ULTIMATE-Subaru science workshop 2016
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Roles of ULTIMATE-Subaru in the ALMA era

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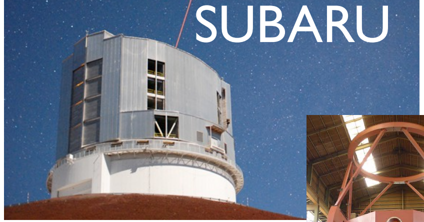
Expected synergies

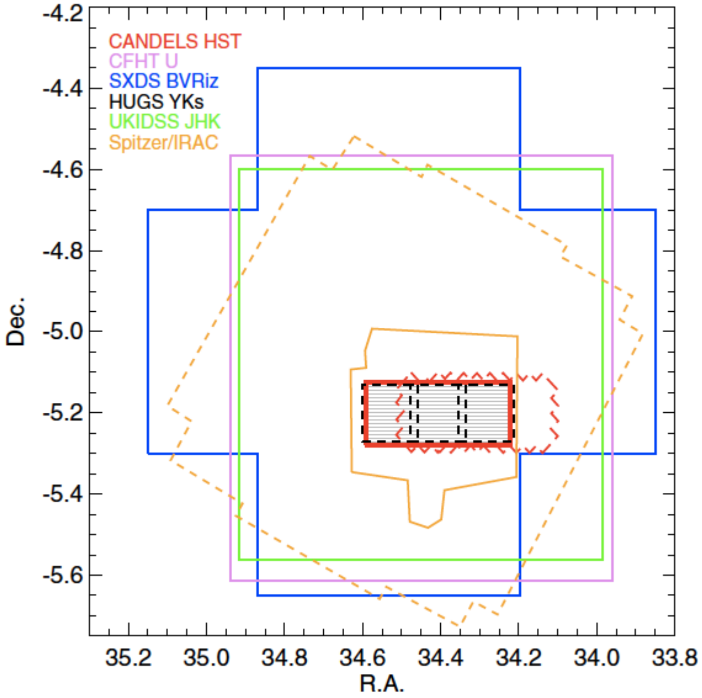


1) Wide area surveys with Subaru → ALMA follow up of (relatively) rare but important sources

- HSC (+TAO/SWIMS) wide surveys of z >5-7 (z>7.2) quasars → ALMA: M(BH)/M(Bulge), growth of spheroidal, feedback, dust enrichment/metallicity, etc.
- Lyα emitters, Hα/[OIII] emitters, etc. → dust + CO/[CII] follow up → SFR-Mstar relation vs gas fraction

2) ALMA deep surveys in ULTIMATE deep fields

- richness of narrow/medium/broad bands by ULTIMATE is essential to study the nature of ALMA sources
- Deep emitter surveys on GOODS-S (Kodama et al.): rich synergies with on-going ALMA deep surveys



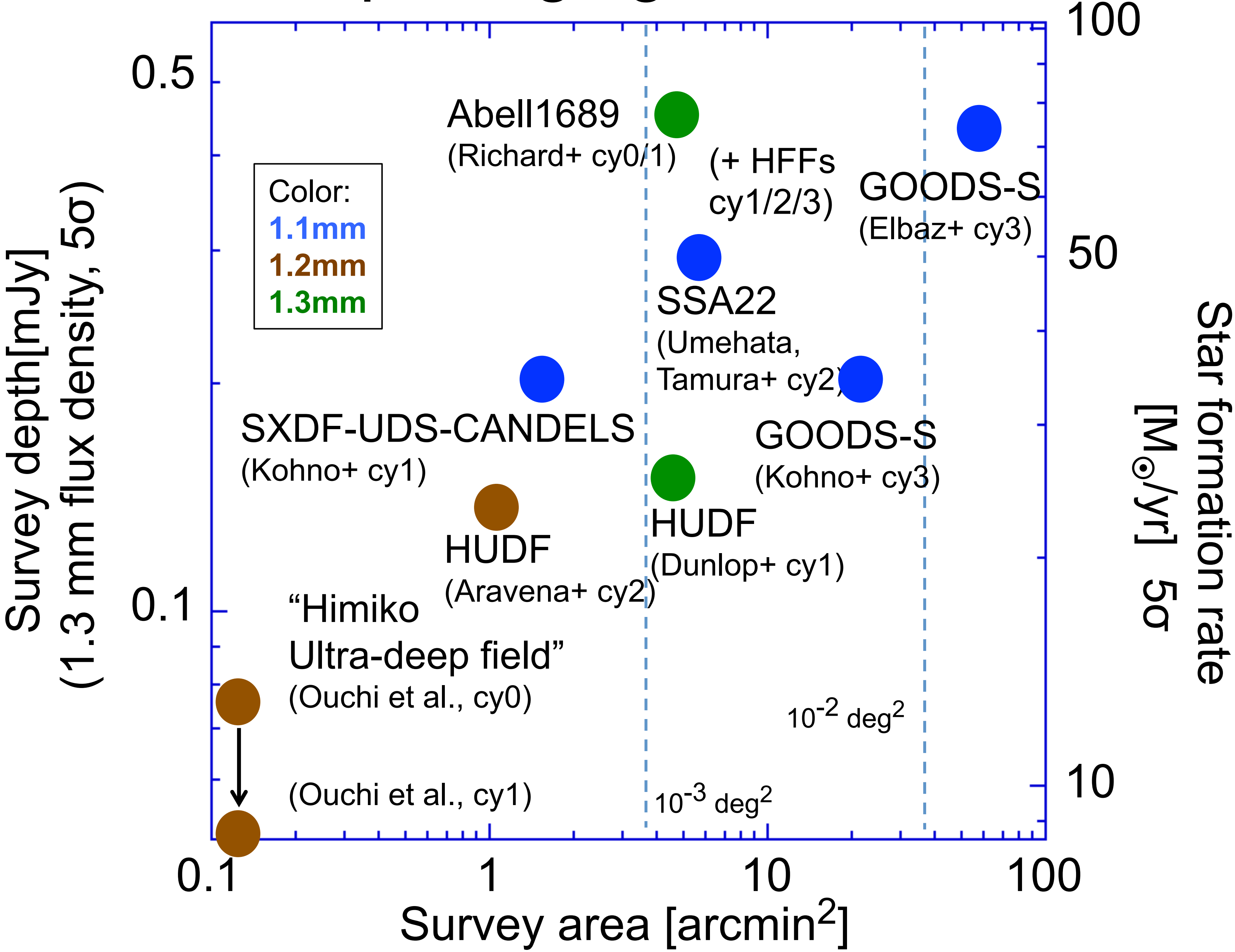
ALMA deep surveys in ULTIMATE (+HSC) fields

(Unbiased) deep surveys using ALMA

- (Currently) a few arcmin^2 – a few 10 arcmin^2 surveys
  - HUDF (cy1,3 Dunlop et al., submitted), SXDF-CANDELS (cy1, Kohno et al., in press; Hatsukade et al. 2016, PASJ, 68, 36; Yamaguchi et al., submitted), SSA22 (cy2, Umehata et al. 2015, ApJ, 815, L8), Abell 1689 (Watson et al. 2015, Nature, 519, 327; Knudsen et al. 2016, MNRAS, submitted), HFFs (cy1/cy2), GOODS-S (cy3, two programs, led by David Elbaz and KK)
  - Serendipitous faint submm sources (Hatsukade et al. 2013, ApJ, 769, 27; Hatsukade et al. 2015, ApJ, 810, 91)
  - From ALMA archive (Carniani et al. 2015, A&A, 584, 78; Fujimoto et al. 2016, ApJS, 222, 1; Oteo et al. 2016, ApJ, 822, 36)
- CO, [CII], (and [OIII] !?) line emitting galaxy survey
  - Successive reports on [CII] emitter candidates at z>5-6 ?

Richness of multi-wavelength data is a key; adding narrow/medium band data w/ ULTIMATE to deep fields

