Witnessing the Build-Up of Massive Galaxies in the (Sub)Millimeter Regime

Helmut Dannerbauer
Instituto de Astrofísicas de Canarias

Motivation

Observations in the submm and mm window give us access to probe two important components of star-forming galaxies:

1) ***dust*: proportional to the rate of star formation**
2) ***gas*: primary ingredient of star formation**

both are major goals of current and planned (sub)mm facilities!

Several questions and issues can be adressed by submm/mm observations:

- **understand assembly and formation of massive galaxies**
- **search for links within the galaxy zoo**
- **are infrared luminous galaxies disappearing at redshift z>3-4**
- **star-forming history (SFR vs z) --- which fraction is obscured?**
- **formation of first galaxy (proto)clusters and their evolution**

Obscured Star Formation

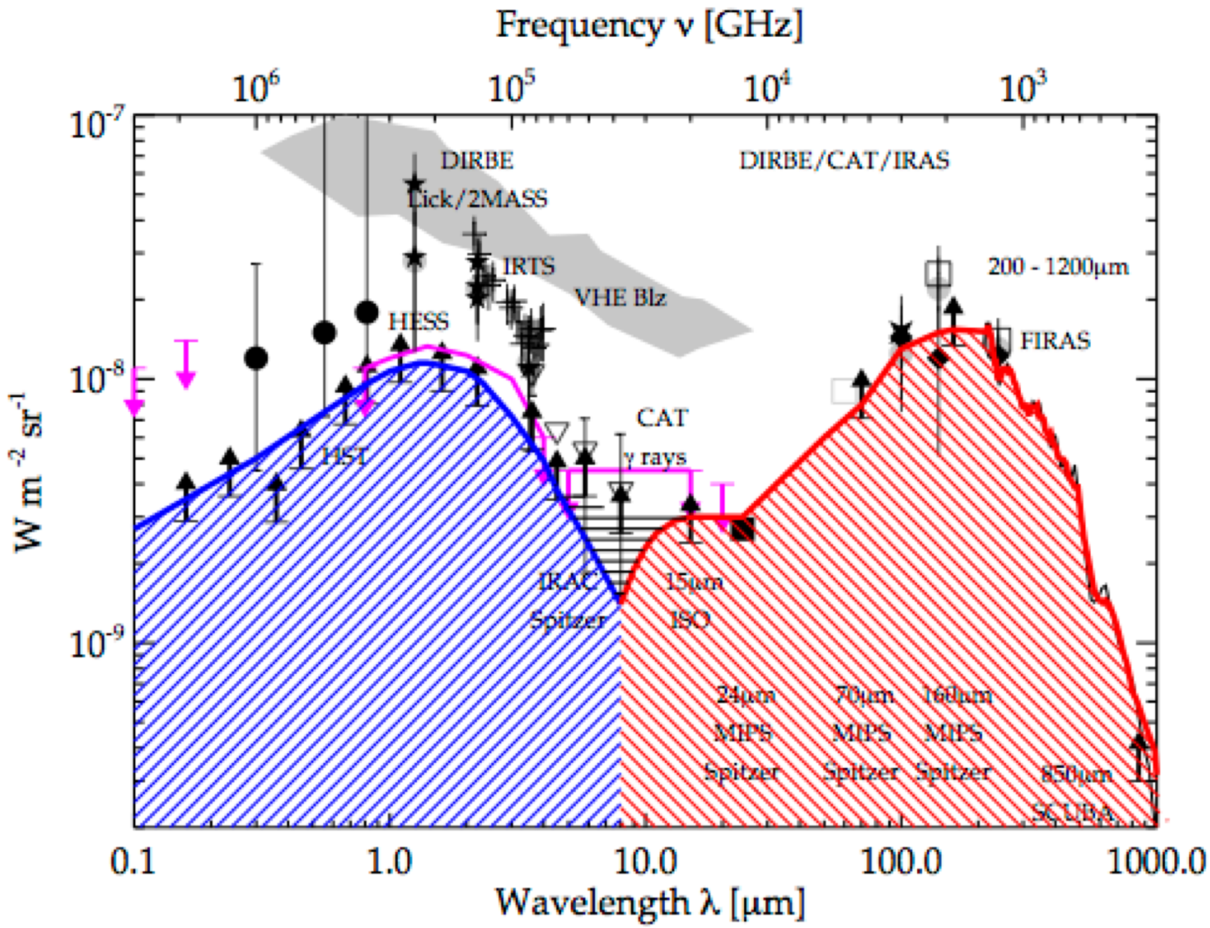
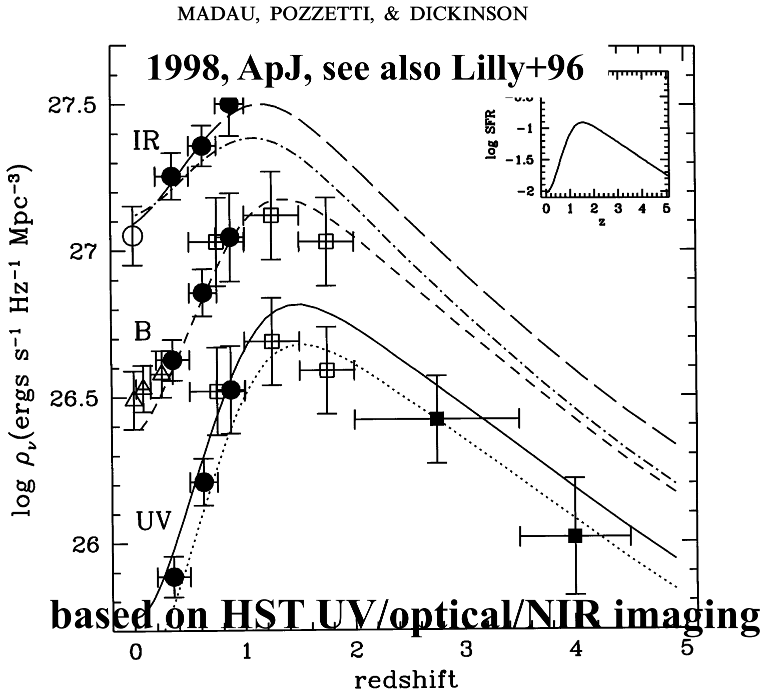
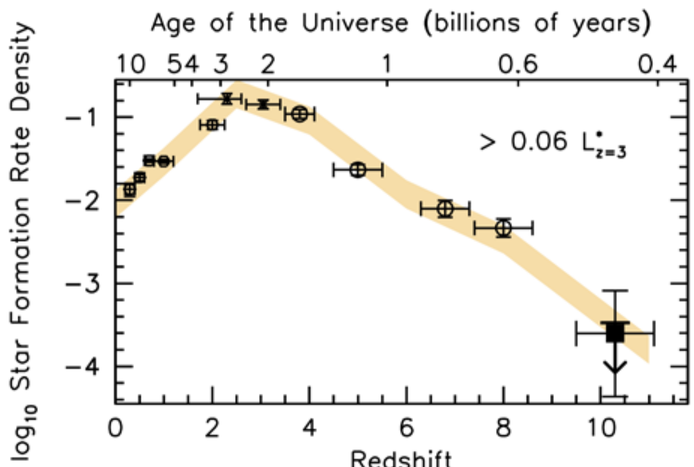


Fig. 13. Our best Cosmic Optical Background (blue-shaded) and Cosmic Infrared Background (red-shaded) estimates. The gray-shaded area represents the region of overlap. See Figure 9 for the other symbols.

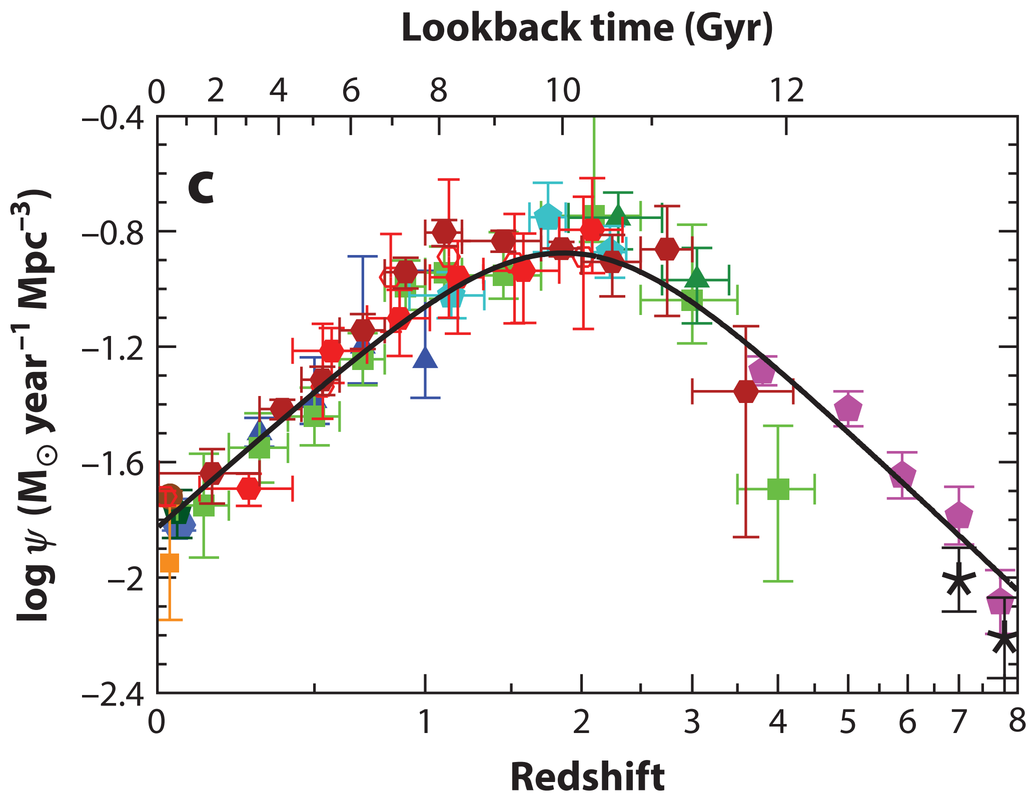
Dole et al.(2006)

Cosmological evolution of the cosmic star-formation rate density





Bouwens et al.(2011)

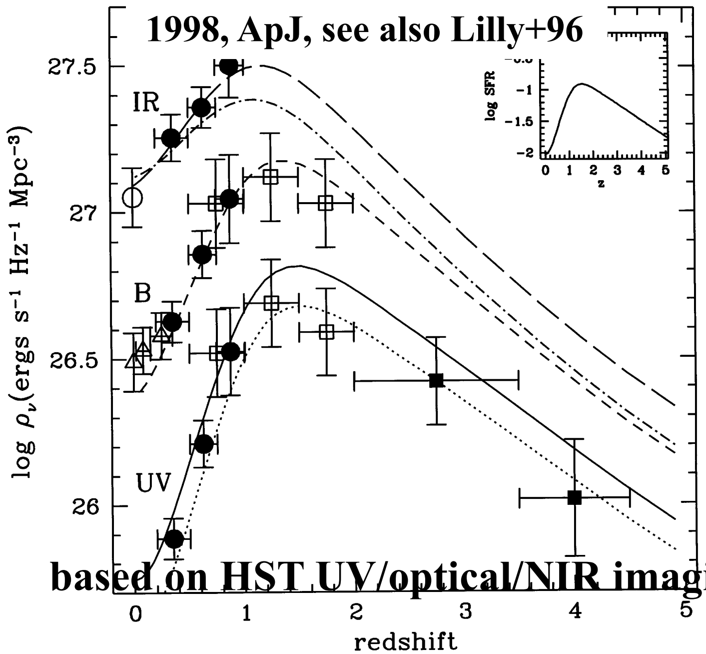


Madau & Dickinson 2014

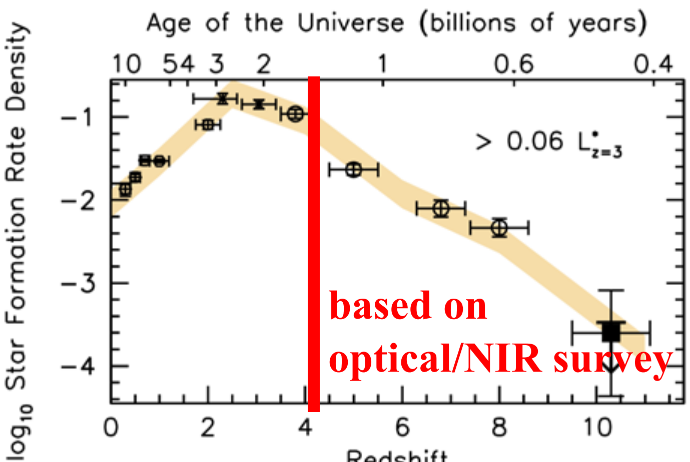
Cosmological evolution of the cosmic star-formation rate density

MADAU, POZZETTI, & DICKINSON

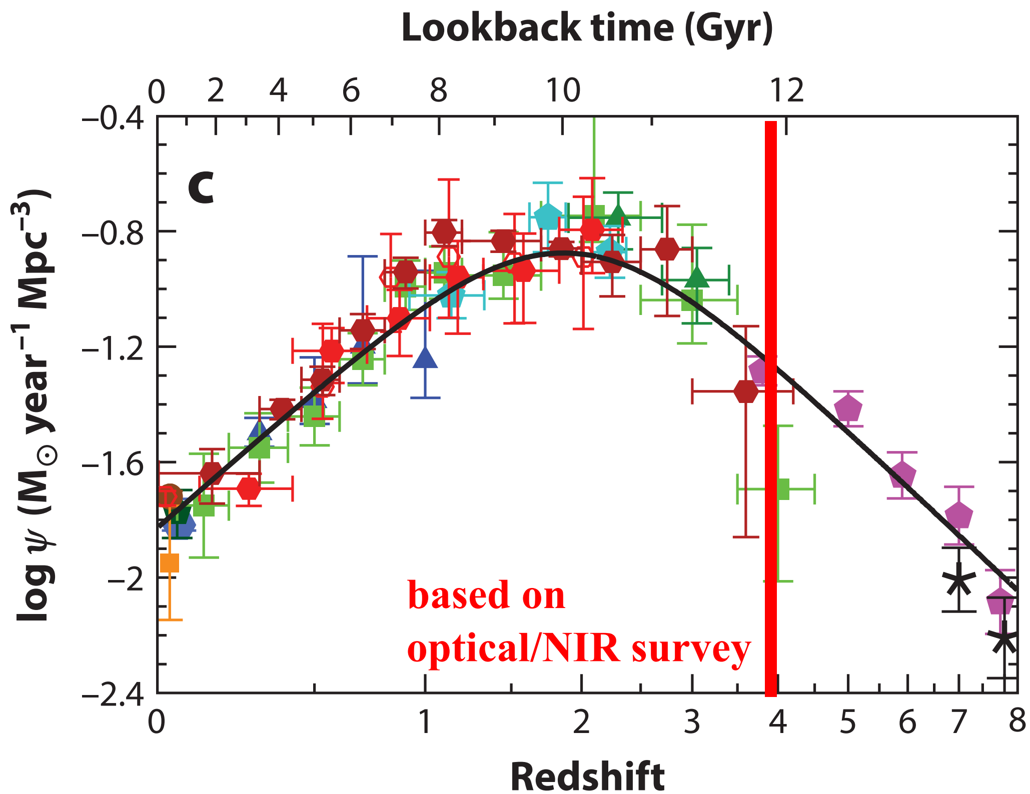
1998, ApJ, see also Lilly+96



based on HST UV/optical/NIR imaging

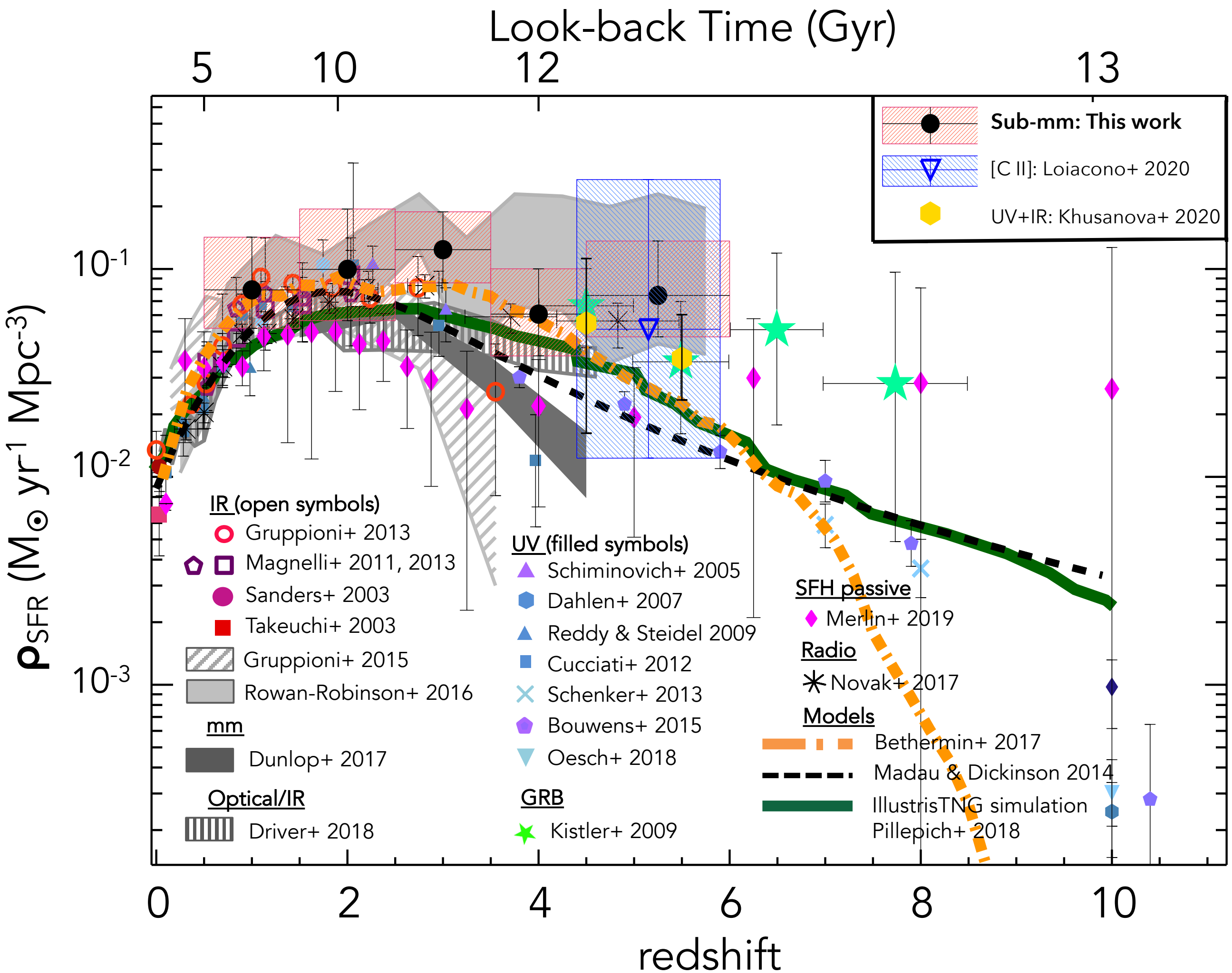


Bouwens et al.(2011)



