Star Formation in Difference Environments 2017 (SFDE17):
From local clouds to distant galaxies
6 – 12 August, 2017, ICISE, Quy Nhon, Viet Nam

Dusty star-forming galaxies explored with ALMA

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Collaborators

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- Thank the JAO and ARCs for their efforts on ALMA operation

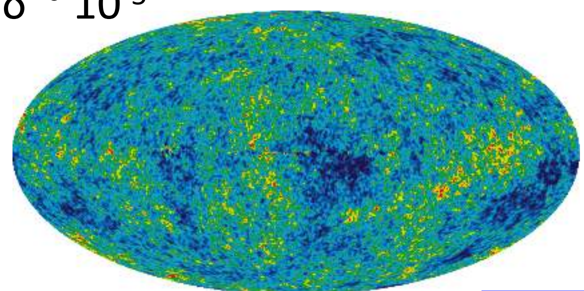
Outline

- Introduction
  - The importance of the dust-obscured part of galaxy formation history
  - Why conduct deep surveys using ALMA?
- Lessons from recent ALMA surveys on SXDF-UDS-CANDELS, HUDF, lensing clusters, and proto-clusters including SSA22 and XCS2215
  - Are we just measuring the dust properties of already known galaxies in the rest-frame UV/optical deep surveys?
  - Or are there any new obscured sources even in faint submillimeter galaxies?

Our current understanding of galaxy formation and evolution

Inflation ➔ Small density fluctuation

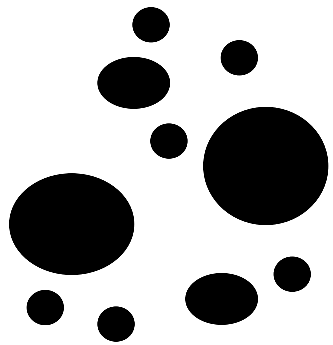
$\delta \sim 10^{-5}$



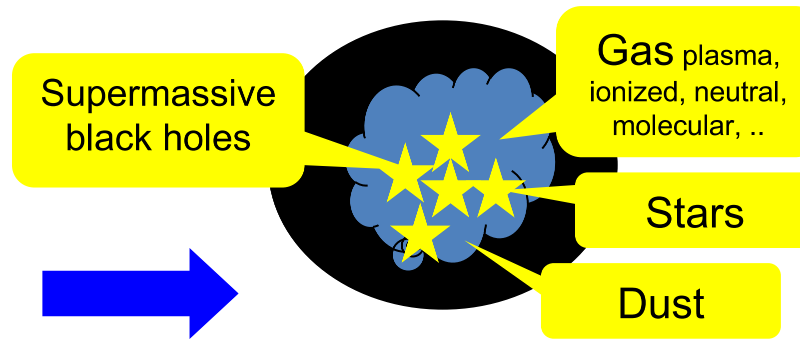
A temperature map of the cosmic microwave background (CMB) imaged using WMAP

redshift ~ 1100 (13.7 Gyr ago)

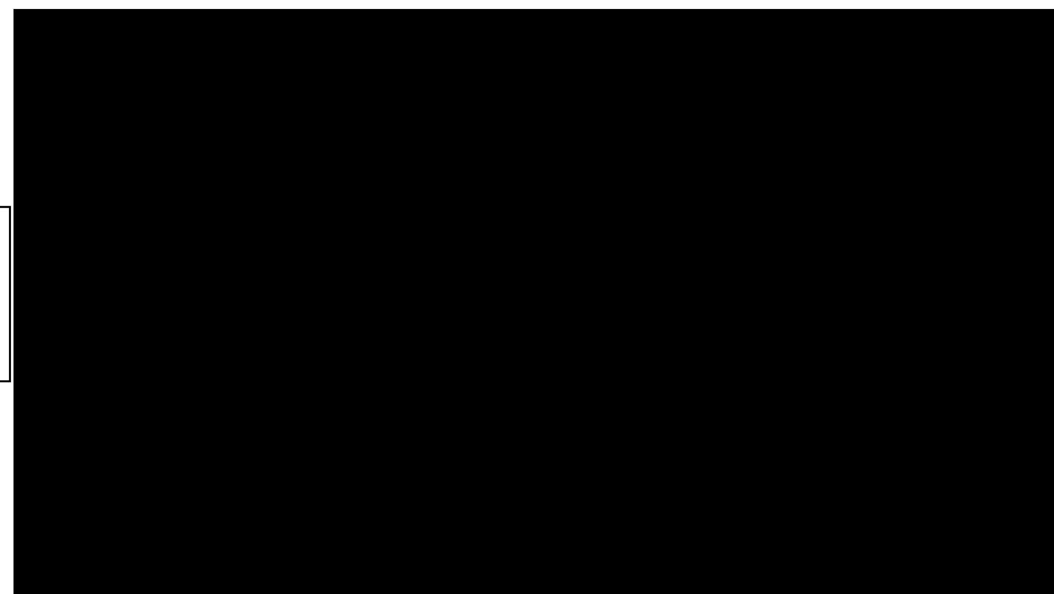
Growth of dark matter halos



Infall of baryons into dark matter halos ➔ formation & growth of galaxies



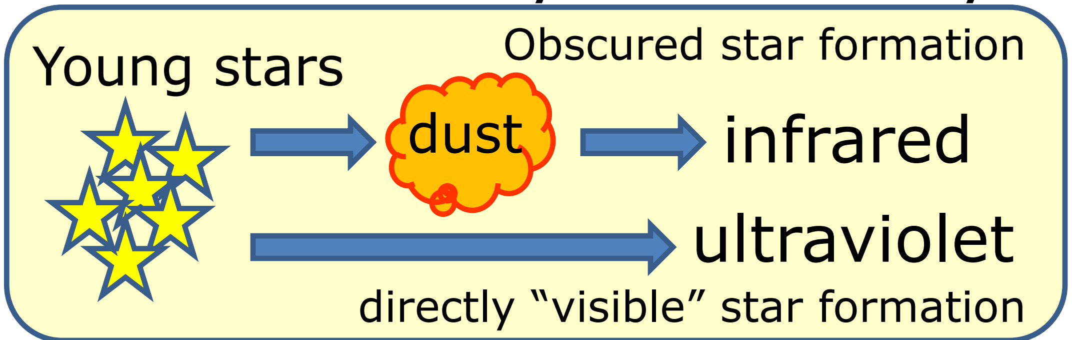
- most distant galaxy known: z ~ 11.09 (13.3 Gyr ago)
- re-ionization: z ~ 6–20? (12.8–13.5 Gyr ago?)
- first stars: z ~ 30? (13.6 Gyr ago?)
- recombination, "transparent to radiation": z ~ 1100

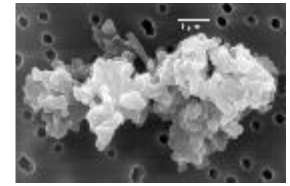


Simulation of dark matter & gas temperature distribution with ΛCDM

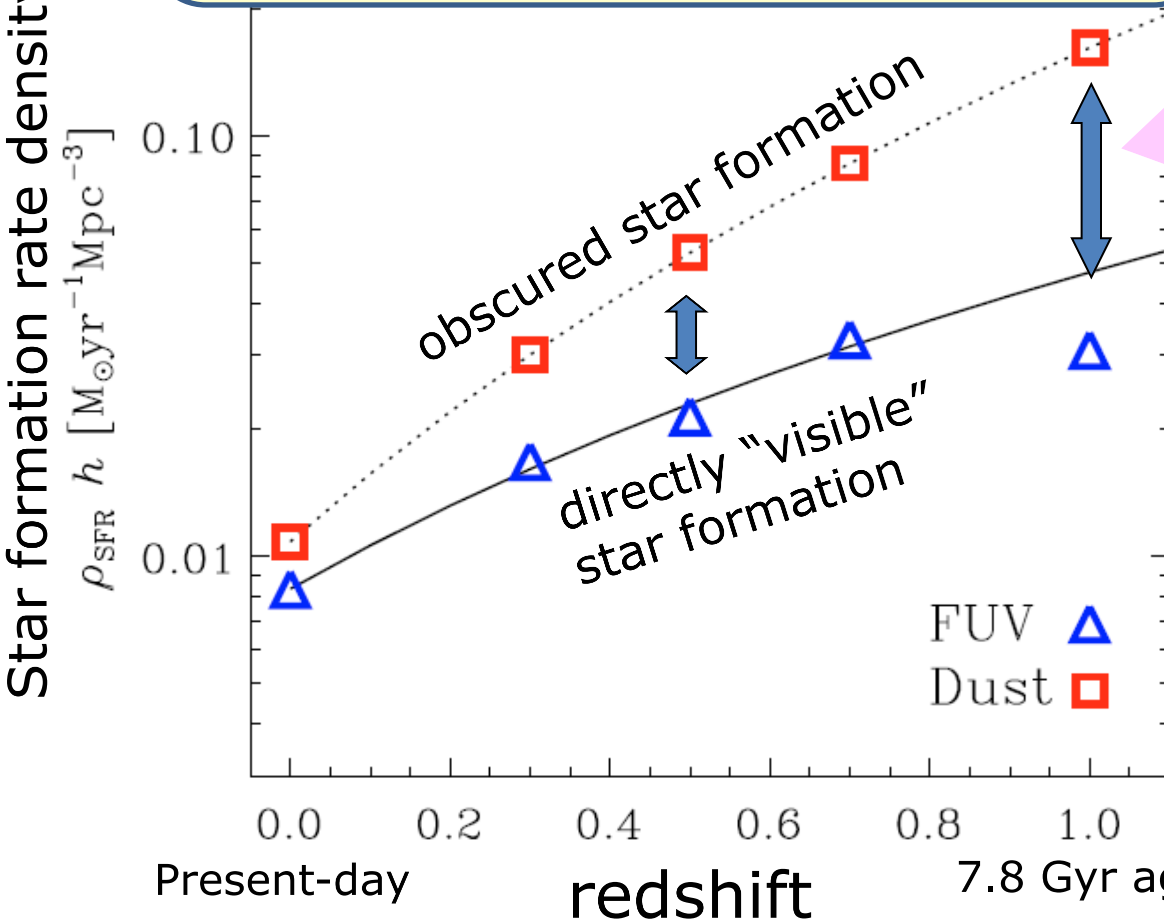
http://www.illustris-project.org/media/

Galaxies in their forming & evolving phases are often heavily obscured by cosmic dust





minerals,
up to ~1 μm
in size



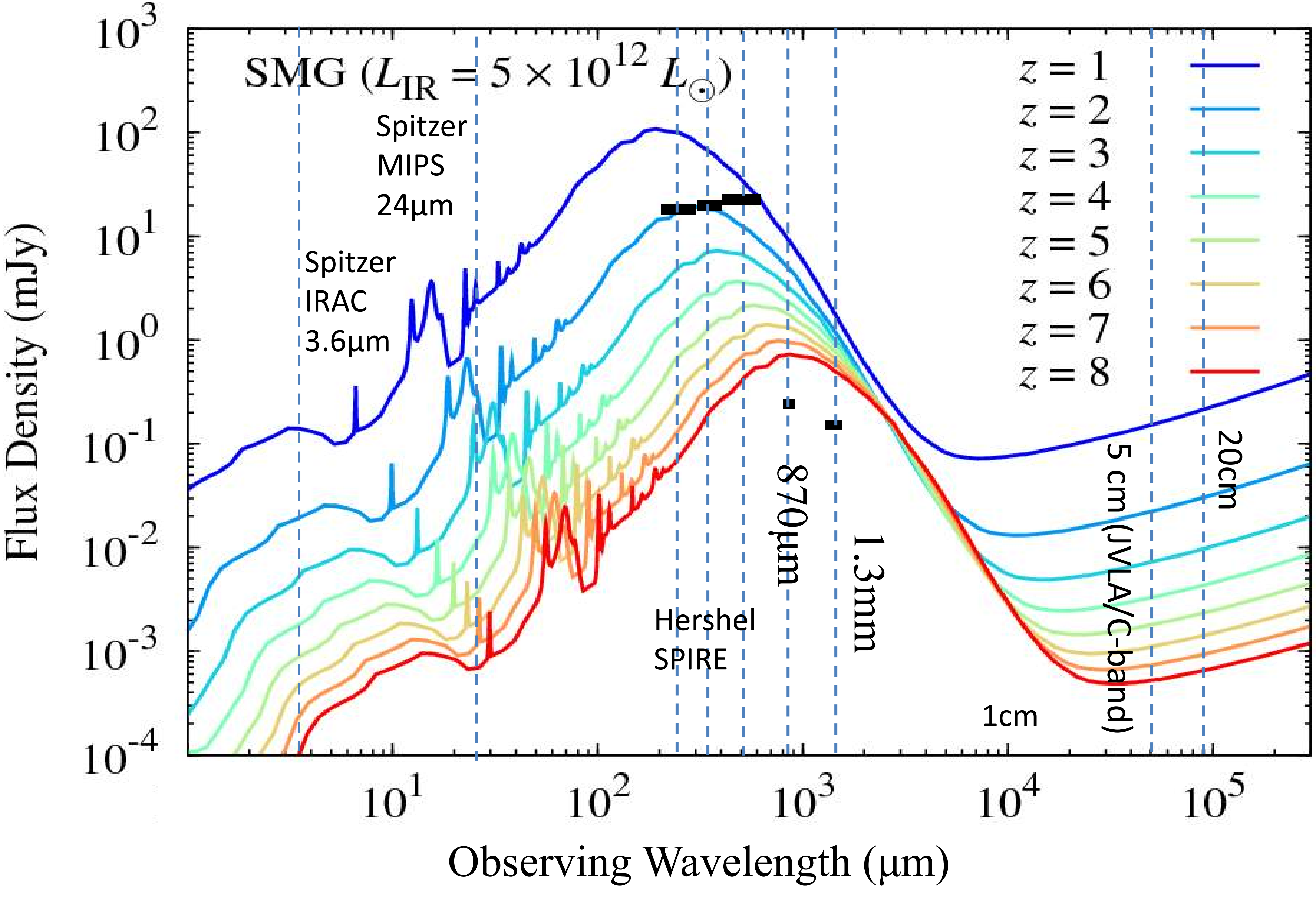
7.8 Gyr ago (Big Bang was ~13.7 Gyr ago)

More obscured star forming activity in earlier epoch of the universe

>70% is obscured
7.8 billion years ago

Takeuchi et al. 2005, A&A, 440, L17

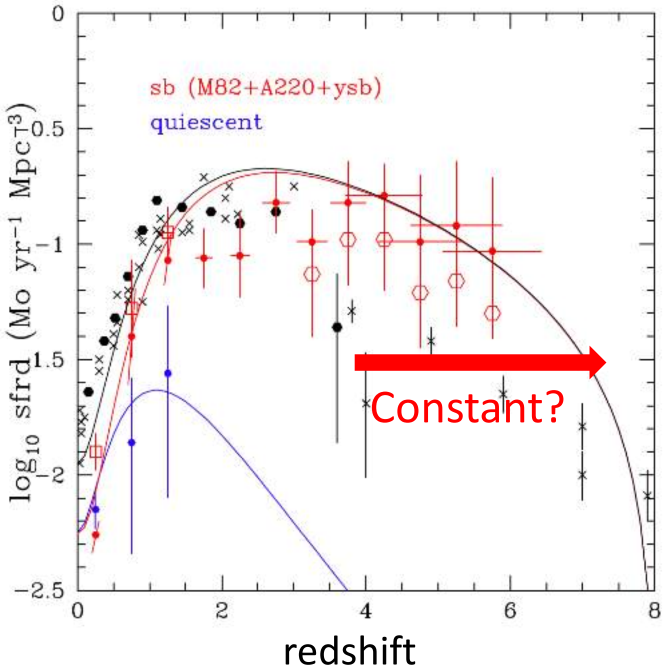
Power of mm/submm galaxy surveys: negative K-correction



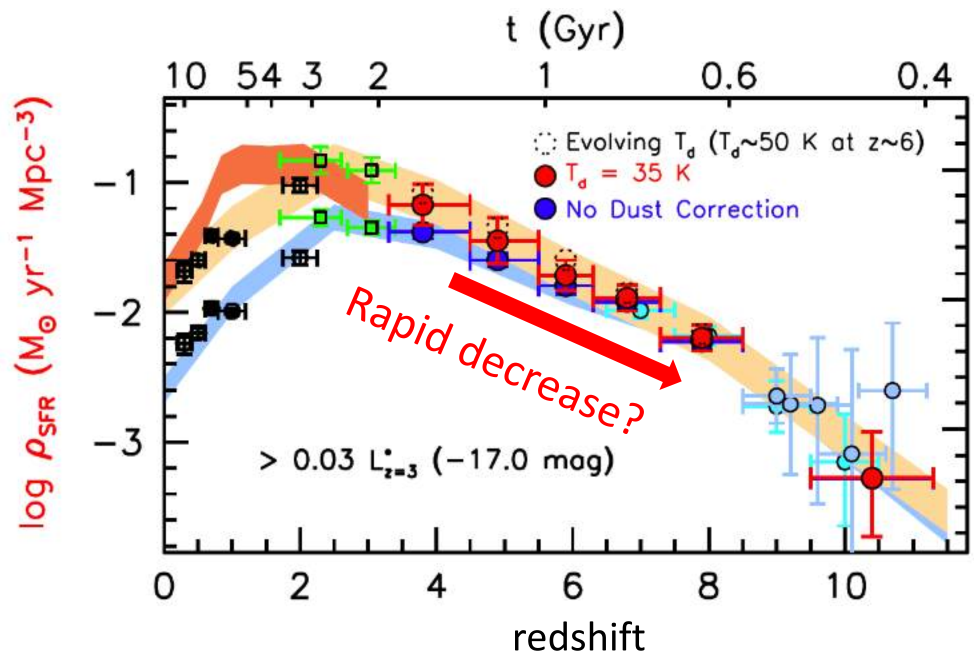
What is the role of the dust-enshrouded star-formation activities in z>3-6 and beyond?

Star formation rate density ($M_\odot$/yr/Mpc^3)

Rowan-Robinson et al. 2016, MNRAS, 461, 1100



Bouwens et al. 2016, ApJ, 833, id. 72

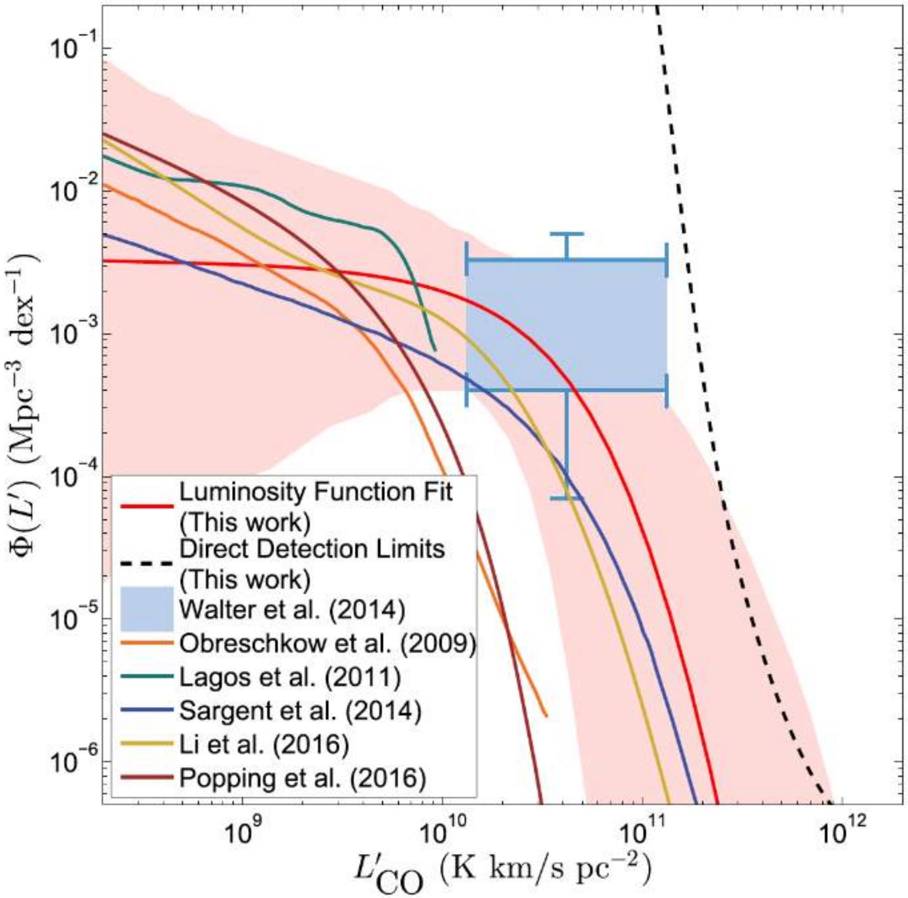


- Herschel wide area surveys of red submm sources ➔ significant amount of dust-obscured star formation up to z~6?
- An ALMA deep survey @HUDF(ASPECS): Dust-observed star-formation plays minor roles on the rest-frame-UV-selected galaxies

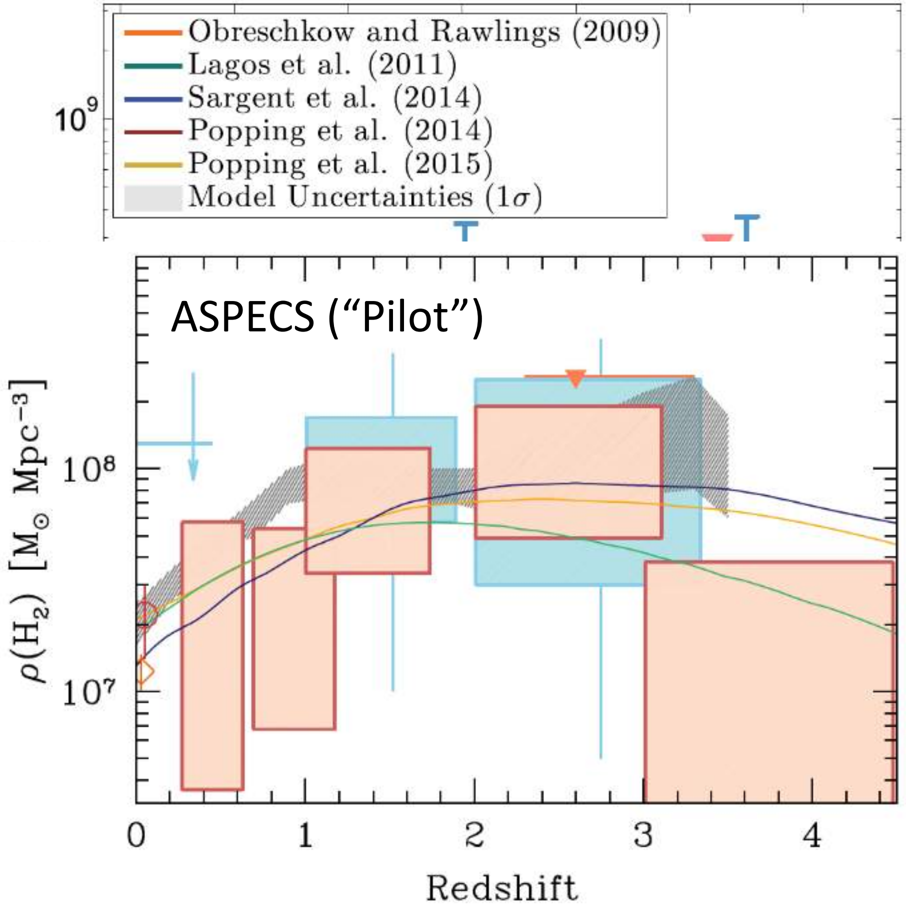
What is the physical cause for the cosmic SFRD evolution? ➔ constraints on CO LF and H_2 mass density evolution