ALMA Deep Imaging at ~1mm



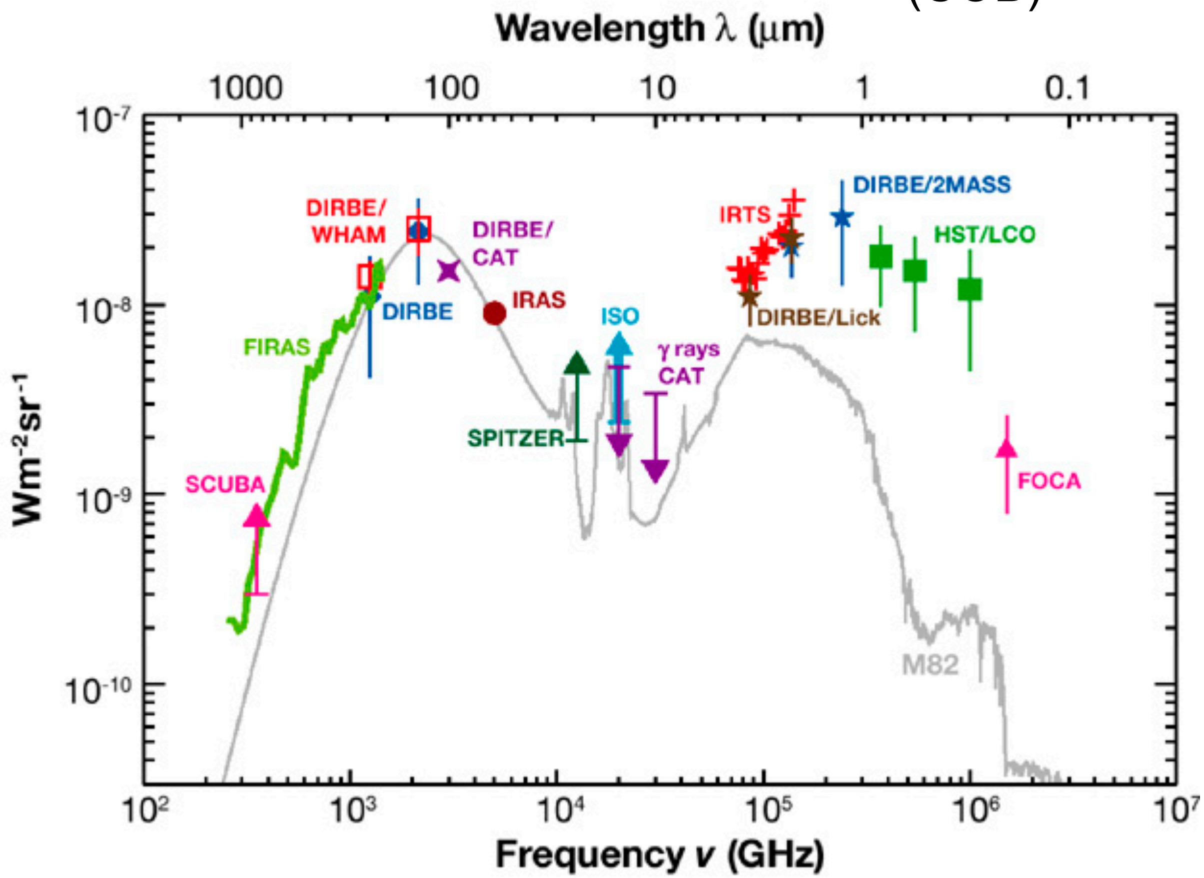
Characterizing newly uncovered ALMA sources: (1) faint submm galaxies

The infrared extragalactic background light (EBL): what is the origin?

Comparable !!!

The cosmic infrared background (CIB)

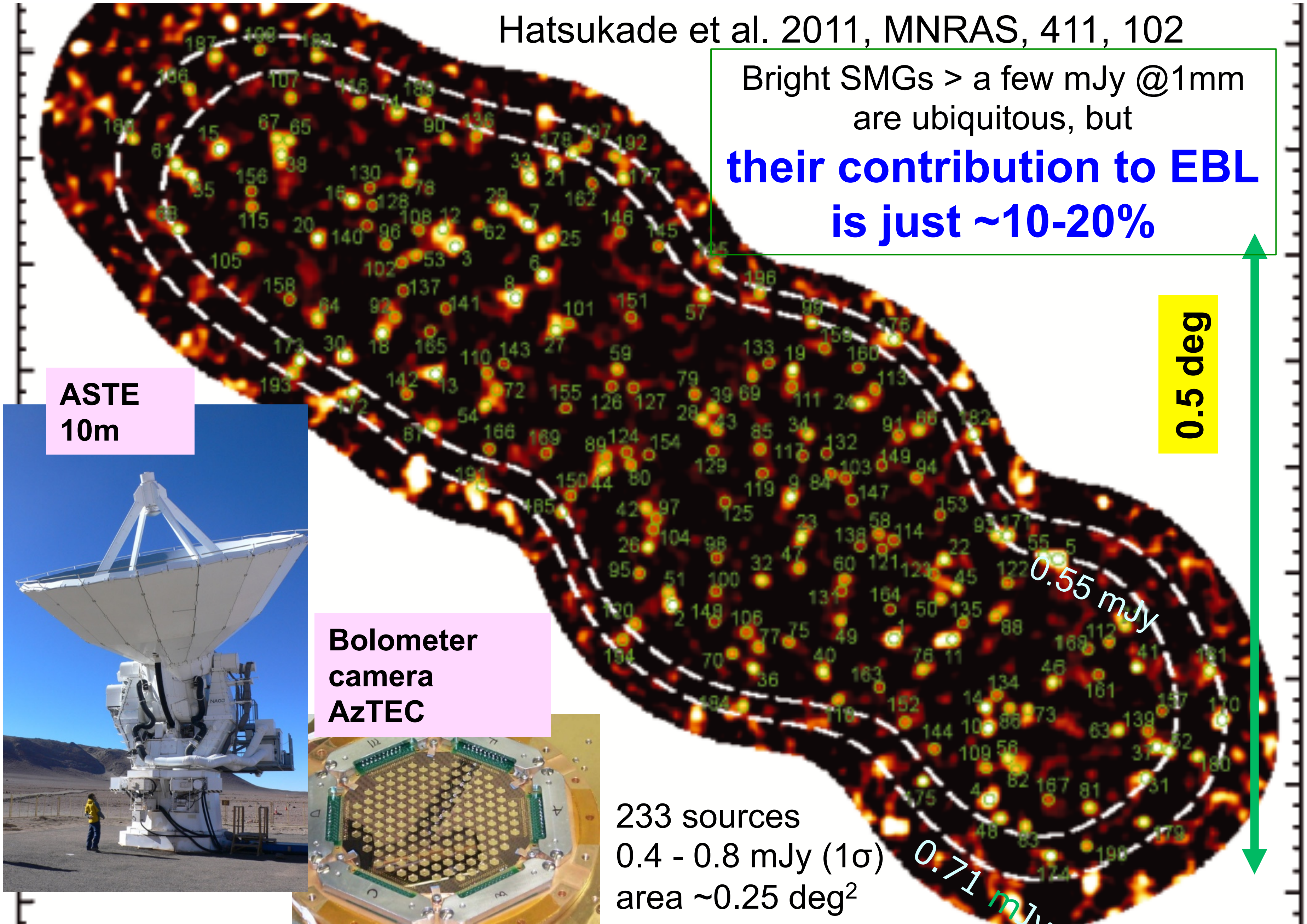
The cosmic optical background (COB)



http://ned.ipac.caltech.edu/level5/March05/Lagache/Lagache3.html

“Submm galaxies” are bright, but..

Hatsukade et al. 2011, MNRAS, 411, 102



Bright SMGs > a few mJy @1mm are ubiquitous, but
their contribution to EBL is just ~10-20%