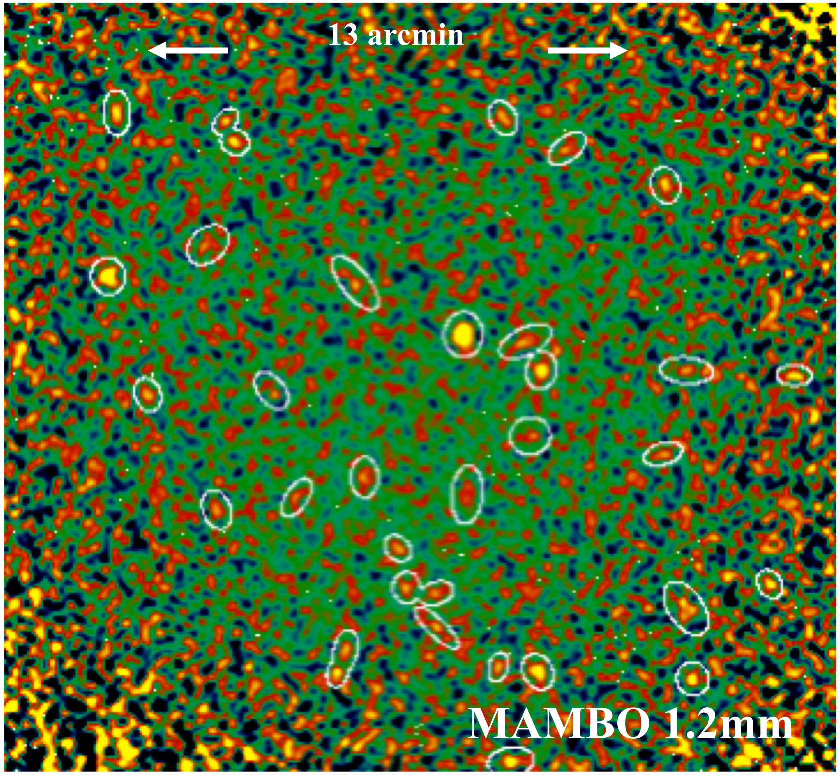
Madau & Dickinson 2014

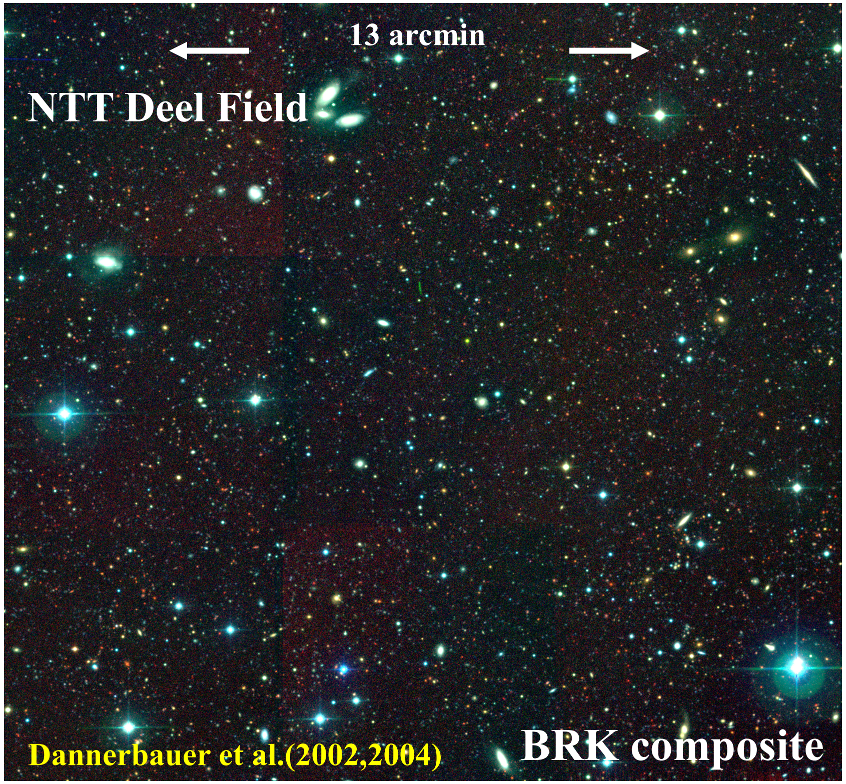
Cosmological evolution of the cosmic star-formation rate density



Gruppioni et al. 2020

Submm Universe





- **completely different view to the universe:**

-observing *cool, dust enshrouded* sources
***-complementary* to e.g., optical surveys**
-interferometry needed to obtain similar resolution as in the optical

Current (Sub)mm Telescope Facilites on the ground

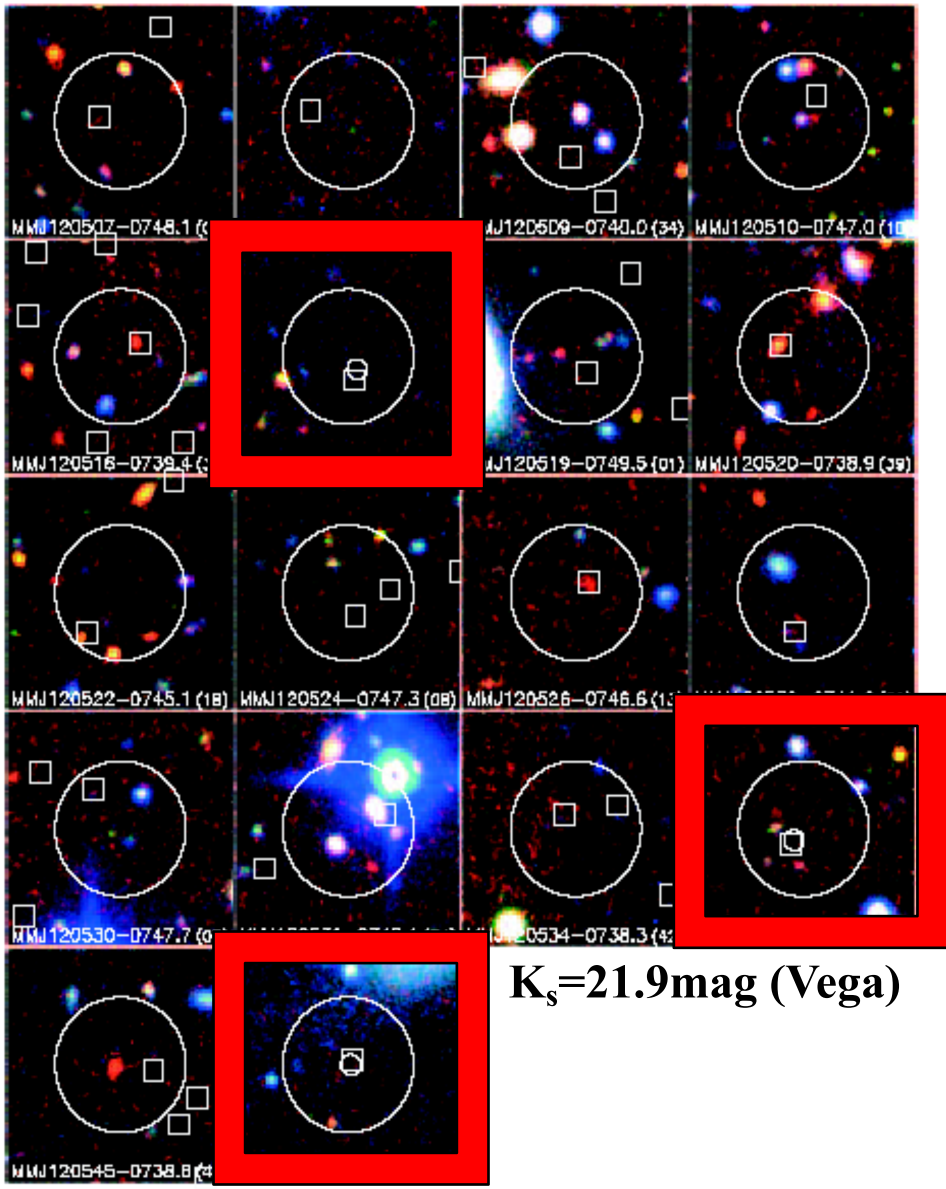








Quantensprung by ALMA



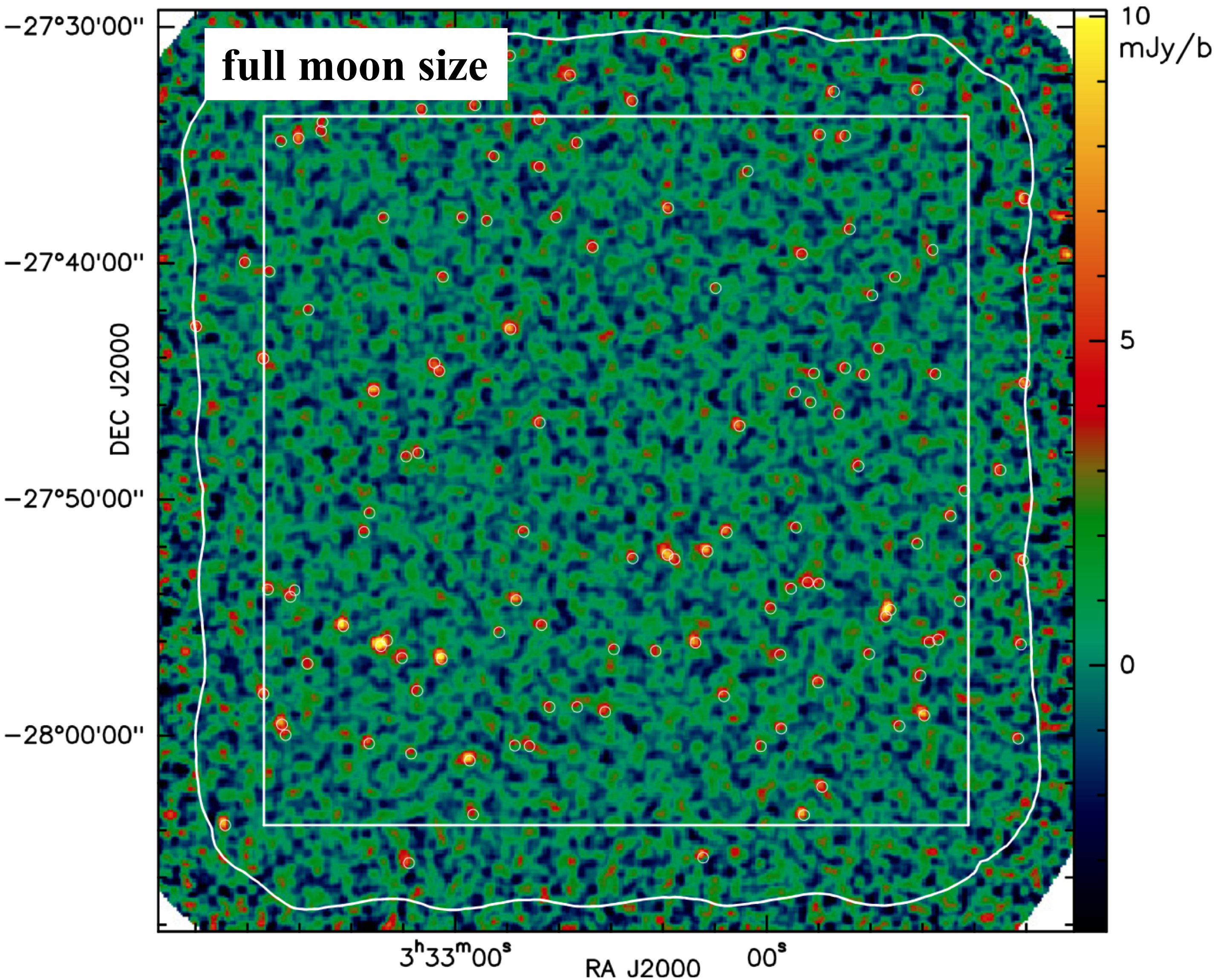
K_s=21.9mag (Vega)

2001 PdBI: 61hrs
2010 PdBI: 1hrs
2011 ALMA SV: 10m
2011 ALMA ES: 2.5m
2012 ALMA C1: <1m
2015 ALMA C3: <20s

Dannerbauer et al., 2002, 2004

Submm Surveys

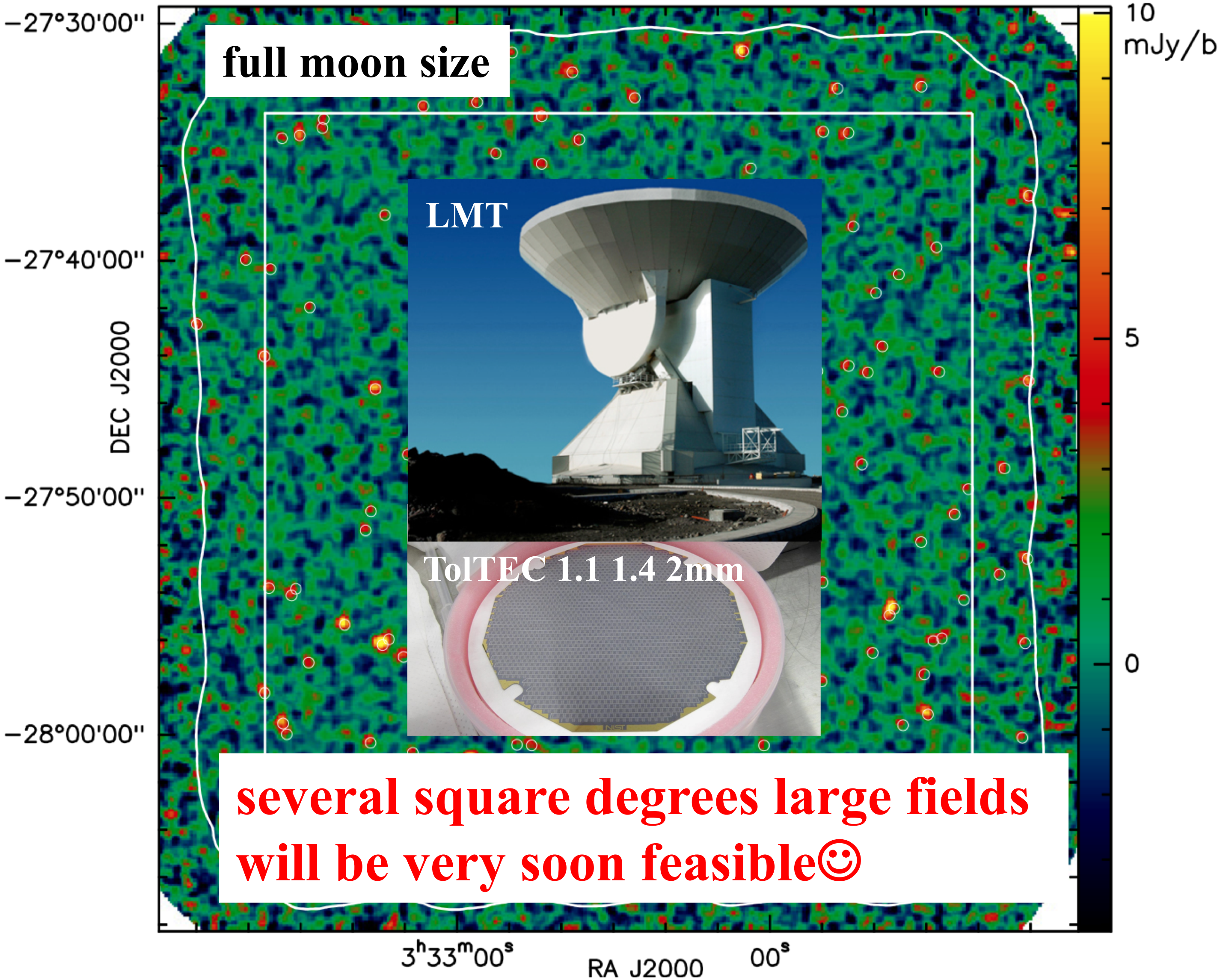
Weiss et al.(2009)



done with APEX-LABOCA 870micron – 310hrs, not feasible with ALMA

Submm Surveys

Weiss et al.(2009)



done with APEX-LABOCA 870micron – 310hrs, not really feasible with ALMA

Measures of the Cold Interstellar Medium

- total molecular gas: CO, [CI], dust (see e.g. Dunne et al. 2022)

- dense molecular gas, linked to SFR: HCN, HNC, HCO^+

- obscured star-formation rate: dust in the (sub)mm, [CII]

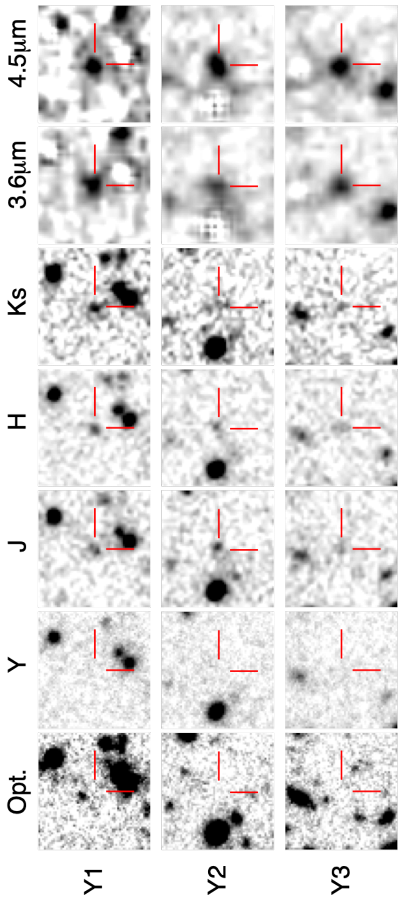
- star-formation efficiency SFE=SFR/MolGas