The Sunyaev-Zeldovich Array
Kavli Institute for Cosmological Physics
Univ. of Chicago

19 fields, 0.7 deg^2, f_{obs} = 27 – 35 GHz ➔ aggregate CO(1-0) emission from z=2.3 – 3.3 galaxies



Keating et al. 2016, ApJ, 830, 34

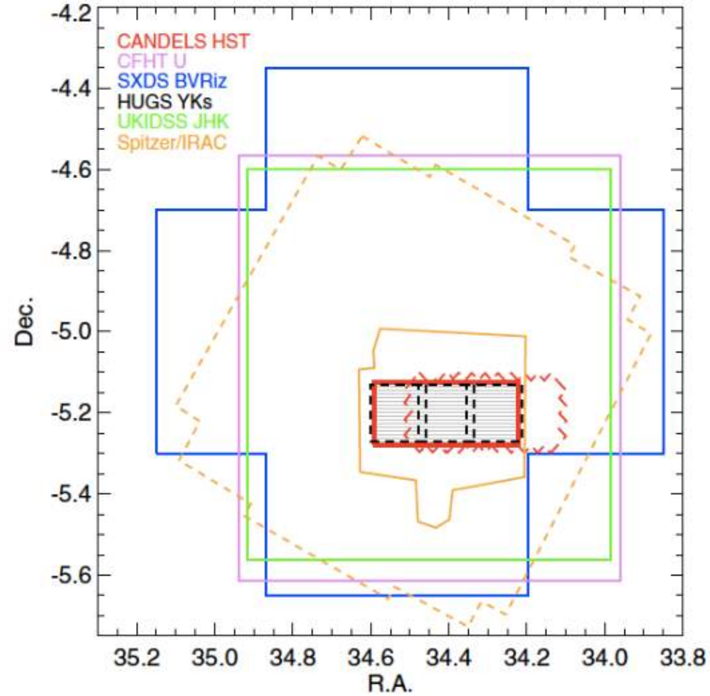


Decarli et al. 2016, ApJ, 833, id. 69

Key questions & Roles of ALMA

- How abundant are **dust-obscured galaxy populations** in the early universe?
- What is their contribution to **the cosmic star formation rate density (SFRD)**?
- What is the evolution of **the cosmic molecular gas density**, which shall be related to the cosmic SFRD?
- When and how do **super-massive BHs** form in these galaxies?
- What is the role of the **environment**?
- → Deep millimeter/submillimeter surveys using ALMA can unveil the population of dusty galaxies without any limit due to source confusion, up to $z \sim 10$ (if dusty galaxies exist)

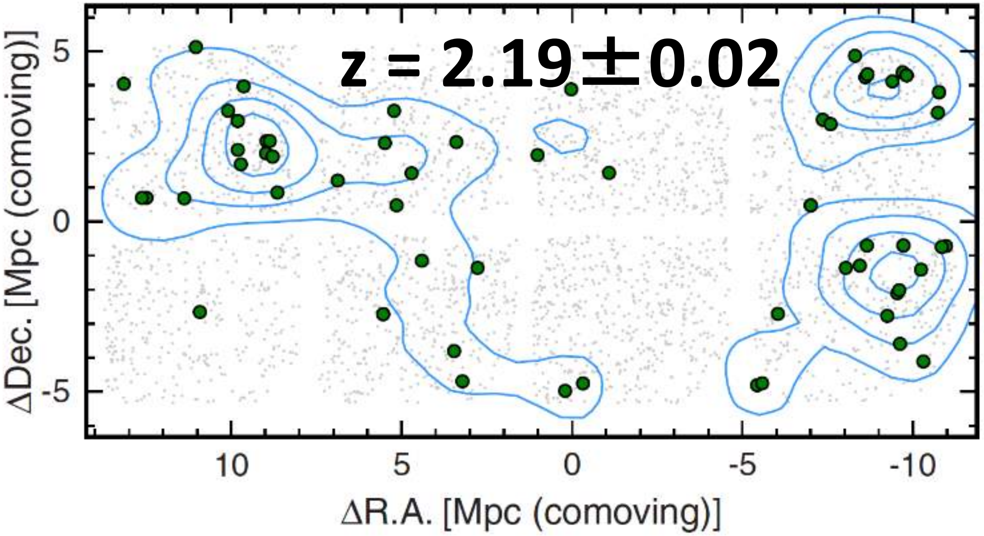
Kohno et al. 2016, IAUS, 319, 92 (arXiv:1601.00195)
Tadaki et al., 2015, ApJ, 811, L3
Hatsukade et al. 2016, PASJ, 68, 36
Yamaguchi et al. 2016, PASJ, 68, 82
Wang, W. et al. 2016, ApJ, 833, 195
Tadaki et al. 2017, ApJ, 841, L25

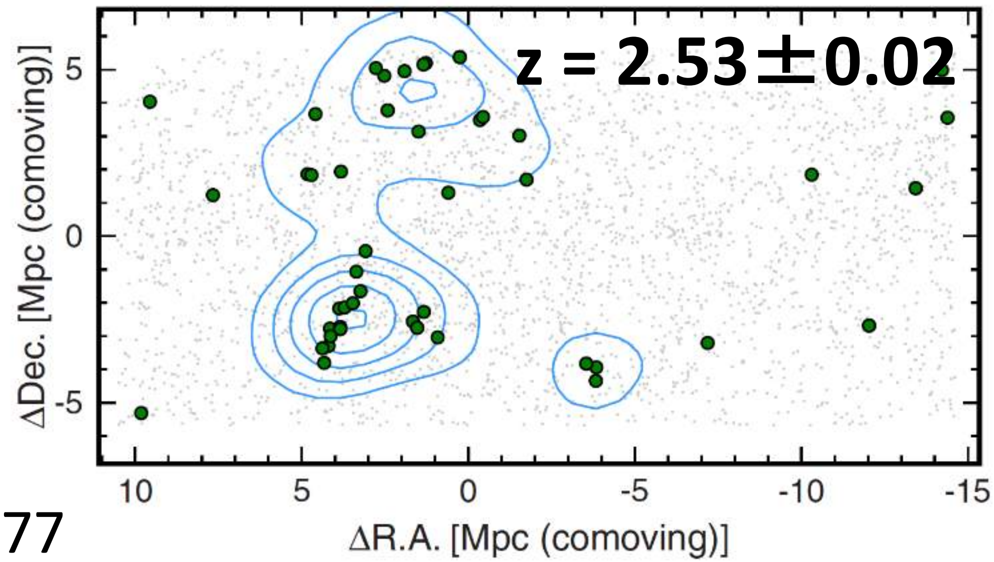


ALMA 2 arcmin^2 imaging of SXDF-UDS-CANDELS

Uniqueness of this field: extensive Hα emitting galaxy surveys (MAHALO/HiZELS)

- Narrow band imaging surveys of Hα emitters (HAEs) using MOIRCS/Subaru at z=2.2 and 2.5 in the SXDF-UDS-CANDELS field
  - See also HAE surveys and ALMA follow ups:
  - 4C23.56 Lee, M., et al., 2017, ApJ, 842, 55
  - XCS2215: Hayashi, M., et al. 2017, ApJ, 841, L21 (later)

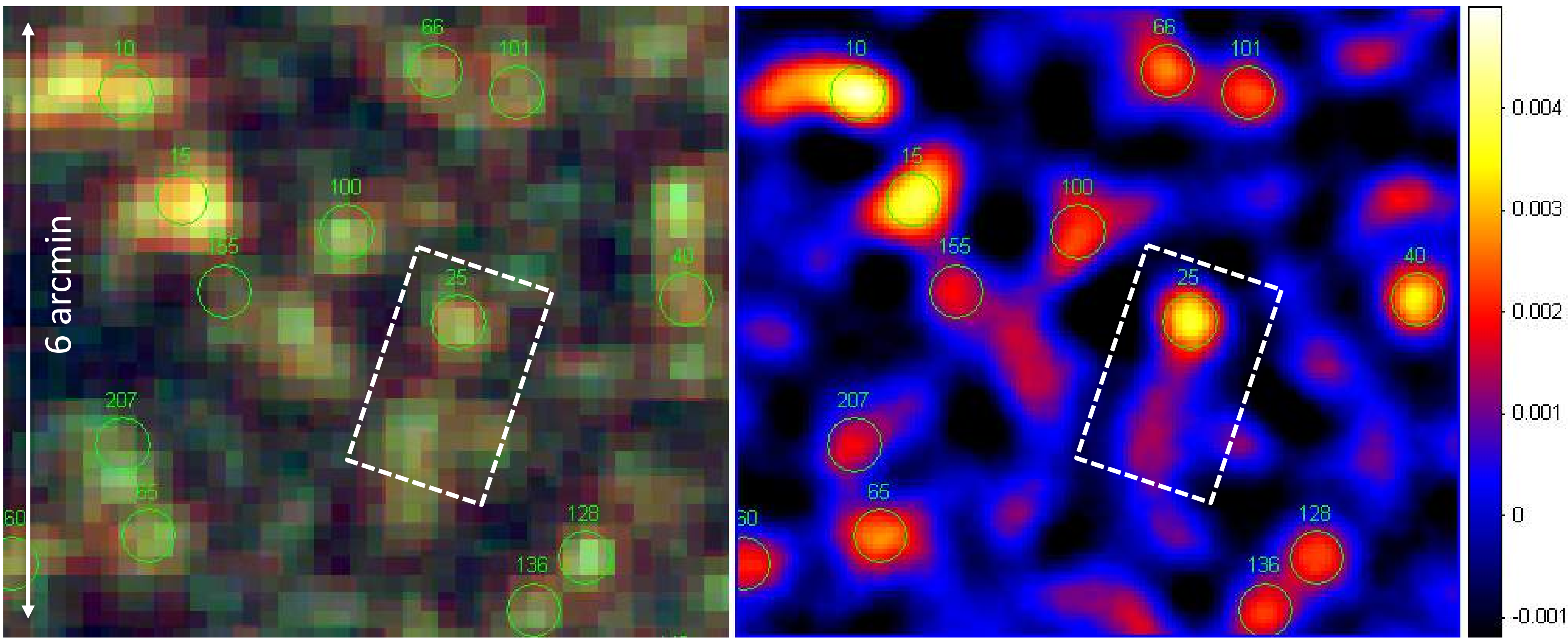




Tadaki et al. 2014, ApJ, 780, 77

Deeply confused Herschel and AzTEC/ASTE images reveal that faint dusty populations are ubiquitous

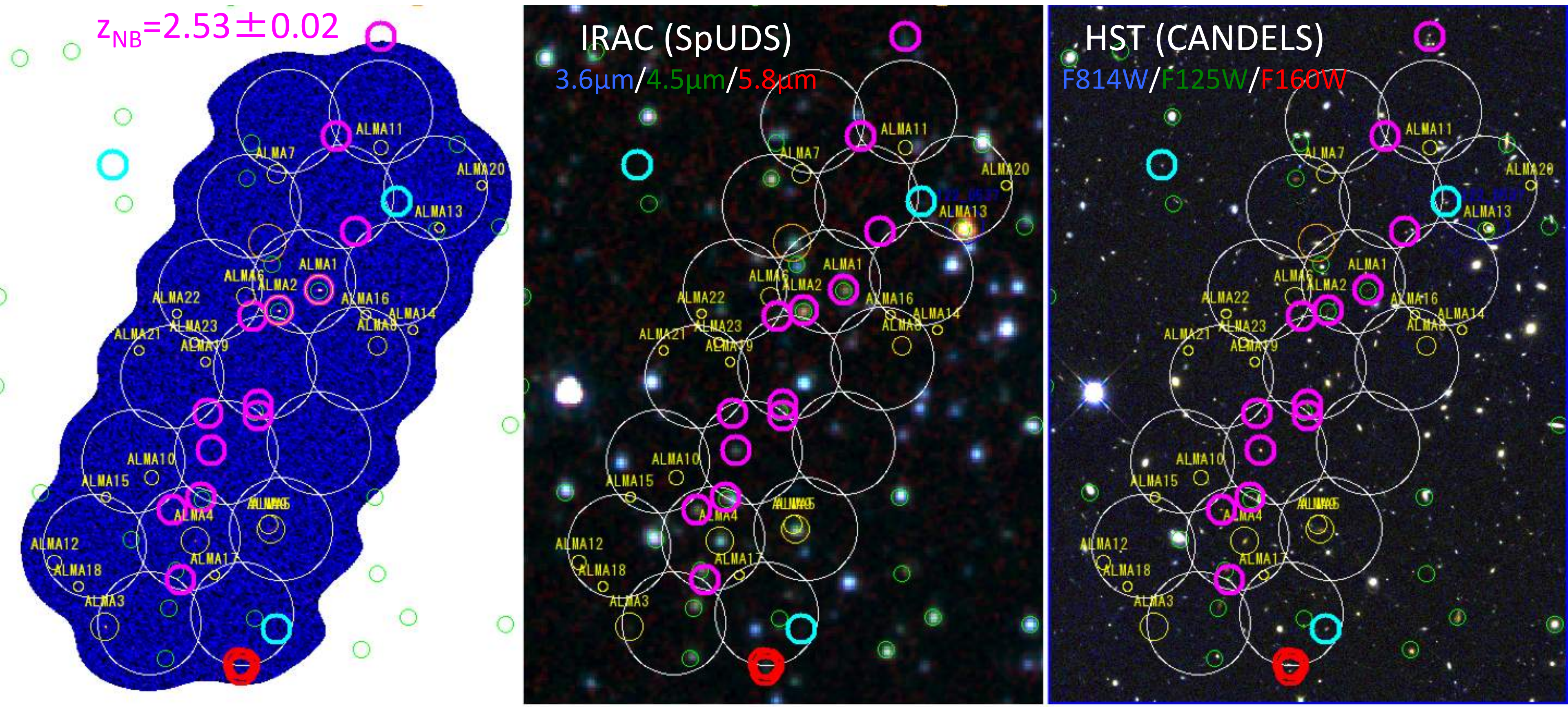
SPIRE 500 μm/350 μm/250 μm AzTEC/ASTE 1100 μm



Subaru-XMM/Newton Deep Field (SXDF) – UDS – CANDELS
+ new Spitzer (SPLASH), ZFOURGE, HSC-Subaru, Chandra etc.

ALMA 1.1mm vs IRAC, ACS/WFC3

Hα emitters
z_{NB}=2.53±0.02



Kohno et al., 2016, IAUS, 319, 92 (arXiv:1601.00195)

ALMA 1.1mm vs IRAC, ACS/WFC3

Hα emitters
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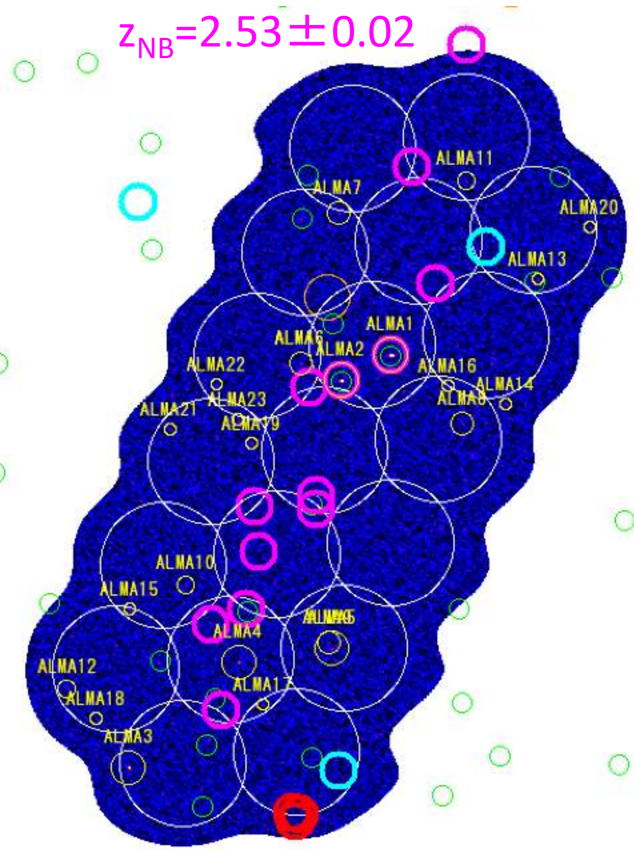
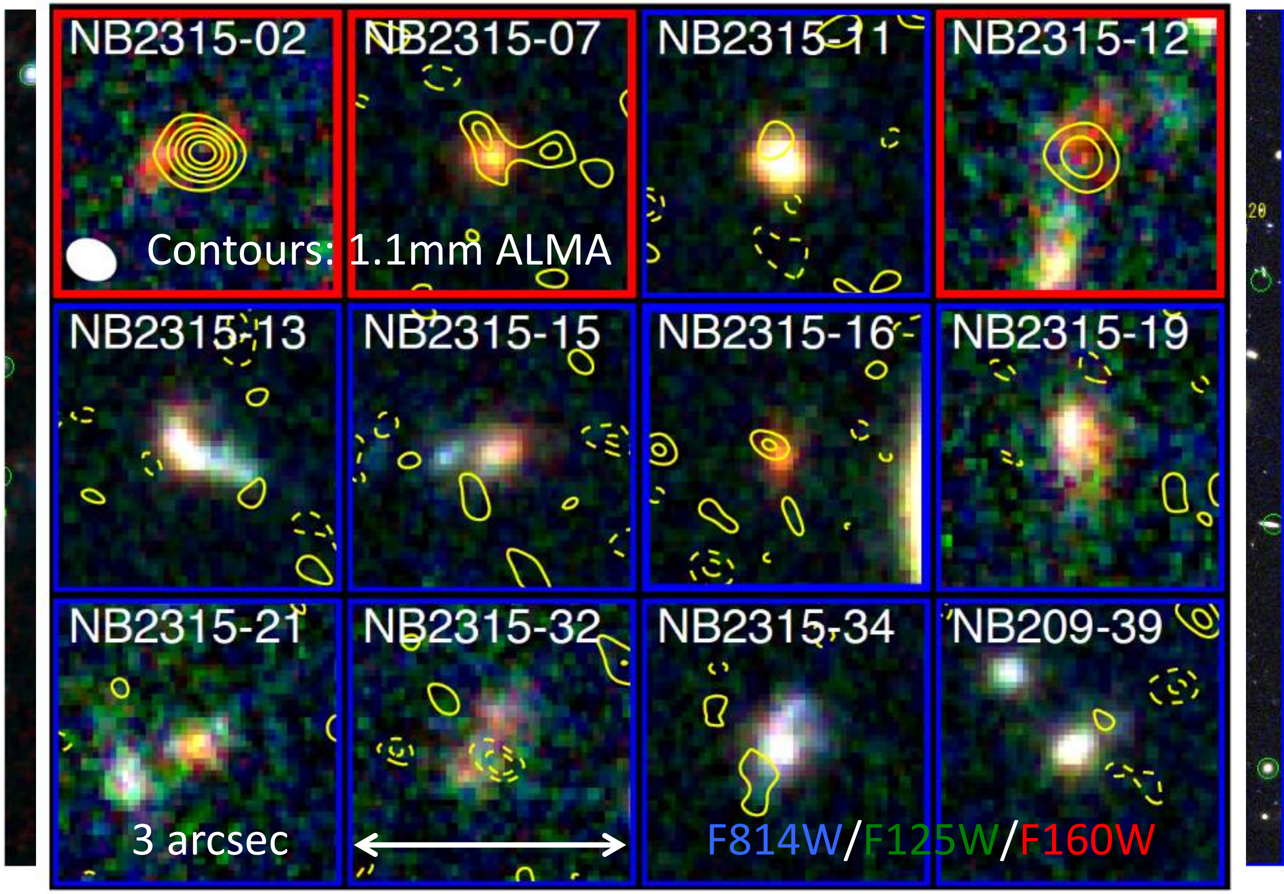


