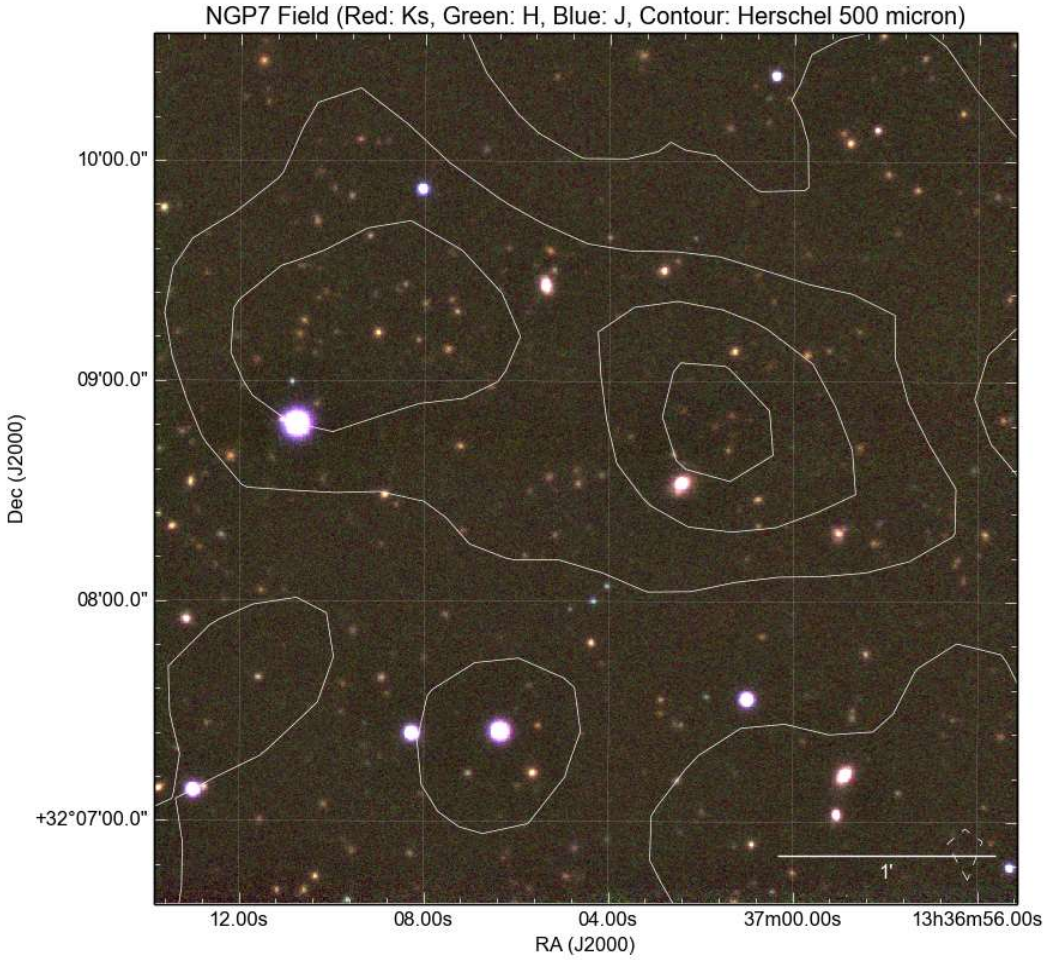


WHT Follow-up

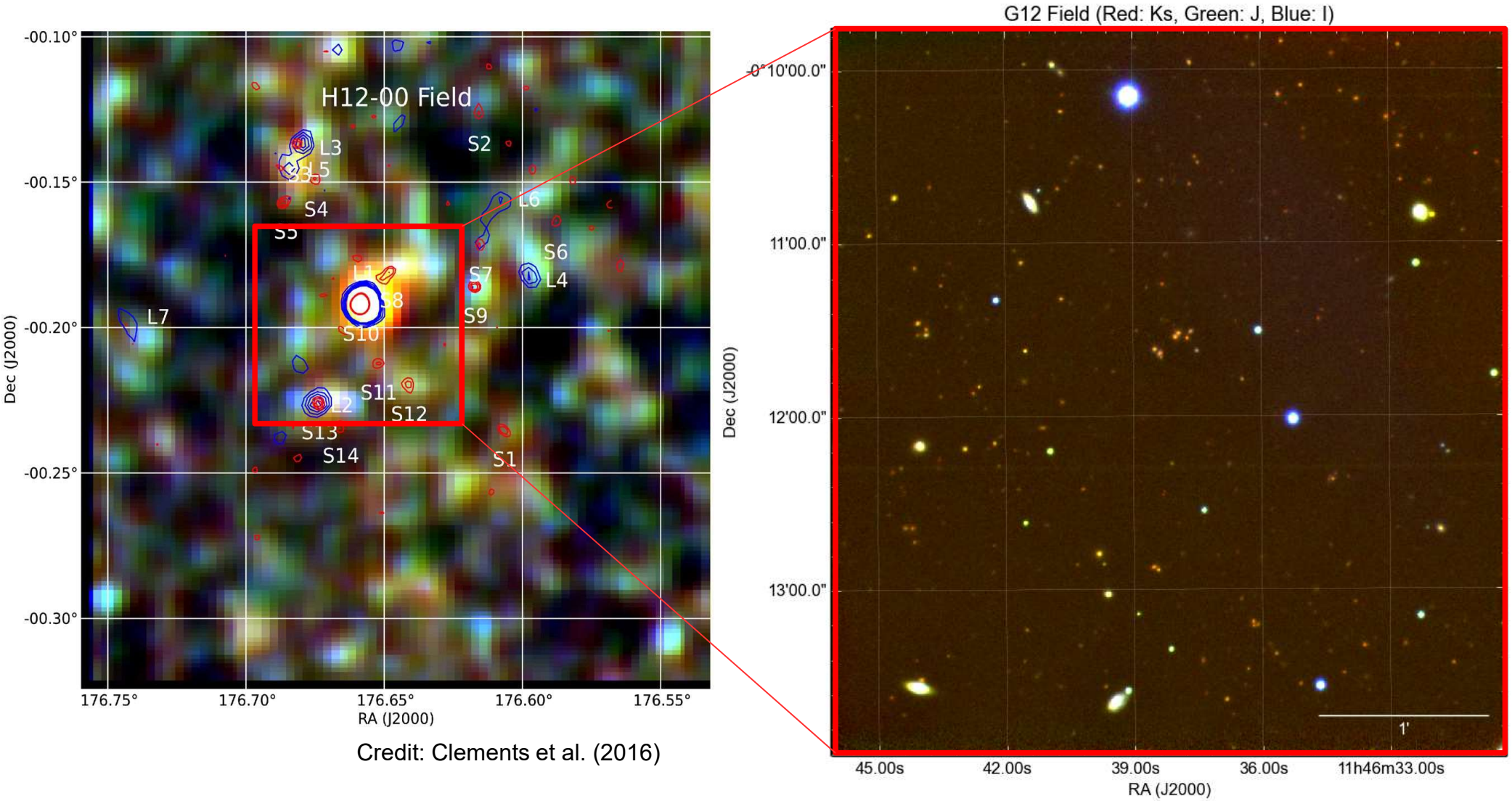
- ACAM & LIRIS: I, J, H, Ks bands (optical-NIR)
- 5 candidate protoclusters