- determining metallicity in obscured regions

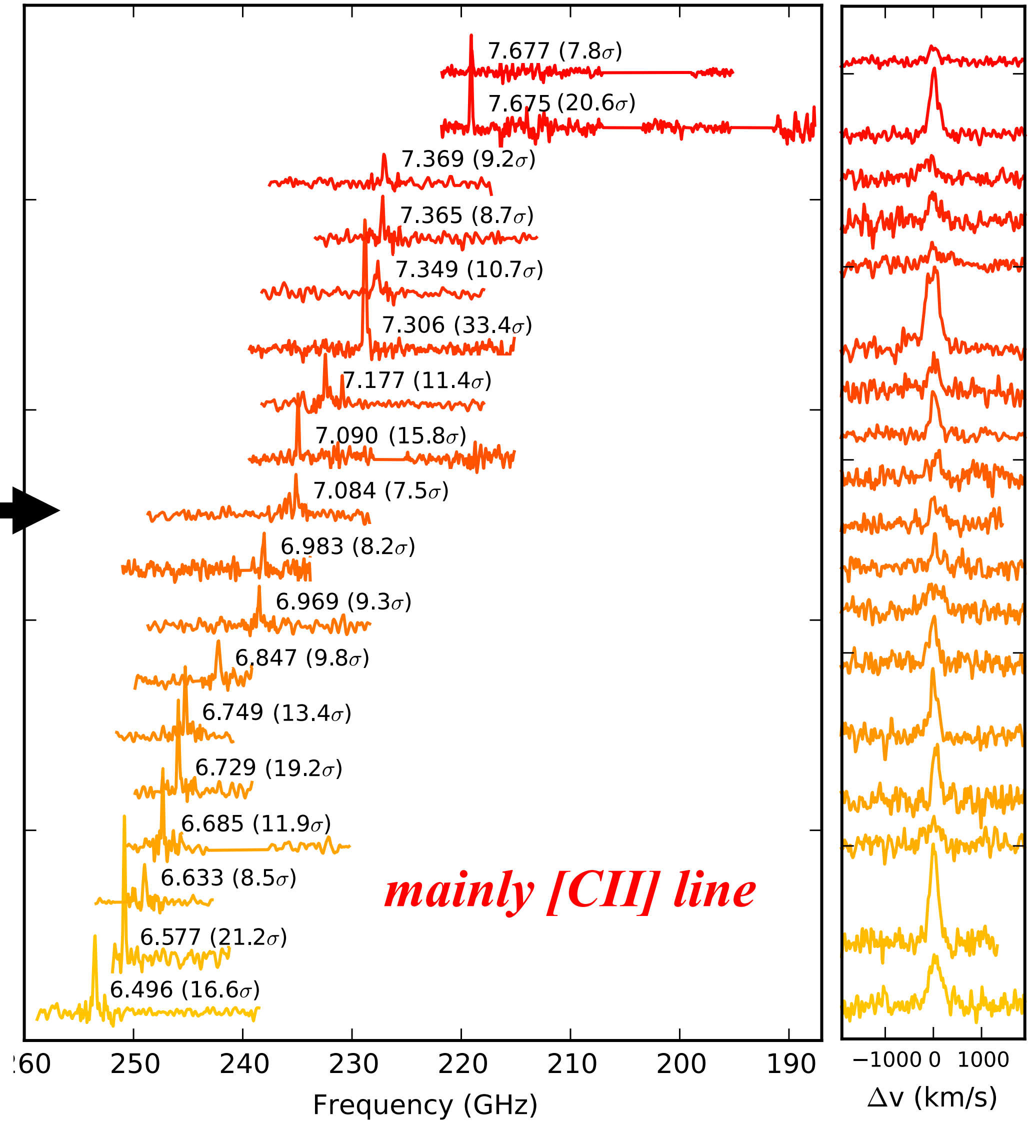
- gas fraction: stellar mass (from the optical/NIR), total cold gas

z-spec's for optical/NIR selected sources via ALMA

see also Richard Bouwen's talk on Friday



Stefanon et al. 2019



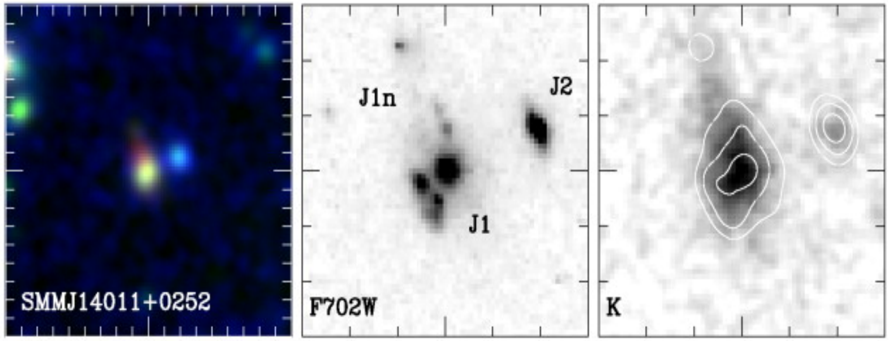
Bouwens et al. 2022

Dusty Star-Forming Galaxies (DSFGs)

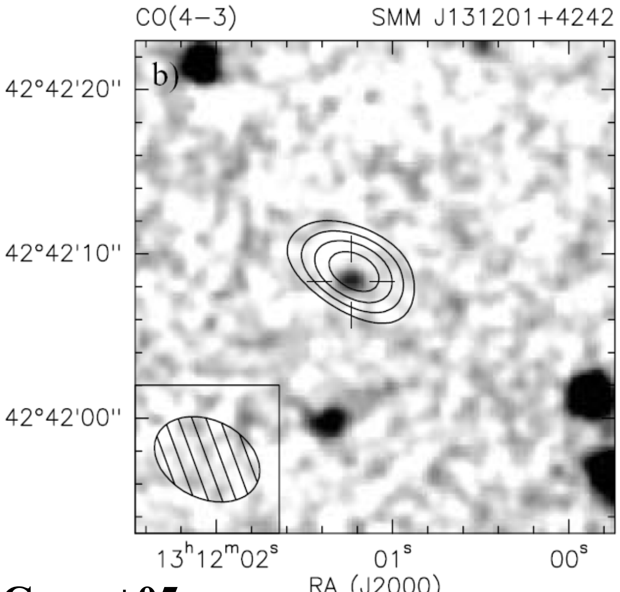
- very massive up to $10^{11} M_\odot$
- gas-rich
- high SFR: several 100 $M_\odot$/yr
- merger-like morphology
- ellipticals in formation
- <z>=2.5

➔ *excellent tracers of mass-density peaks*

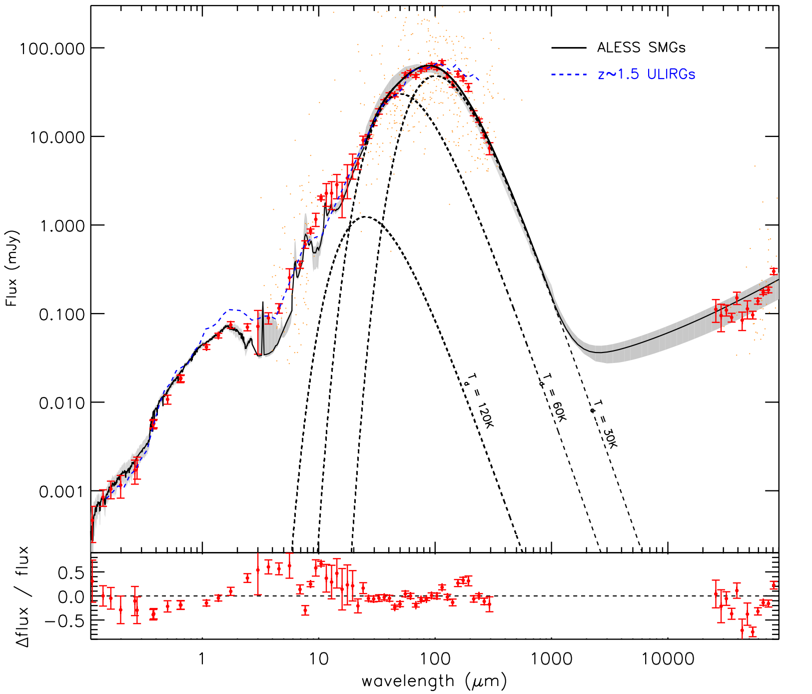
see also review by Casey+2014



Ivison+00



Greve+05



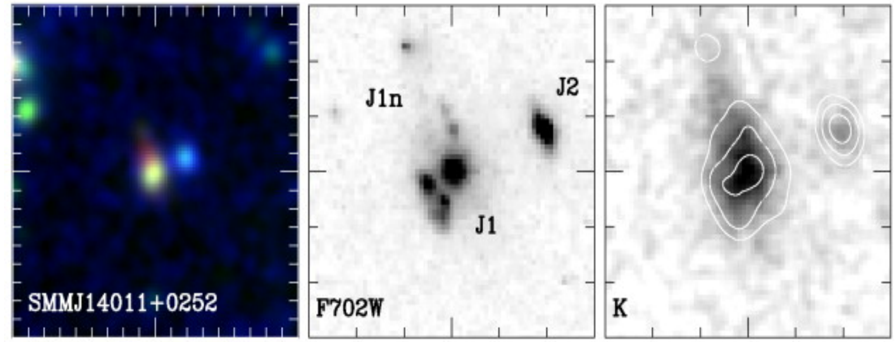
Swinbank+14

alias Submillimeter Galaxies (SMGs)

old school definition ☺

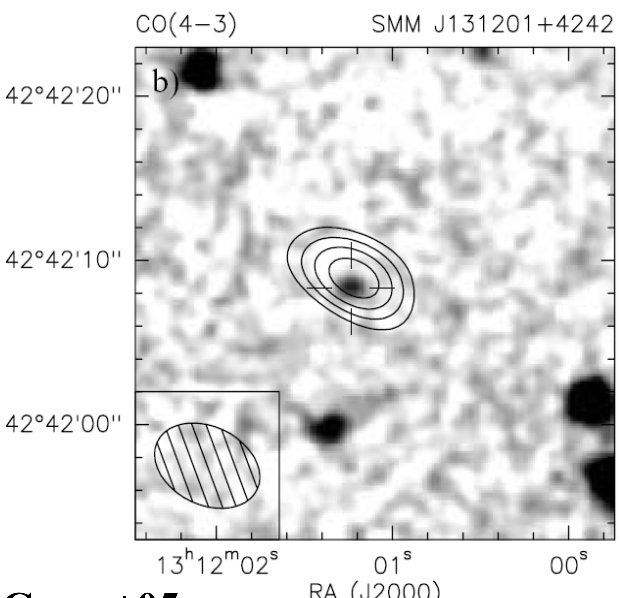
- very massive up to $10^{11} M_{\odot}$
- gas-rich
- high SFR: several 100 $M_{\odot}$/yr
- merger-like morphology
- ellipticals in formation
- $<z>=2.5$

➔*excellent tracers of mass-density peaks*

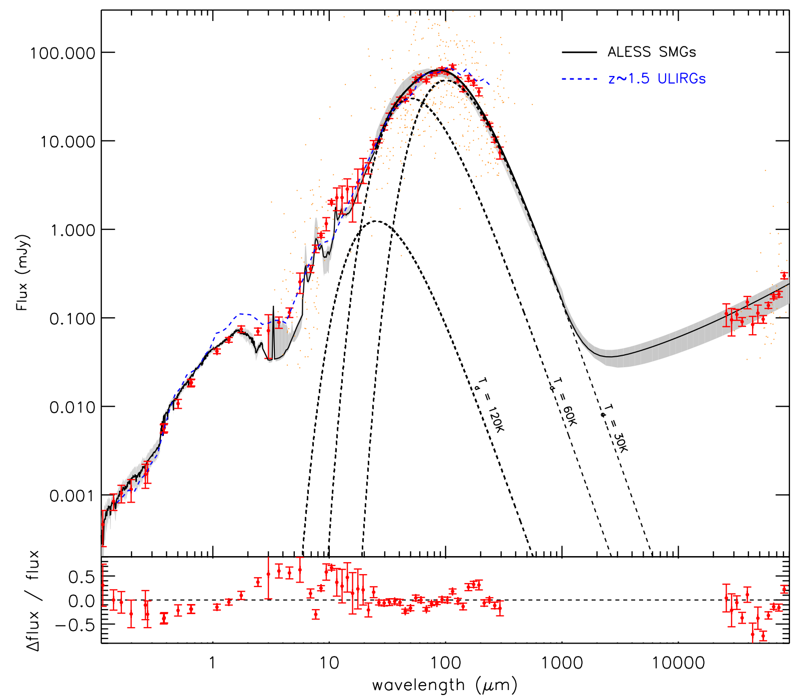


Ivison+00

see also review by Casey+2014



Greve+05



Swinbank+14

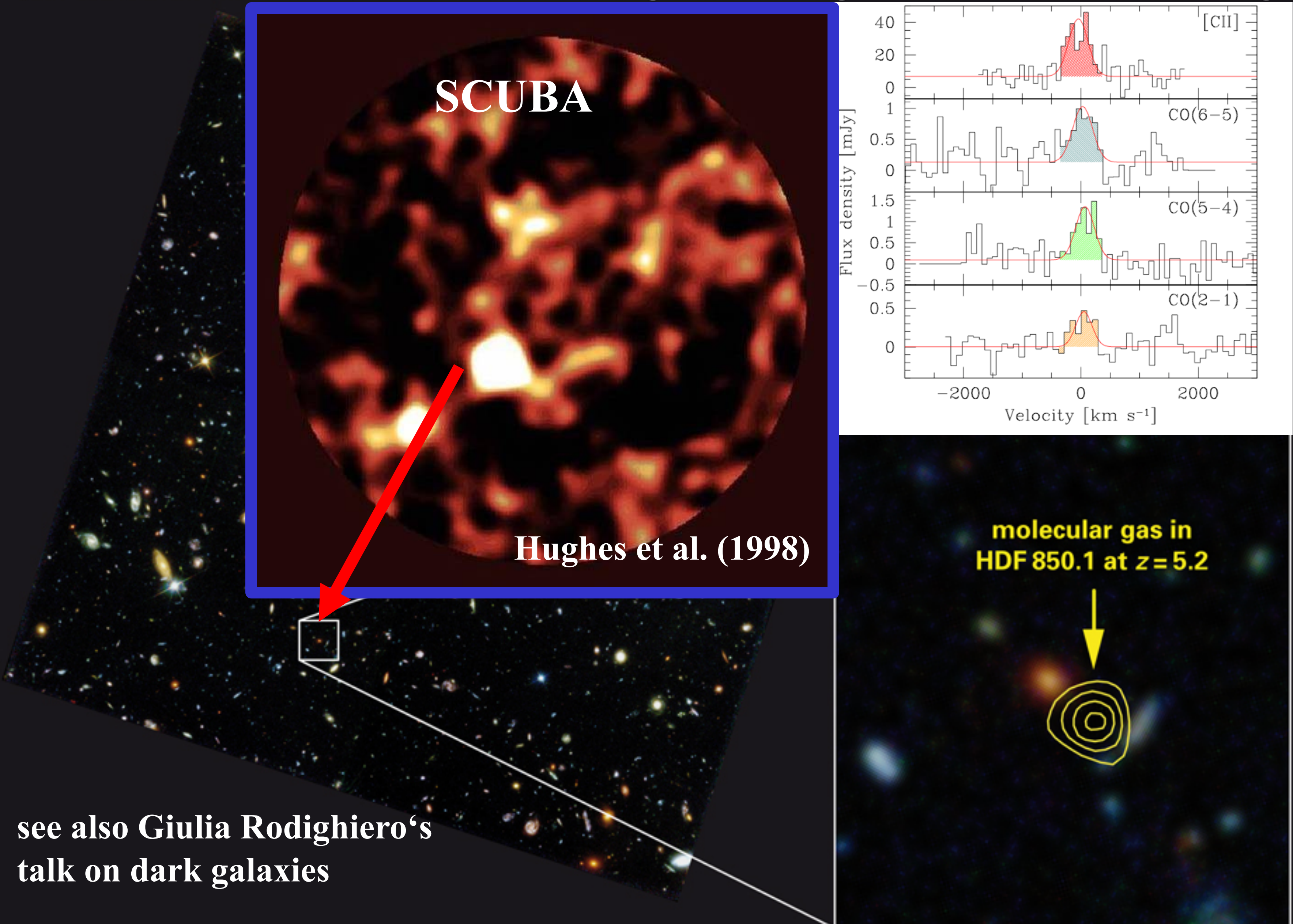
DSFGs resp. SMGs observable with Euclid-wide