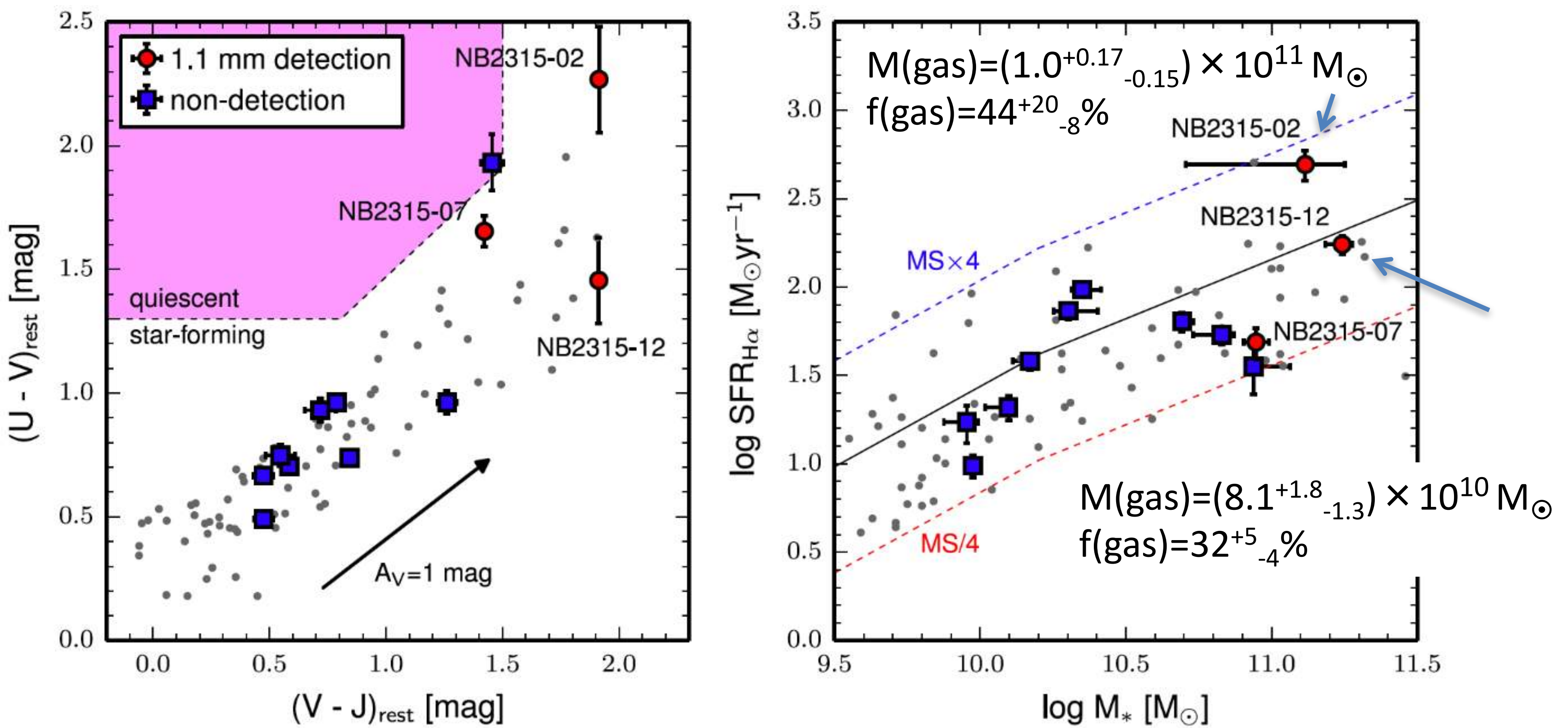
HST(CANDELS) 3 color images of Hα emitters at z=2.53



2 Hα emitters: clearly detected in ALMA
Another 1 Hα emitter: marginally detected in ALMA
remaining Hα emitters: no detection in ALMA ➔ bluer color, less massive

Tadaki et al. 2015, ApJ, 811, L3

Hα emitters with/without 1.1mm emission



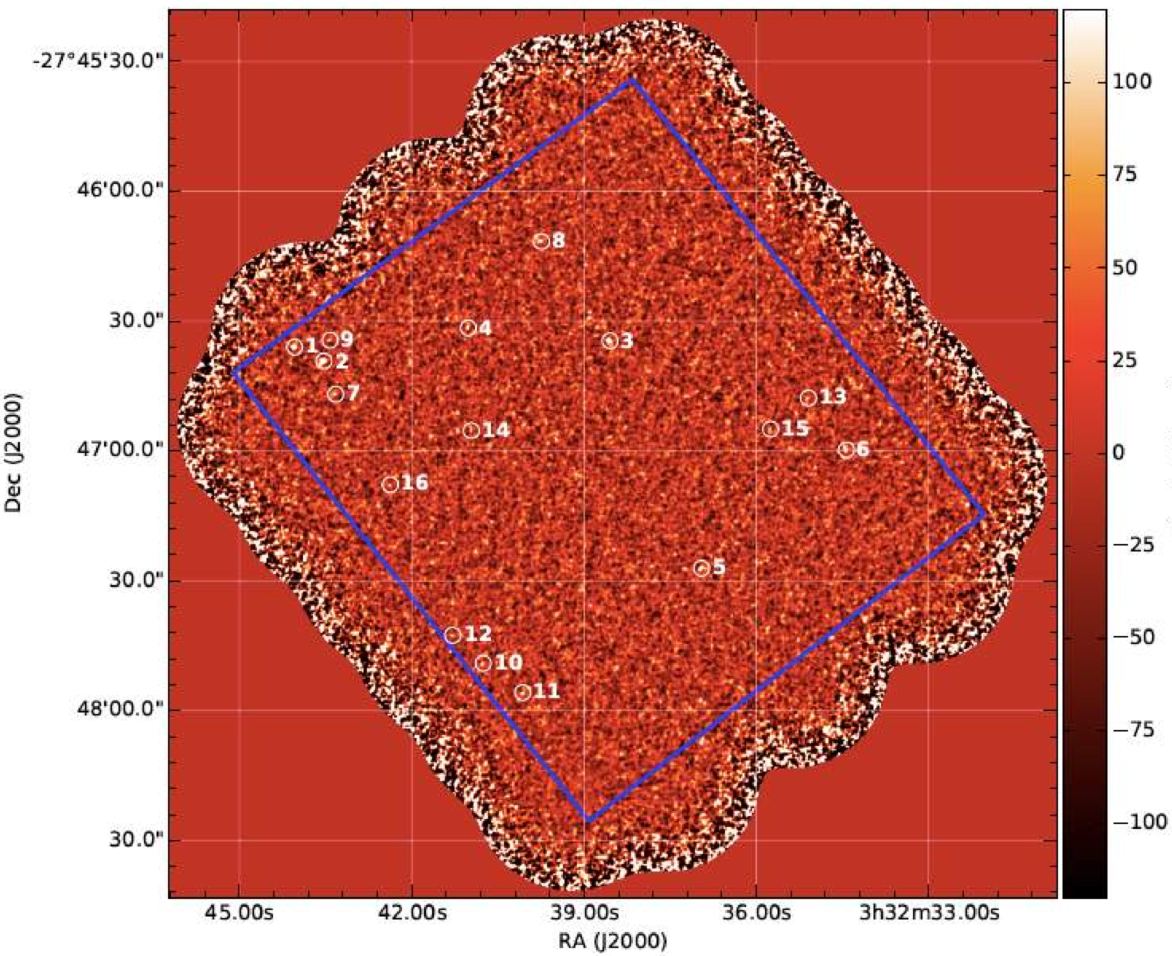
- Hα emitters with 1.1mm emission
  - red in the rest-frame optical, massive
- Hα emitters without 1.1mm S(1.1mm) < 290 μJy (2σ upper limit).
  - blue, main-sequence galaxies

Massive galaxies tend to host more dust obscured star formation

Tadaki et al. 2015, ApJ, 811, L3

HUDF-ALMA 4.5 arcmin^2 field

Dunlop et al. 2017, MNRAS, 466, 861
Rujopakarn et al. 2016, ApJ, 833, 12



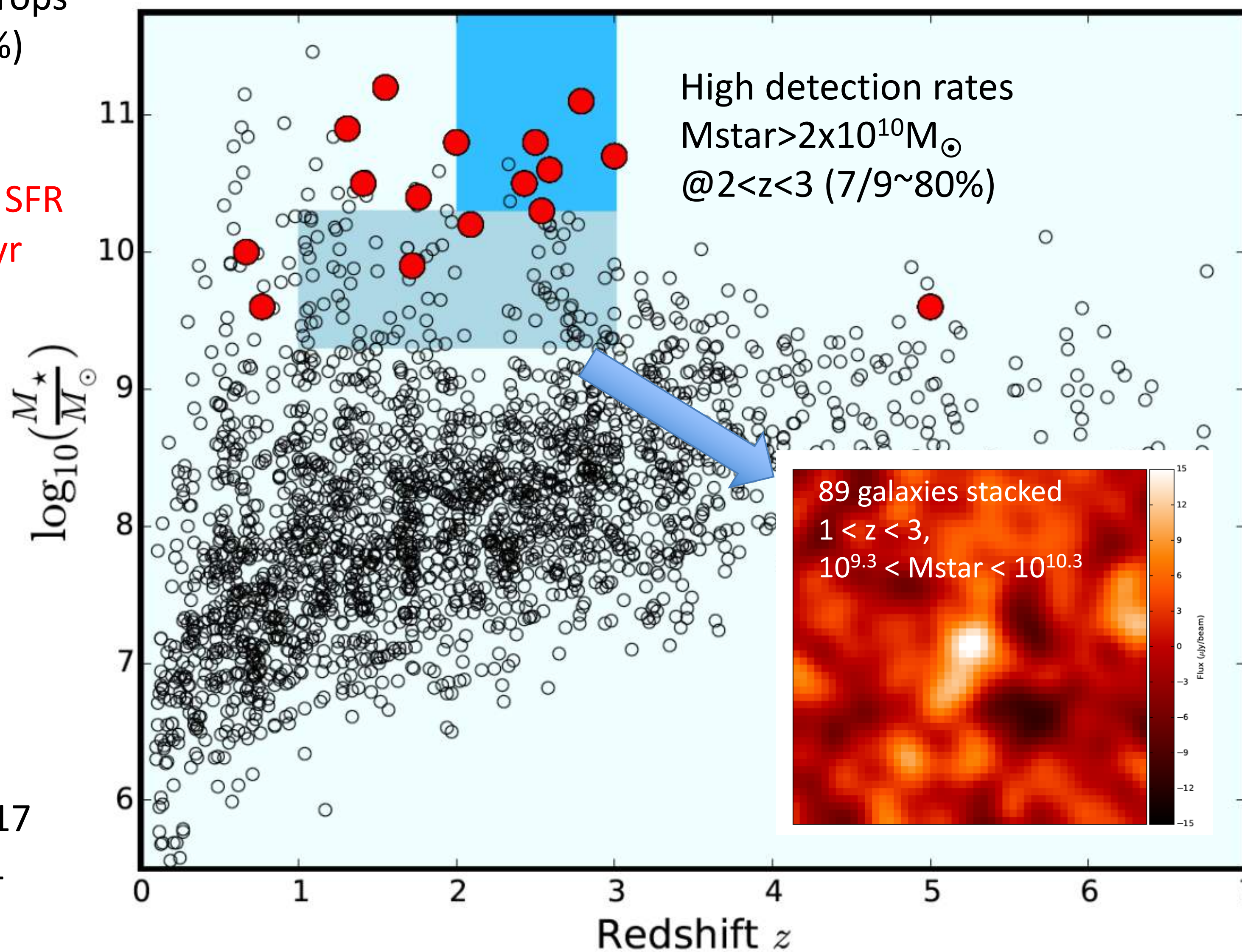
- 9 execution blocks in July – Sep. 2014, 4 blocks in May 2015, ~20 hours
- 1.3 mm (230 GHz)
- 45-point mosaic (separation: 0.8x FoV)
- 0.71” x 0.67”
- 35 μJy/beam (1σ)

Obscured star forming activities uncovered by ALMA: Current ALMA surveys tend to uncover dusty star-formation in massive galaxies

Detection rate drops @z<2 (5/19~25%)

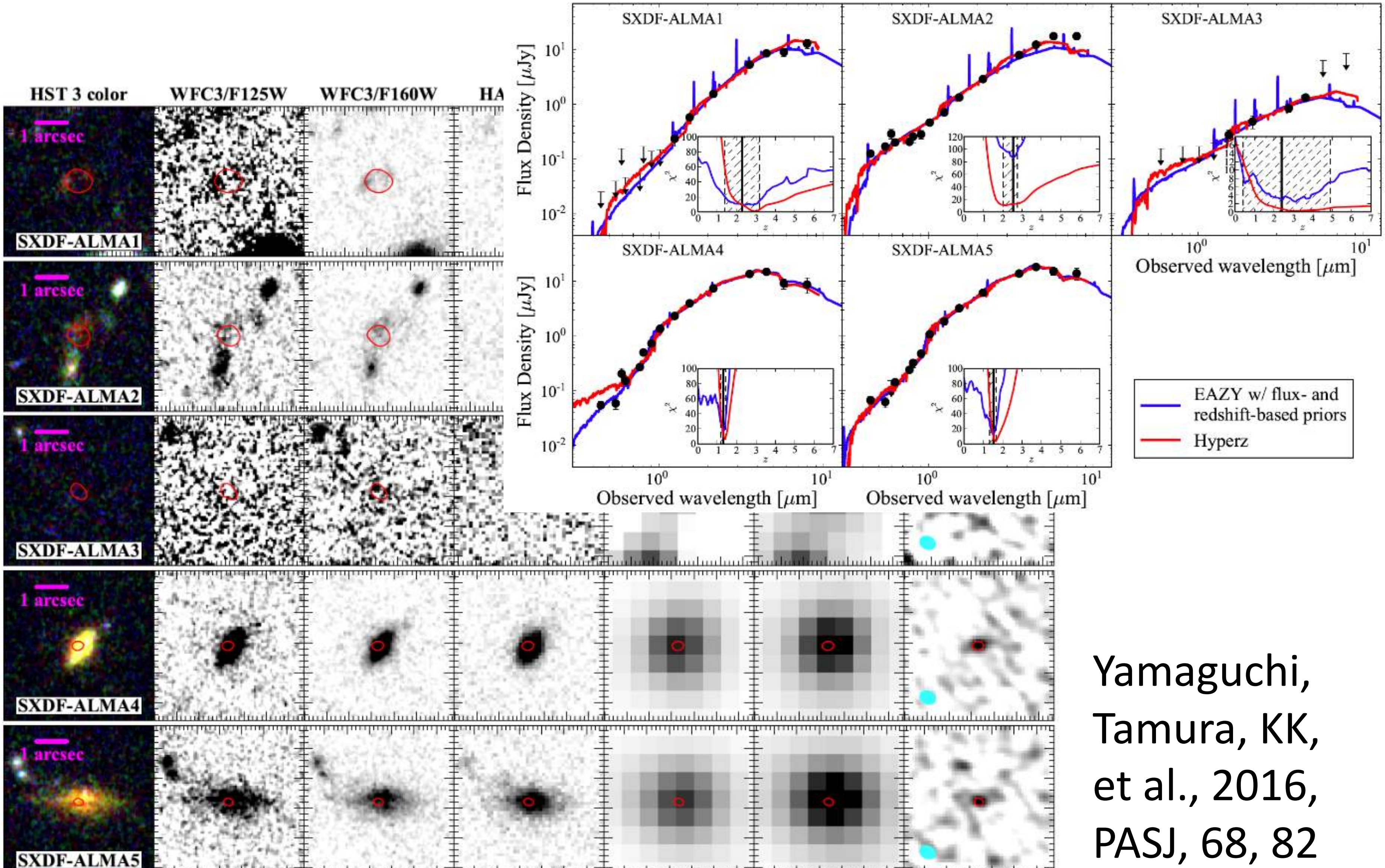
Stacking:
Dust enshrouded SFR = 530±130 $M_\odot$/yr
Rest-UV SFR = 160 $M_\odot$/yr

➔ ~80% obscured !



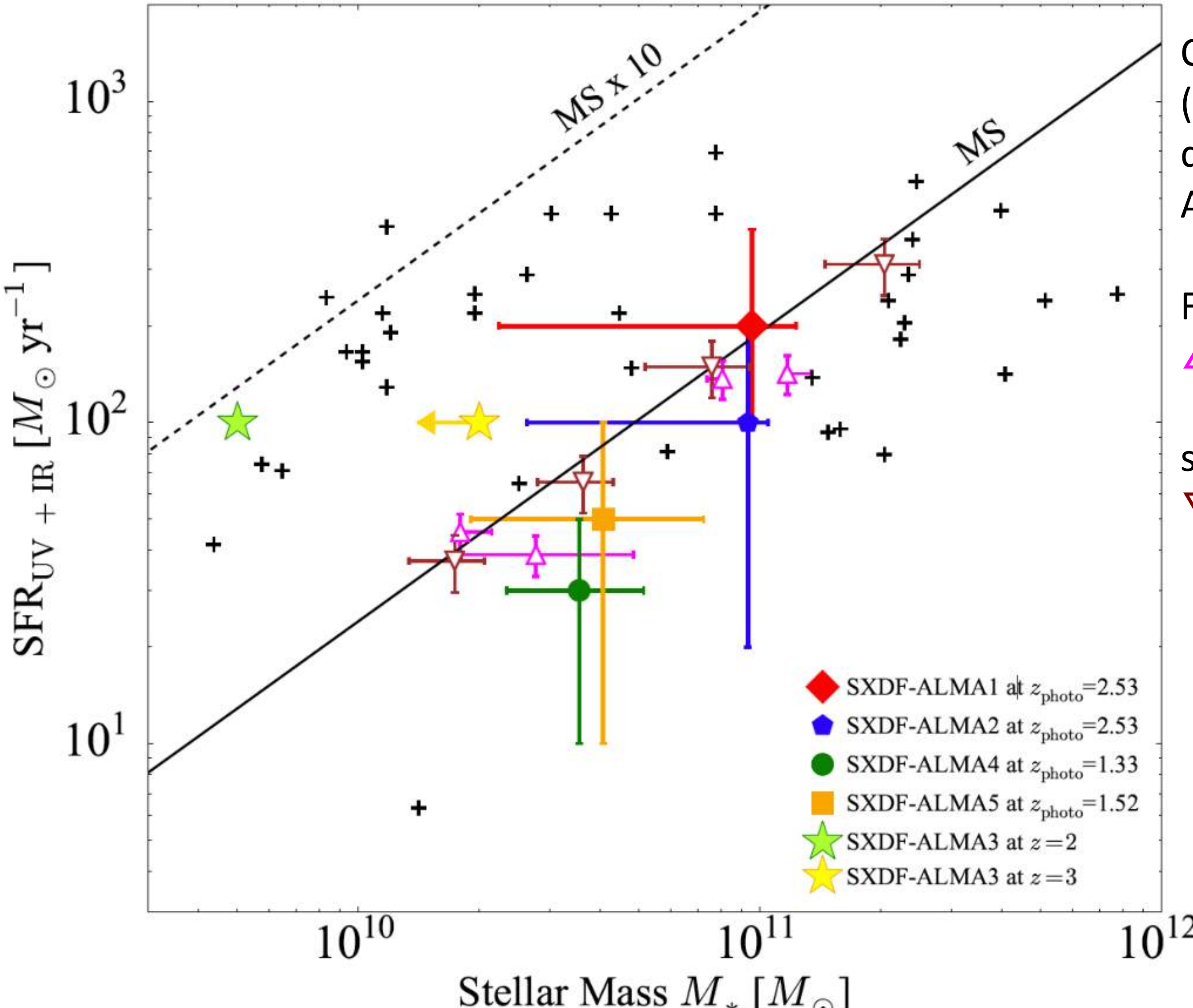
Dunlop et al. 2017
MNRAS 466, 861

Characterization of ALMA sources in SXDF-UDS-CANDELS



Yamaguchi, Tamura, KK, et al., 2016, PASJ, 68, 82

Faint submm galaxies detected by ALMA: dusty star-forming galaxies (mainly) on the main sequence at z = 1 - 3



Comparison with
(+) ALESS sources
da Cunha et al. 2015, ApJ, 806, 110

Faint submm galaxies
△ Hatsukade et al. 2015

sBzK galaxies
▽ Rodighiero et al. 2015

Yamaguchi, Tamura, KK, et al., 2016, PASJ, 68, 82

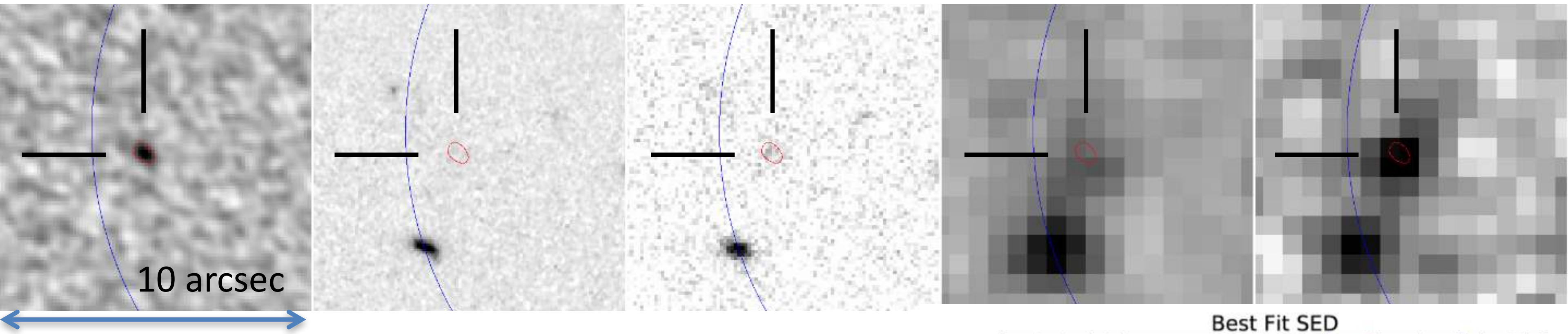
So, does ALMA only detect dust emission from "already known galaxies" at $z = 1 – 3$, selected by rest-frame UV/optical deep surveys?

→ NO

An obscured ULIRG at z >2 uncovered in SXDF-ALMA 2 arcmin^2 survey?