William Herschel Telescope

Credit: https://www.nrao.edu/pr/2000/vla20/background/vlafacts/



WHT Follow-up

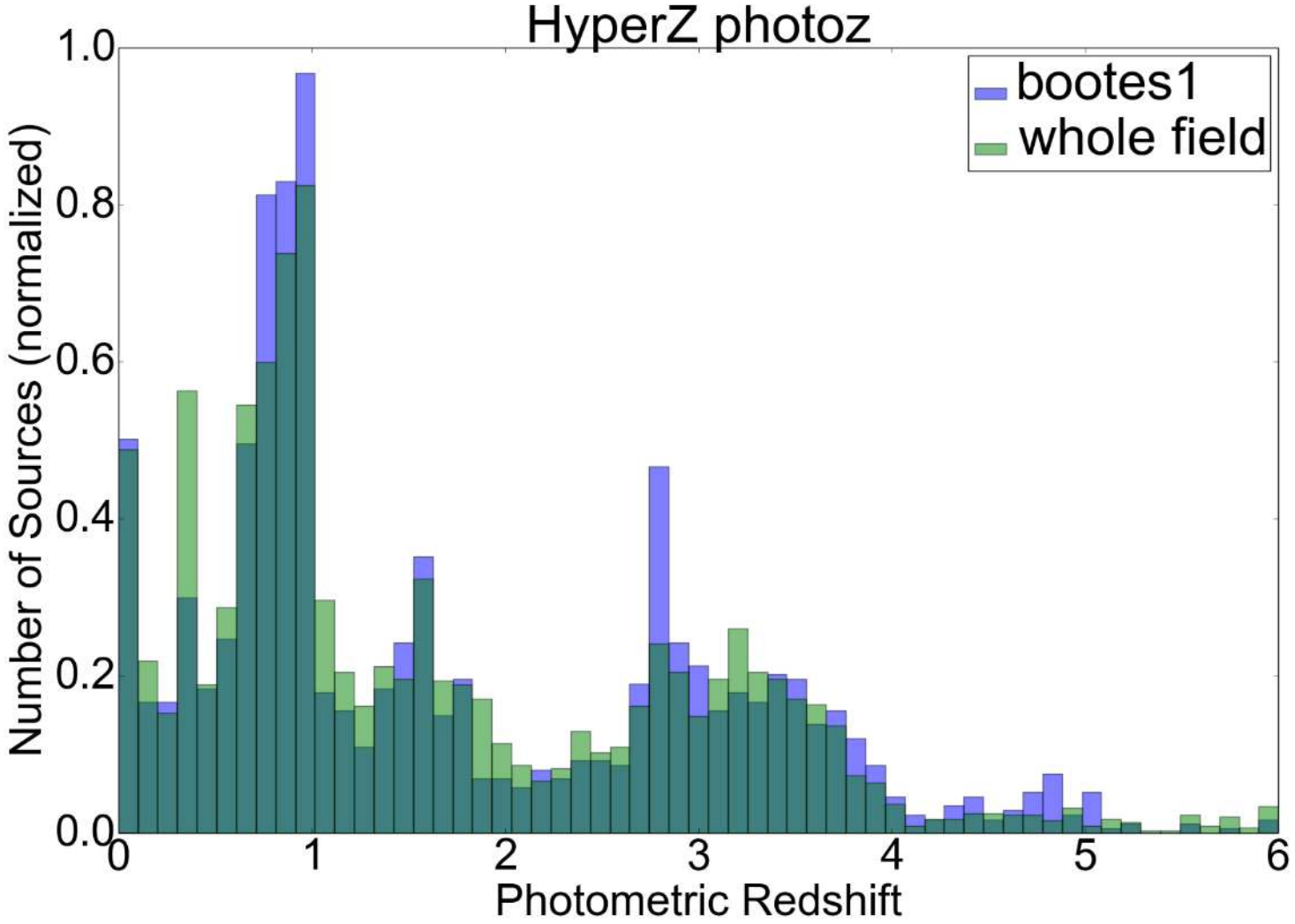


Credit: Clements et al. (2016)

- Lensed DSFG at the center, spectroscopically confirmed at z=3.26

WHT Follow-up

- Photometric Redshifts
- EAZY or HyperZ



Summary

- Follow-up observations:
- Submm: SCUBA-2

Number counts, colors, photo-z, IR luminoristy, SFR,
6/13 are high-z (z>2) protoclusters

- Radio: ATCA

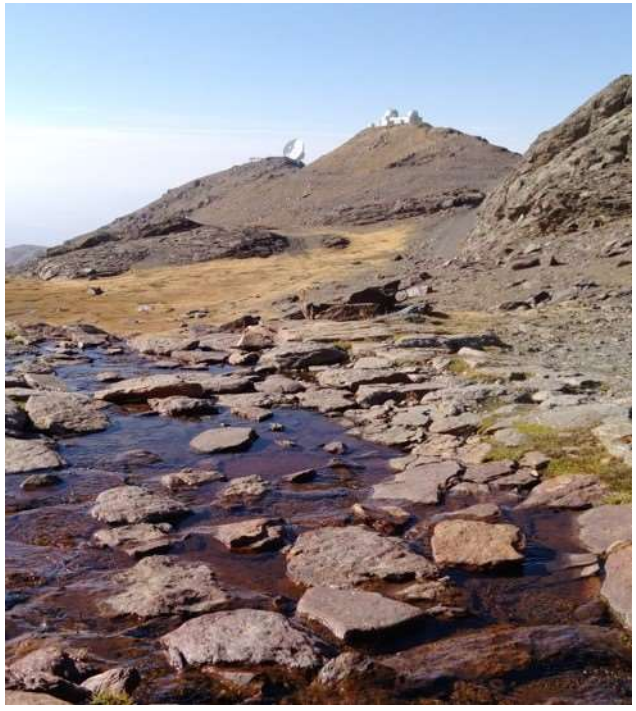
Overdensity in differential number counts