Table 1.
Log of SMG sample with NICMOS imaging

ID	Short Name	z	Type	F160W (AB)	r_{pet}^{nir} (kpc)	r_{h}^{nir} (kpc)	r_{pet}^{opt} (kpc)	r_{h}^{opt} (kpc)
SMM J030227.73+000653.5[1]	CFRS03-15	1.408	SB	20.73 ± 0.02	14.4±2.0	2.8±0.4	13.1±1.5	2.3±0.5
SMM J105158.02+571800.2	LOCKMAN-03	2.239	SB	21.58 ± 0.04	9.9±1.3	3.7±0.3	7.8±1.3	3.3±0.4
SMM J105200.22+572420.2	LOCKMAN-08	0.689	SB	22.98 ± 0.08	5.3±0.5	2.1±0.4	5.0±1.3	2.4±0.4
SMM J105230.73+572209.5	LOCKMAN-06	2.611	SB	22.11 ± 0.05	10.2±0.5	4.1±0.4	15.9±2.5	8.2±0.9
SMM J105238.30+572435.8	LOCKMAN-02	3.036	SB	22.43 ± 0.08	8.6±0.6	3.2±0.4	5.7±2.0	3.7±1.0
SMM J123553.26+621337.7	HDFN-082	2.098	SB	24.30 ± 0.21	3.1±0.2	1.6±0.4	3.7±0.4	1.9±0.5
SMM J123600.10+620253.5[2]	HDFN-092	2.701	SB	23.75 ± 0.16	5.0±1.5	2.9±0.4	3.6±1.2	2.4±0.4
SMM J123600.15+621047.2	HDFN-093	1.994	SB	22.64 ± 0.08	4.2±2.0	2.3±0.4	5.0±0.8	1.5±0.4
SMM J123606.85+621021.4	HDFN-105	2.509	SB	21.61 ± 0.03	4.2±0.5	1.7±0.5	7.6±0.5	2.7±0.4
SMM J123616.15+621513.7	HDFN-127	2.578	SB	23.59 ± 0.10	9.7±2.0	2.1±0.6	7.6±1.2	2.0±0.4
SMM J123622.65+621629.7	HDFN-143	2.466	SB	23.32 ± 0.09	9.7±0.4	3.9±0.4	6.1±2.0	2.3±1.0
SMM J123629.13+621045.8	HDFN-153	1.013	SB	21.23 ± 0.03	12.0±0.9	4.5±0.4	13.8±2.5	5.6±0.9
SMM J123632.61+620800.1	HDFN-161	1.993	AGN	22.74 ± 0.07	5.0±0.4	2.0±0.5	2.5±0.5	0.9±0.4
SMM J123635.59+621424.1	HDFN-172	2.005	AGN	21.59 ± 0.03	9.2±0.4	3.7±0.4	10.6±1.2	1.8±0.5
SMM J123701.59+621513.9	GN17	1.260	SB	21.50 ± 0.05	12.5±0.4	5.3±0.4	....	....
SMM J131201.17+424208.1	SA13-332	3.405	AGN	22.87 ± 0.08	3.3±0.4	1.3±0.4	2.2±0.4	0.4±0.4
SMM J131225.20+424344.5[1]	SA13-516	1.038	SB	21.46 ± 0.03	10.3±1.2	3.9±0.4	8.9±0.5	2.7±0.4
SMM J131232.31+423949.5	SA13-570	2.320	SB	22.85 ± 0.09	7.5±0.9	2.5±0.5	3.6±1.5	1.1±1.0
SMM J141741.81+522823.0[1]	CFRS14-13	1.150	AGN	18.67 ± 0.02	5.6±1.5	< 1	6.6±2.0	1.0±0.4
SMM J141800.40+522820.3[1]	CFRS14-3	1.913	SB	22.74 ± 0.07	3.7±0.6	< 1	8.3±0.3	2.3±0.4
SMM J163631.47+405546.9	ELAIS-13	2.283	AGN	24.47 ± 0.18	8.6±0.6	4.2±0.4	7.3±2.0	4.3±1.0
SMM J163639.01+405635.9	ELAIS-07	1.495	SB	23.88 ± 0.09	8.3±0.7	3.0±0.4	12.7±3.0	3.6±0.8
SMM J163650.43+405734.5	ELAIS-04	2.378	SB/AGN	21.85 ± 0.04	9.7±0.6	3.4±0.4	5.0±1.5	1.5±0.4
SMM J163658.78+405728.1	ELAIS-08	1.190	SB	21.20 ± 0.03	9.9±0.6	3.5±0.4	6.8±2.0	1.9±0.4
SMM J163704.34+410530.3	ELAIS-01	0.840	SB	22.36 ± 0.03	6.9±1.2	2.3±0.5	6.1±0.5	2.4±0.5

Swinbank+10

The Intense Starburst HDF 850.1 in a Galaxy Overdensity at $z = 5.2$ in the Hubble Deep Field



see also Giulia Rodighiero's talk on dark galaxies

Hubble Deep Field: Image credit STScI and NASA

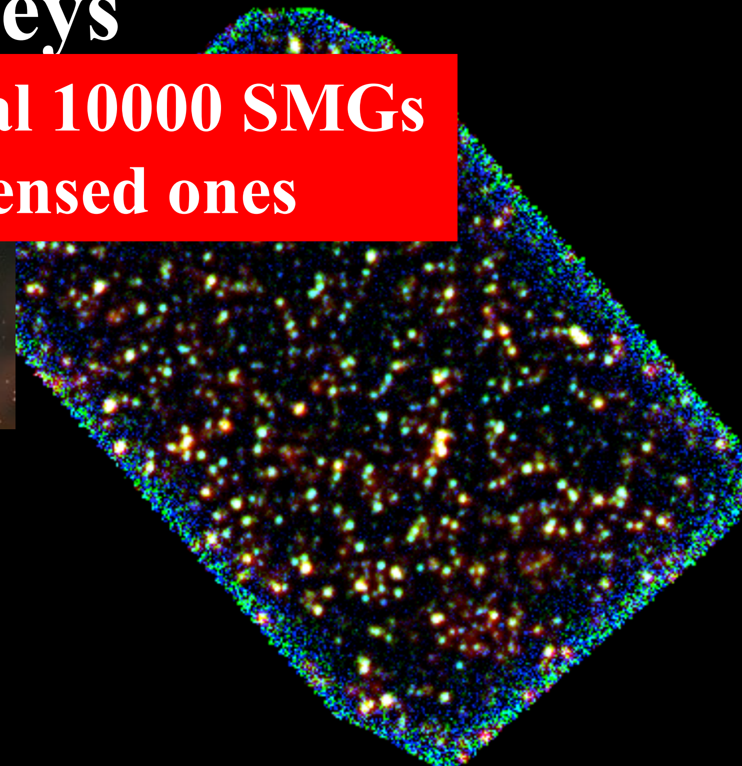
Walter et al., Nature, June 2012

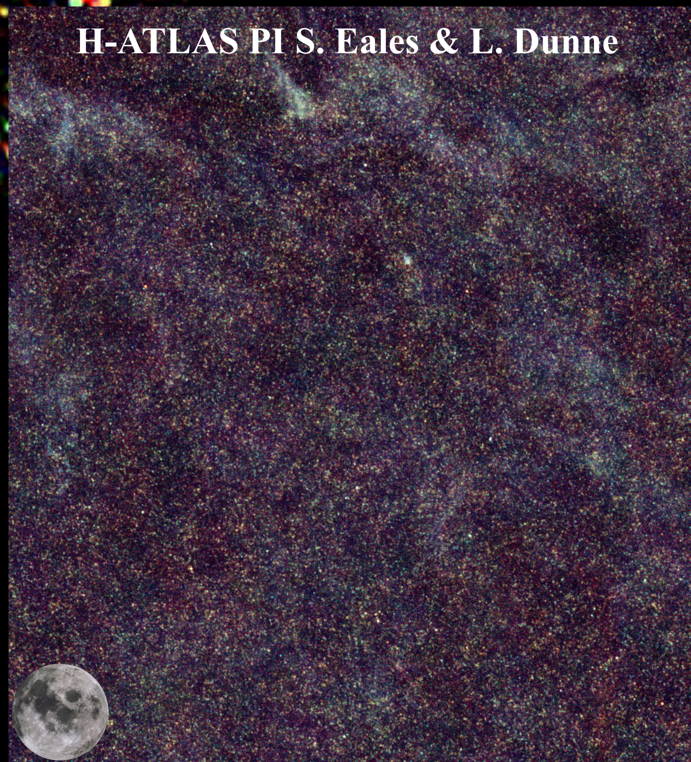
PEP PI D. Lutz

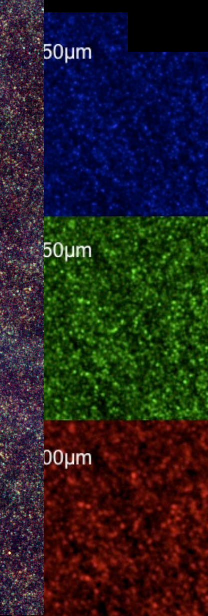
GOODS-H PI D. Elbaz

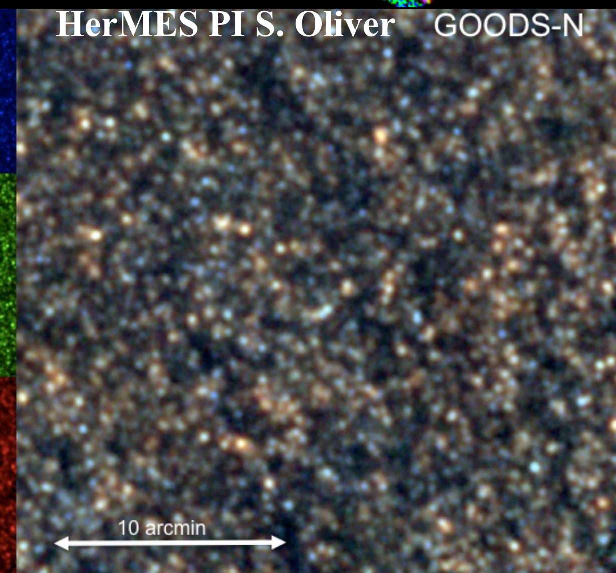
Herschel Surveys

provided a sample of several 10000 SMGs including several hundred lensed ones







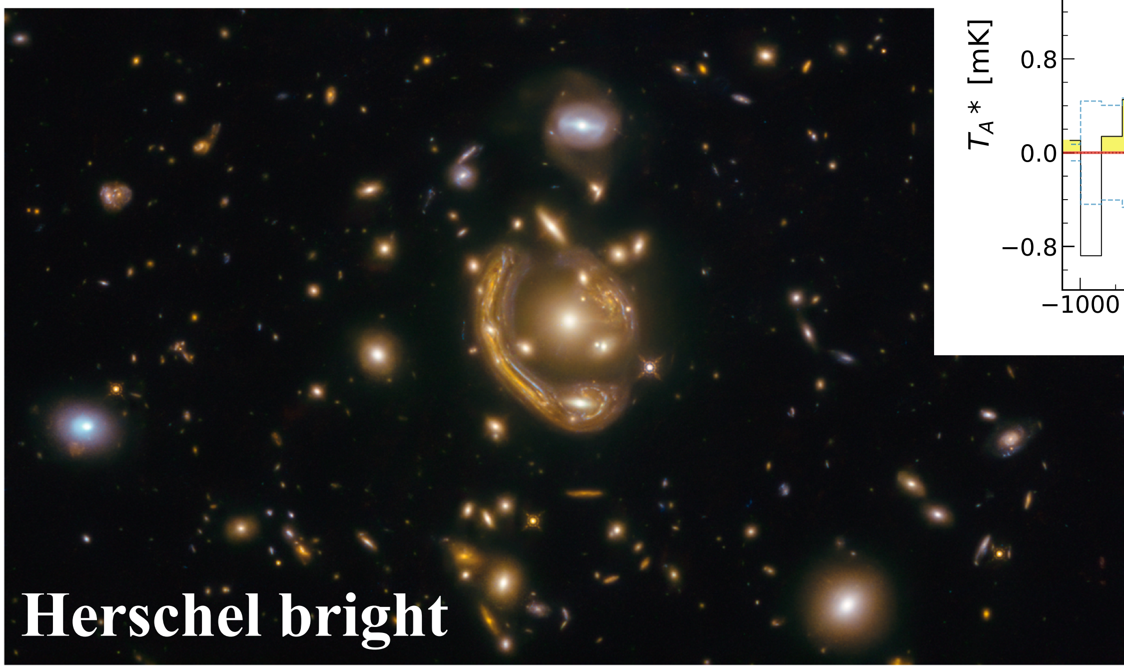


The Molten Ring @ z=1.48

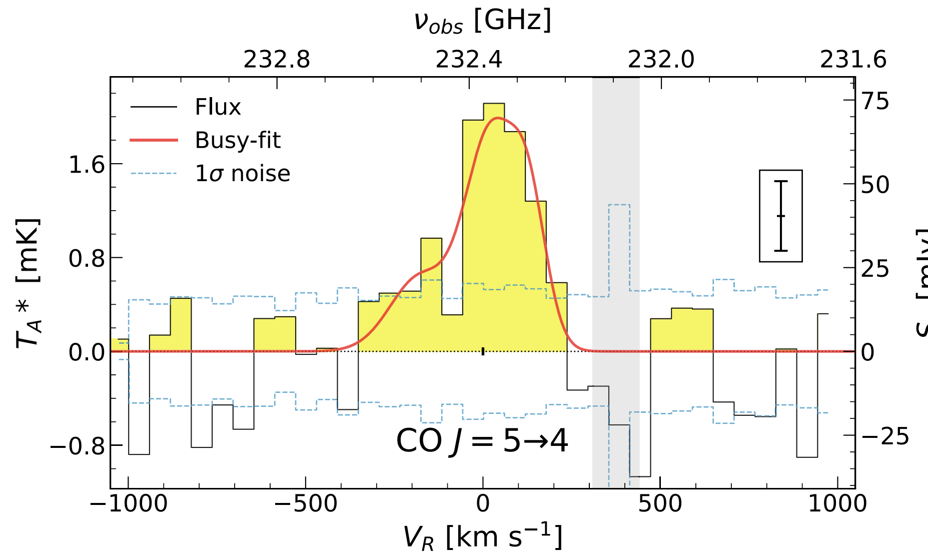
heic2109 — Science Release

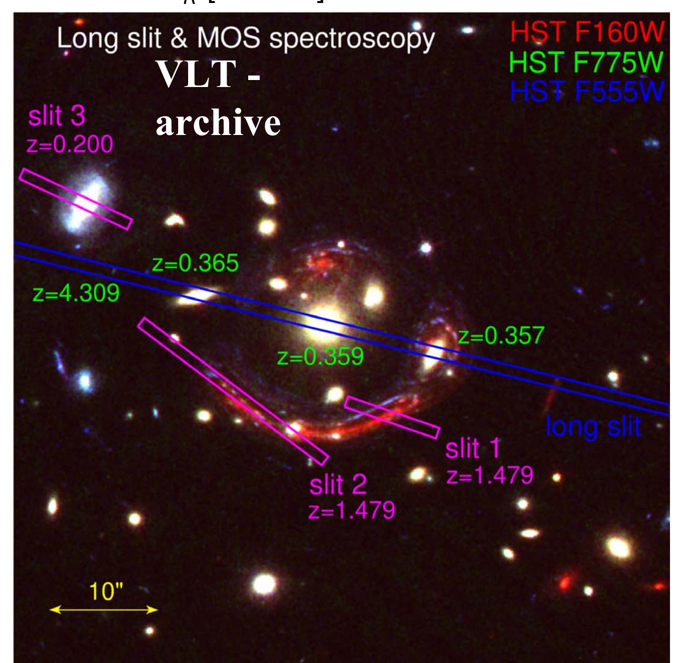
ESA/Hubble Picture of the Week Prompts New Understanding of Einstein Ring

23 September 2021



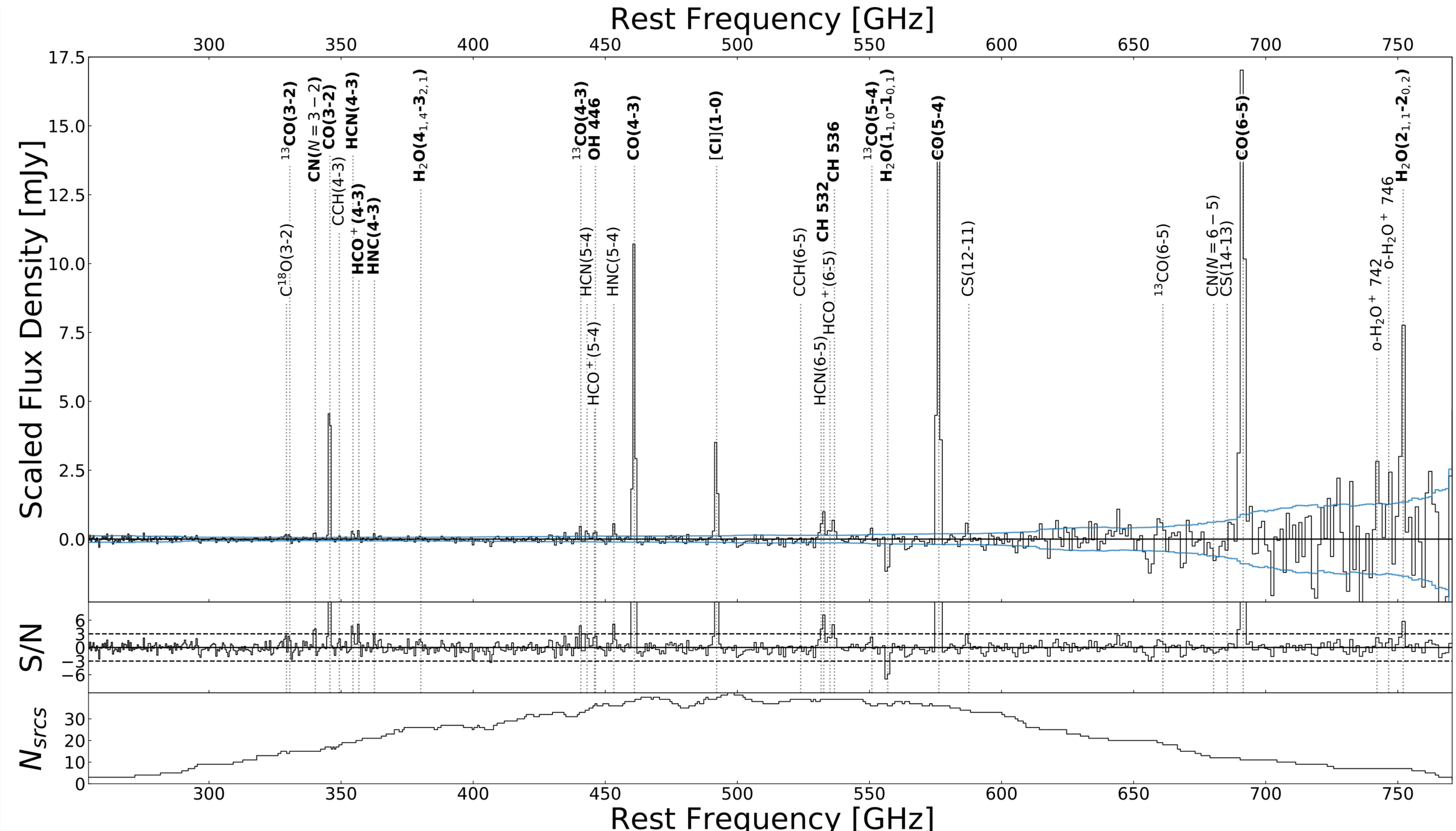
APEX Telescope





Diaz-Sanchez, Dannerbauer, Sulzenauer et al. 2021, ApJ

Dusty Star-Forming Galaxies (DSFGs)