Kohno et al. 2016
Yamaguchi et al. 2016

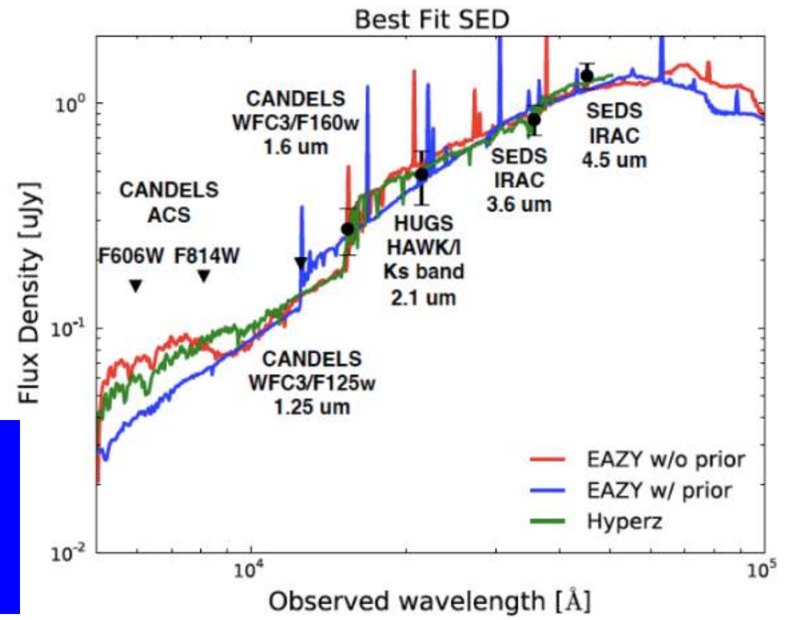
ALMA/B6 1.1mm	CANDELS WFC3/F160W 1.6μm	HUGS HAWK-I/Ks-band 2.1μm	SEDS IRAC 3.6μm	SEDS IRAC 4.5μm



$z_{photo} = 3.1^{+3.9}_{-1.8}$ (Hyperz), $2.4^{+2.5}_{-2.0}$ (EAZY)

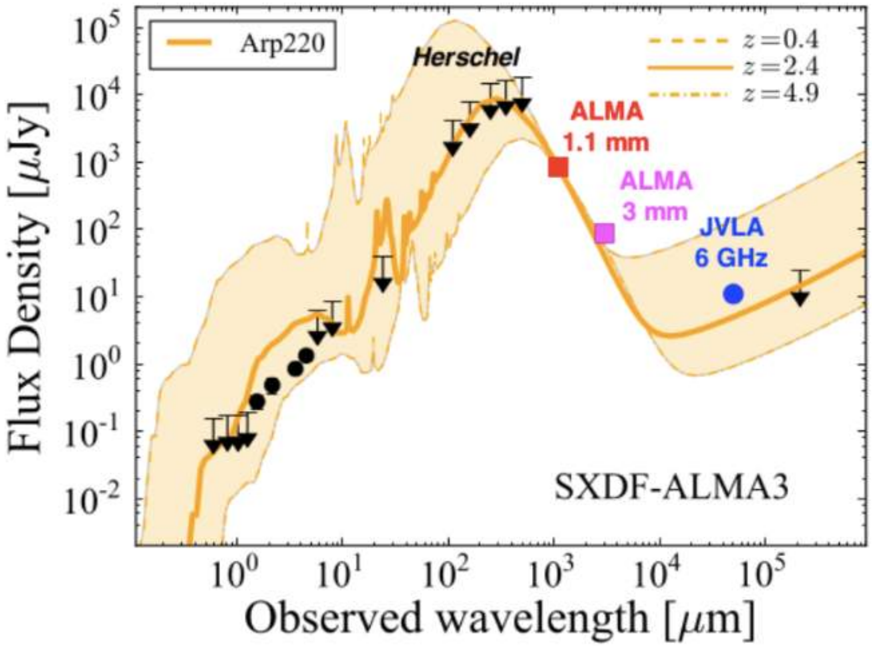
- One $L(IR) = (1^{+1}_{-0.7}) \times 10^{12} L_{\odot}$ galaxy in the survey volume (2 arcmin^2, z = 0.9 – 3.6)
- ➔ SFRD = (0.1 – 1) $\times 10^{-2}$ $M_{\odot}$/yr/Mpc^3
- ➔ 1 – 10% contribution to the IR SFRD??

additional contributions to the SF history from faint submm galaxies, not fully overlapped with UV/optical-selected galaxies (e.g., Chen et al. 2014, ApJ, 789, 12)

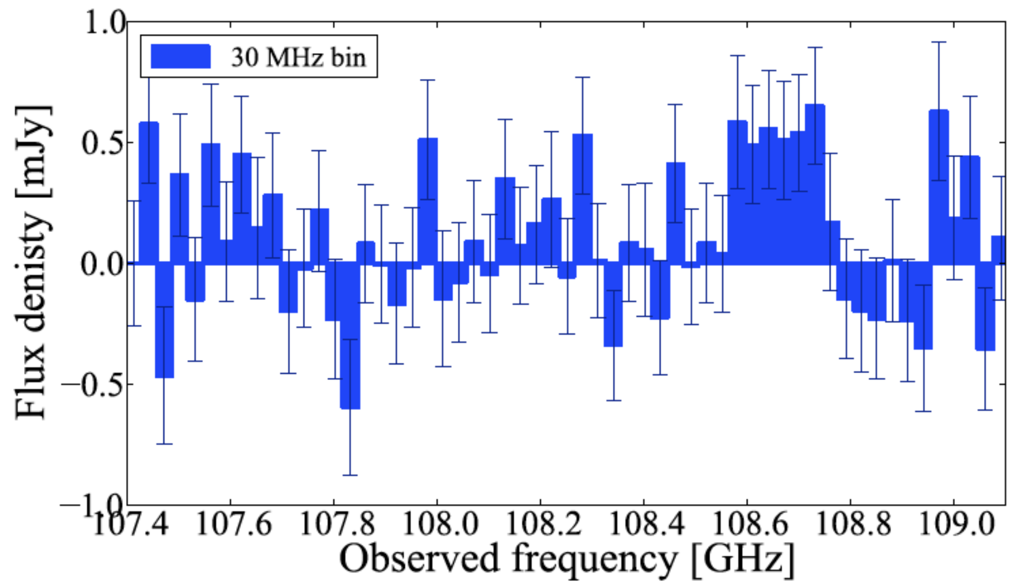


Interesting, but not easy to follow up..

- Nothing can do in the optical/near-infrared??
- ALMA spectral scan is the only way currently, though it is fairly expensive
- JWST and SPICA for mid-infrared spectroscopy using PAH features?



CO(5-4)@z=3.24 or CO(4-3)@z=2.18?

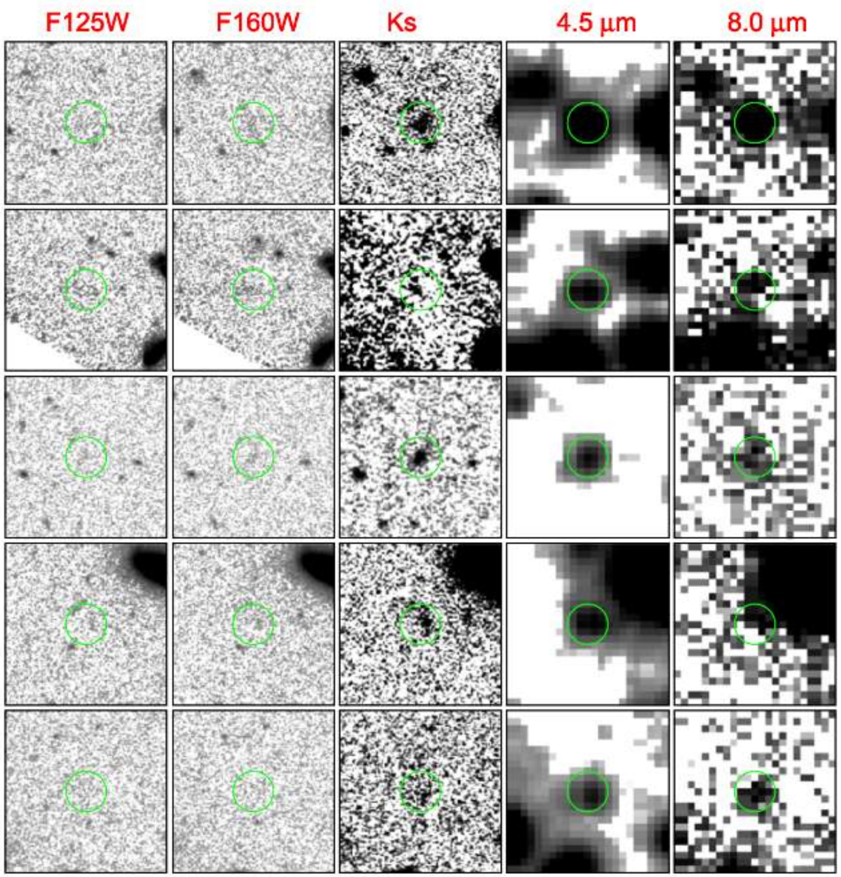


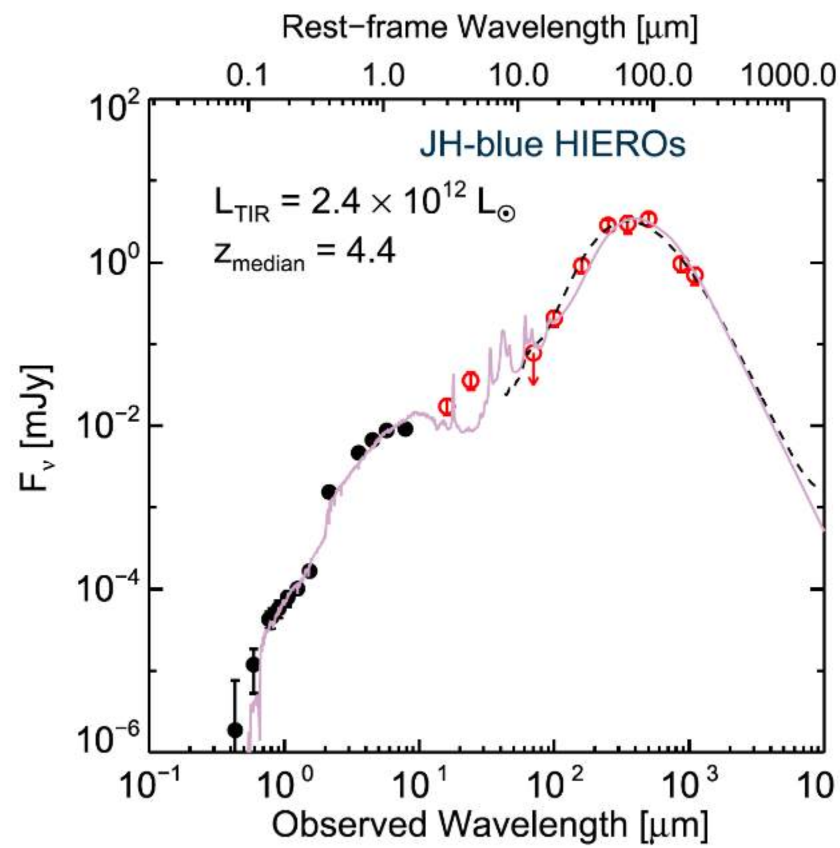
Yamaguchi, Kohno, et al., in prep.

IR-color selected massive galaxies @z>3

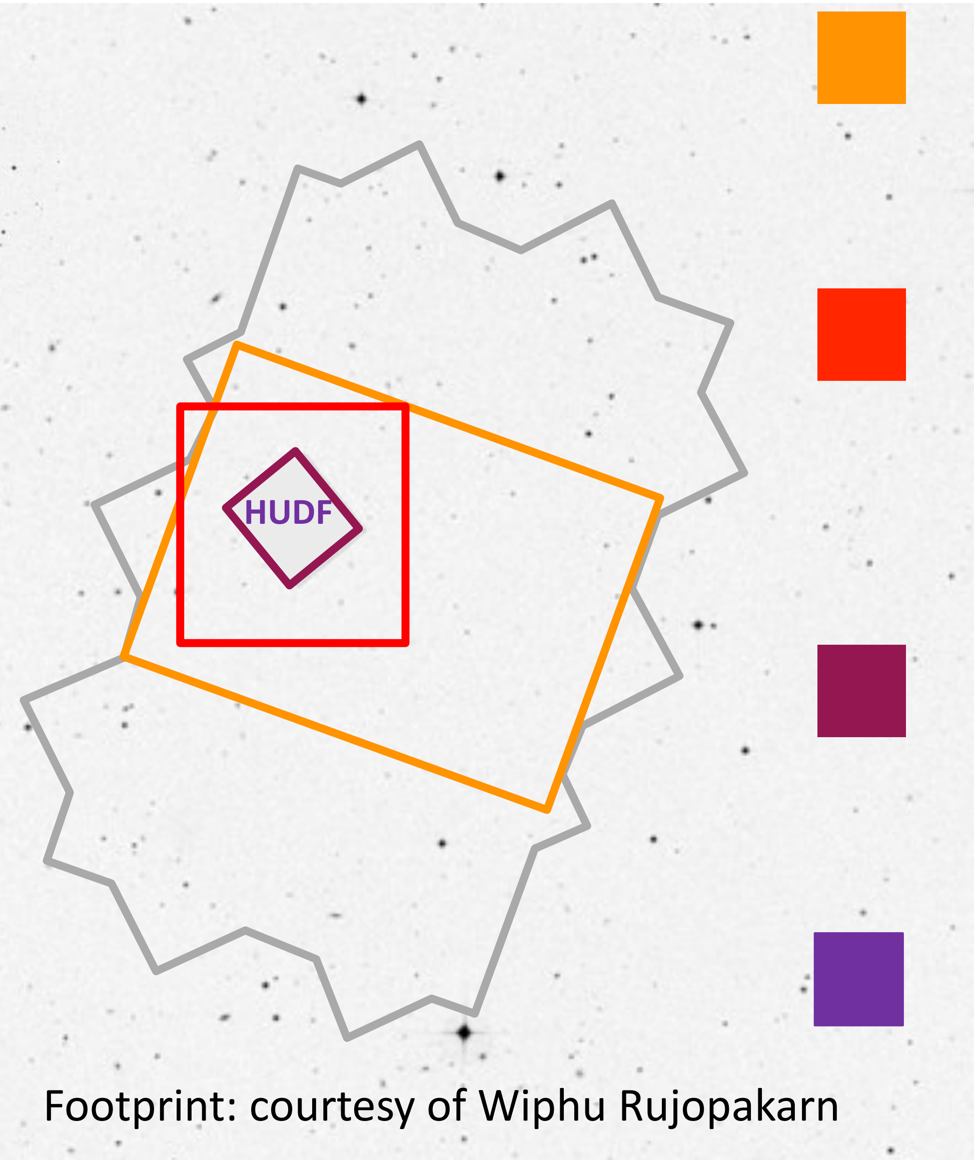
- H-dropouts selected from F160W, Ks, and IRAC
- Massive galaxies at z > 3-4?
- ALMA follow-up in progress.

Wang, T., Elbaz, D., et al. 2016, ApJ, 816, 84





ALMA "wedding-cake" deep λ~1 mm surveys in HUDF and GOODS-S



GOODS-S ALMA – PI: D. Elbaz

68 arcmin^2, 1 tuning (256 GHz)
1σ = 128 μJy/beam

JVLA-ALMA (ASAGAO) – PI: K. Kohno

26 arcmin^2, 2 tuning (262 GHz + 253 GHz)
1σ = 60 μJy/beam

HUDF ALMA – PI: J. Dunlop

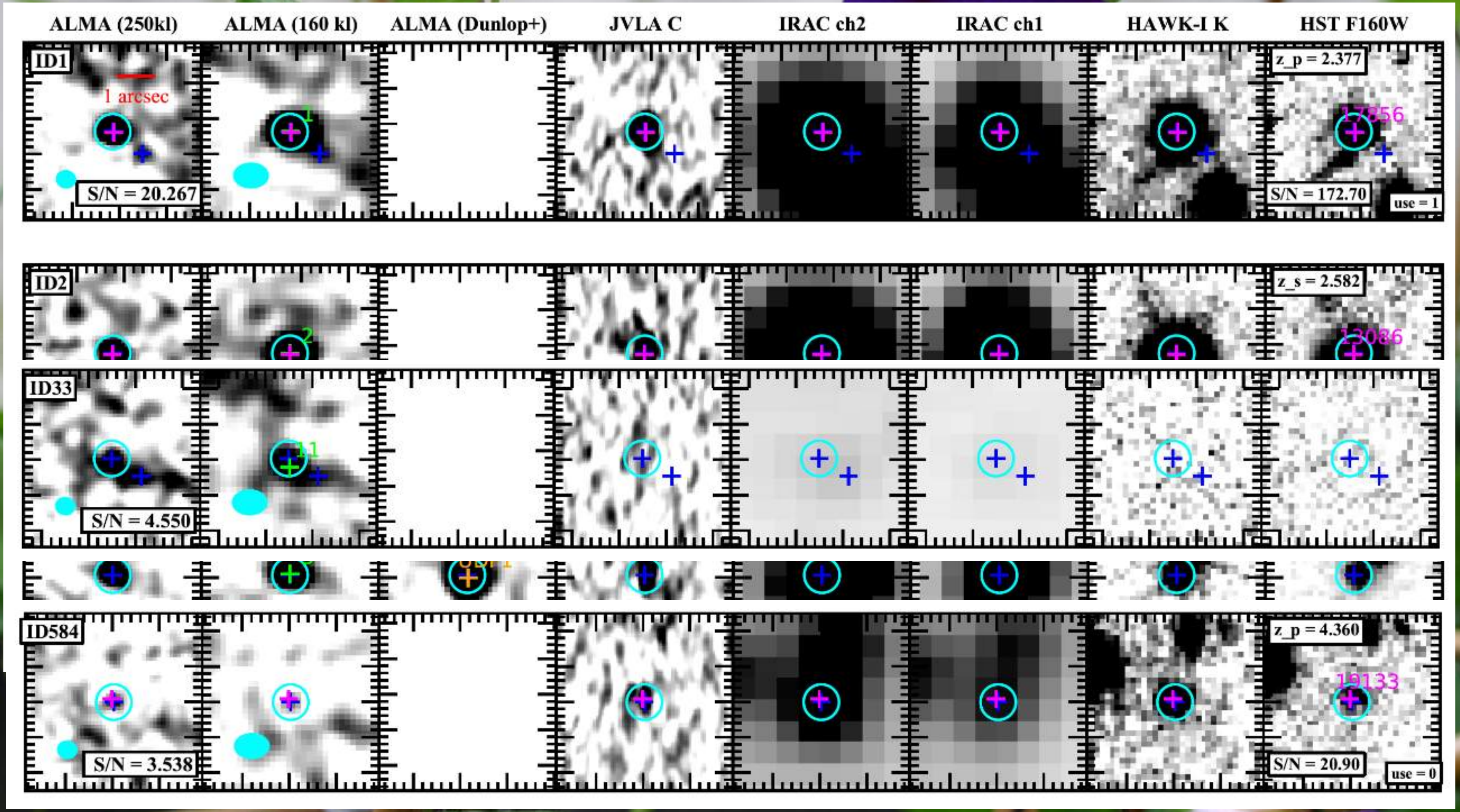
4.5 arcmin^2, 1 tuning (220 GHz)
1σ = 29 μJy/beam

HUDF ASPEC – PI: F. Walter

4.5 arcmin^2, 8 tuning (210 – 270 GHz)
1σ = 13 μJy/beam

ALMA twenty-Six Arcmin^2 survey of Goods-south At One-millimetre (ASAGAO)

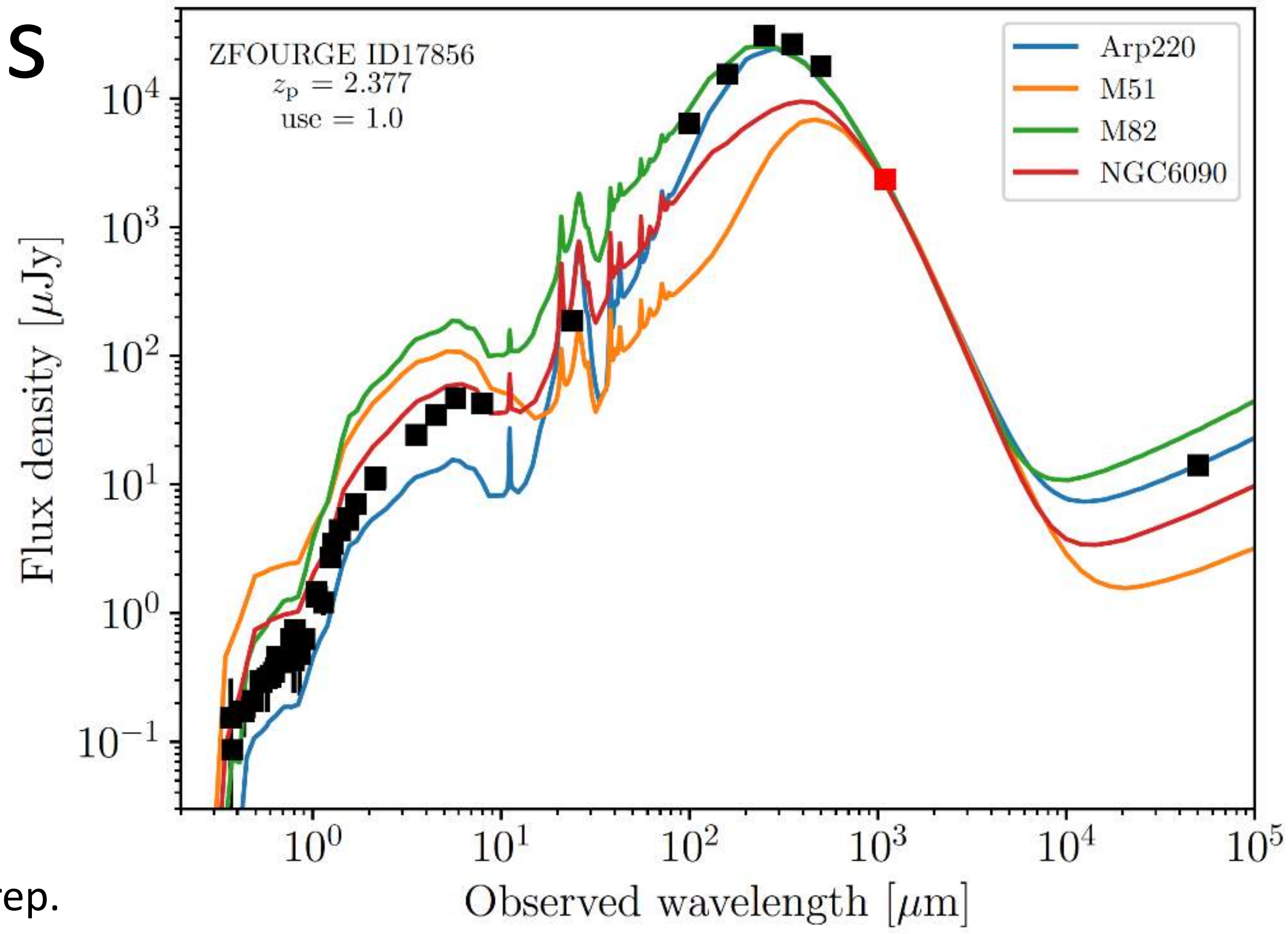
- We are currently making multi-wavelength IDs of >600 (!) ALMA candidate sources



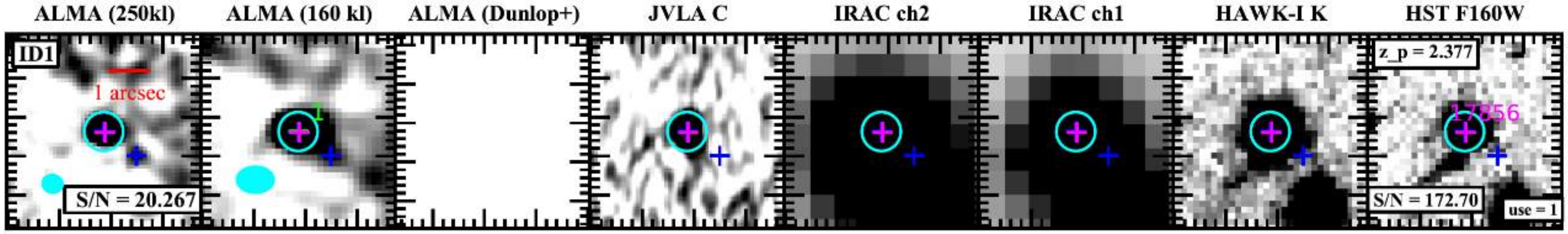
Hatsukade et al., in prep; Yamaguchi, Hatsukade, KK, Rujopakarn, et al., in prep.