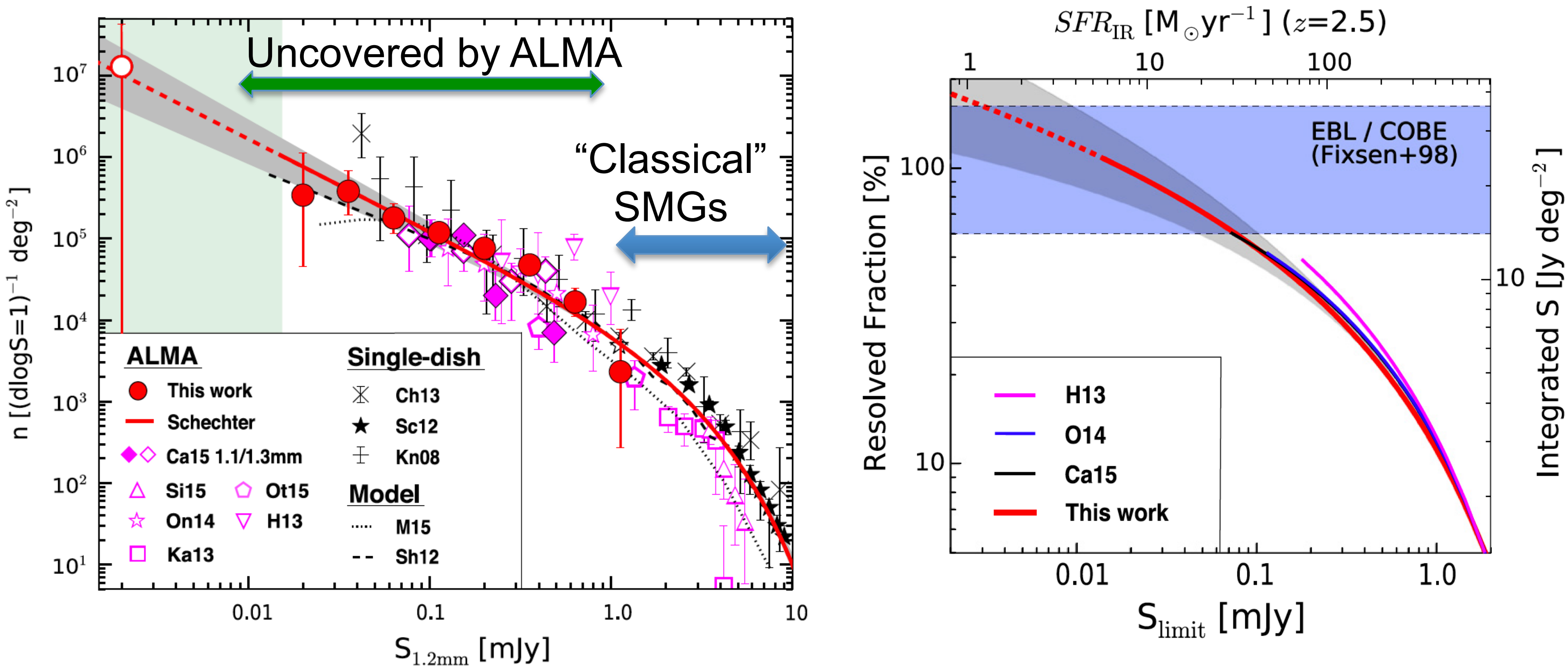
ASTE 10m

Bolometer camera AzTEC

233 sources
0.4 - 0.8 mJy (1σ)
area ~0.25 deg^2

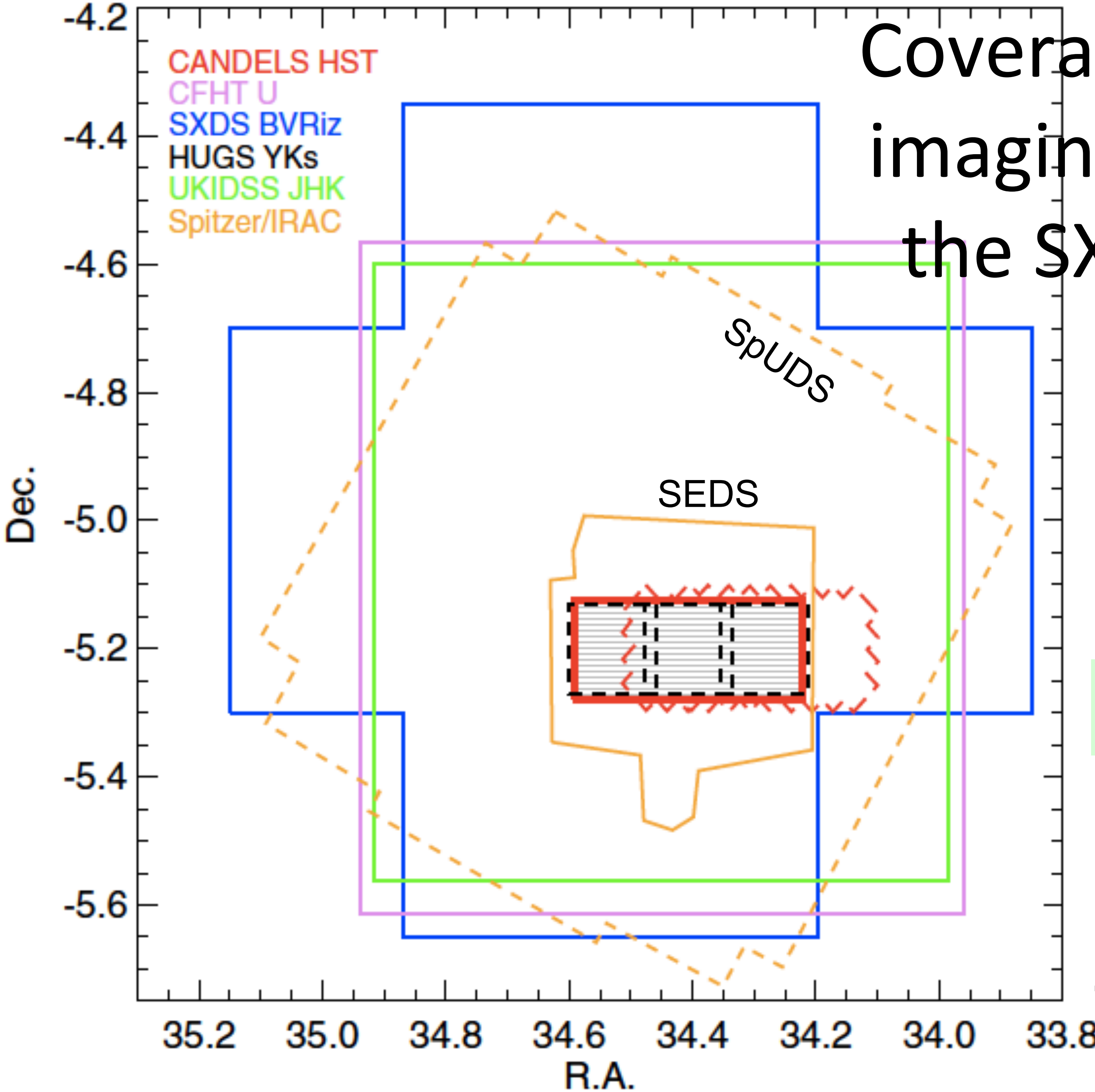
Now ALMA resolves the EBL into discrete sources

Fujimoto, S., et al. 2016, ApJS, 222, 1



- Almost ~100% of EBL is resolved into "faint submm galaxies" ?
- Their physical properties (redshift distribution, stellar mass, halo mass, gas fraction, SMBH?, etc..) remain unexplored (see also Hatsukade et al. 2015, ApJ, 810, 91)

Coverage of the imaging data in the SXDS-UDS

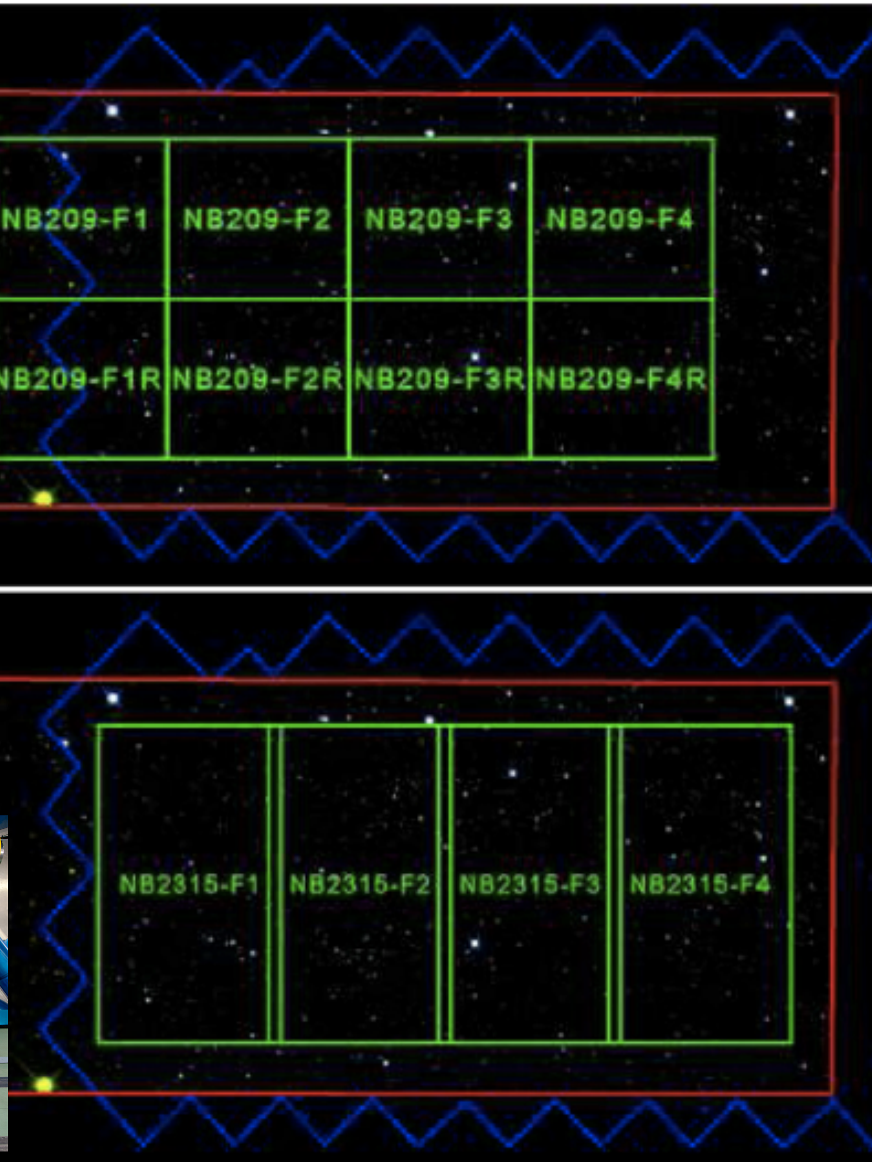


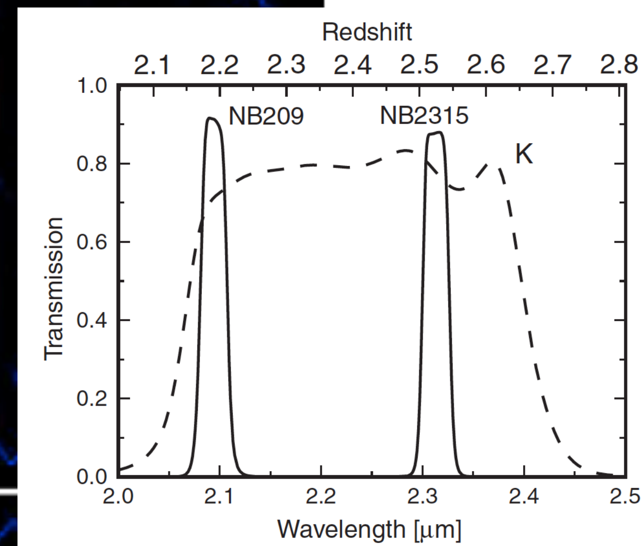
CANDELS-UDS
HUGS

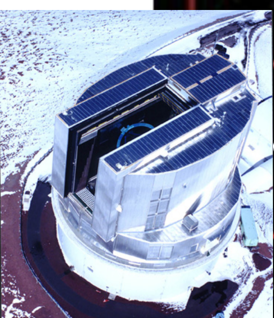
Galametz et al. 2013, ApJS, 206, 10

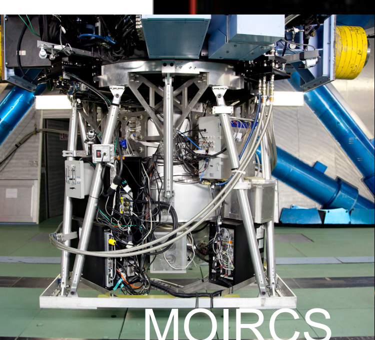
+ further new data HSC/Subaru, Spitzer, Chandra, ZFOURGE (Lee' s talk)