- Radio: VLA

FIR-radio correlation, AGNs, multiplicity, morphology

- Optical/Near-Infrared: WHT

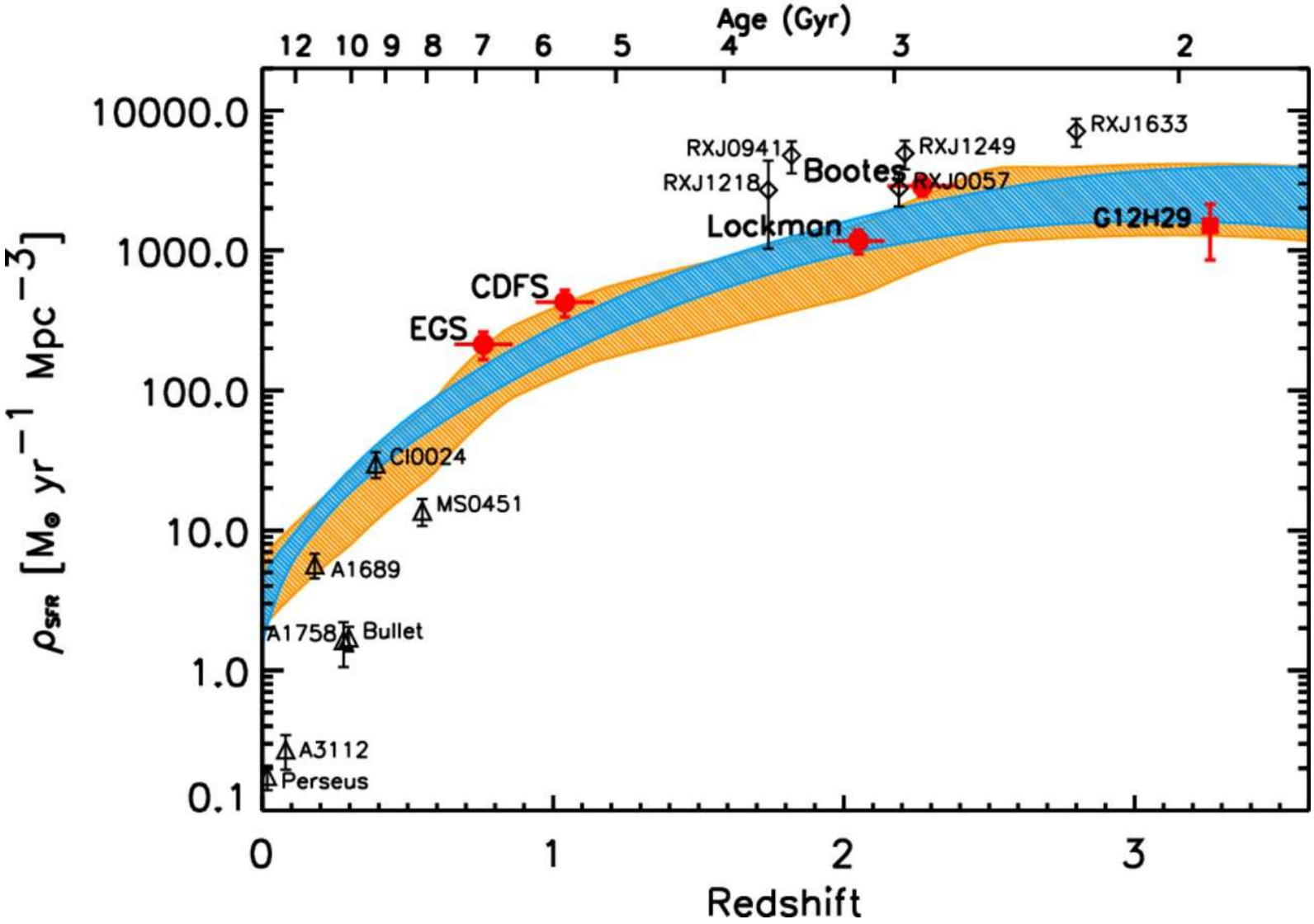
photo-z



Thank you!