SED analysis

including deblended SPIRE fluxes

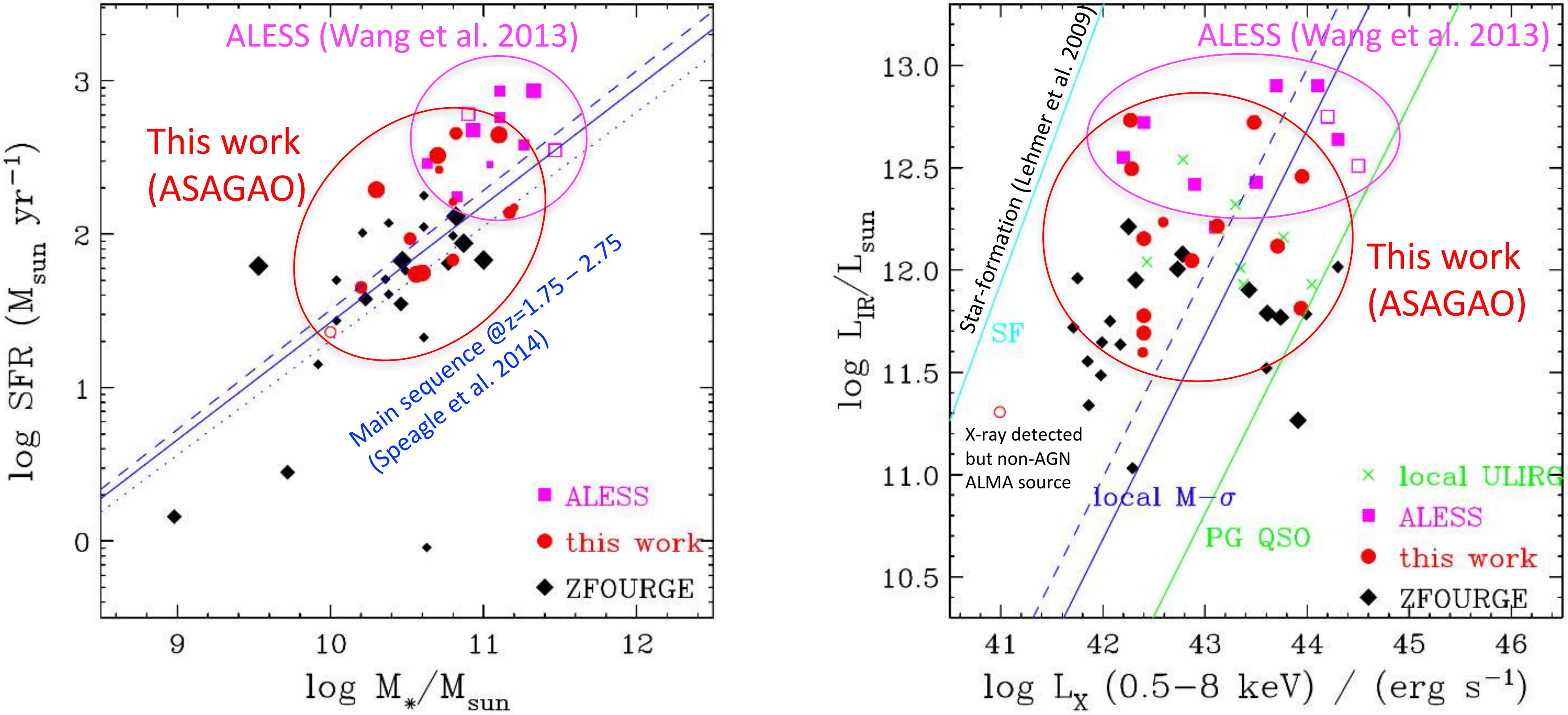


Wang, T., et al., in prep.
Yamaguchi, Y., et al., in prep.



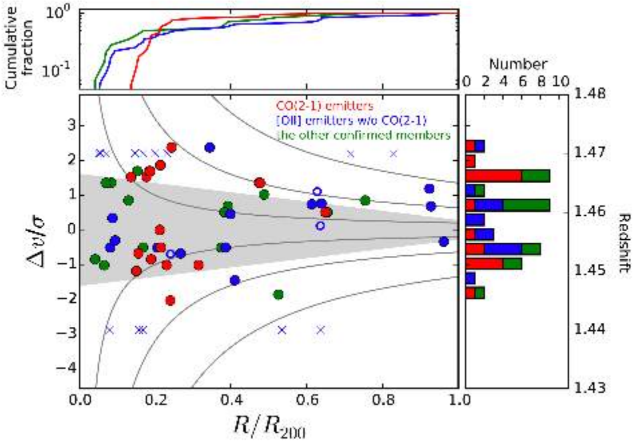
X-ray AGNs in ASAGAO (+ UDF) sources at z = 1.5 - 3

Ueda, Y., Hatsukade, B., KK, et al., submitted to ApJ



sources, up to 88^{+10}_{-24}% (!) using Chandra 7Ms data

- At X-ray flux limits of ~5×10^{-17} erg cm^{-2} s^{-1} @0.5 – 7 keV band
- Host growth first ➔ an AGN-dominant phase follows later?



Dusty star-formation
vs.
environment

Galaxy formation & evolution under biased environments

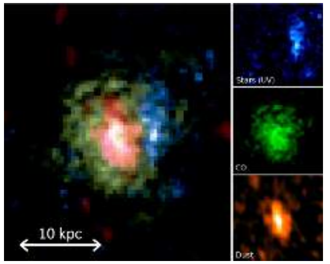
- Frequent interactions among galaxies
  - Merger-induced formation of "submm-bright galaxies"

    e.g., Narayanan et al. 2010, MNRAS, 401, 1613

  ⇔ formation of submm galaxies via cold accretion

    e.g., Dave et al. 2010, MNRAS, 404, 1355

e.g., GN20



Hodge et al. 2015
ApJ, 798, L18

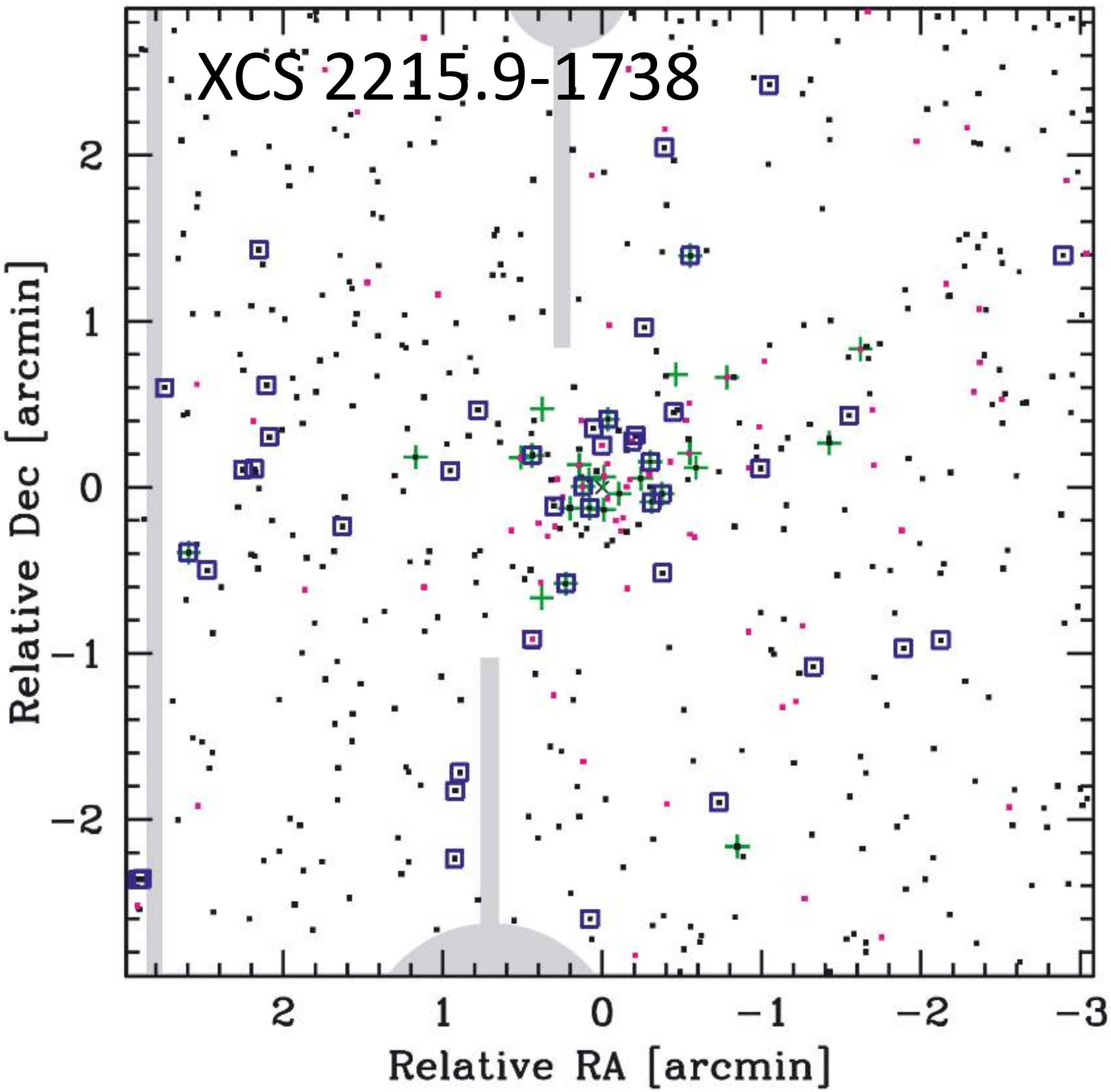
- Key issues:

  Onset of the density-morphology relation (Dressler 1980)

  Comparison with physical properties of galaxies in field (normal) environments

  Formation and (co-)evolution of SMBH/quasars

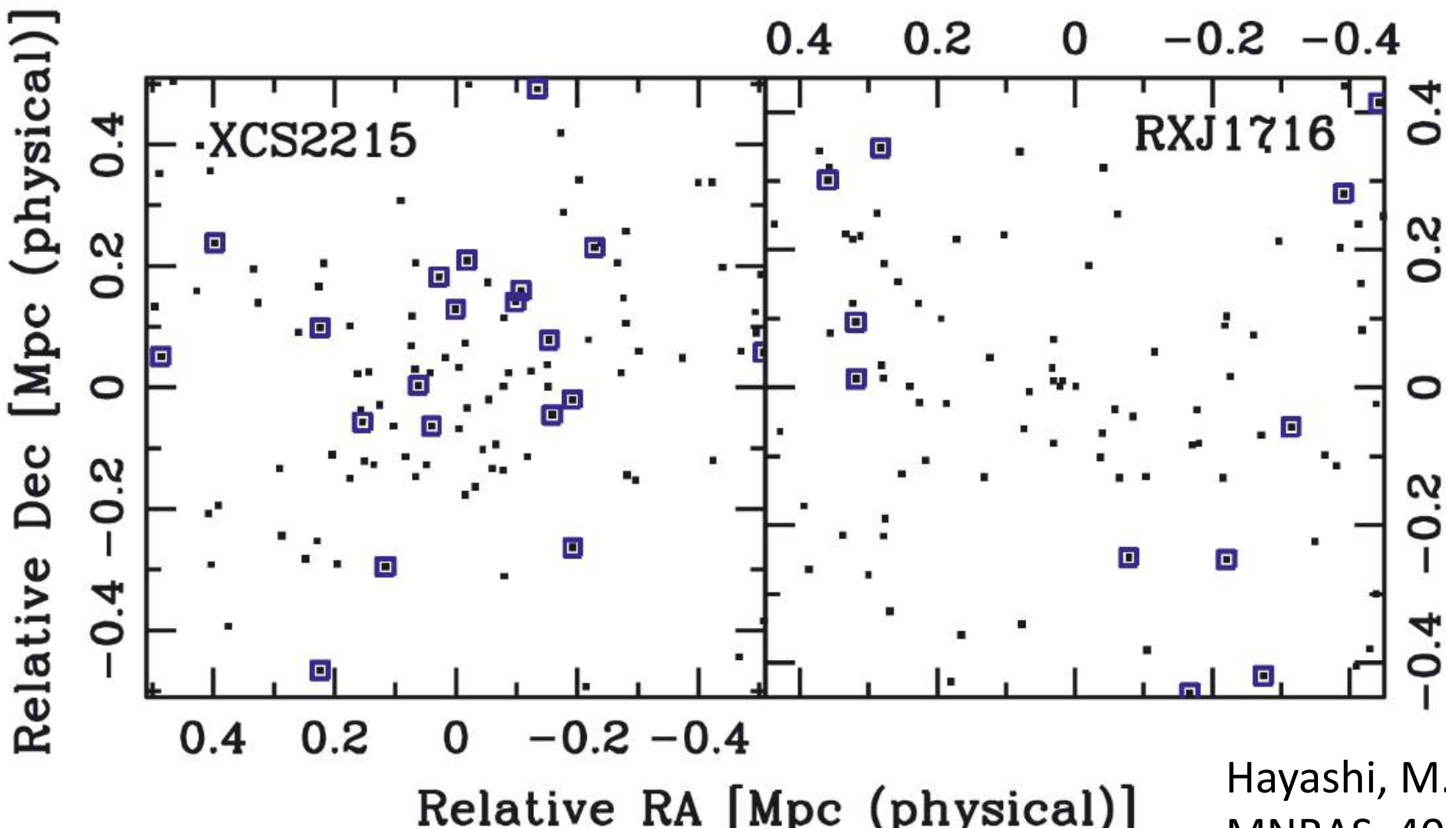
Overdensity of star-forming galaxies traced by [OII] line emitters at z = 1.46



- SuprimeCam + NB912 (FoV 34 x 27 $arcmin^2$), 260 min. integration
- 44 [OII] emitters (@6'x6')
- SFR limit ~2.6 $M_{\odot}$/yr (3σ) using [OII]-SFR calibration in Kennicutt (1998)
- ~4σ overdensity
- clear contrast in low-z clusters (e.g., RXJ1716 @z=0.81, Koyama et al. 2007, MNRAS, 382, 1719)

Hayashi, M., et al. 2010 MNRAS, 402, 1980

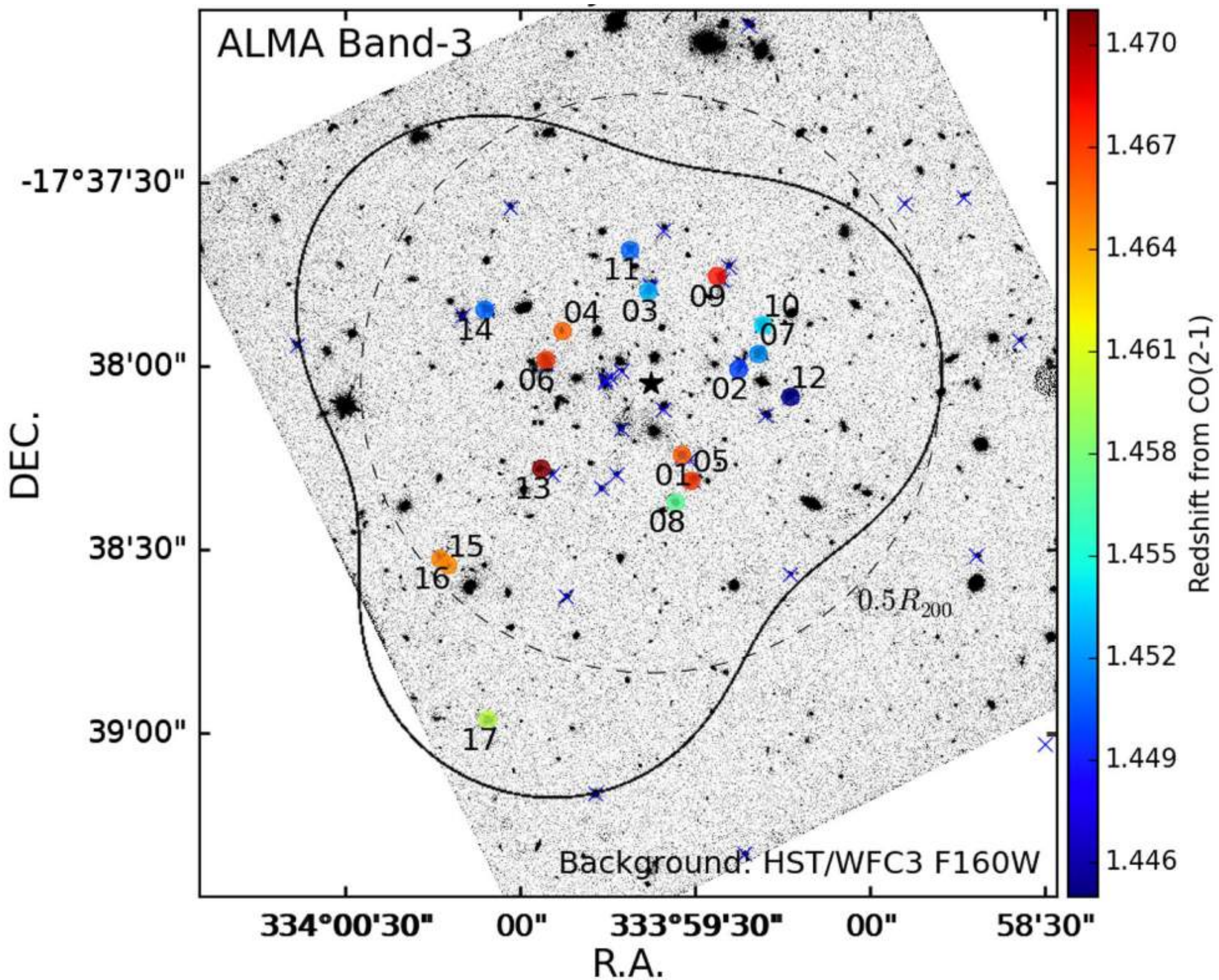
Overdensity of star-forming galaxies traced by [OII] line emitters at z = 1.46



Hayashi, M., et al. 2010
MNRAS, 402, 1980

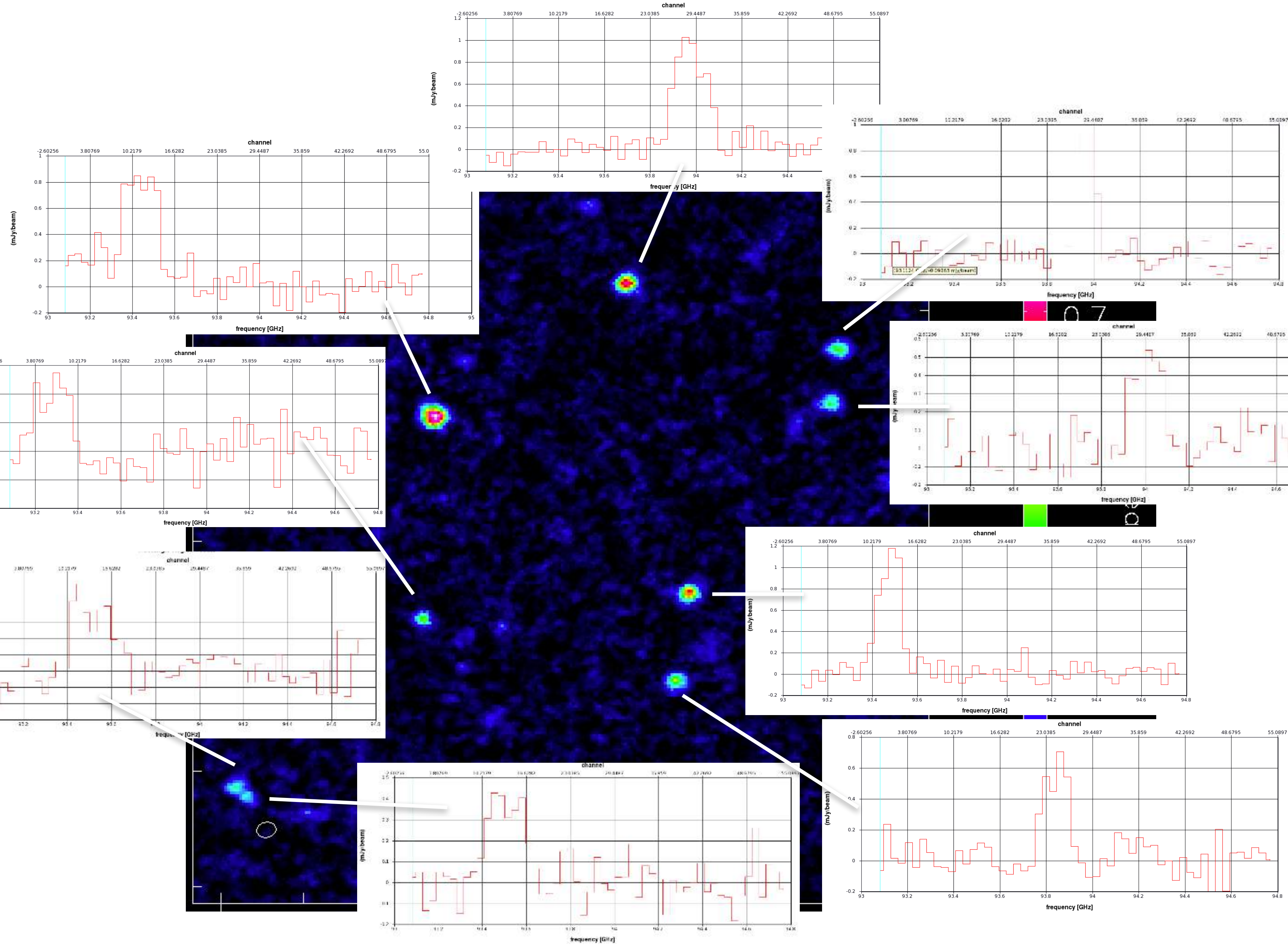
- clear contrast in low-z clusters (e.g., RXJ1716 @z=0.81, Koyama et al. 2007, MNRAS, 382, 1719)