Subaru/MOIRCS NB survey of UDS-CANDELS









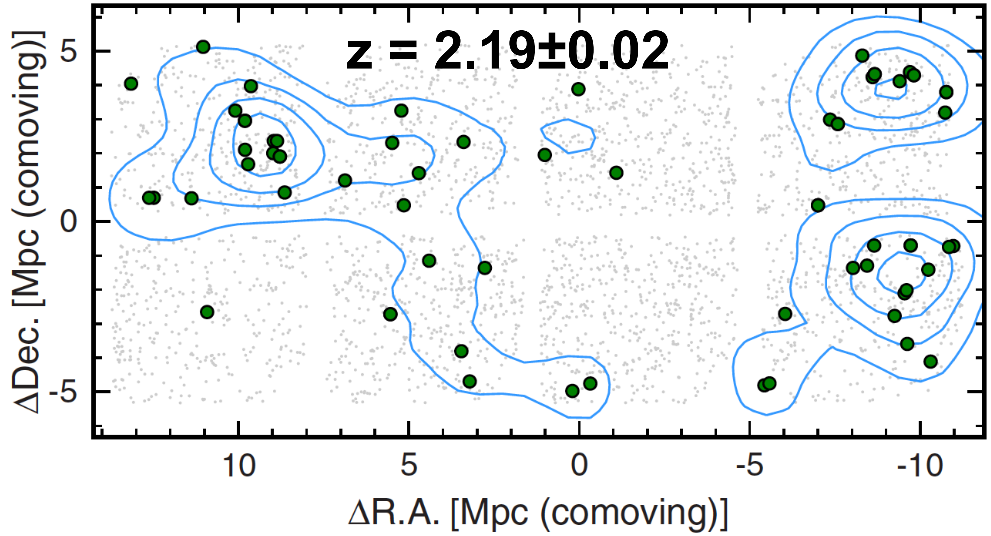
Tadaki et al. 2013, ApJ, 778, 114

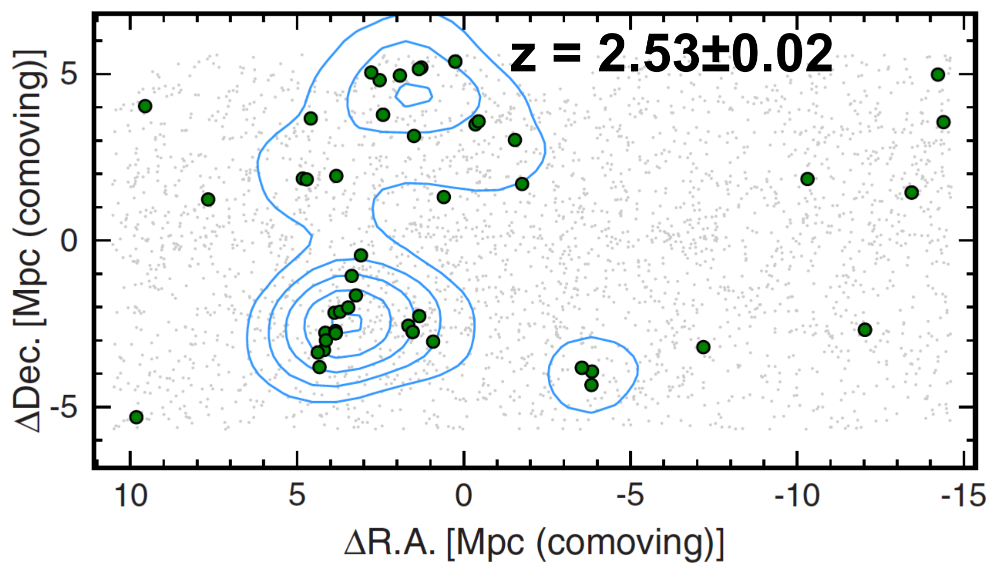
Hα emitting galaxies (MAHALO/HiZELS)

See also [OIII] emitters; Suzuki, T., et al., 2015, ApJ, 806, 208

- 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 + ALMA, JVLA (Lee Minju et al.)
  - More (MAHALO sampe)

Tadaki et al. 2014, ApJ, 780, 77

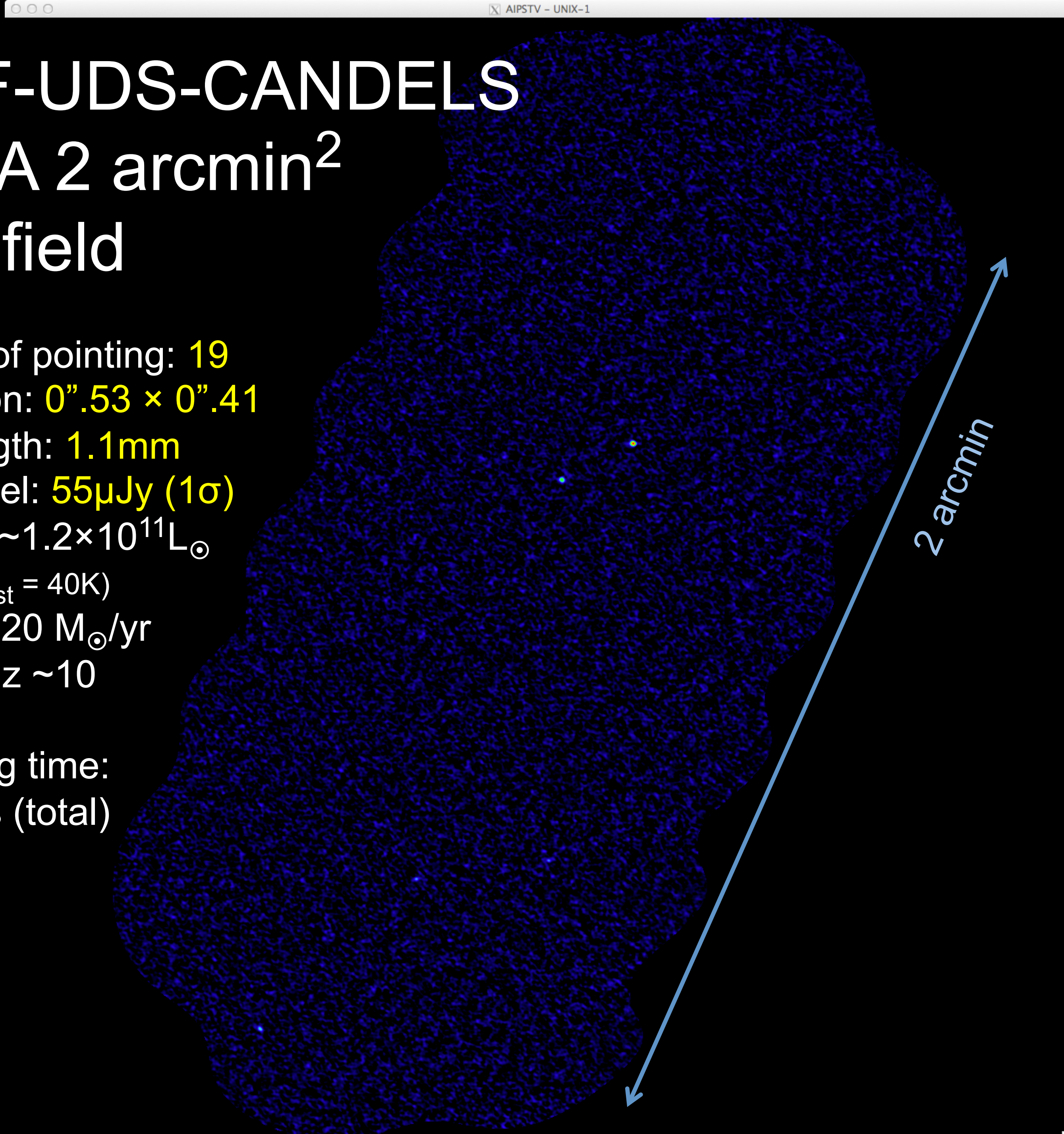




SXDF-UDS-CANDELS -ALMA 2 arcmin^2 deep field

Number of pointing: 19
Resolution: 0".53 × 0".41
Wavelength: 1.1mm
Noise level: 55μJy (1σ)
⇔ L(IR) ~$1.2\times10^{11} L_{\odot}$
(if T_{dust} = 40K)
⇔ SFR ~20 $M_{\odot}$/yr
up to z ~10