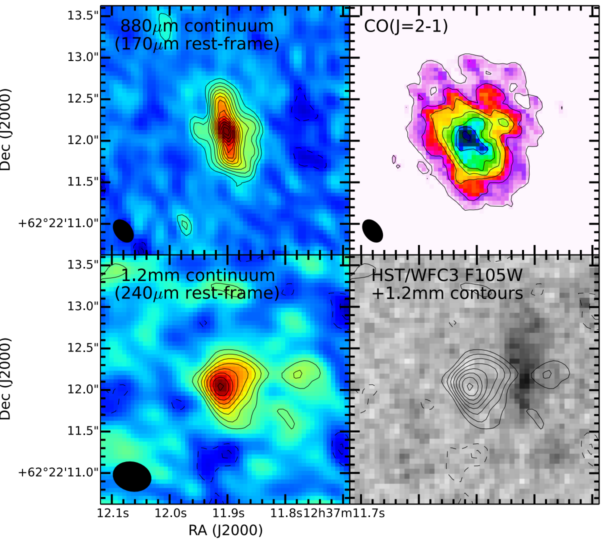


Reuter+22

stacked spectrum from 78 SPT selected lensed SMGs observed with ALMA

Protocluster traced via DSFG in GOODS-N

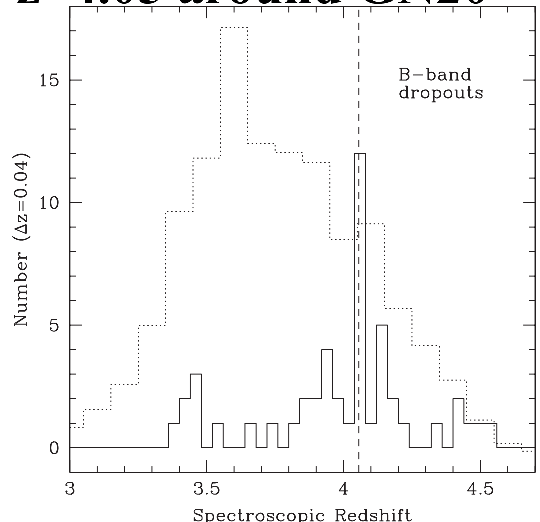
Hodge…HD et al. 2015

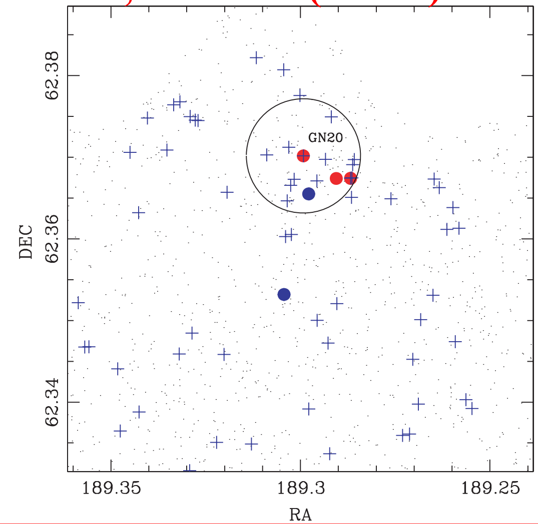


SMG GN20 @ z=4.05

z=4.05 around GN20

Daddi, HD et al.(2009a)

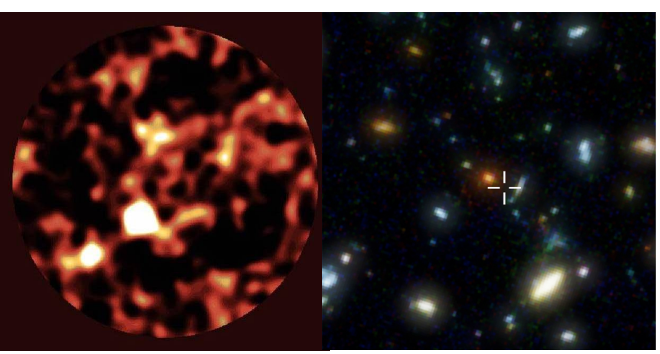


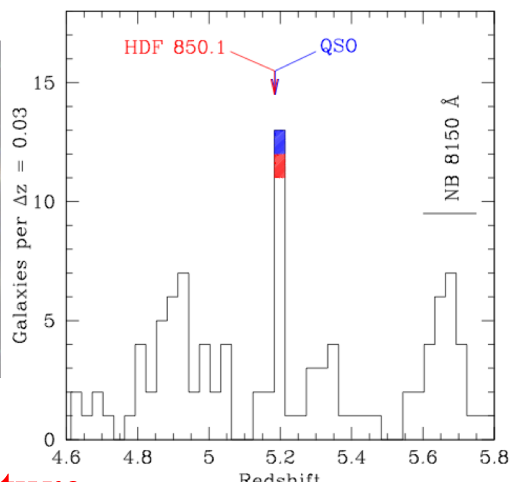


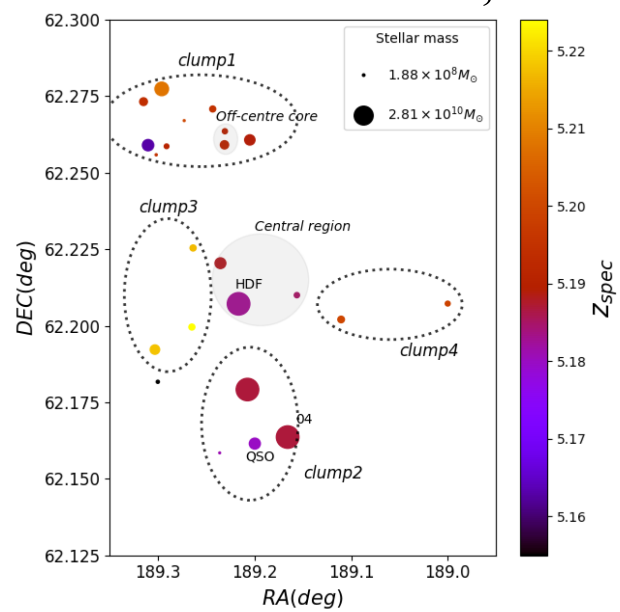
first time protocluster density enhancement found around a SMG

work extended with GTC: Calvi, HD+2021

PCL-HDF850.1 at z=5.2





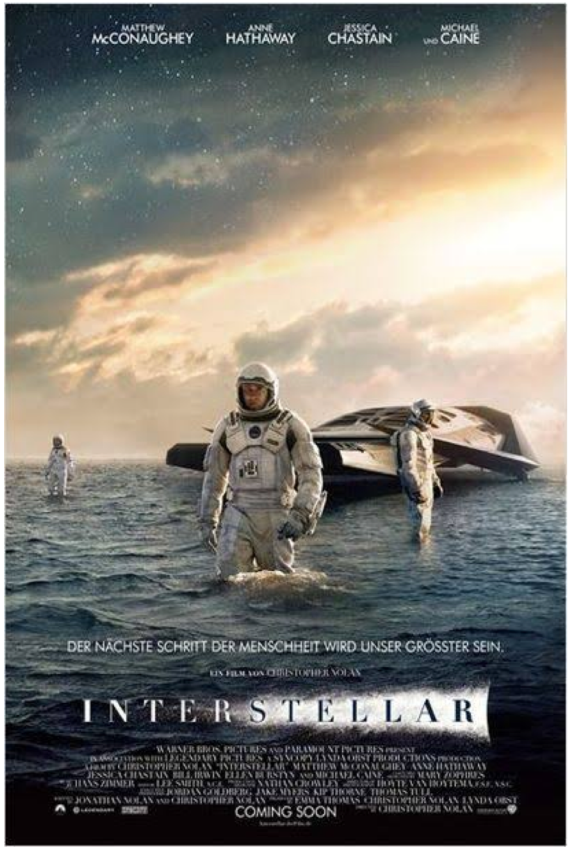


Walter … HD +, 2012, Nature

Galaxy Protoclusters (Clusters in Formation)

no official definition!

„Clusters of galaxies have back-stories worthy of a Hollywood blockbuster: their existences are marked by violence, death and birth, arising after extragalactic pile-ups where groups of galaxies crashed into each other“
by N. Seymour in on-line journal The Conversation

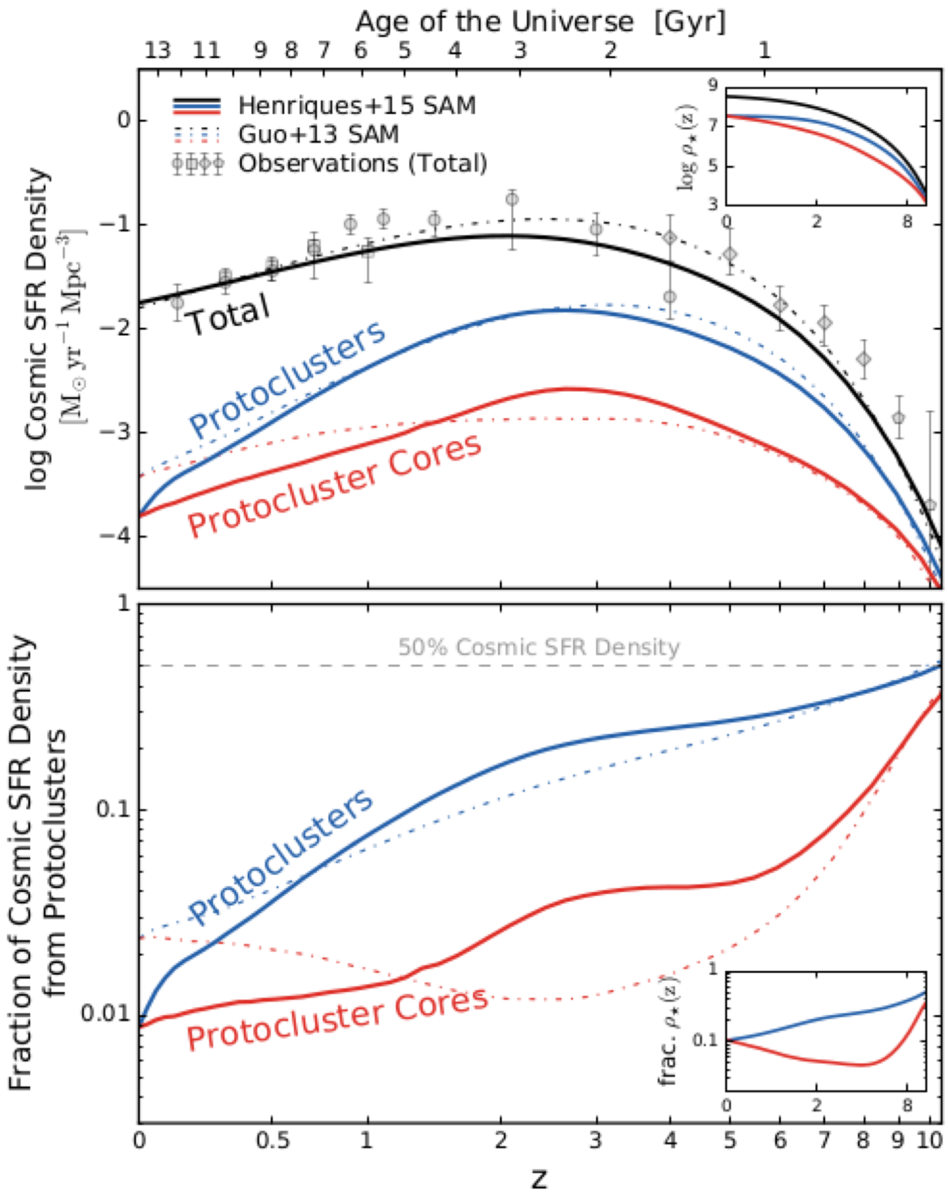


“a non-virialized structure in the distant universe which will finally collapse into a typical local galaxy cluster, a virialized system of a mass larger than 10^{14} M_{sun}”
R. Overzier, 2016, A&ARv, 24, 14

see talks by Kodama, Toshikawa and Kubo on this topic later today

for a review on dusty protoclusters see also Alberts & Stacey 2022

Protocluster contribution to the cosmic SFRD

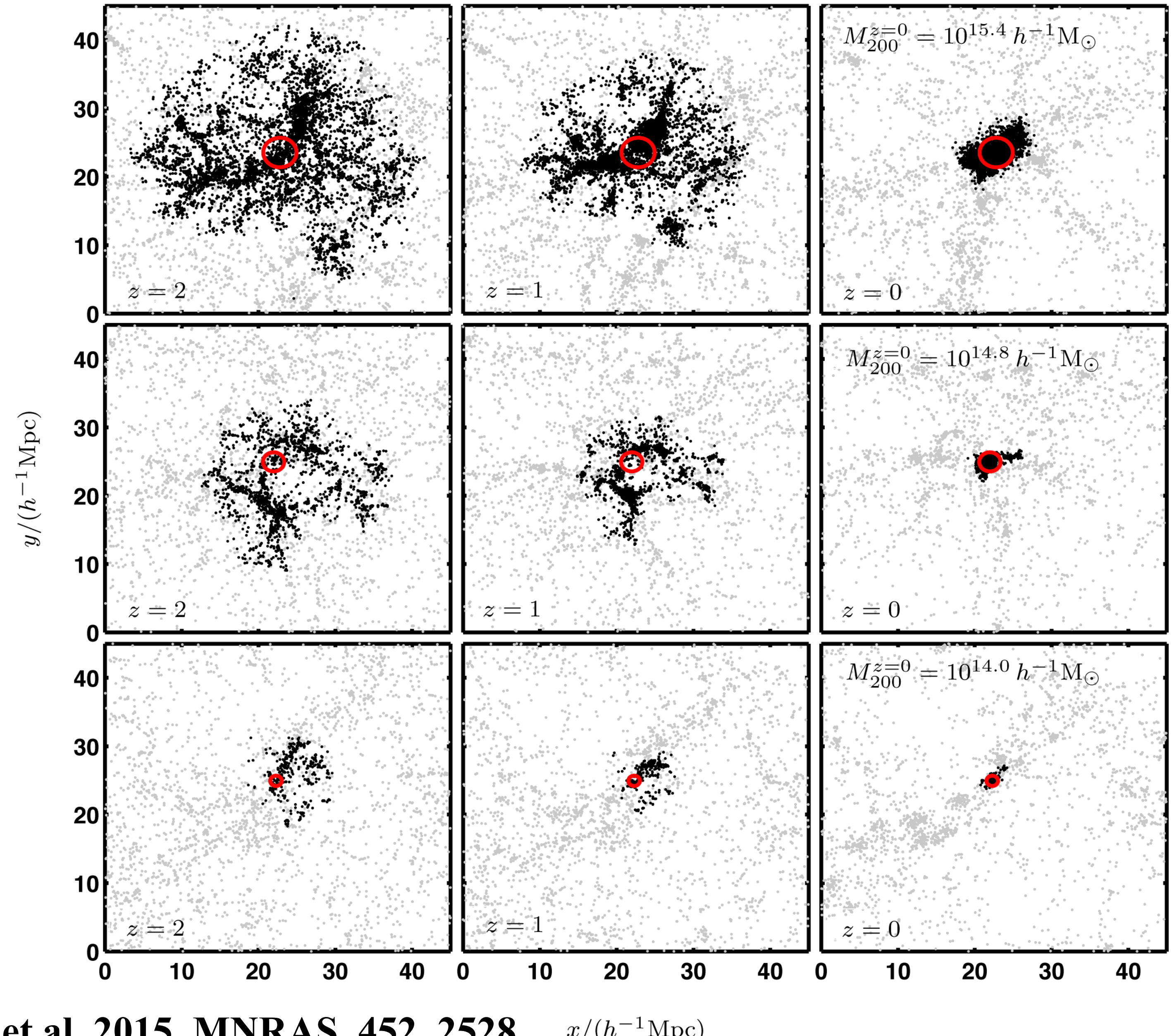


predictions!

still has to be tested

Chiang+2017

Sizes

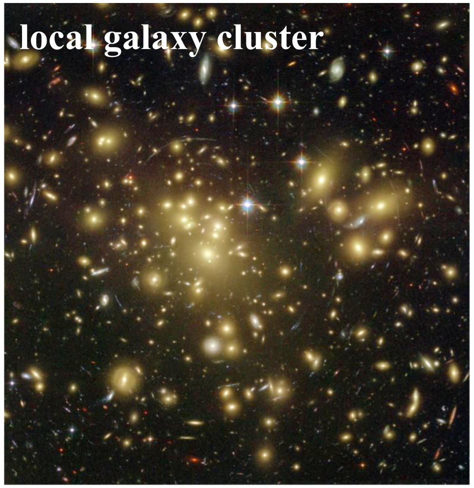


Muldrew et al. 2015, MNRAS, 452, 2528

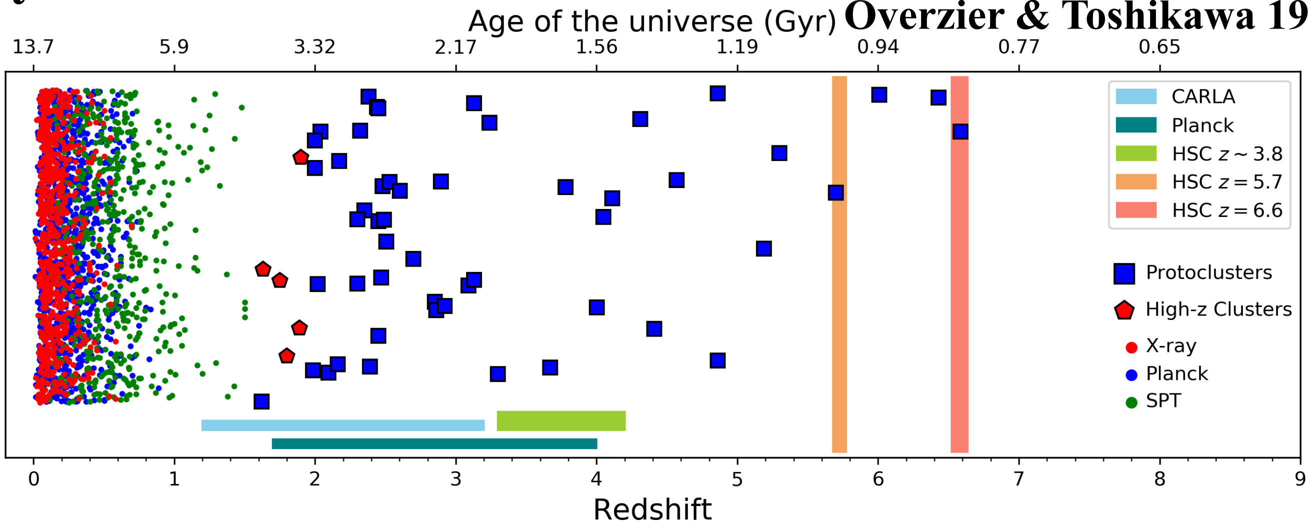
Some facts about protocluster searches

- often targeted observations of very massive galaxies e.g HzRG
- discoveries are often serendipitous
- how they are composed? which fraction is obscured?
- dusty star forming galaxies are progenitors of elliptical galaxies which dominate local galaxy clusters
- up to now not too many DSFGs overdensities found through dedicated large (sub)mm-surveys

for a review on dusty protoclusters see also Alberts & Stacey (2022)