ALMA Band3 survey of CO(2-1) emitters in the proto-cluster XCS J2215.9-1738 (z=1.46)

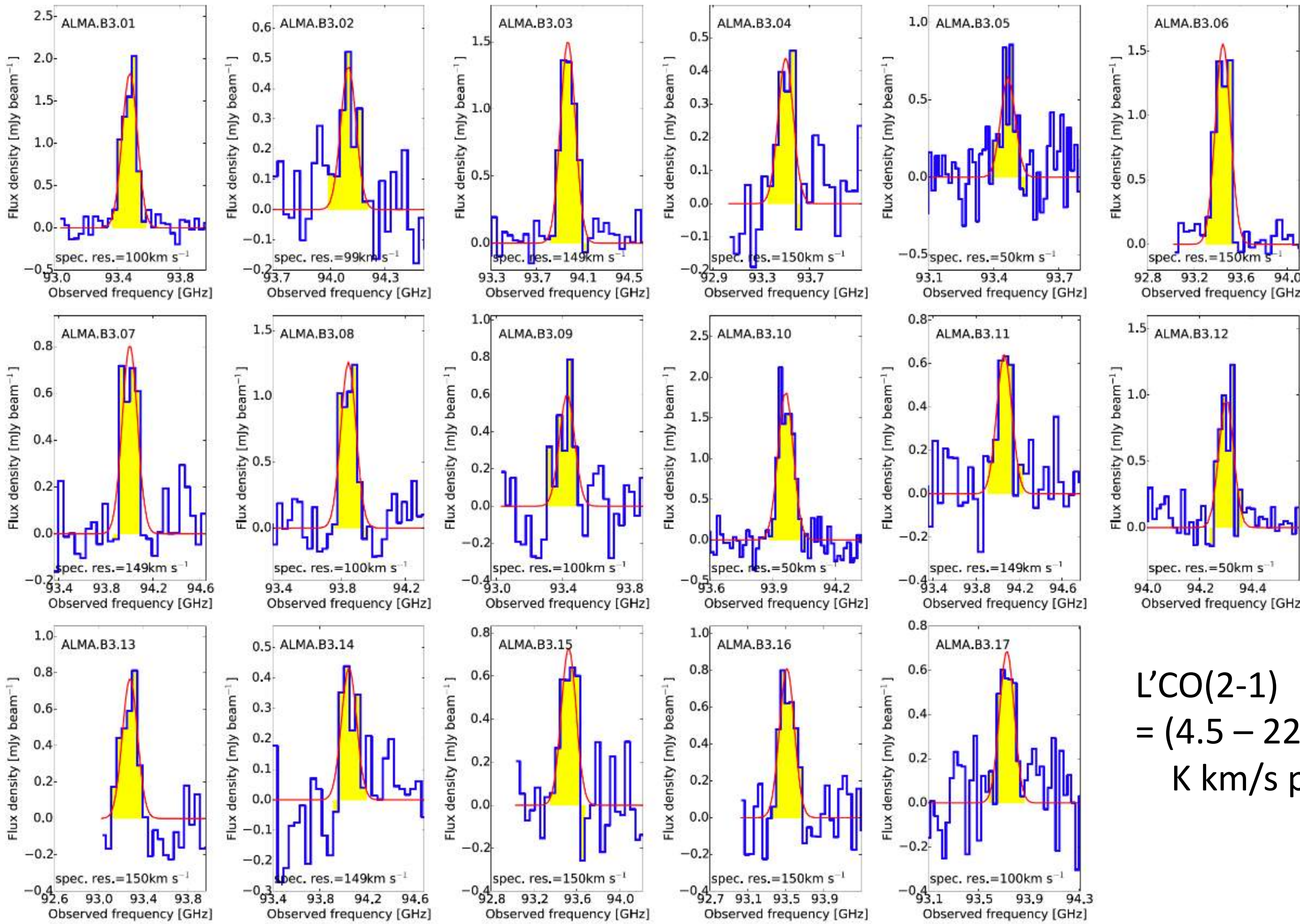


- 3 point mosaic
- 2.33 arcmin^2
- f(obs) = 93.03 – 94.86 GHz ➔ z = 1.430 – 1.478
- 1.04 hr on-source per pointing
- 1σ = 0.17 mJy/beam for dv = 50 km/s
- Clumpfind
- Cross-matched with optical data with 1” search radius

Hayashi, M., Kodama, T., Kohno, K., Yamaguchi, Y., et al., 2017, ApJ, 841, L21


channel
frequency [GHz]
(mJy/beam)

17 CO(2-1) emitters identified

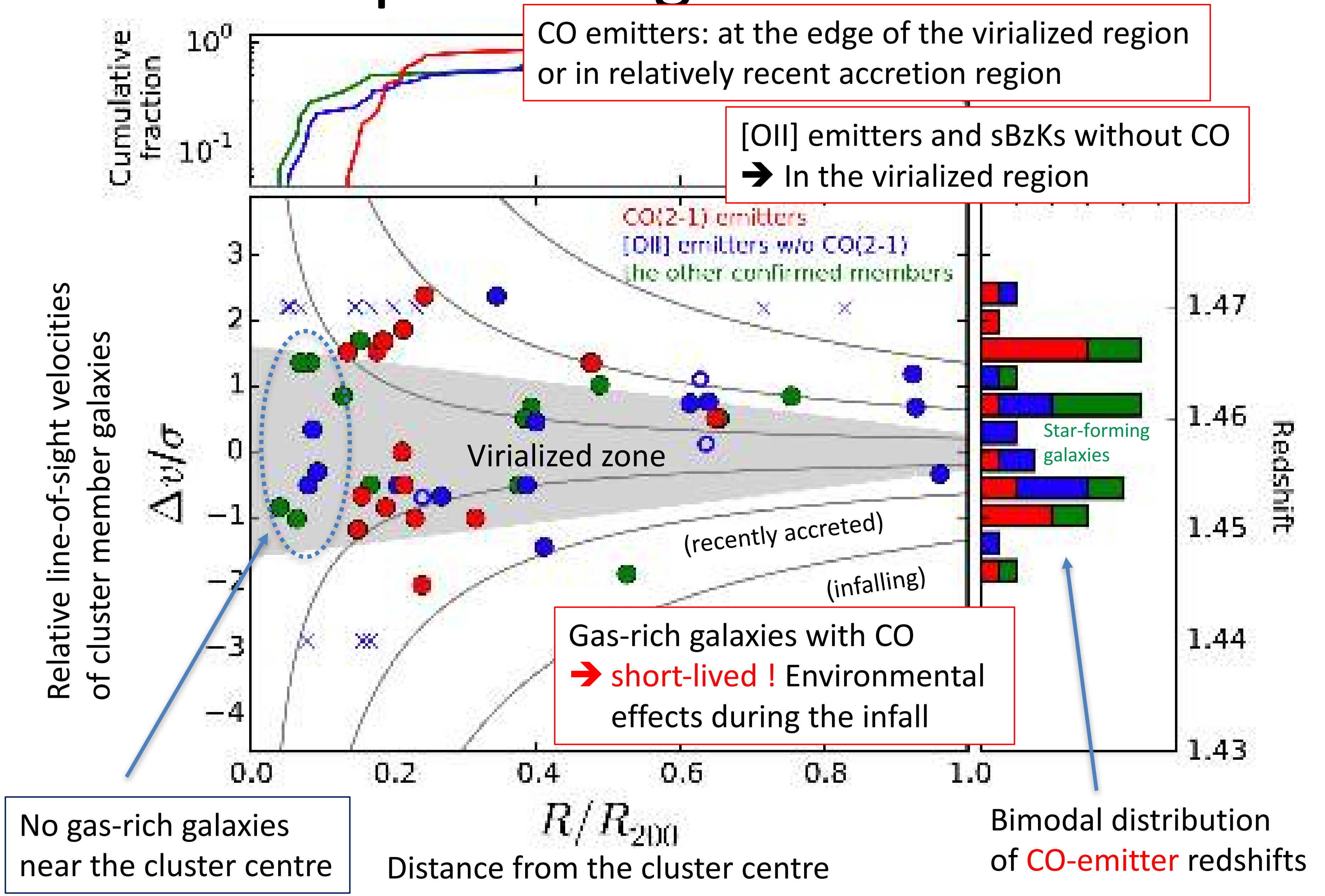


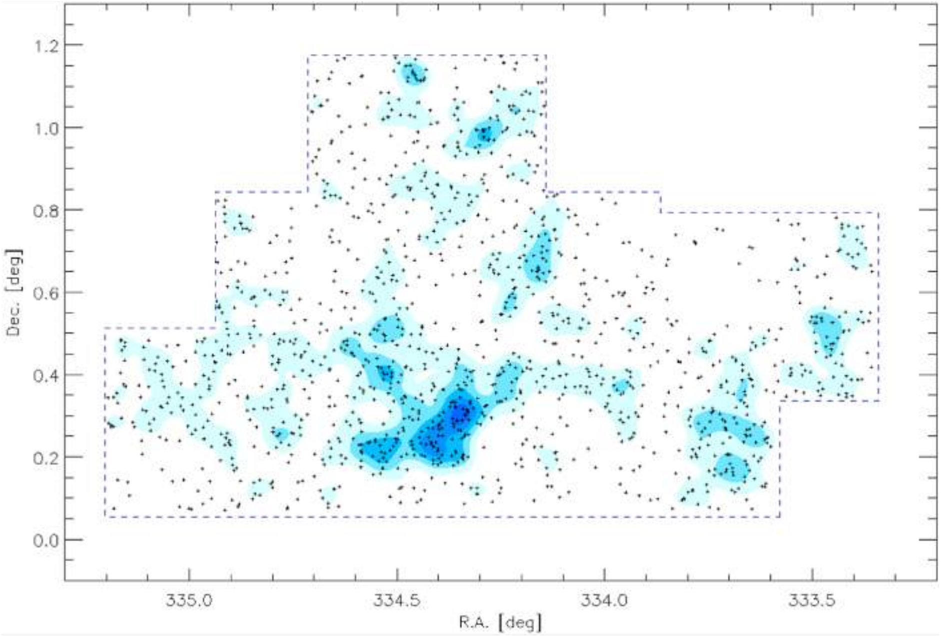
L'CO(2-1)
= (4.5 – 22) x 10^9
K km/s pc^2

Phase-space diagram

- A useful tool to characterize the accretion state of cluster member galaxies relatively free from effects due to the 2D projected positions with respect to the cluster centre (Noble et al. 2013, 2016; Muzzin et al. 2014; Jaffe et al. 2015)
- If the motions of member galaxies are virialized around the cluster centre, the line-of-sight velocities have larger dispersions toward the cluster centre and lower dispersions at larger radii.
- Galaxies that are accreted to the cluster recently tend to be offset from that virialized relation and tend to show large relative velocities at any radii.

Phase-space diagram in XCS2215



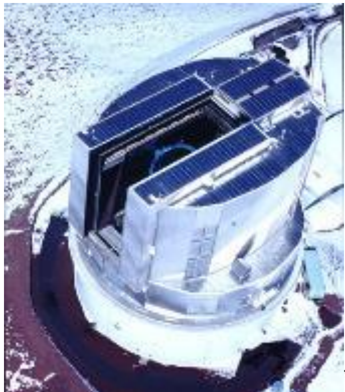


Umehata et al. 2015, ApJ, 815, L8
Umehata et al. 2017, ApJ, 835, 98

SSA22-ALMA
6 (→ 20) $arcmin^2$ imaging

Clustered dusty extreme starbursts at the deep potential well of the SSA22 large scale structure at z = 3.1

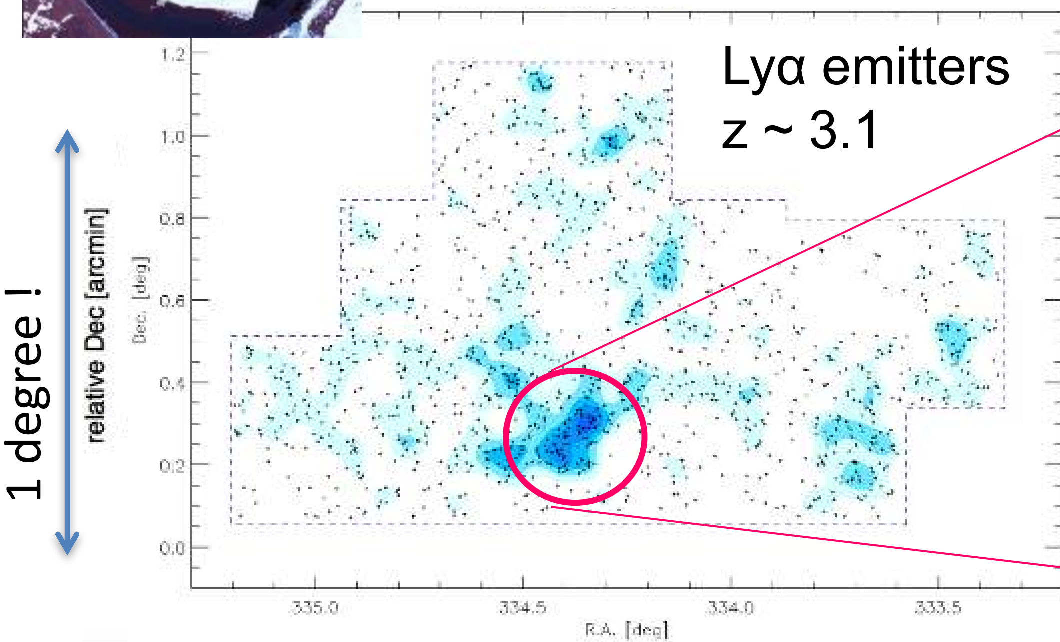
SuprimeCam + NB filters on SUBARU



LAEs

Low mass star-forming galaxies

Yamada et al. 2012, AJ, 143, 79

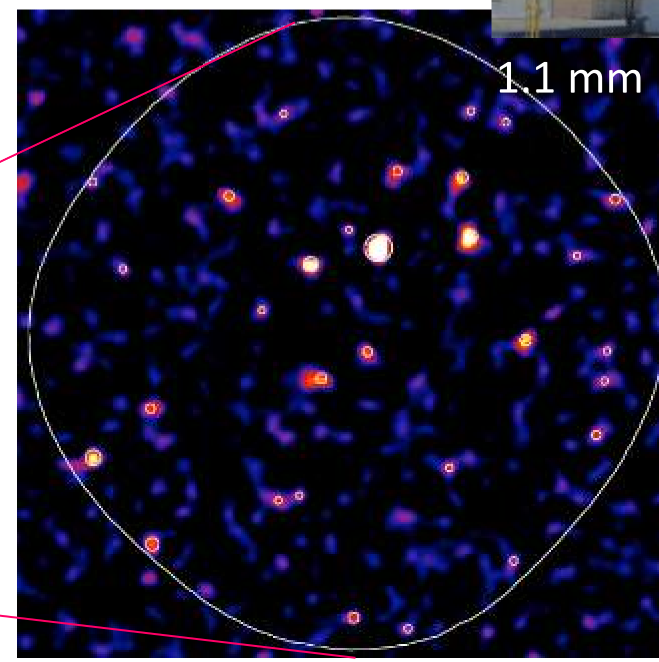


No one-by-one correspondence to LAEs, but SMGs are clustered at the LAE density peak

SMGs

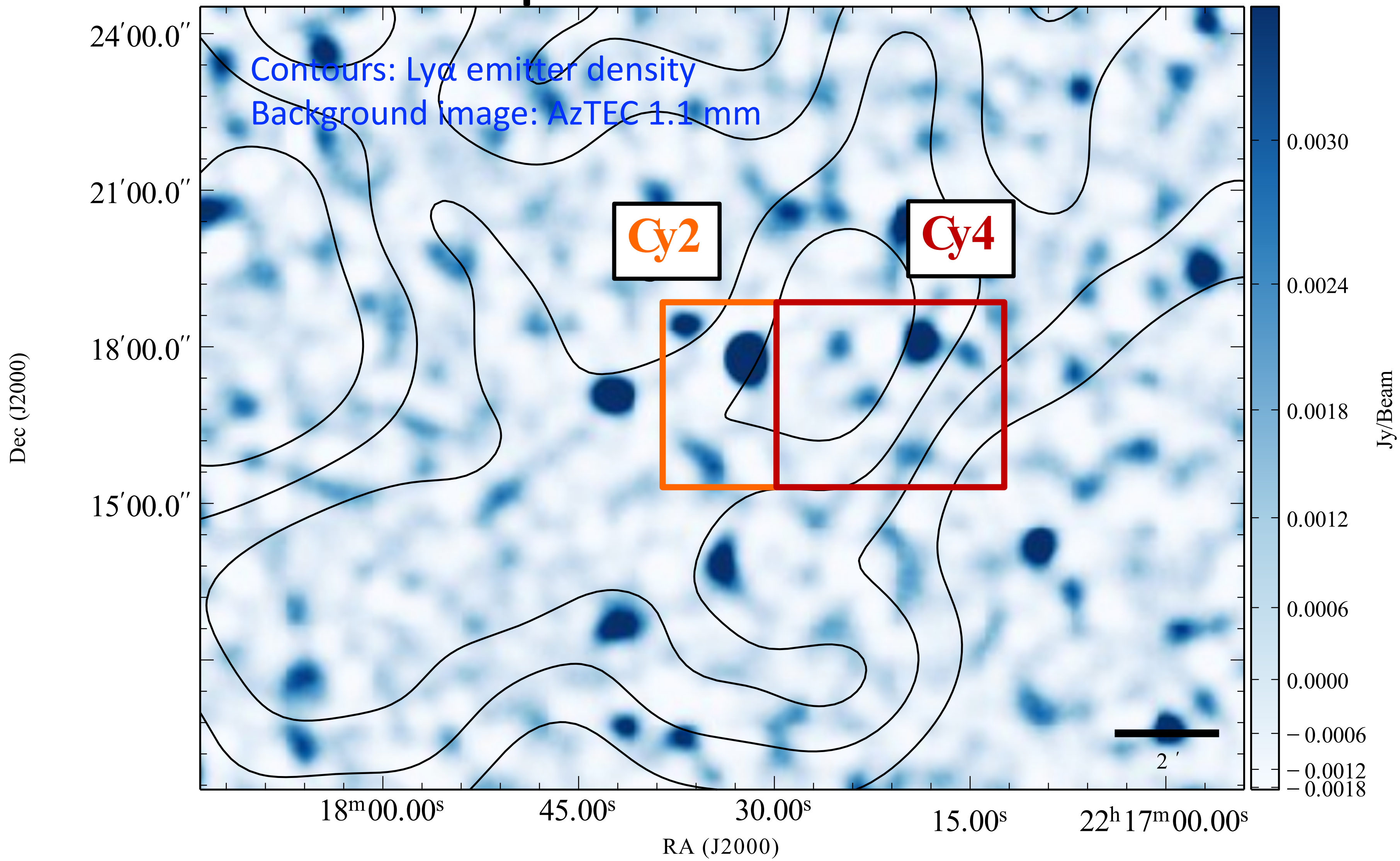
SFR ~ a few 100 – a few 1000 $M_{\odot}$/yr