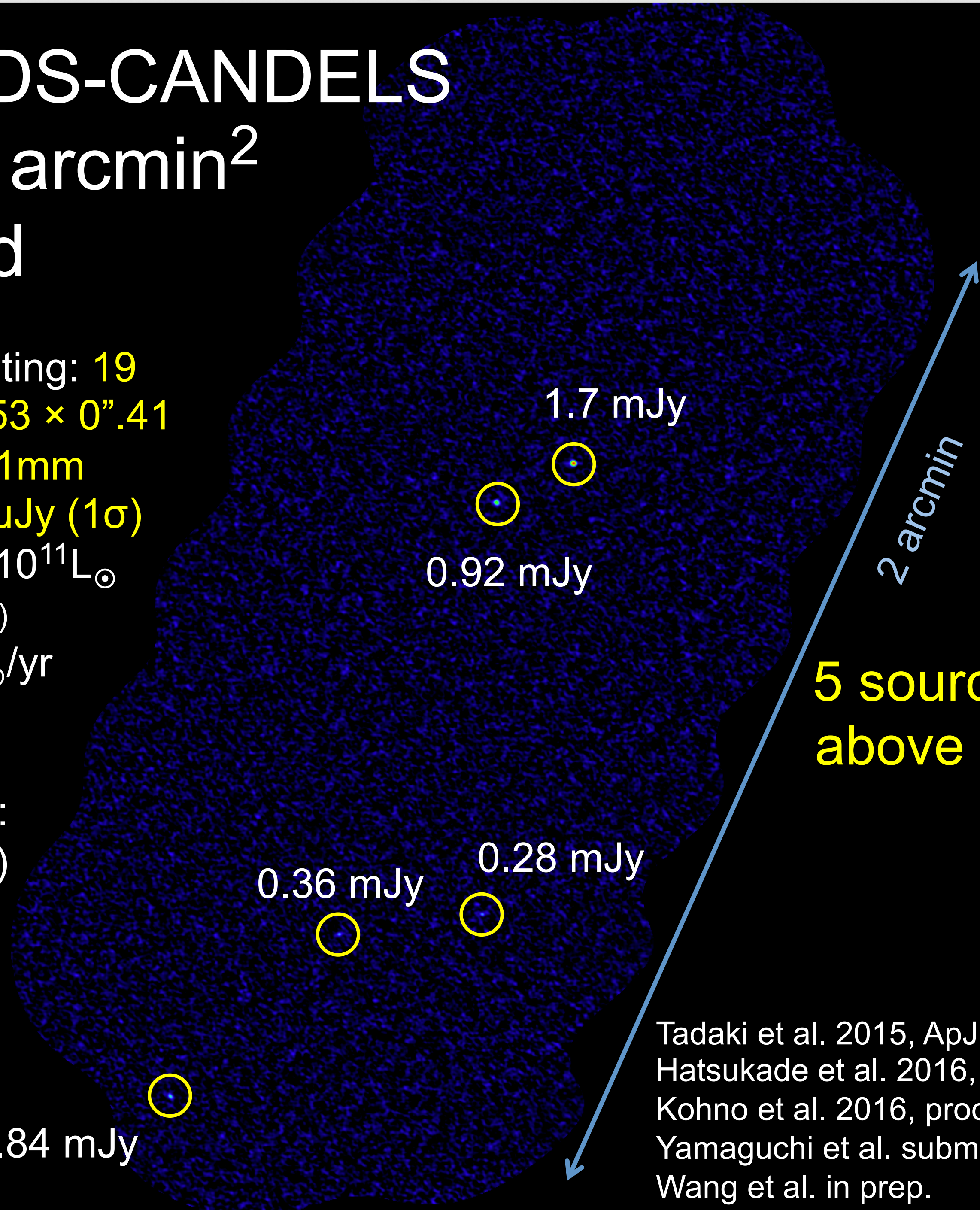
Observing time:
3.8 hours (total)



SXDF-UDS-CANDELS -ALMA 2 $arcmin^2$ deep field

Number of pointing: 19
Resolution: 0".53 × 0".41
Wavelength: 1.1mm
Noise level: 55μJy (1σ)
⇔ L(IR) ~$1.2 \times 10^{11} L_{\odot}$
(if T_{dust} = 40K)
⇔ SFR ~20 $M_{\odot}$/yr
up to z ~10

Observing time:
3.8 hours (total)



5 sources above 6σ

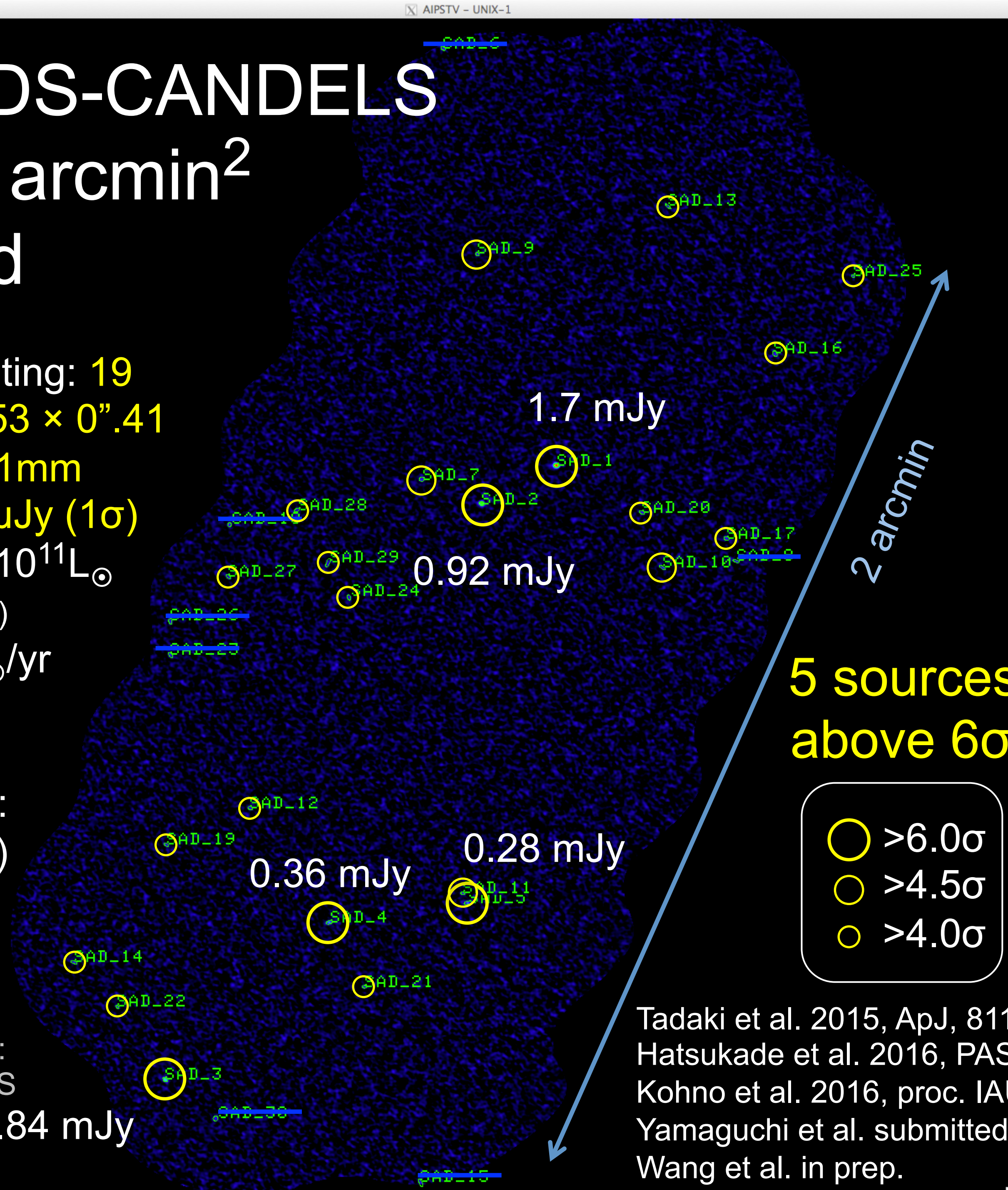
Tadaki et al. 2015, ApJ, 811, L3
Hatsukade et al. 2016, PASJ, 68, 36
Kohno et al. 2016, proc. IAUS319, in press
Yamaguchi et al. submitted to PASJ
Wang et al. in prep.