Overzier & Toshikawa 19



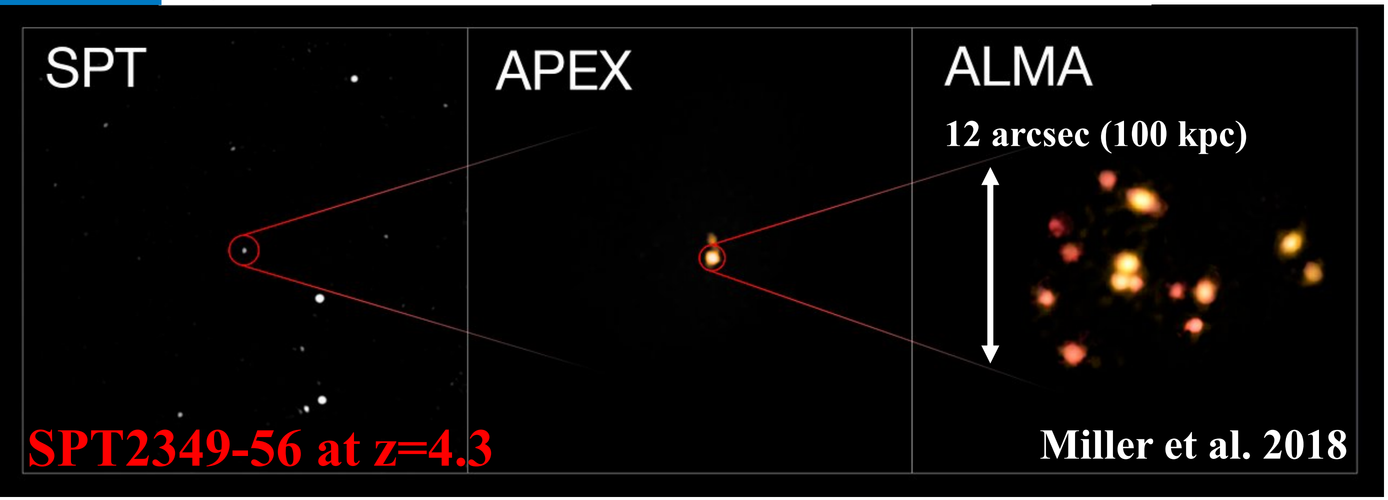
number of protoclusters will increase dramatically! ***Euclid will be crucial***

Ancient Galaxy Megamergers

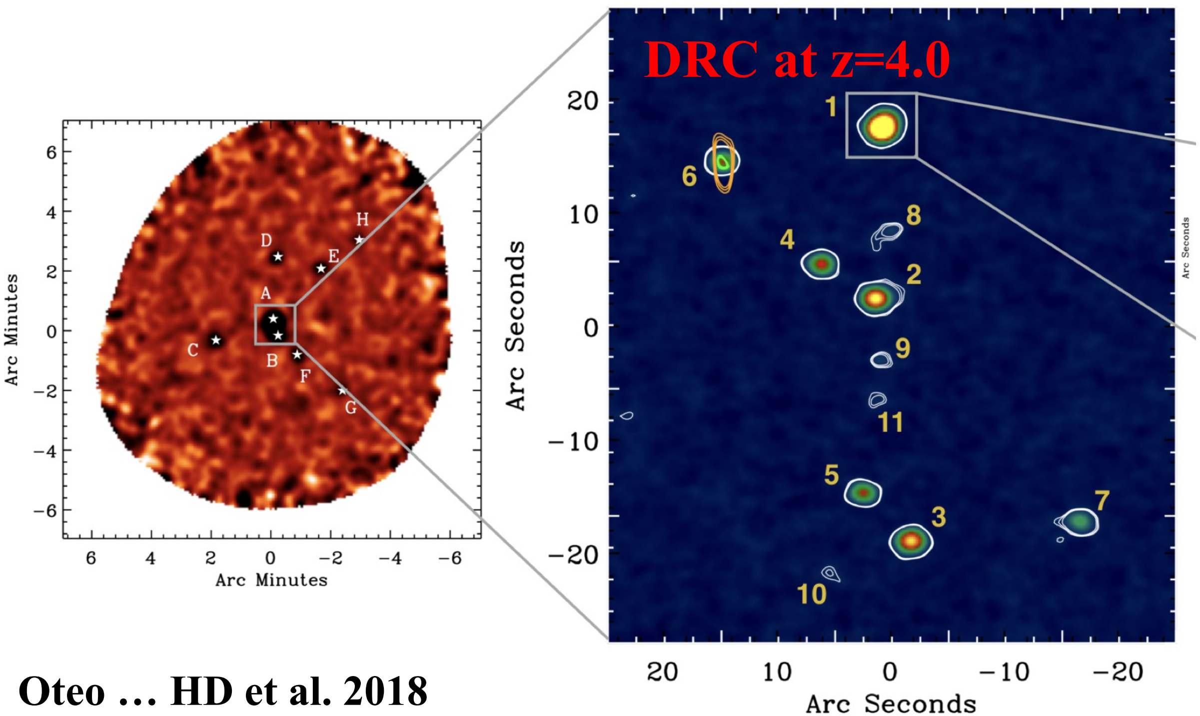
ALMA and APEX discover massive conglomerations of forming galaxies in early Universe

25 April 2018

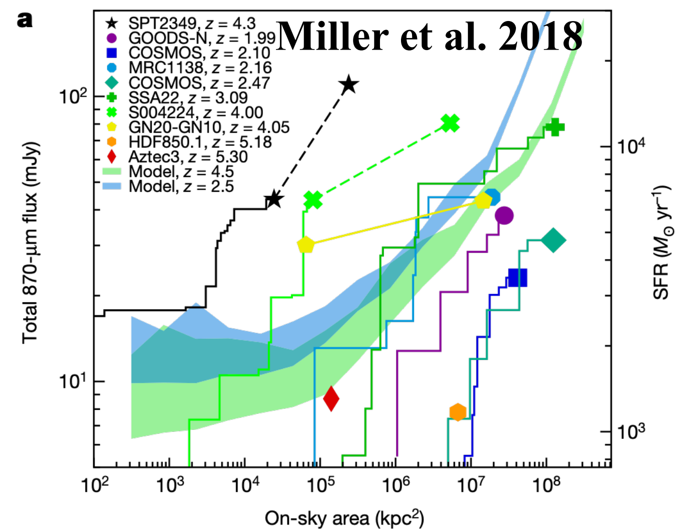
- **formation of protocluster core** $\longrightarrow$ **BCG in formation**



more than a handful discovered now by SPT-team



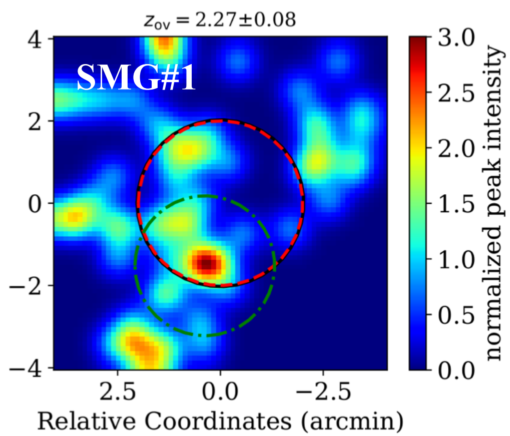
Oteo … HD et al. 2018

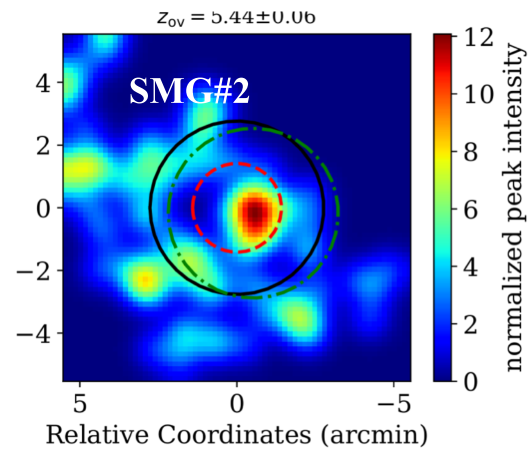


SFR not consistent with simulations – but see now work by Remus+2022

Could SMGs be signposts of protoclusters?

- we are using the PPM (Poisson Probability Method) cluster finder (Castignani et al. 2014ab), now tailored to find protoclusters (Castignani+19)
- prior is needed, find Mpc-scale structures
- pilot study, priors are 12 SMGs with CO-spectroscopic redshifts
- using several photometric catalogues (UV-sel; opt-NIR; FIR)



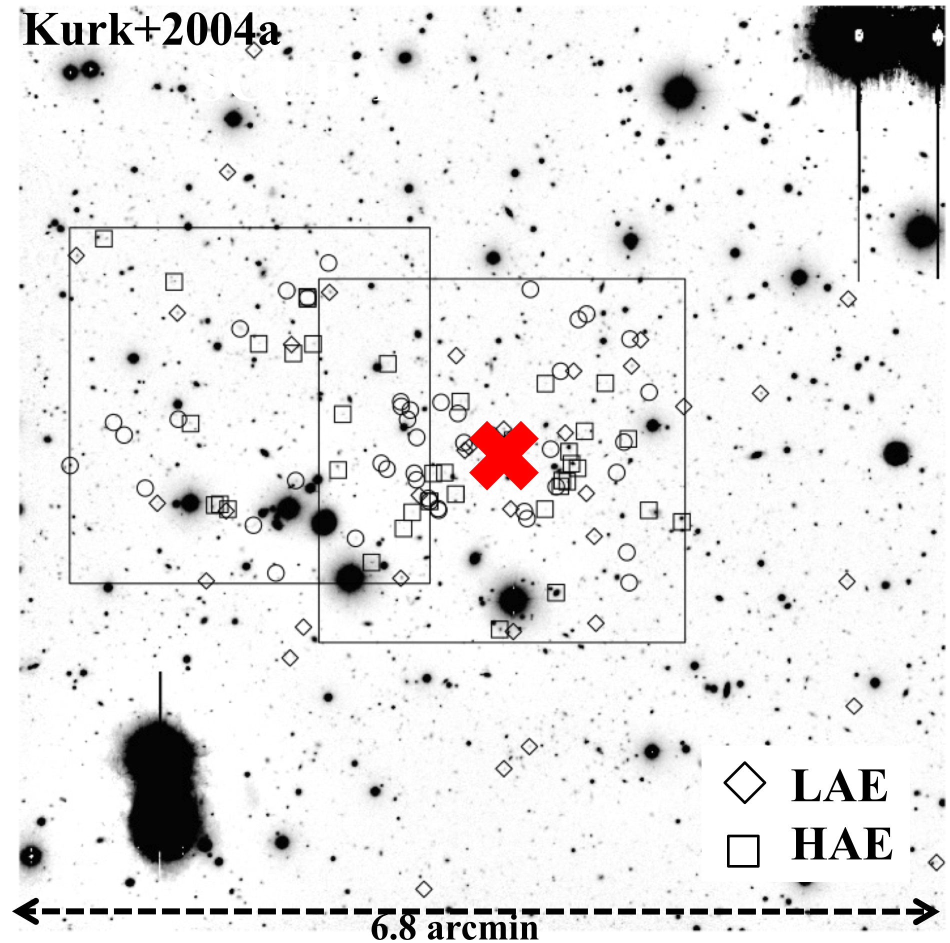


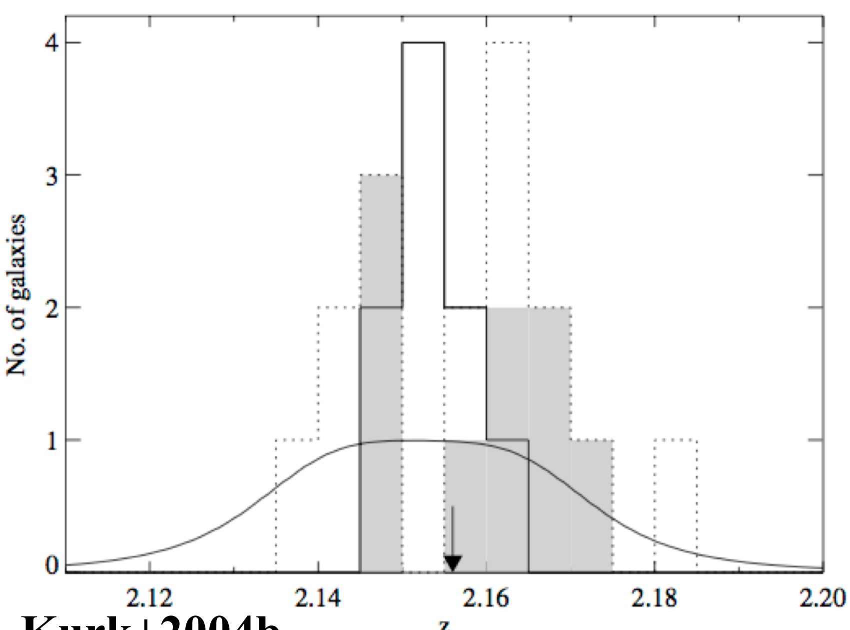
- 10 of 12 SMGs are found to be located in protoclusters
- we find five new one
- in some cases mis-centering between cluster center and SMG
- apply this pilot study on forthcoming surveys such as Euclid, LSST, wFIRST, MOONS

Calvi, Castignani & Dannerbauer, in prep.

Protocluster MRC1138 @ z=2.16

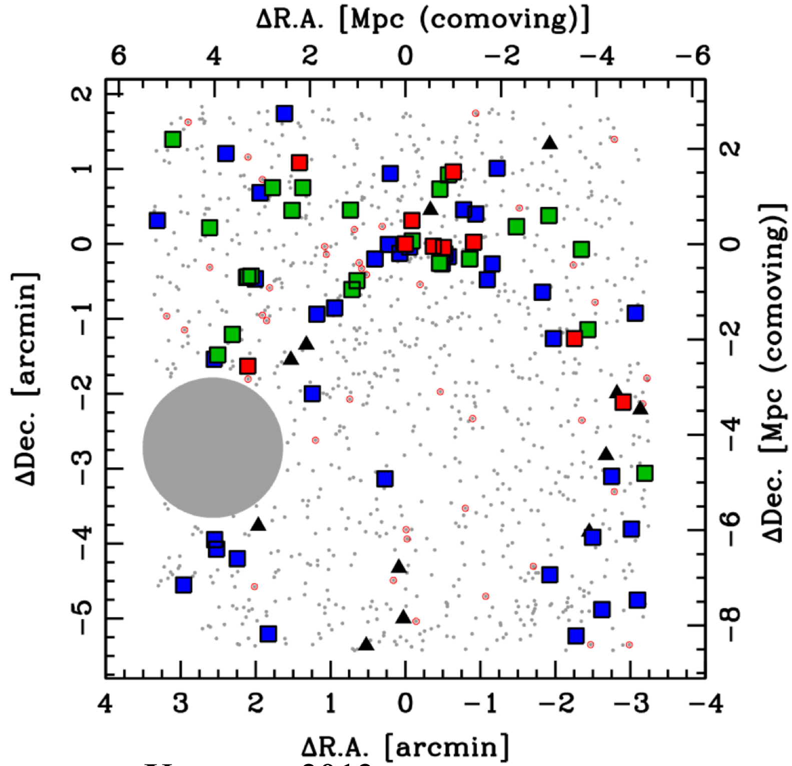
good example for combination of optial/NIR & (sub)mm/FIR telescopes