Planck + *Herschel* selected protoclusters (candidates)

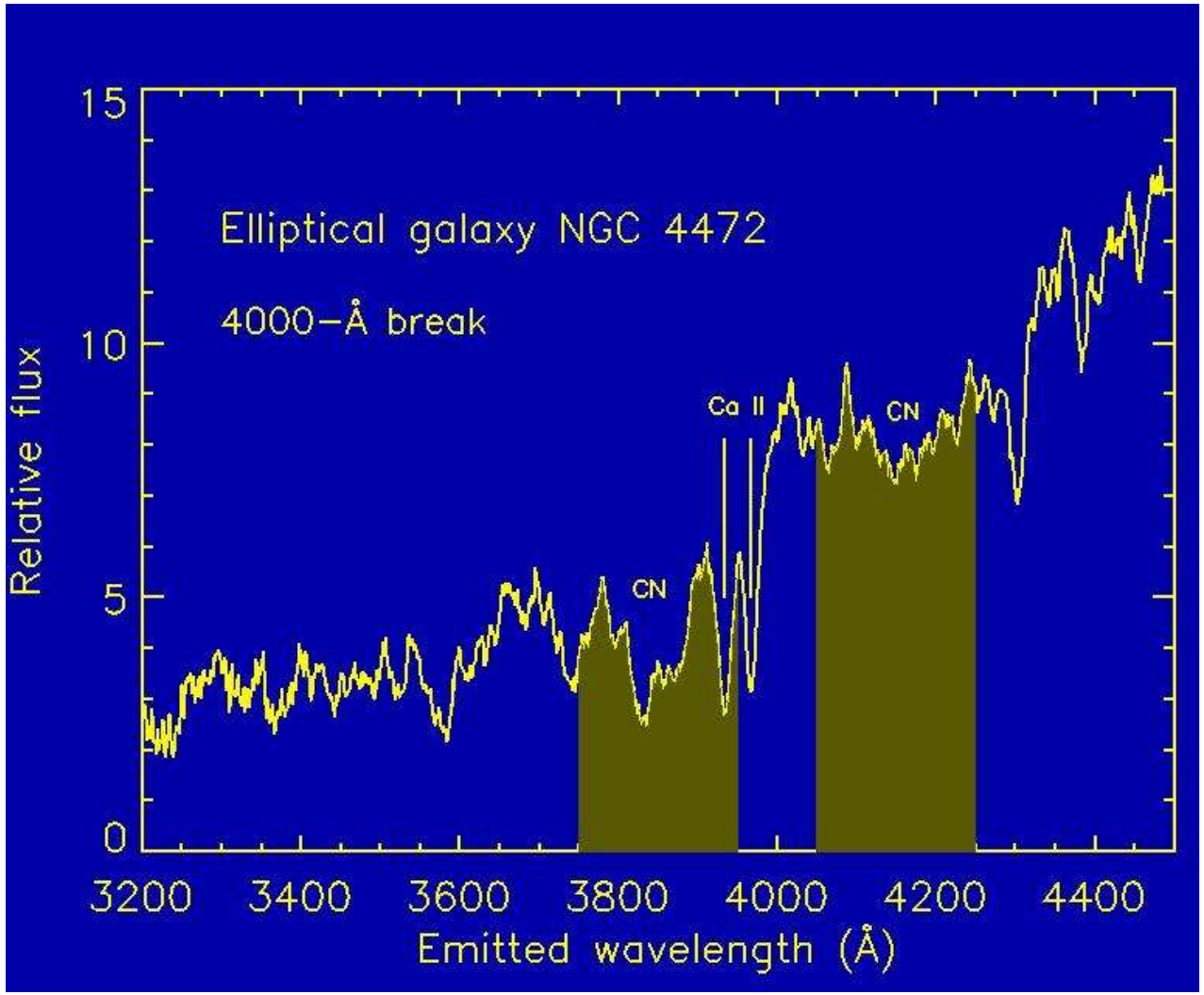
Star-formation rate density (SFRD)



Clements et al. (2014)