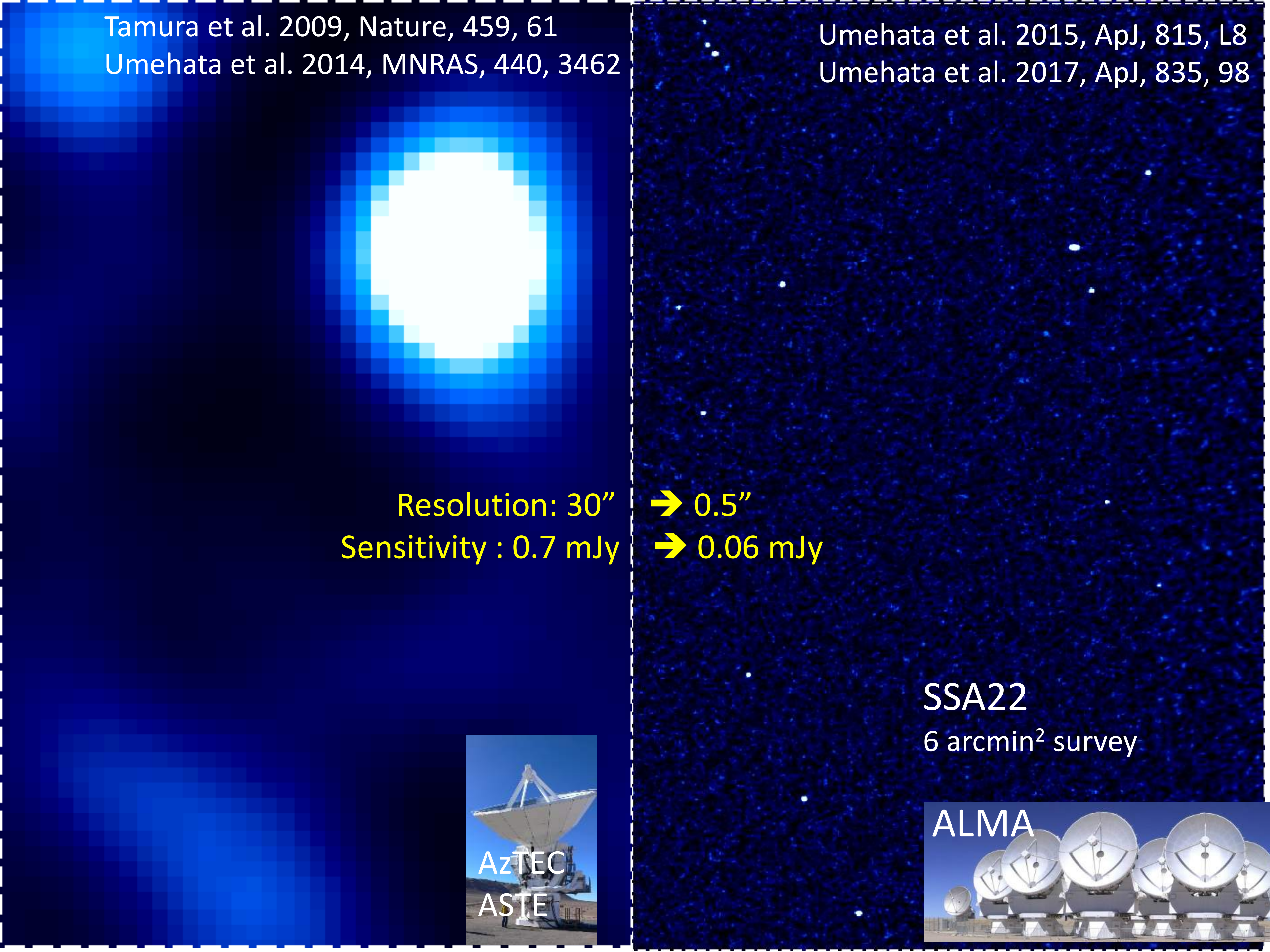
AzTEC on ASTE

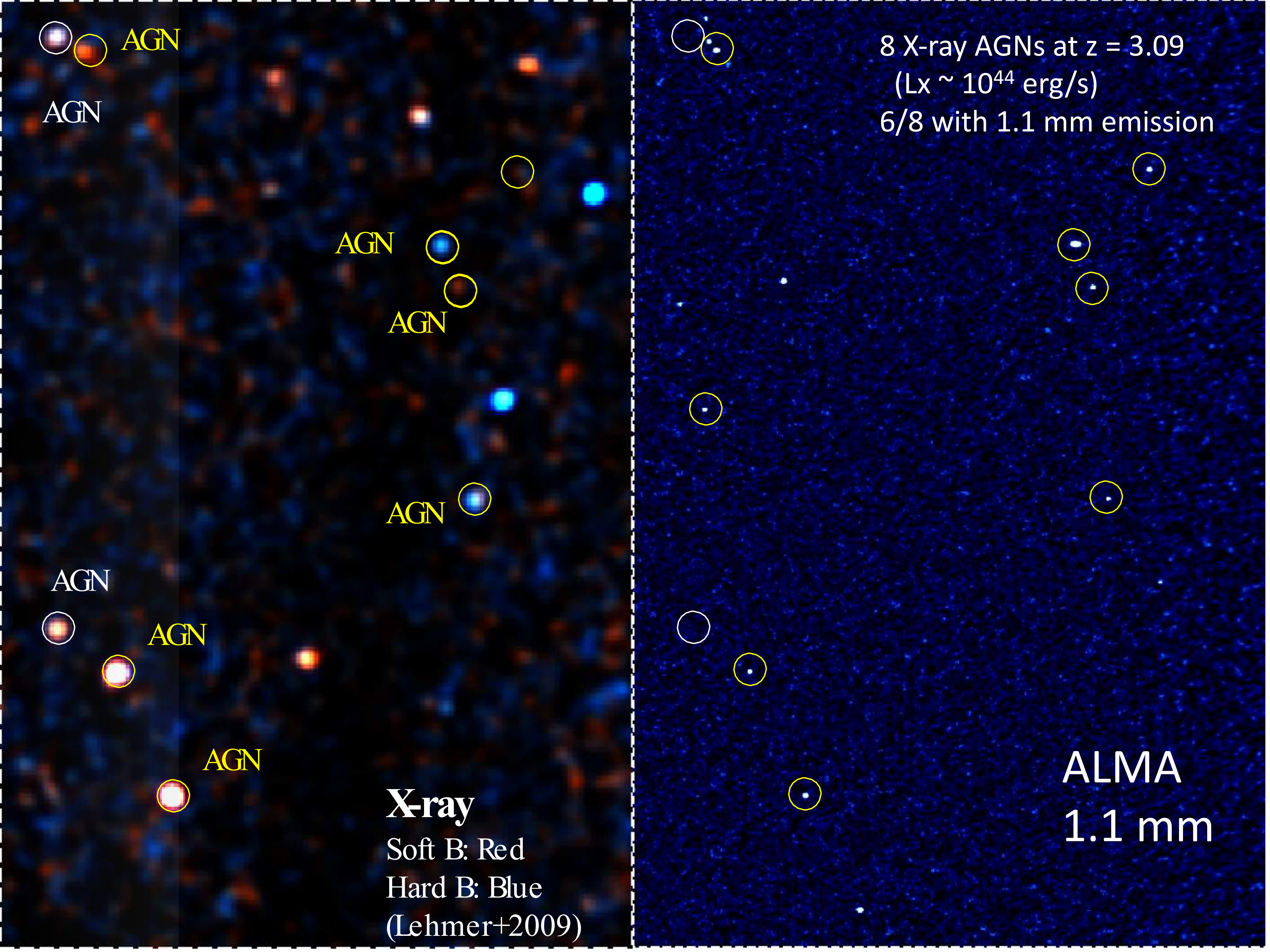


Tamura et al. 2009, Nature, 459, 61
Umehata et al. 2014, MNRAS, 440, 3462

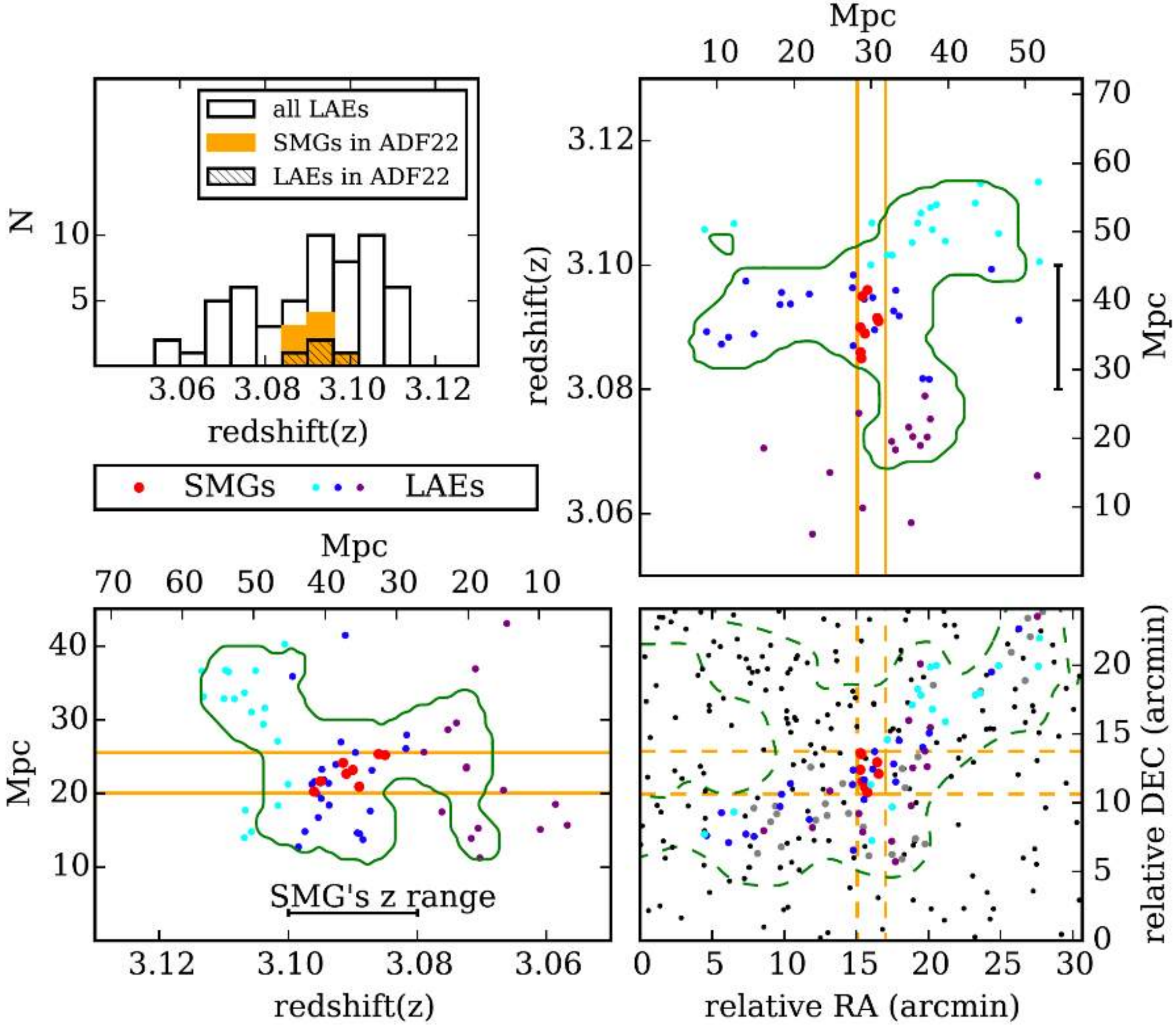
Contiguous ALMA survey at the core of the SSA22 proto-cluster at z = 3.1



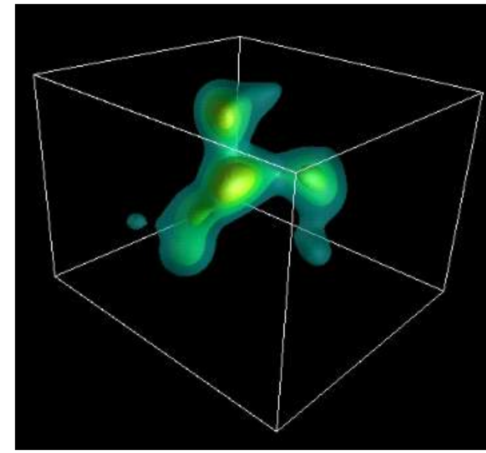

Tamura et al. 2009, Nature, 459, 61
Umehata et al. 2014, MNRAS, 440, 3462
Umehata et al. 2015, ApJ, 815, L8
Umehata et al. 2017, ApJ, 835, 98
Resolution: 30” → 0.5”
Sensitivity : 0.7 mJy → 0.06 mJy
SSA22
6 arcmin2 survey
AzTEC
ASTE
ALMA


AGN
AGN
AGN
AGN
AGN
AGN
AGN
AGN
X-ray
Soft B: Red
Hard B: Blue
(Lehmer+2009)
8 X-ray AGNs at z = 3.09
(Lx ~ 10^44 erg/s)
6/8 with 1.1 mm emission
ALMA
1.1 mm

A SMG cluster at the node of the giant cosmic web at z = 3.1



Umehata et al. 2015, ApJ, 815, L8



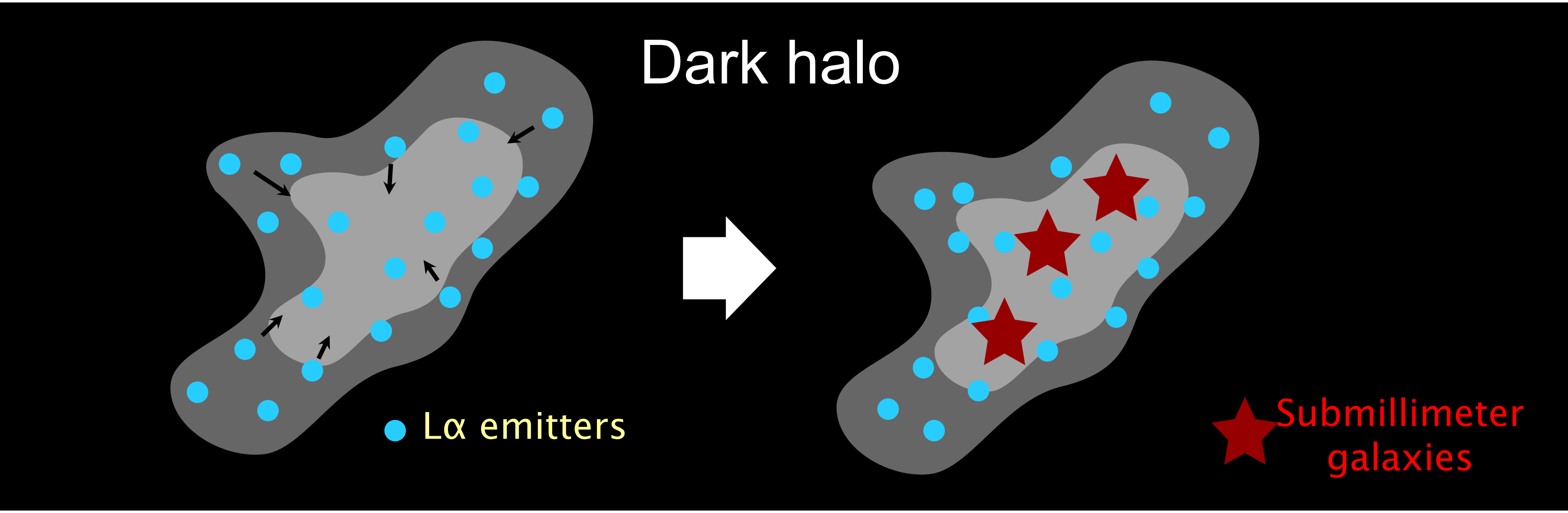
- The most active star-formation and SMBH growth occur simultaneously at the center of the z = 3.1 proto-cluster.

Zooming into the density peak of the cosmic large scale structures

– Low mass galaxies (e.g., Lyα emitting galaxies seen in Subaru) trace the overall structure of dark halos; falling into the deepest part of the halo

– At the bottom of the gravitational potential, low mass galaxies are colliding and evolving into violently star-forming massive galaxies (i.e., "submillimeter galaxies") rapidly

➔ Can "invisible" dark halos become "visible" via such massive starbursts? (see Casey 2016, ApJ, 824, 36)



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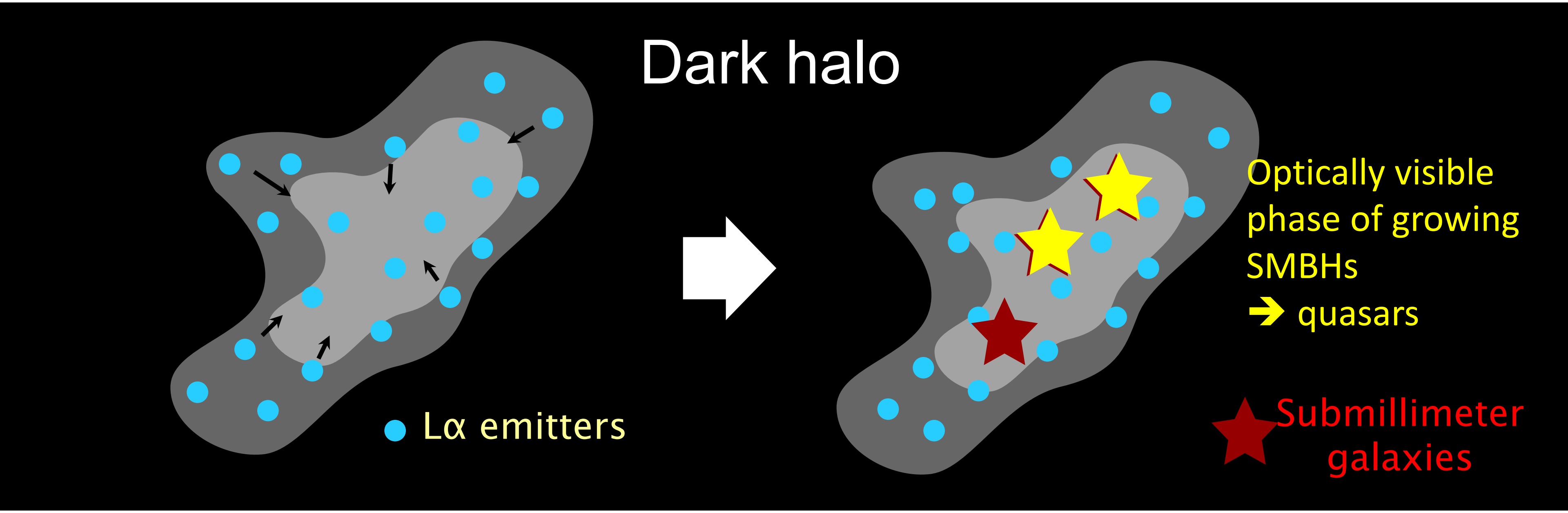
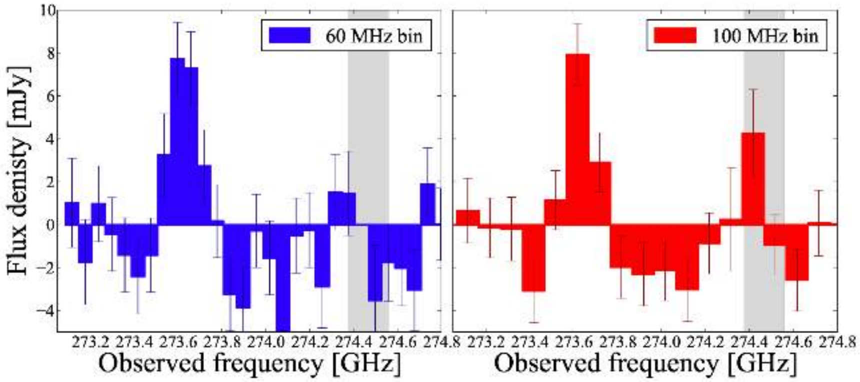
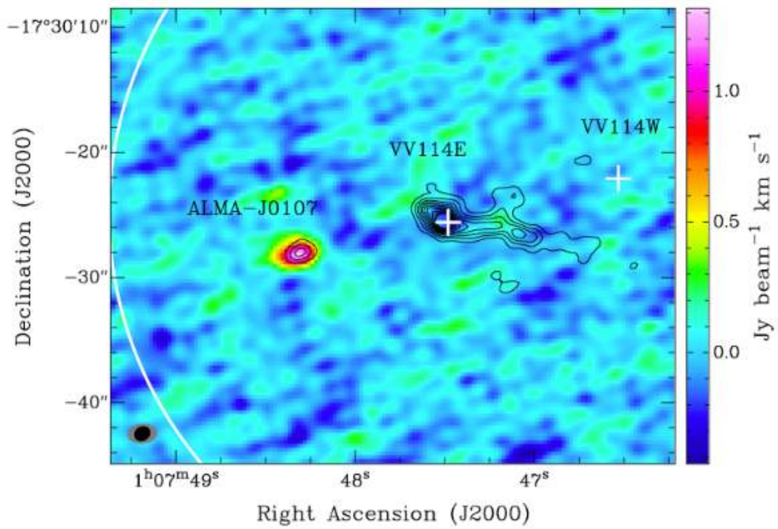
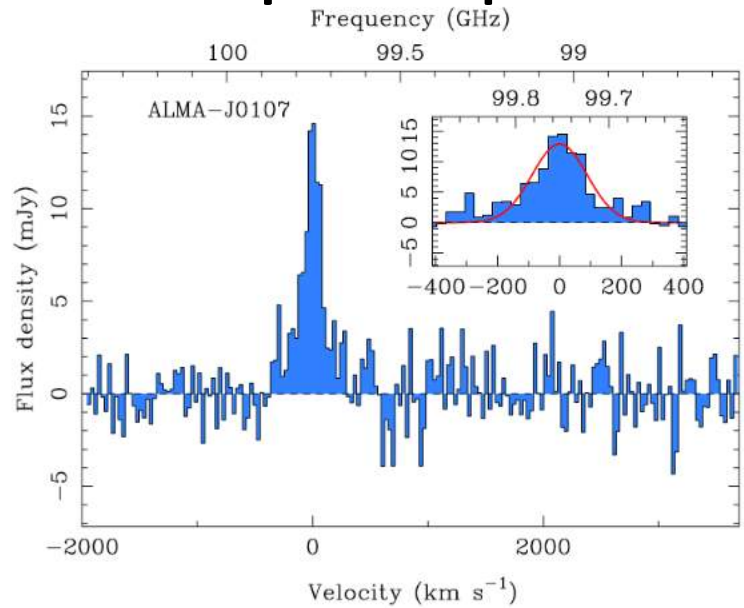




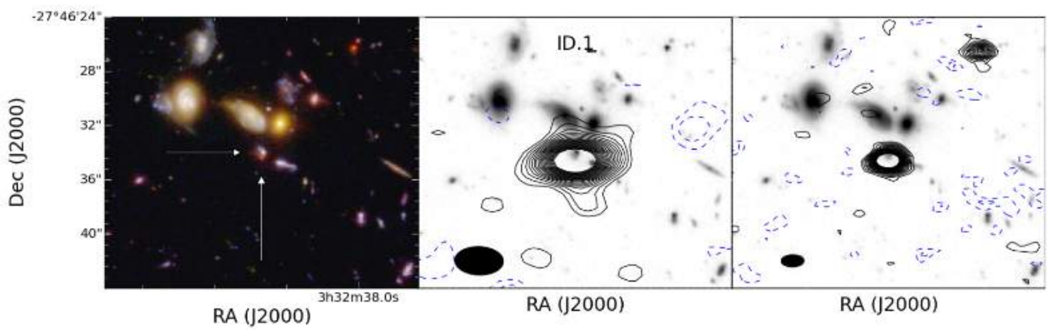
Mm/submm line-emitting galaxies

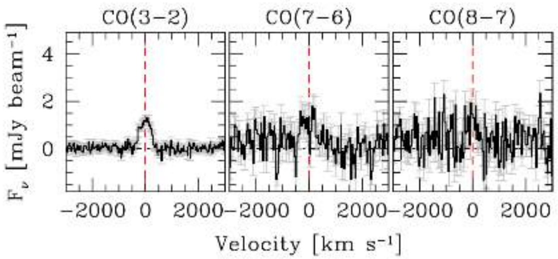
Mm/submm line-emitting galaxies: Exploiting ALMA 3D imaging-spectroscopic capabilities