SXDF-UDS-CANDELS -ALMA 2 arcmin^2 deep field

Number of pointing: 19
Resolution: 0".53 × 0".41
Wavelength: 1.1mm
Noise level: 55μJy (1σ)
⇔ $L(IR) \sim 1.2 \times 10^{11} L_\odot$
(if T_{dust} = 40K)
⇔ SFR ~20 $M_\odot$/yr
up to z ~10

Observing time:
3.8 hours (total)

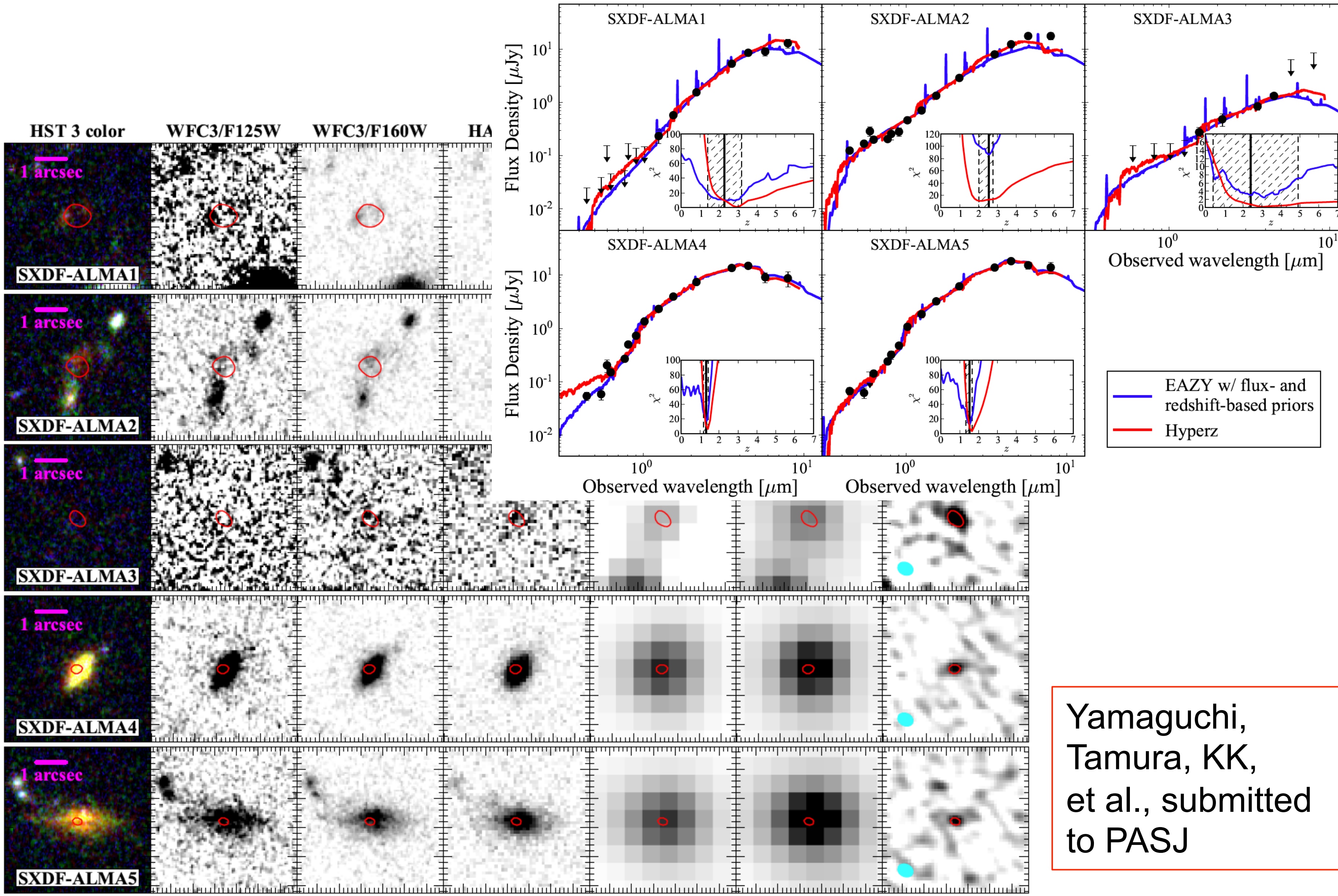
Source extraction:
task "SAD" in AIPS



⚠ Lower S/N sources will contain spurious detections

Tadaki et al. 2015, ApJ, 811, L3
Hatsukade et al. 2016, PASJ, 68, 36
Kohno et al. 2016, proc. IAUS319, in press
Yamaguchi et al. submitted to PASJ
Wang et al. in prep.

Characterization of ALMA sources

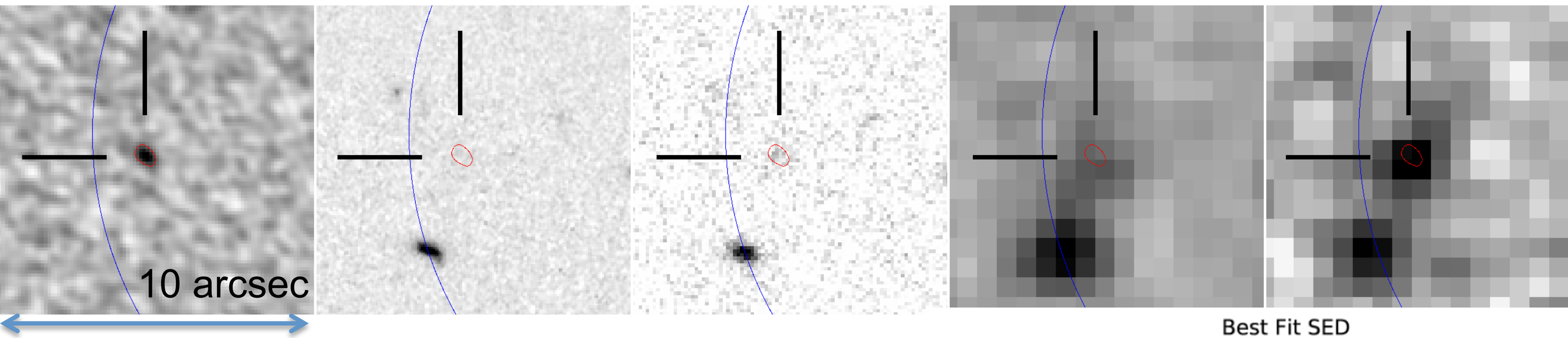


Yamaguchi, Tamura, KK, et al., submitted to PASJ

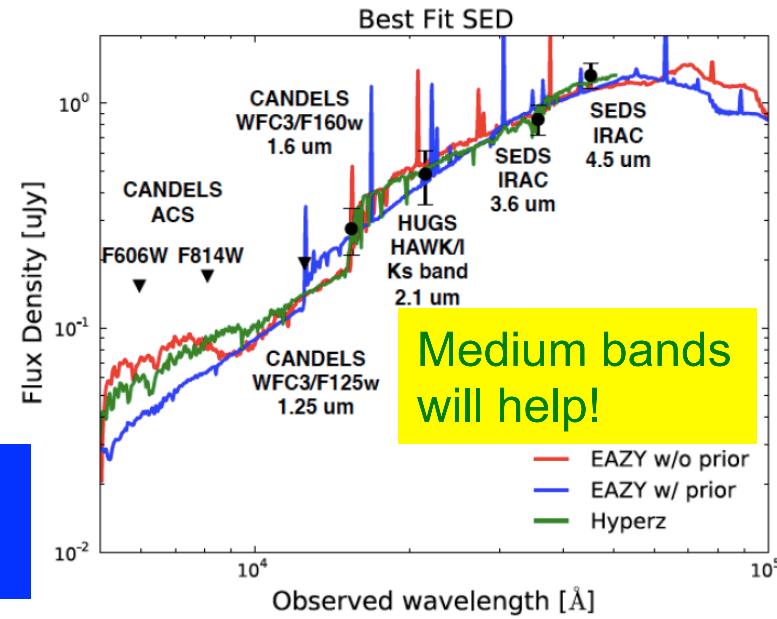
An obscured ULIRG at z~2-3 uncovered in SXDF-ALMA 2 arcmin^2 survey?