WHT Follow-up

•4000-Angstrom break



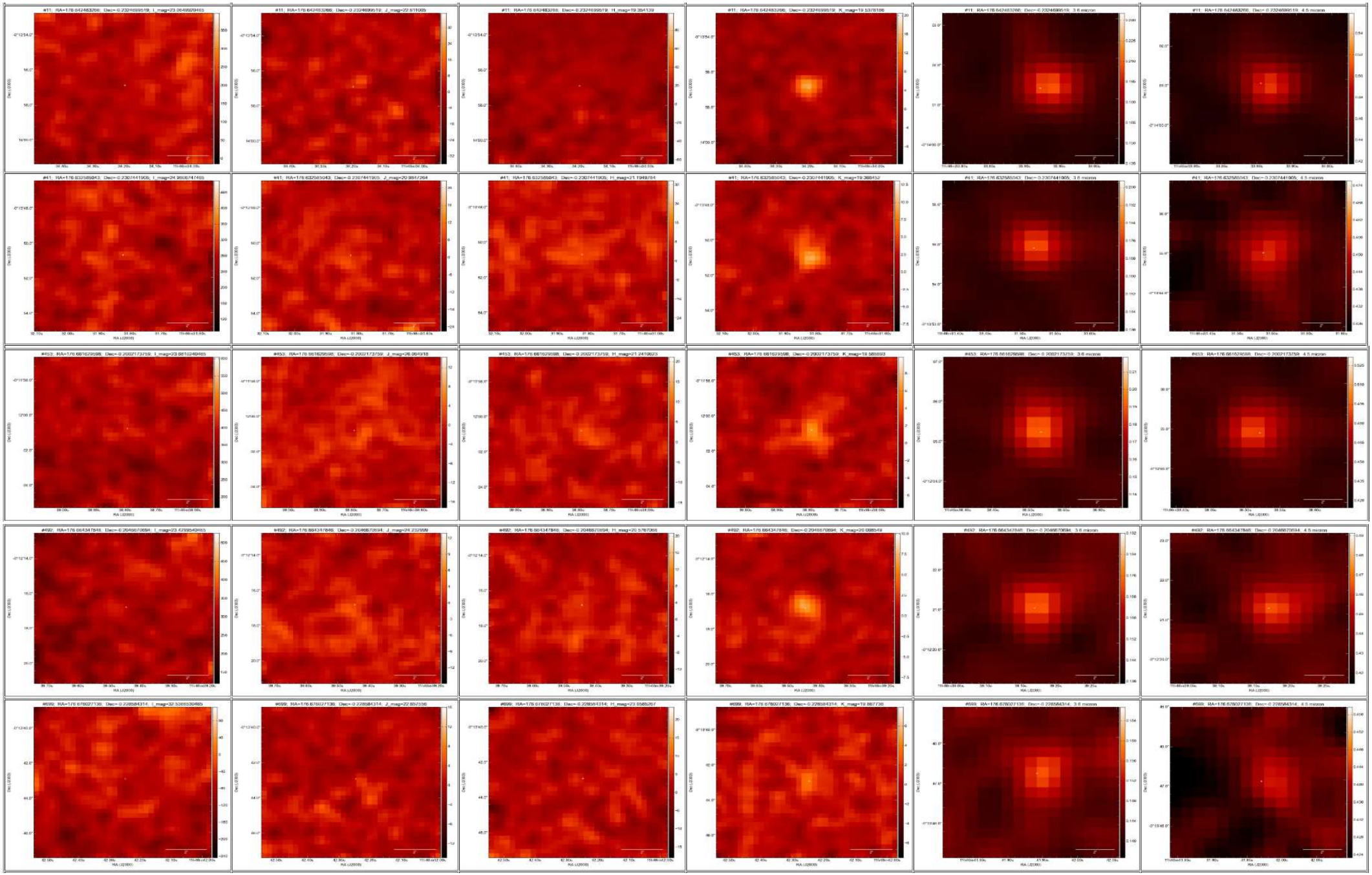
Flux →

Wavelength →

Credit: http://www.galaxyzooforum.org/index.php?topic=1923.0

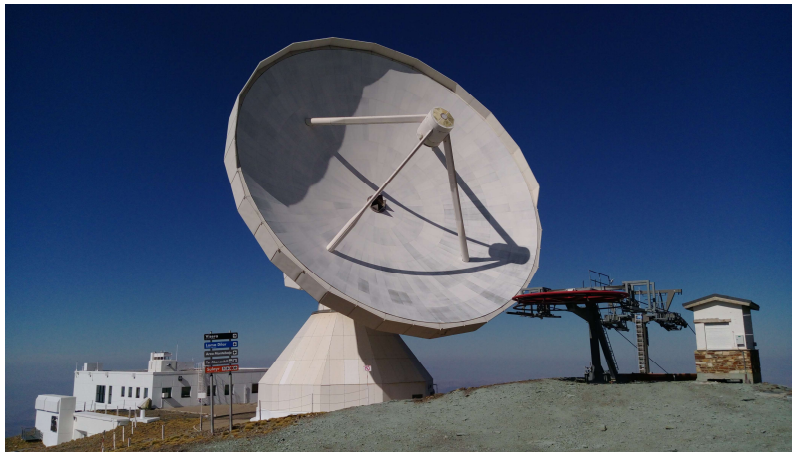
•Balmer absorption
•Prominent in elliptical (quiescent) galaxies
•Lies within H filter at z~3

1 I J H Ks 3.6μm 4.5μm

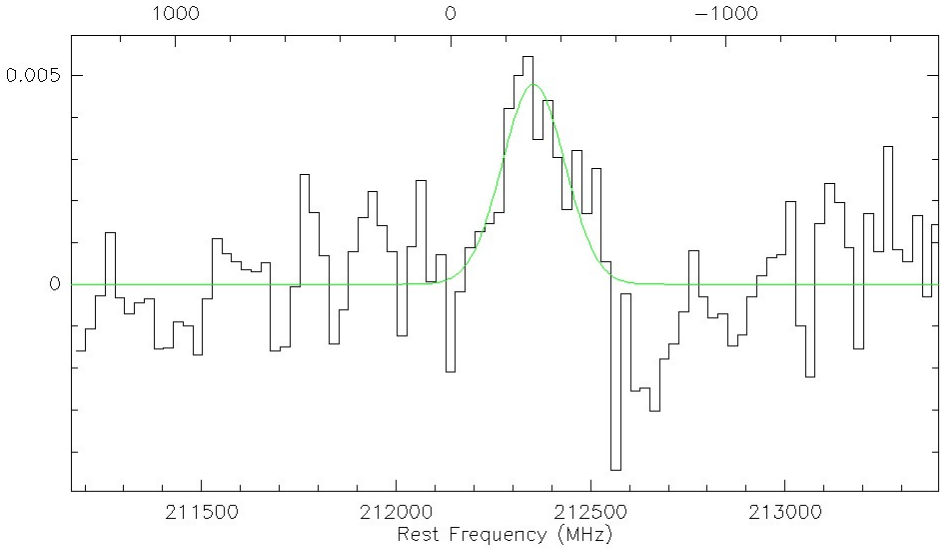


IRAM 30m Telescope Follow-up

- 1 & 3-mm (230 & 90 GHz) spectroscopy
- EMIR: Heterodyne receivers
- 4 FIR/submm sources within Bootes1 candidate protocluster
- Two lines suggest z=2.26 source (?)
- CO(6-5) & CO(3-2)



0:0 SOURCE−2 CO(6−5) 2 30ME2VLO−F06 0:15−OCT−2017 R:06−NOV−2017
RA: 14:34:29.66 DEC: 35:32:10.3 Eq 2000.0 Rad. 0.0° Offs: +0.0 +0.0
Unknown tau: 0.303 Tsys: 385. Time: 2.4hr El: 57.9
N: 161 I0: 92.0078 V0: 0.000 Dv: −35.33 LSR
F0: 212140.000 Df: 25.00 Fi: 230999.017



0:0 SOURCE−2 CO(3−2) 2 30ME0HUI−F02 0:15−OCT−2017 R:06−NOV−2017
RA: 14:34:29.66 DEC: 35:32:10.3 Eq 2000.0 Rad. 0.0° Offs: +0.0 +0.0
Unknown tau: 0.079 Tsys: 131. Time: 2.4hr El: 57.9
N: 161 I0: 92.0078 V0: 0.000 Dv: −70.87 LSR
F0: 105750.000 Df: 25.00 Fi: 93250.6518