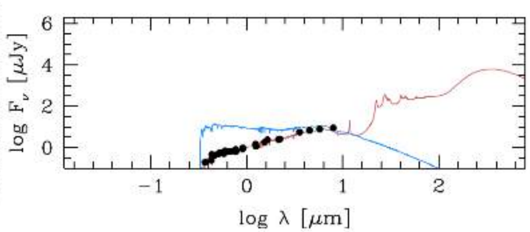




Tamura et al. 2014
ApJ, 781, L39





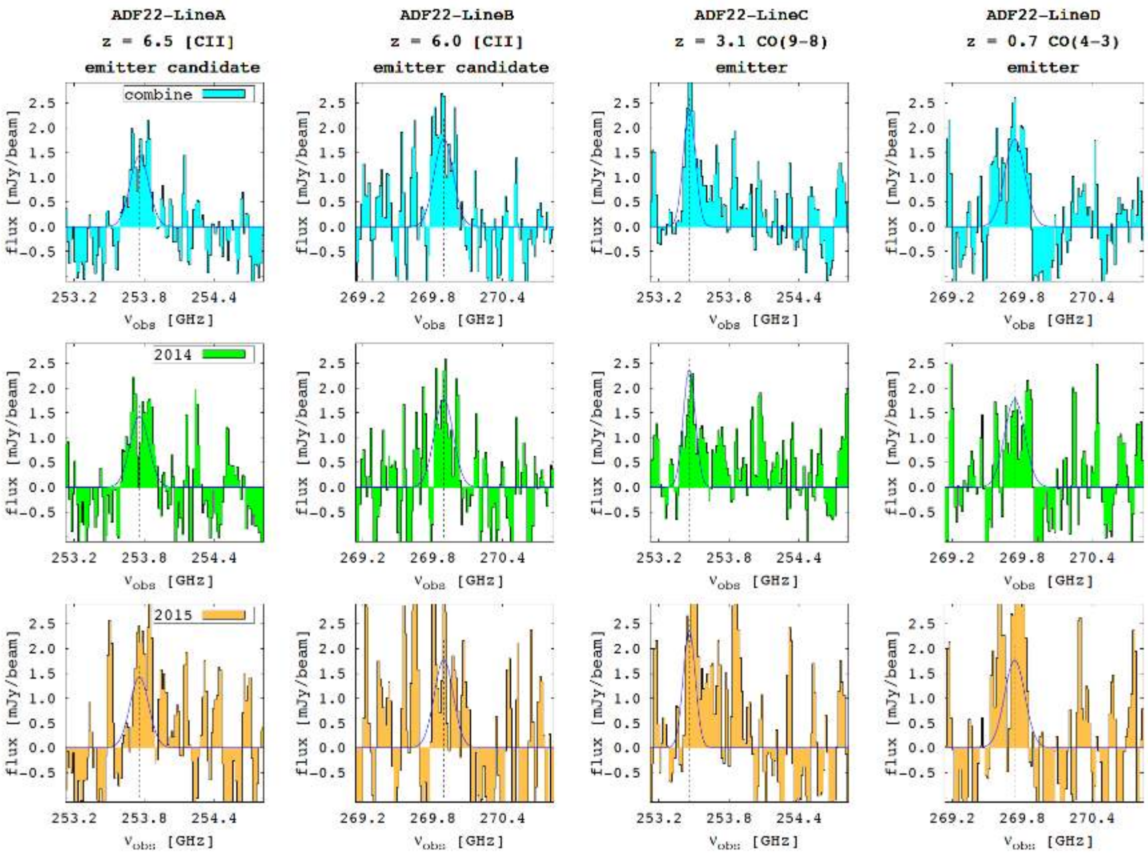


ASPECS

A CO emitter @z=2.543
in Hubble Ultra Deep Field
Decarli et al., 2016, ApJ, 833, 69

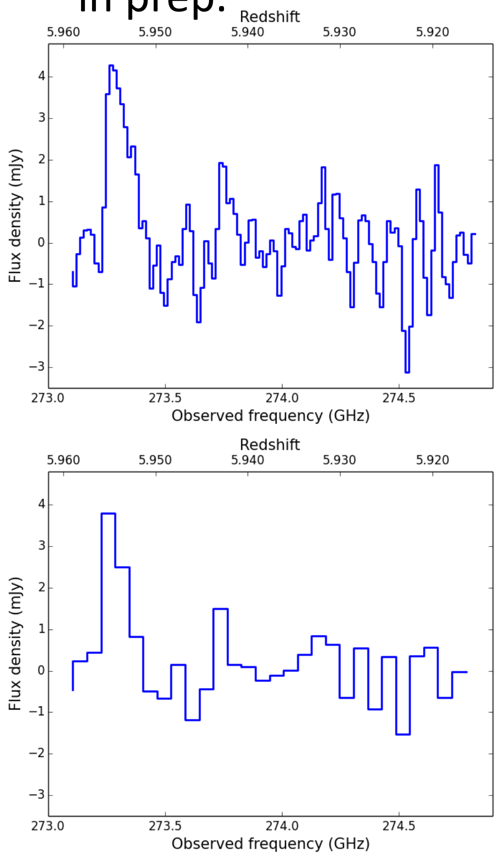
More emittes in ALMA deep surveys

- ALMA-SSA22 (ADF22) 6 arcmin^2



Hayatsu, KK, et al. 2017, PASJ, 69, 45

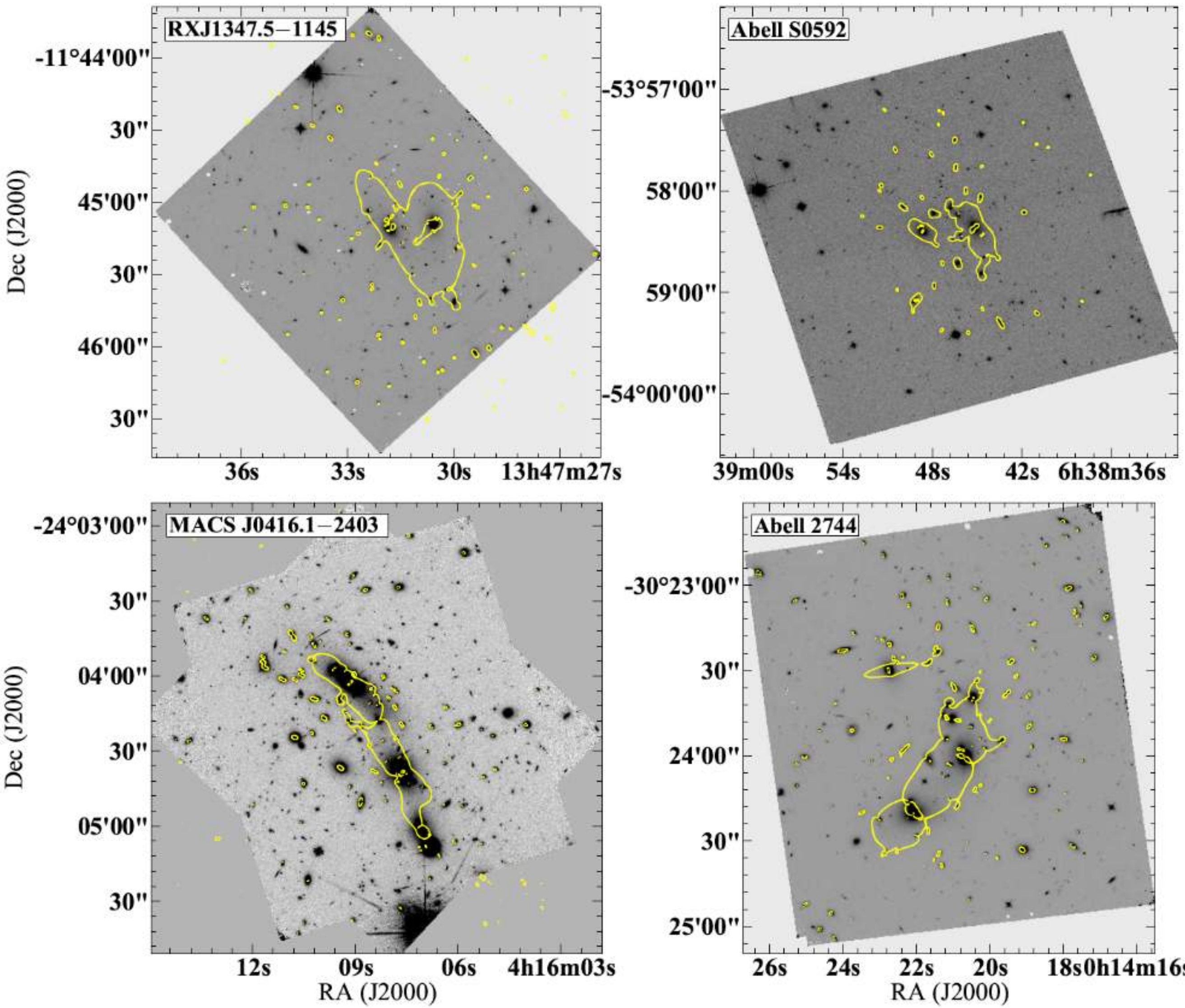
Yamaguchi, KK, et al. in prep.



- SXDF-ALMA 2 arcmin^2

And more.. (Decarili, R., Walter, F., et al., 2017, Nature, 545, 457)

Search for line-emitting galaxies in lensing clusters

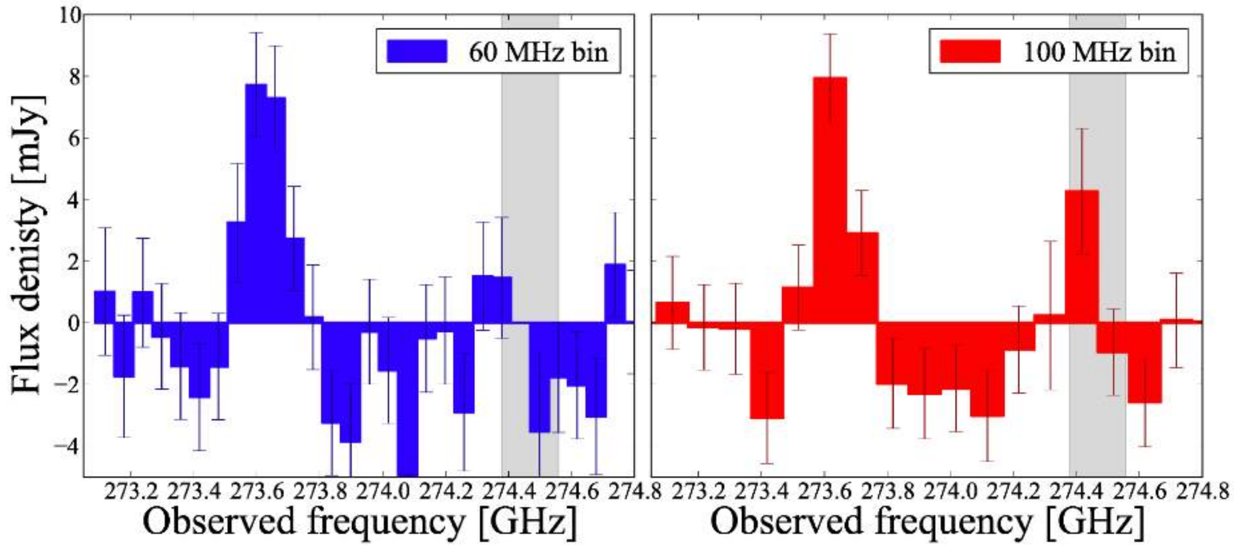


RXJ1347.5-1145 (CLASH)
Abell S0592
MACS J0416.1-2403 (HFF)
Abell 2744 (HFF)

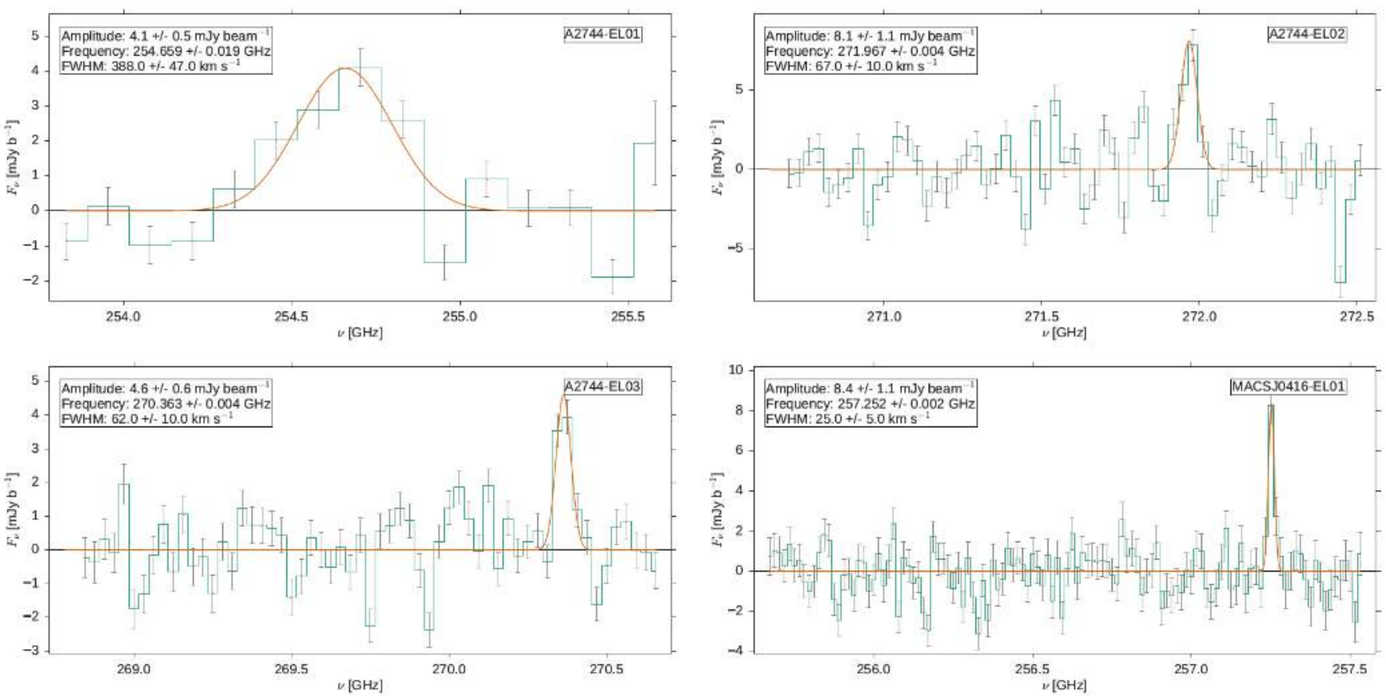
Band-6
Continuum sensitivity
1σ = 70 – 150 μJy

Yamaguchi, Y., KK et al. 2017, ApJ, in press.

Emission line candidates in lensing cluster fields



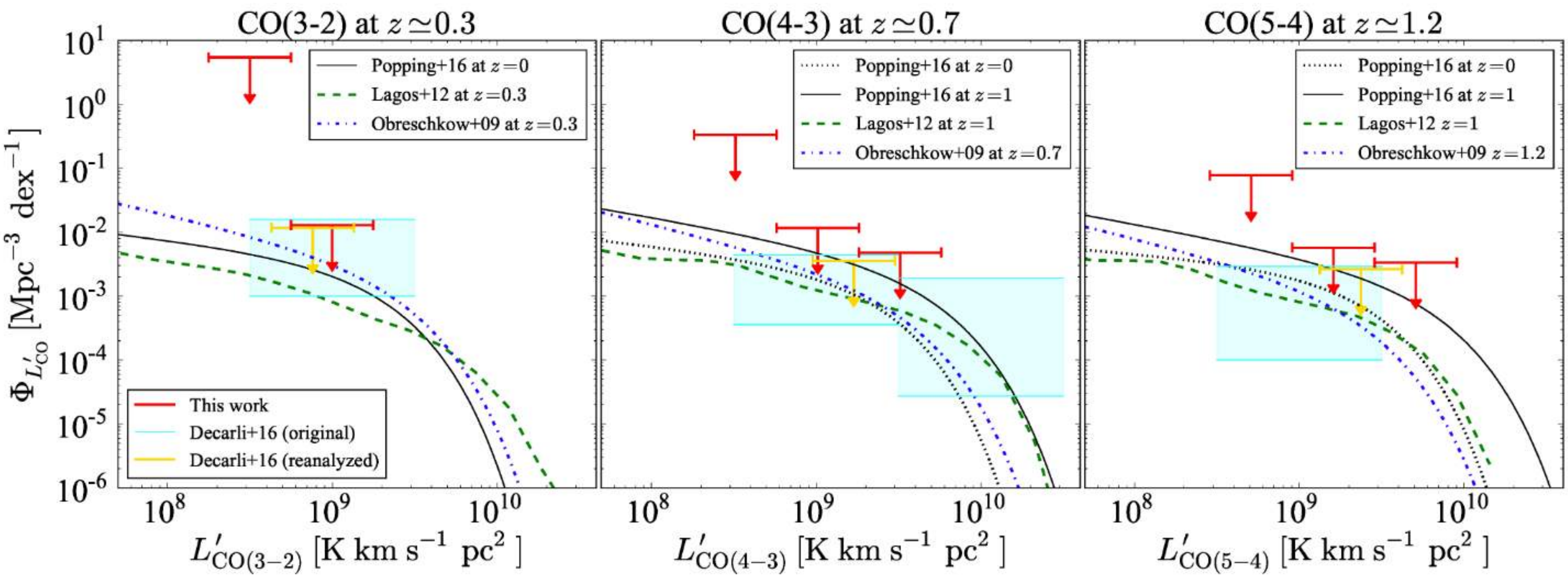
RXJ 1347-emitter1
Yamaguchi, Y., KK et al. 2017, ApJ, in press.



Emitters in Hubble Frontier Field clusters
Gonzalez-Lopez, J., Bauer, F., et al., Submitted to A&A
arXiv:1704.03007

Constraints on CO luminosity functions using ALMA observations of 4 lensing clusters

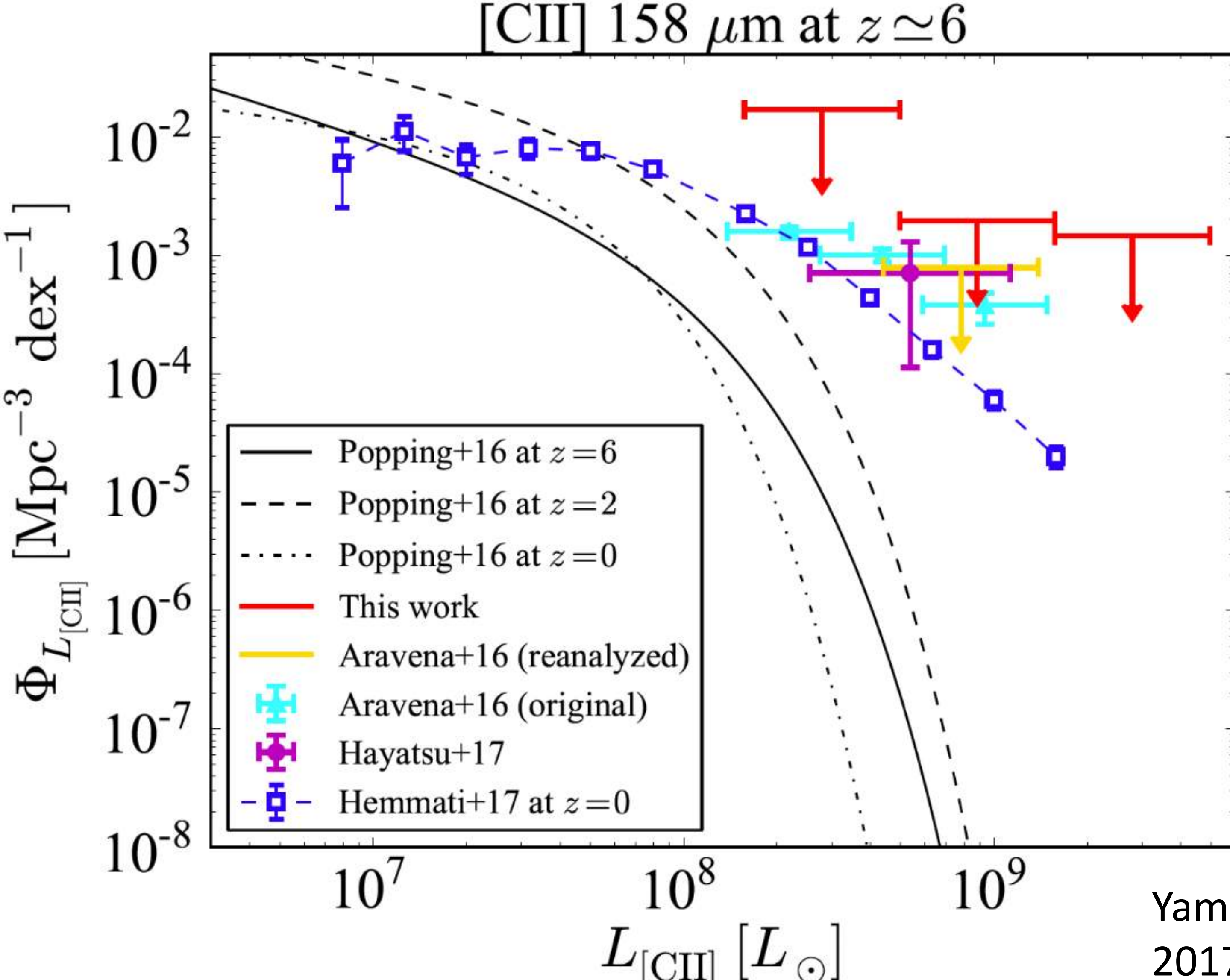
Targets: RXJ1347.5-1145, Abell S0592, MACS J0416.1-2403, Abell 2744



- Mm/submm line-emitting galaxy surveys toward lensing clusters are anther way go to

Yamaguchi, Y., KK et al. 2017, ApJ, in press.

Constraints on [CII] luminosity functions using ALMA observations of 4 lensing clusters



Yamaguchi, Y., KK et al. 2017, ApJ, in press.

Conclusions

- Unbiased galaxy surveys using ALMA
  - Capturing obscured star-forming activities on the star-forming main-sequence
  - Mostly depend on stellar mass, but some near-infrared (WFC3/F160 or H-band) drop dusty galaxies are also found
  - More surveys in GOODS-S (including ASAGAO) are in progress
- Contiguous surveys in proto-clusters
  - A rich cluster of CO(2-1) emitters at XCS2215 at $z = 1.5$, unveiling the gas stripping process during the infall
  - A rich SMG cluster, with growing SMBHs (6/8 are X-ray AGN), at the node of the giant cosmic web at $z = 3.1$
- (sub)mm line emitting galaxies
  - Unbiased ALMA deep surveys are detecting line emitters → to constrain CO and [CII] luminosity functions
  - Usefulness of lensing clusters