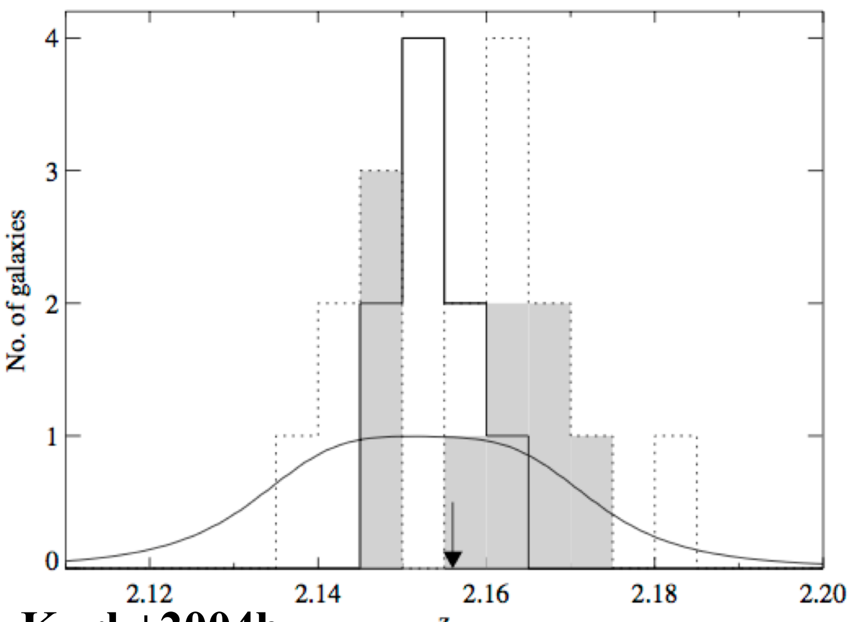


Kurk+2004b

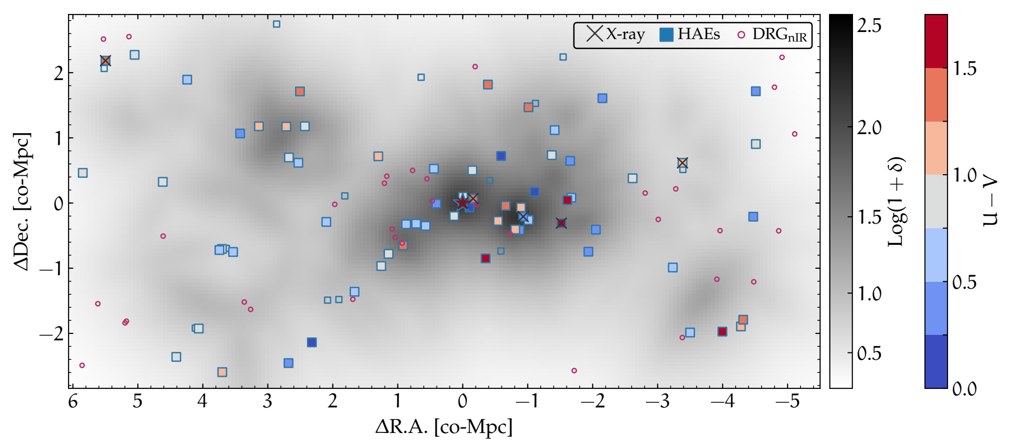
Protocluster MRC1138 @ z=2.16



Koyama+2013



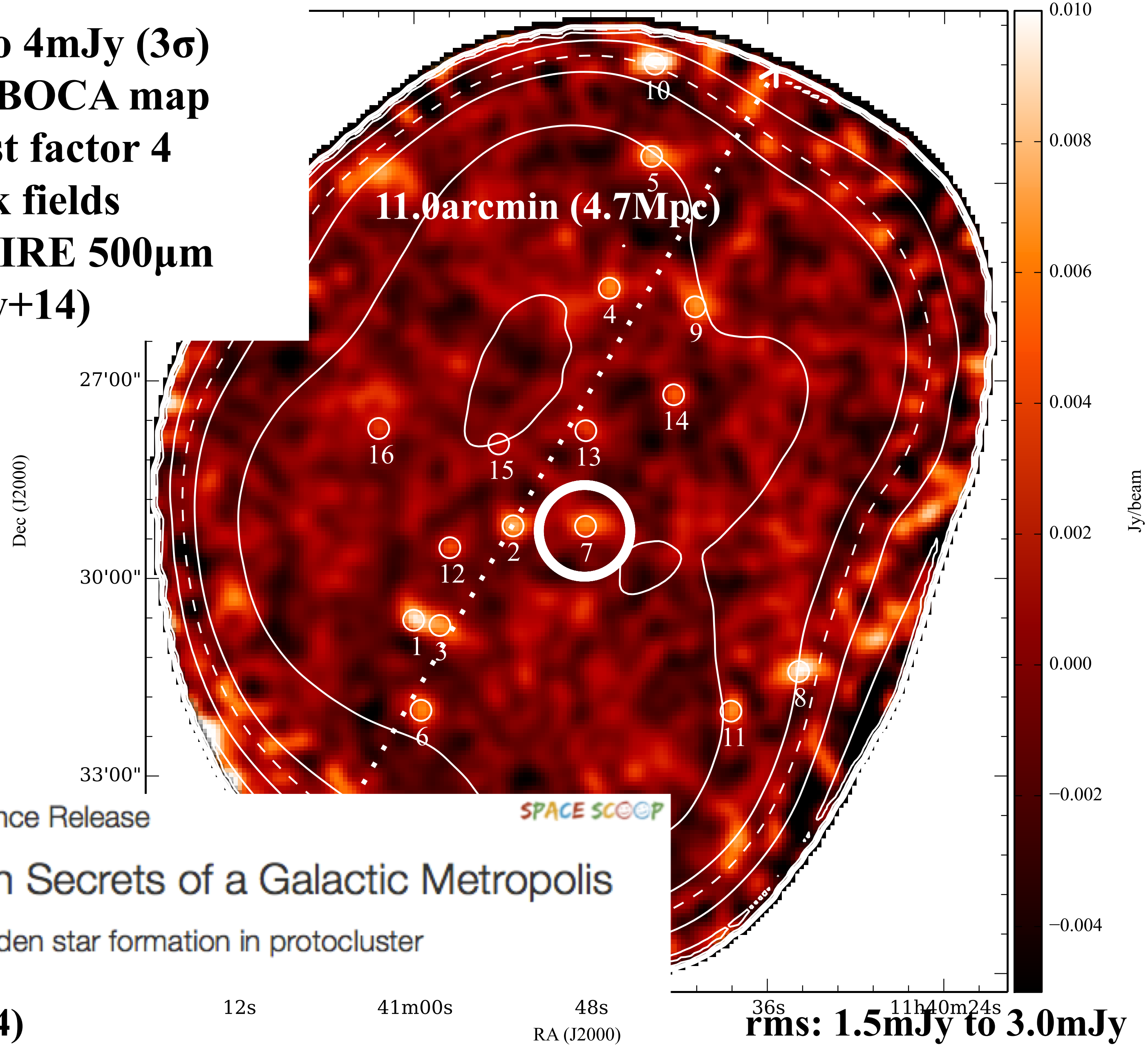
Kurk+2004b



Shimakawa … HD et al. 2018, MNRAS

APEX LABOCA Observations

- 16 sources down to 4mJy (3σ)
- one of deepest LABOCA map
- overdensity at least factor 4 compared to blank fields
- consistent with SPIRE 500μm overdensity (Rigby+14)



eso1431 — Science Release

SPACE SCOOP

Construction Secrets of a Galactic Metropolis

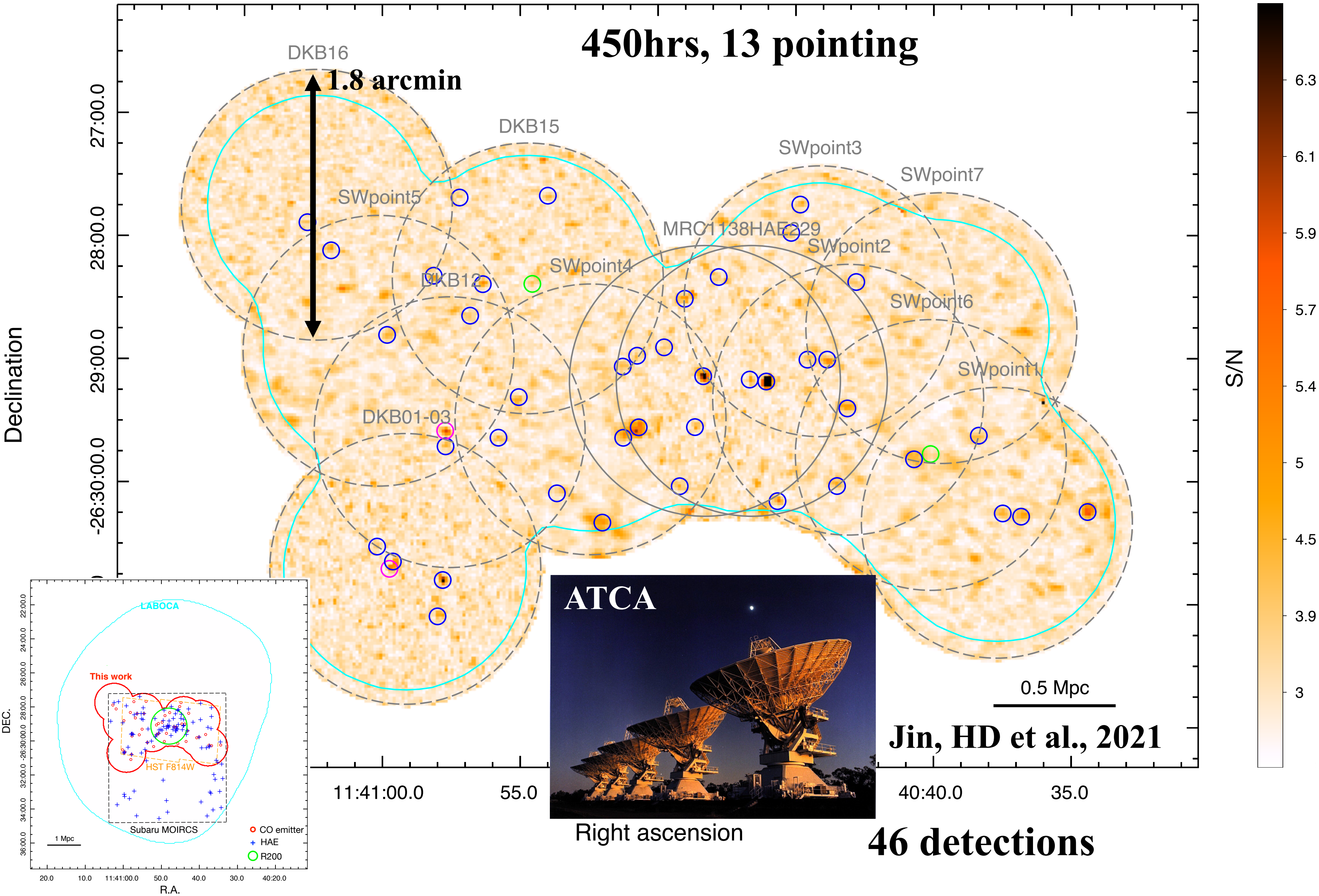
APEX reveals hidden star formation in protocluster

15 October 2014

Dannerbauer et al. (2014)

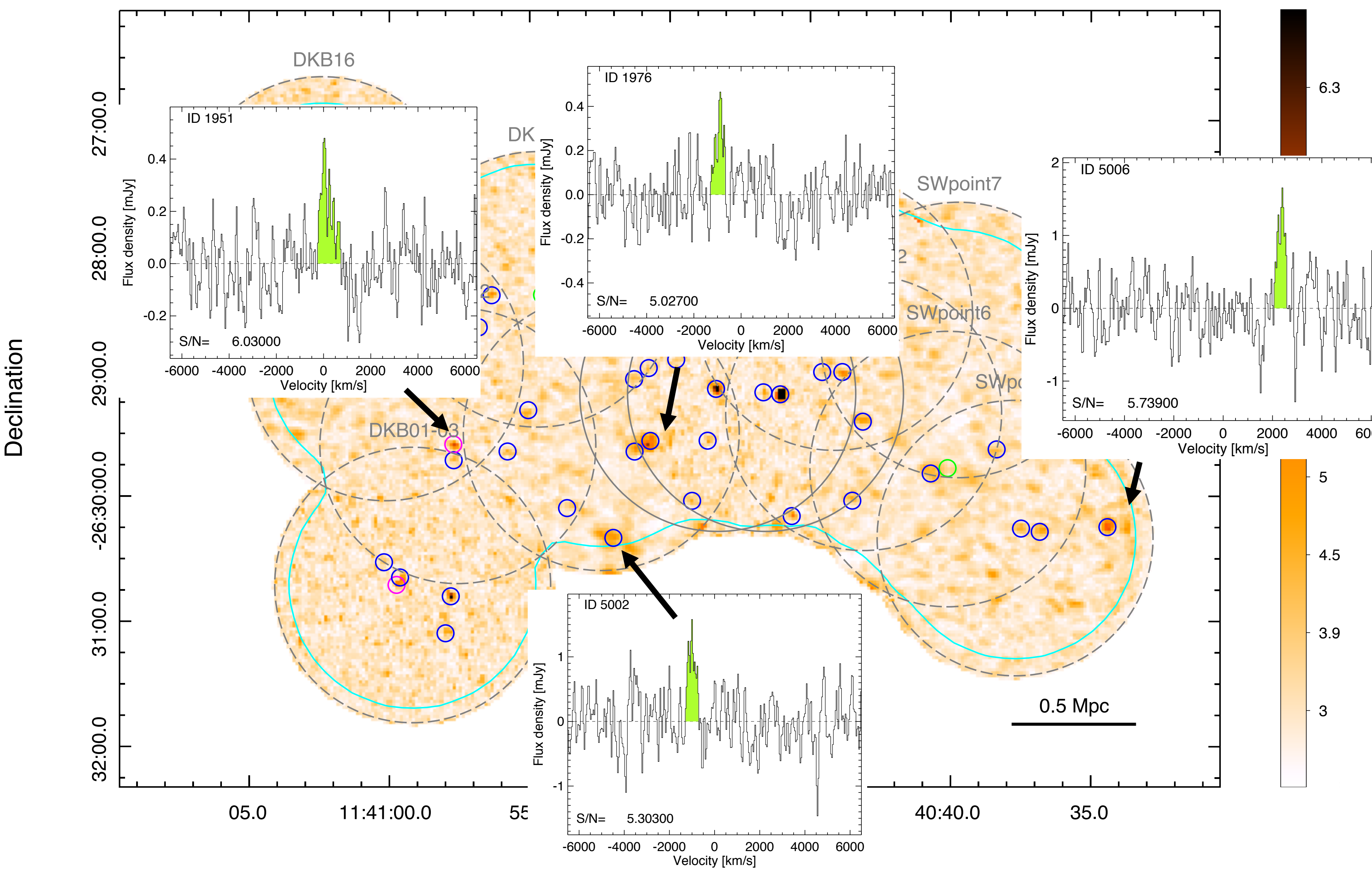
rms: 1.5mJy to 3.0mJy

COALAS survey: ATCA CO(1-0) map



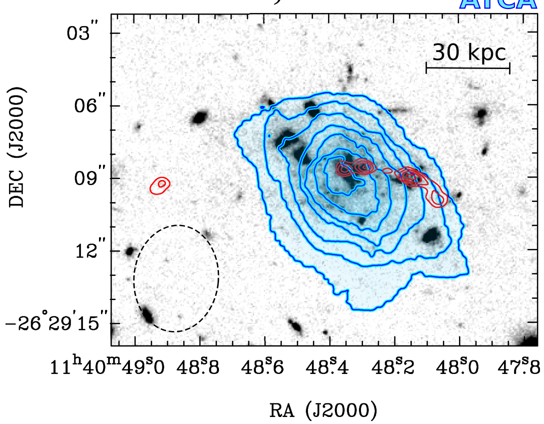
46 detections

COALAS survey: ATCA CO(1-0) map

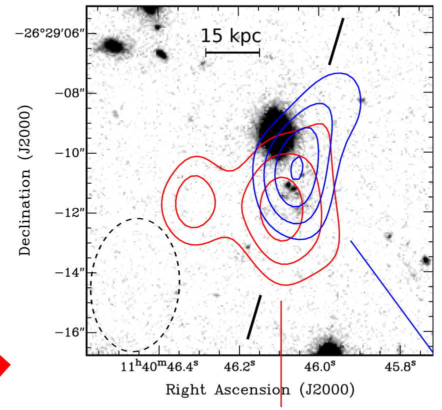


Search for large molecular gas reservoirs

Emonts+2016, 2018

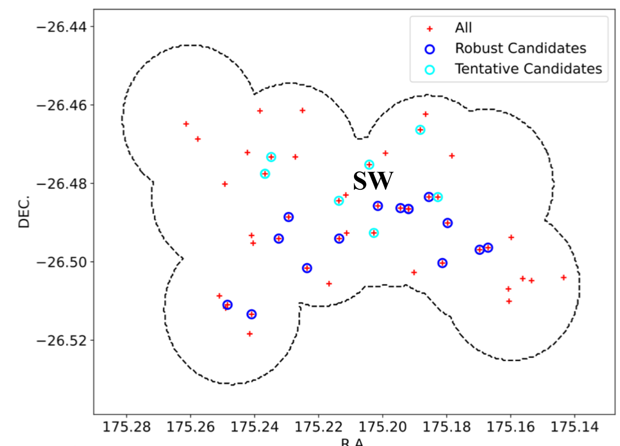


Dannerbauer+2017



PhD student Zhengyi Chen, Nanjing U + IAC

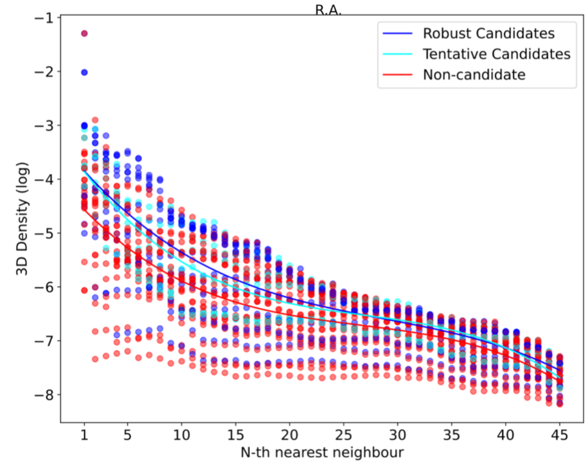
large molecular gas reservoirs could feed the ICM through truncation



<u>Triggered systematic search for such phenomena</u>

→Results

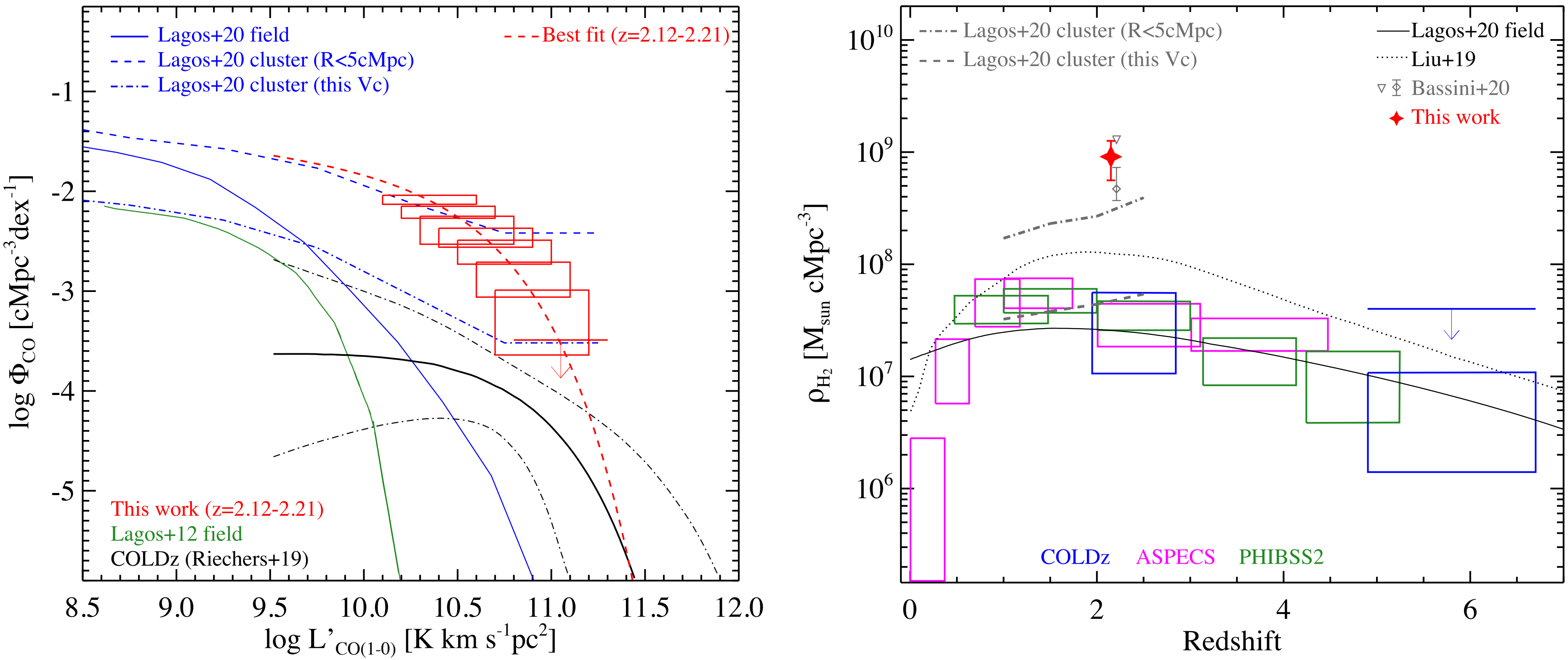
- **14 robust + 7 tentative candidates of large gas reservoirs found**
- **candidates locations concentrated on the core region of the Spiderweb protocluster**
- **candidates tend to be located in the dense local environment**



Chen, Dannerbauer et al. in prep.