Yamaguchi, Tamura, KK et al. submitted

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

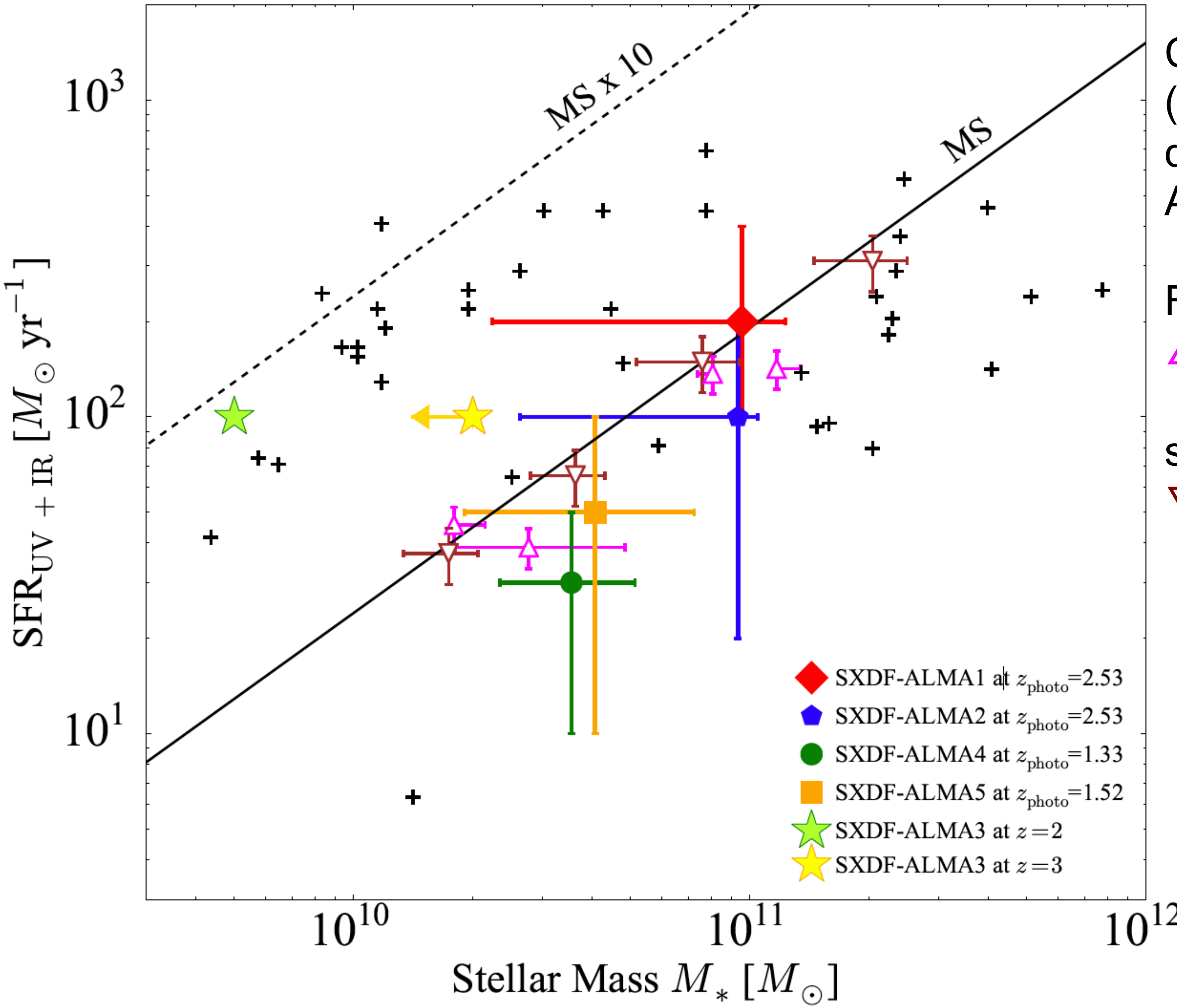


- $z_{photo} = 3.1^{+1.8}_{-1.5}$ (Hyper-z),
- $2.4^{>+1.7}_{-1.6}$ (EAZY)
  - One L(IR) = $1\times10^{12} L_\odot$ galaxy in the survey volume (2 arcmin^2, z ~ 1 – 4)
  - ➔ SFRD ~$(0.1\text{-}1)\times10^{-2}\ M_\odot/\text{yr}/\text{Mpc}^3$



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

Faint submm galaxies detected by ALMA contiguous imaging: dusty star-forming galaxies (mainly) on the main sequence



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

Faint submm galaxies
△ Hatsukade et al. 2015

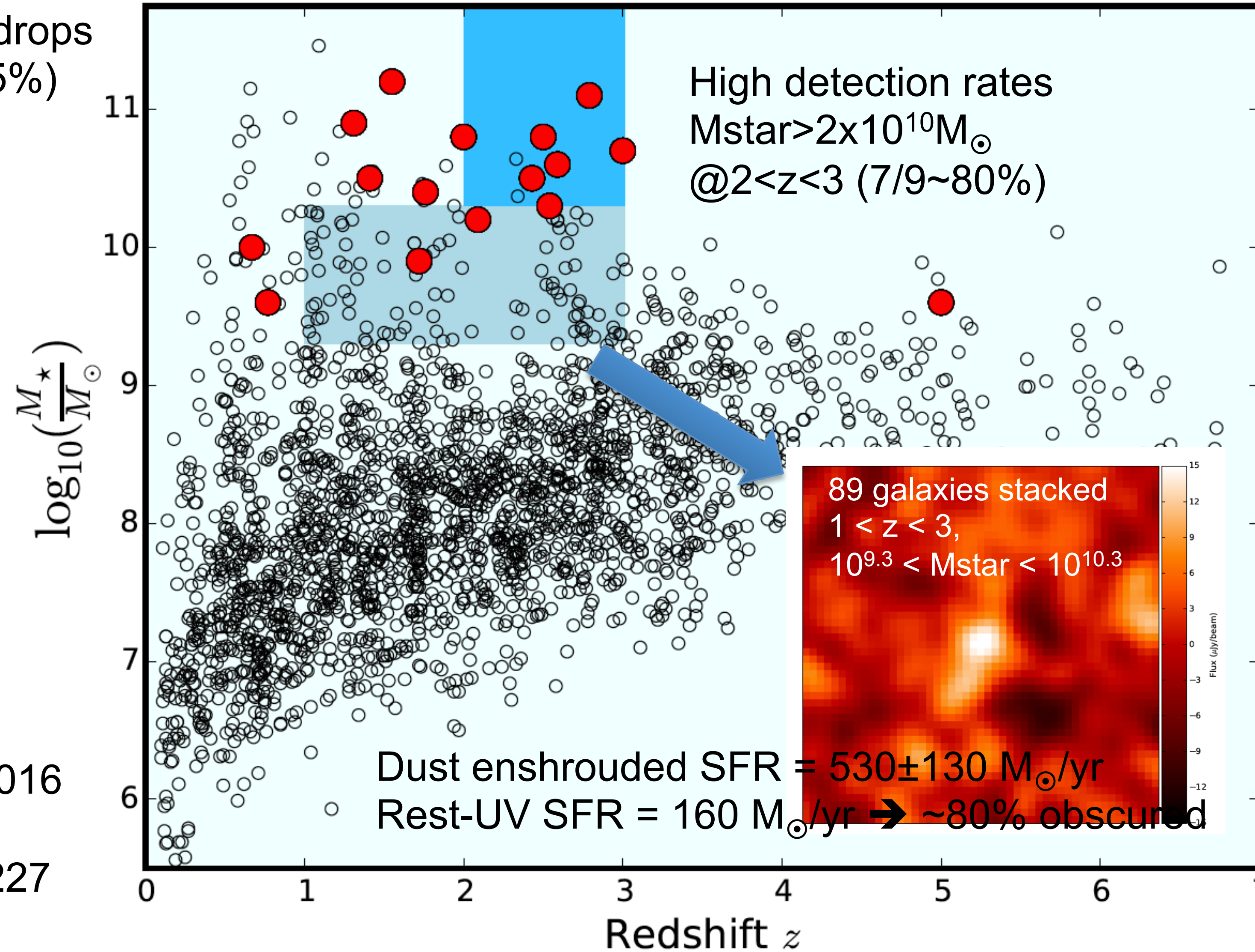
sBzK galaxies
▽ Rodighiero et al. 2015

Yamaguchi, Tamura, KK, et al., submitted to PASJ

Stellar mass is important!