CO luminosity function in protocluster

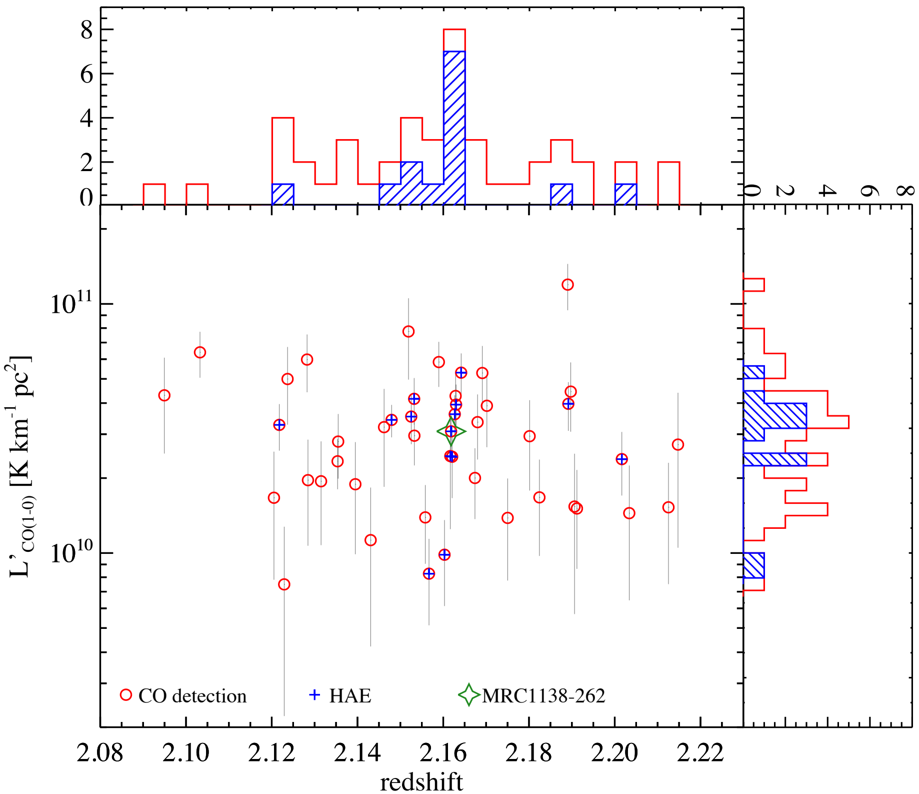
Jin, HD et al., 2021

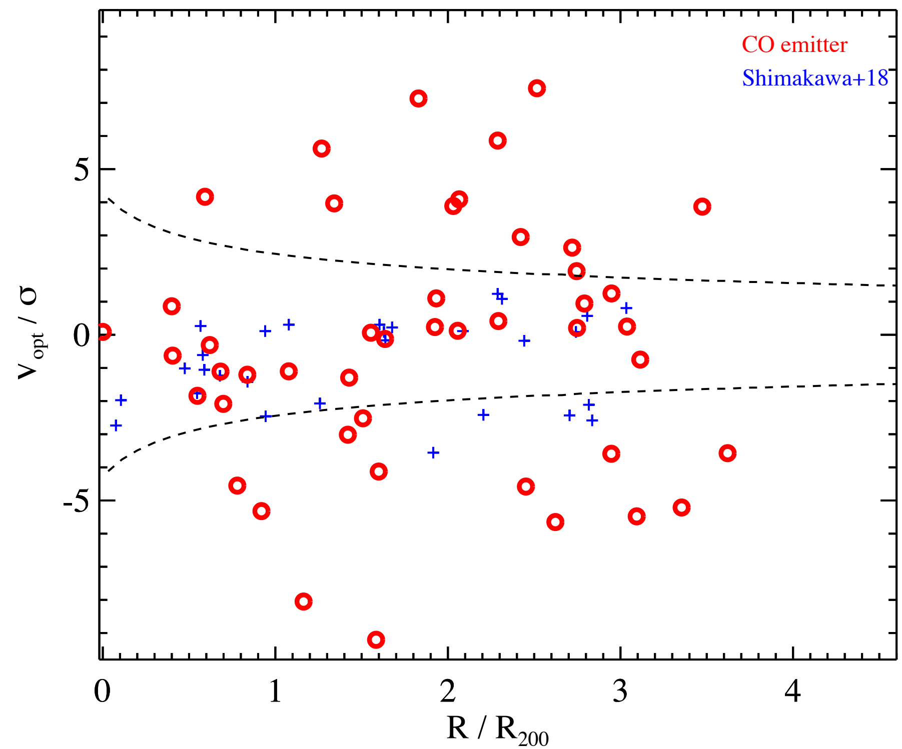


The CO LF in Spiderweb cluster is higher than the field CO survey COLDz in 1.5—2 order of magnitude, indicating that this cluster has 20-60x higher H2 density than field environment.

Superprotocluster or filaments

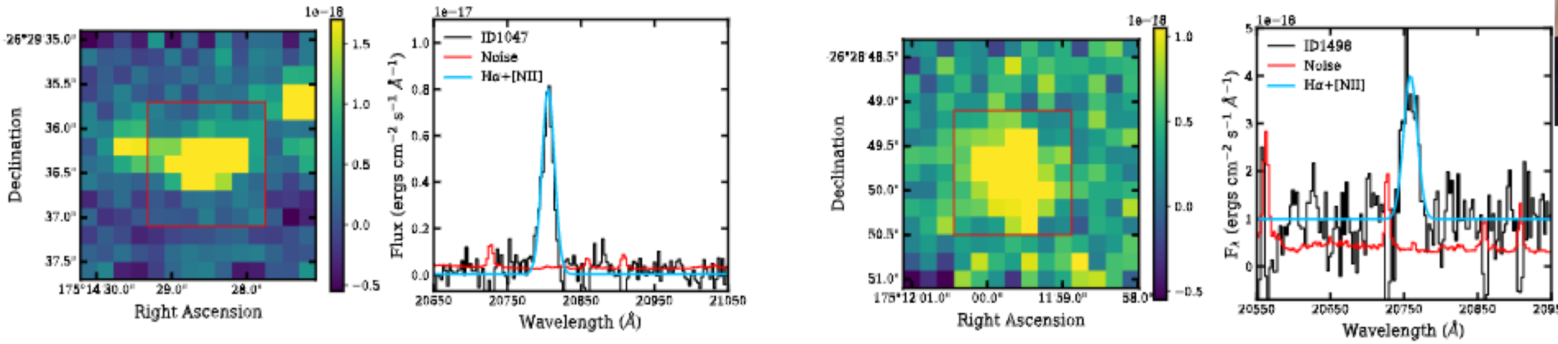
Jin, HD et al., 2021

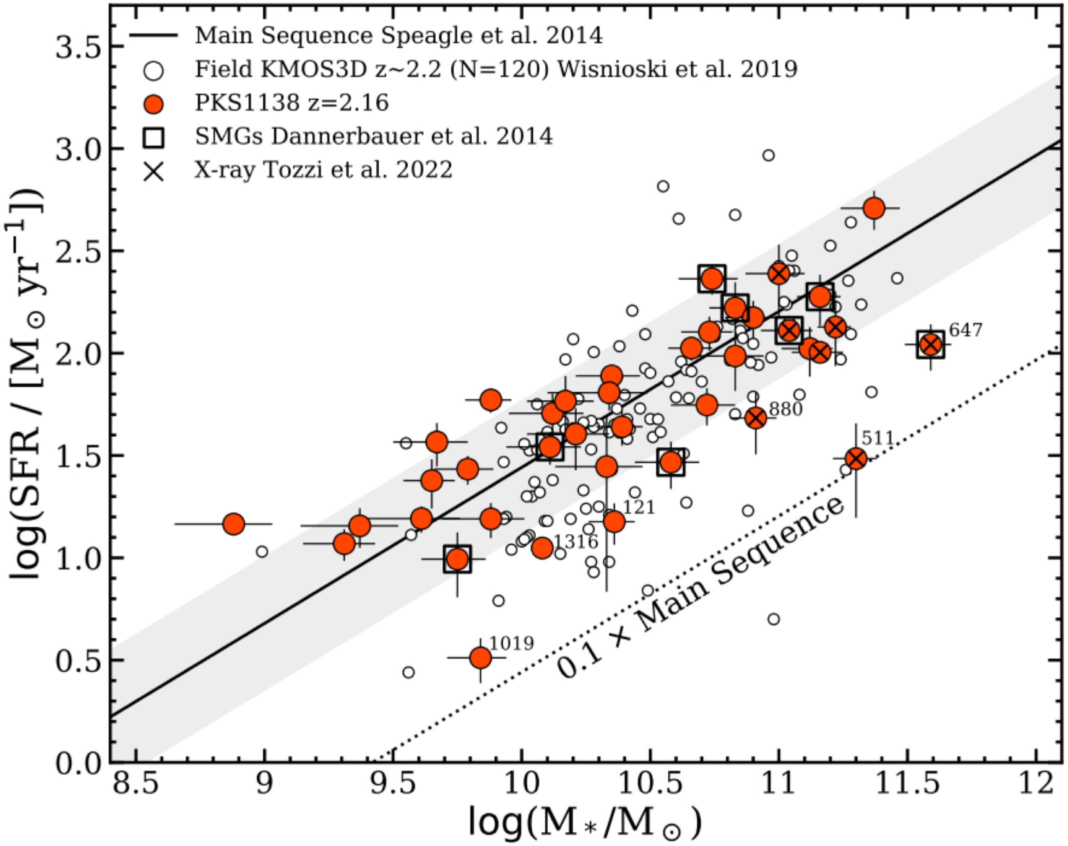




approx. 120 cMpc size

VLT-KMOS spectroscopy of ~40 HAEs





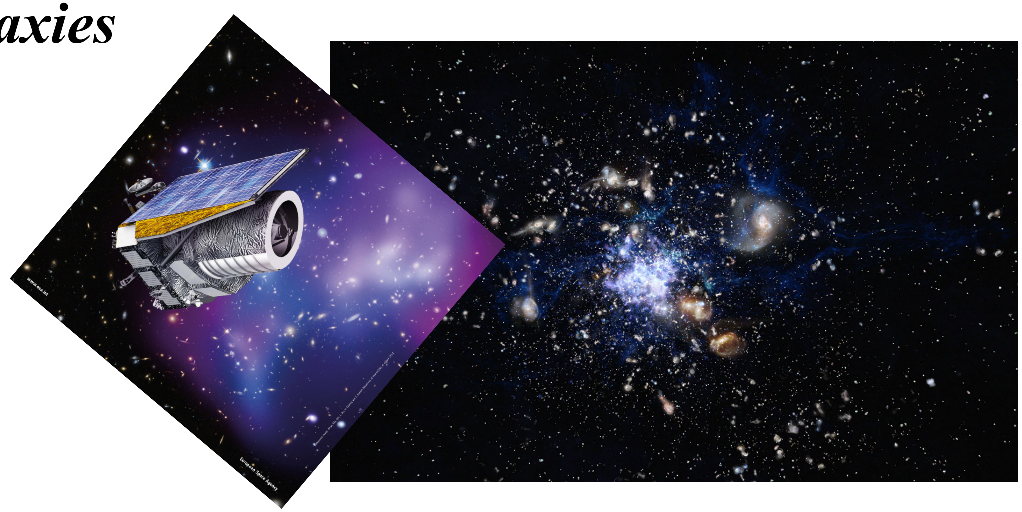
Jose Manuel Pérez-Martínez, HD et al., 2022

Protoclusters in Euclid

two work packages in Euclid deal with the topic *protocluster*

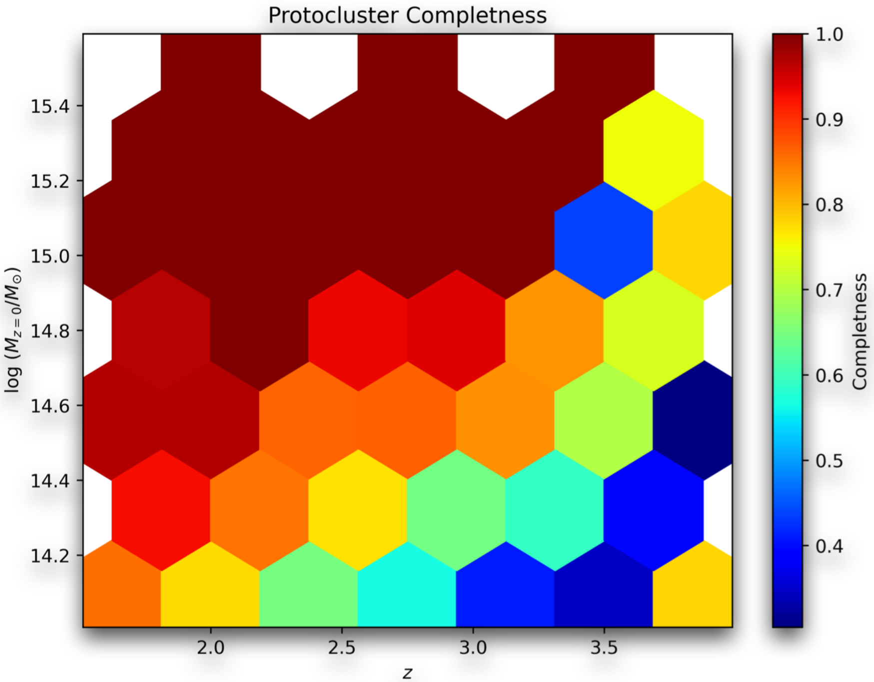
- ***Clusters of Galaxies Science Working Group <u>WP11 protoclusters </u>(co-leads: Olga Cucciati & Helmut Dannerbauer): search for protoclusters and conduct their study as a whole***

- ***GAESWG Galaxy Evolution & AGN Science Working Group <u>WP3 Galaxy Evolution in different environments </u>(co-leads: Manuela Magliocchetti & Jenny Sorce): study the environment and evolution of protocluster galaxies***

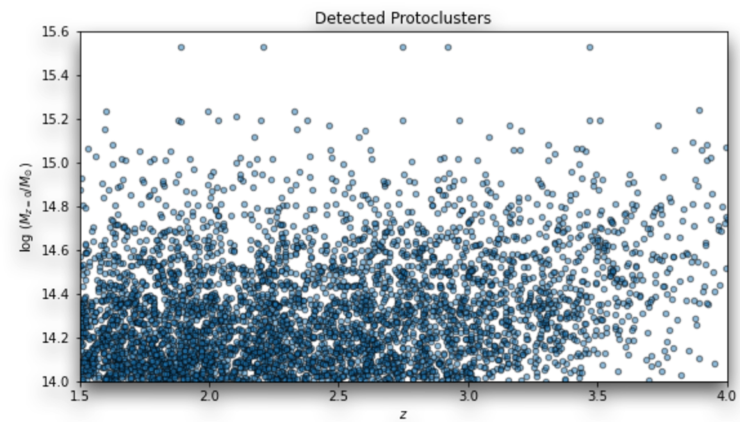


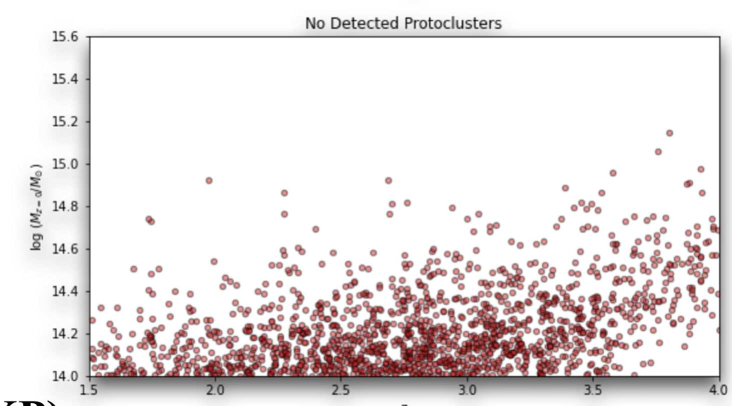
Search for Protoclusters in Euclid

CARTHAGO developed A. Díaz-Sanchez (UCPT). Efficient algorithm using multi-scalingTopHat convolution and FoF methods.



based on GAEA simulations (~22 deg^2) **(Fontano+2020)**





Purity 83 %
8190 detections: 3676 Clusters (45%) & 4363 Protoclusters (55%)

Expectations: Q1~200 pcl & DR1~10000 pcl

Díaz-Sanchez et al., in prep. (Euclid pre-launch KP)

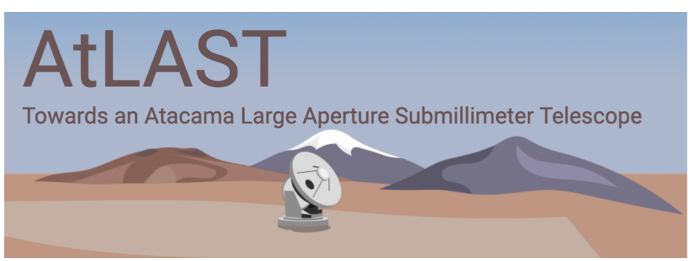
Conclusion

- **(sub)mm observations are indispensable to obtain a complete census of the cosmic star-formation rate density**

- **Euclid will be crucial to increase significantly the number of known galaxy clusters in formation (protoclusters)**

- **to get a full picture of galaxy clusters in formation and evolution of its members complementary observations in the (sub)mm are indispenable**

- **“MOS” unit in the (sub)mm window at a big telescope is needed**



- **submm follow-up of pre-selected targets, can be challenging, tedious but possible☺**