Current ALMA surveys tend to uncover dusty star-formation in massive galaxies

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

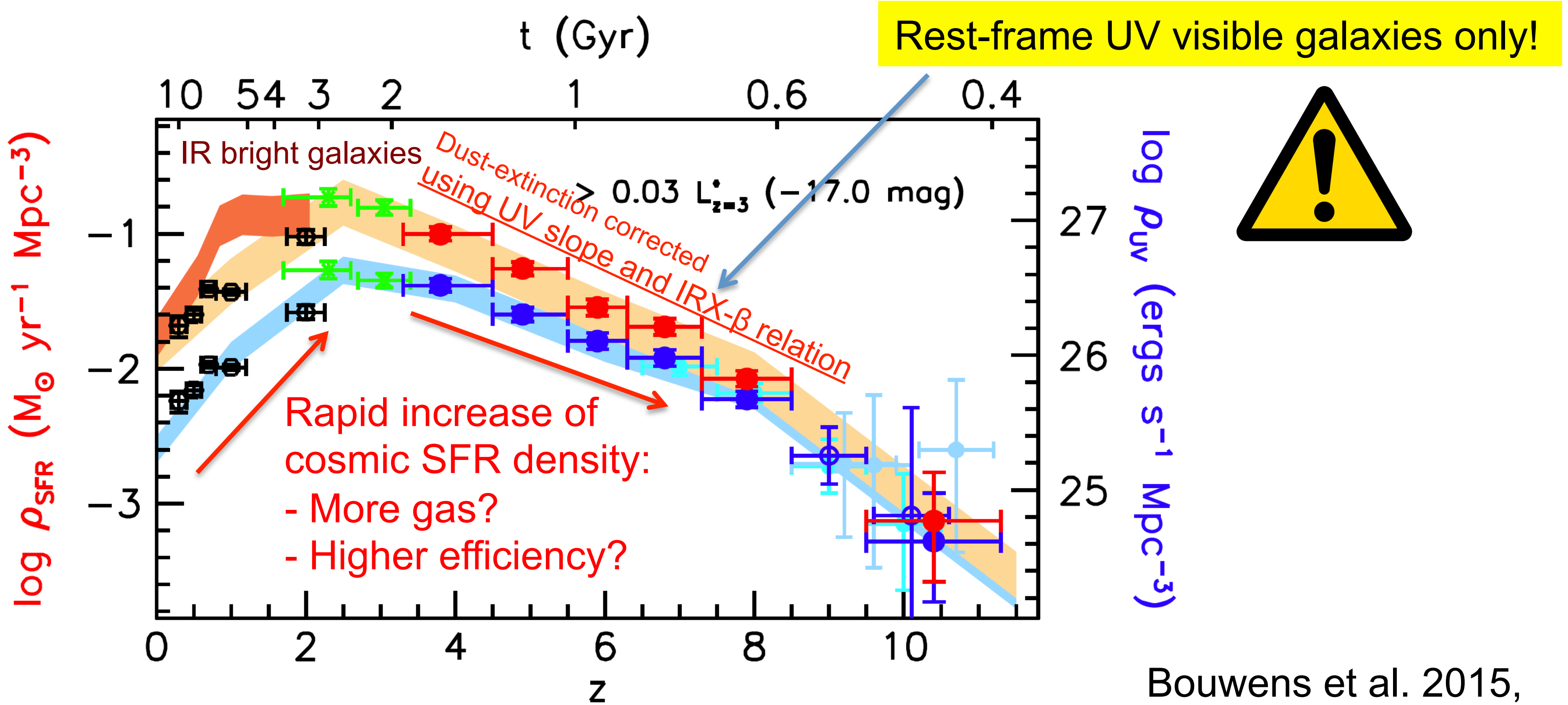


HUDF
ALMA
1.3mm
35μJy(1σ)

Dunlop et al. 2016 submitted arXiv:1606.00227

Characterizing newly uncovered ALMA sources: (2) mm/submm line emitting galaxies

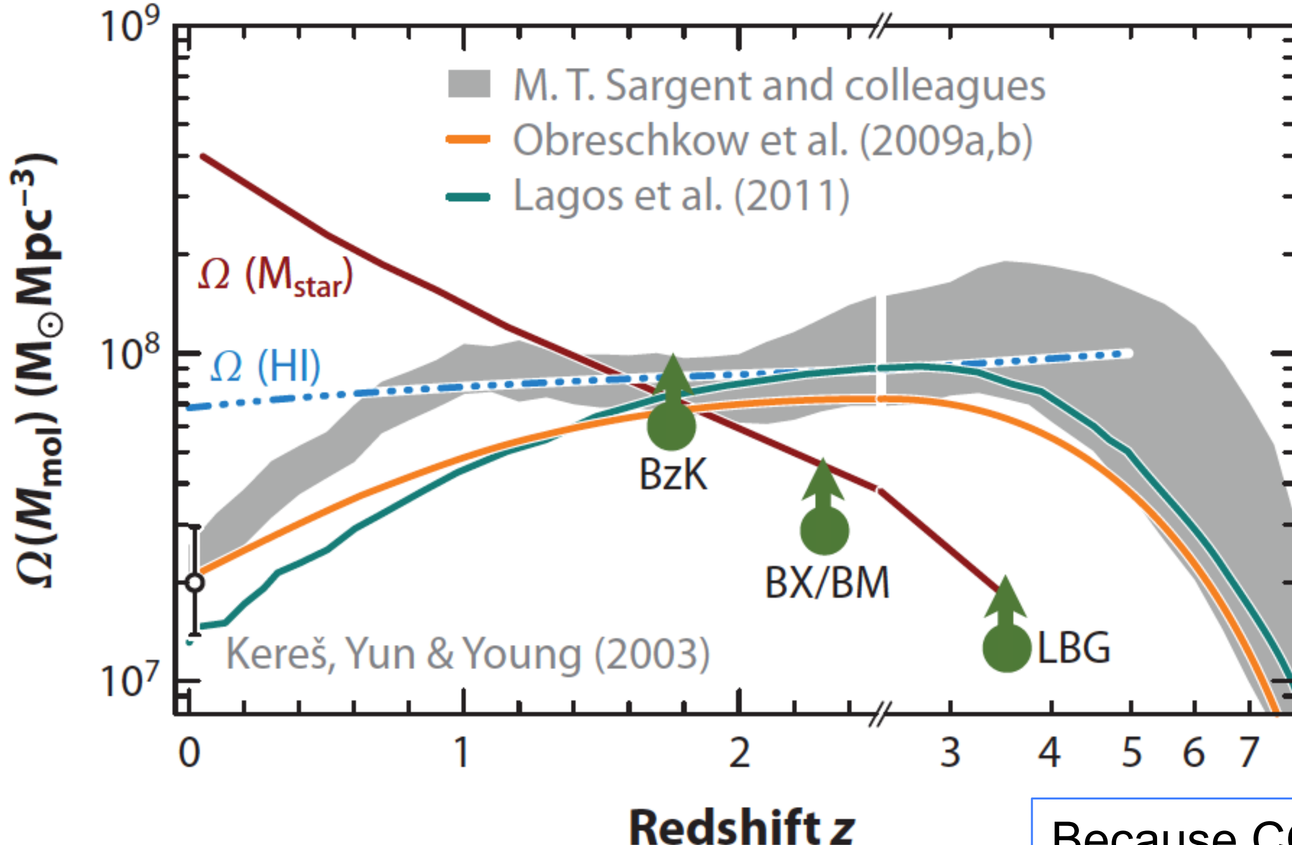
Understanding the cosmic star formation history ➔ understand the cosmic evolution of molecular gas



Bouwens et al. 2015, ApJ, 803, 34

- What is the roles of dusty galaxies?
  - What drives the cosmic star formation history?

Cosmological evolution of molecular gas contents is poorly understood..



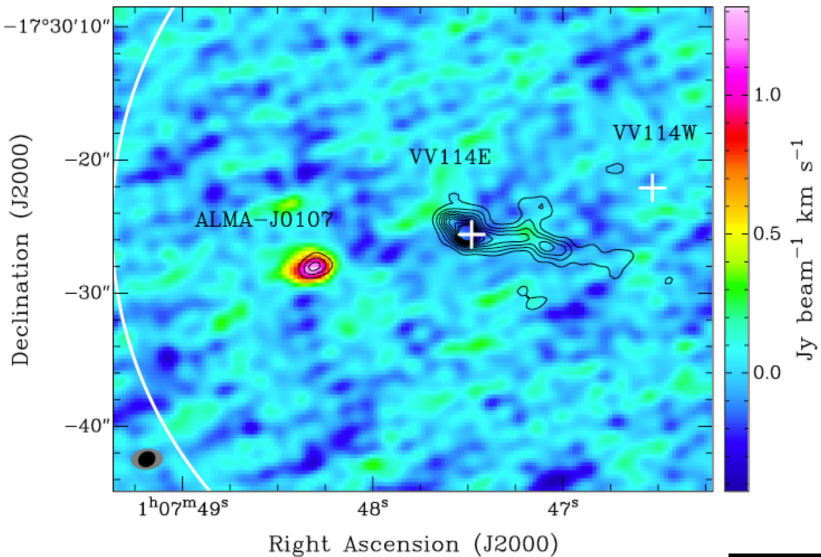
"Sargent, M.T. et al. in prep."

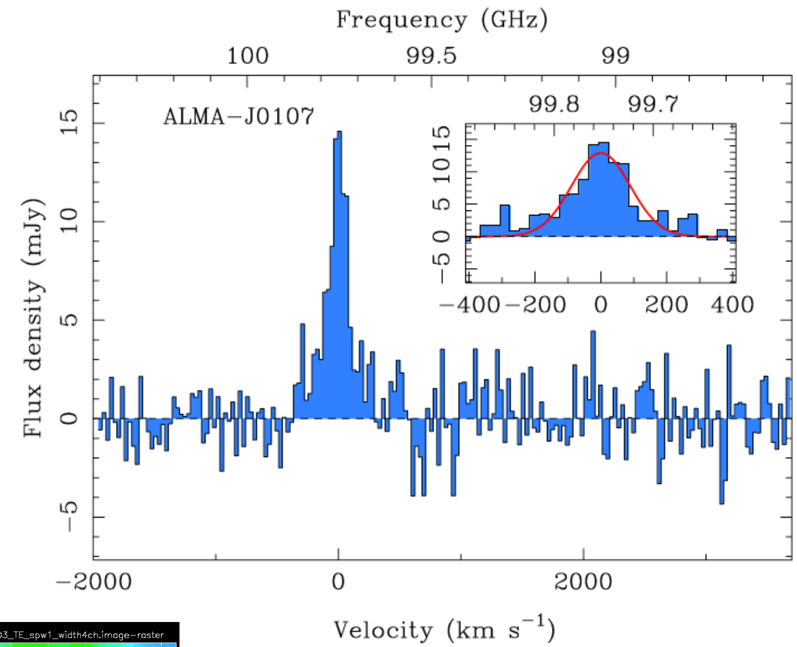
Carilli & Walter 2015, ARAA, 51, 105

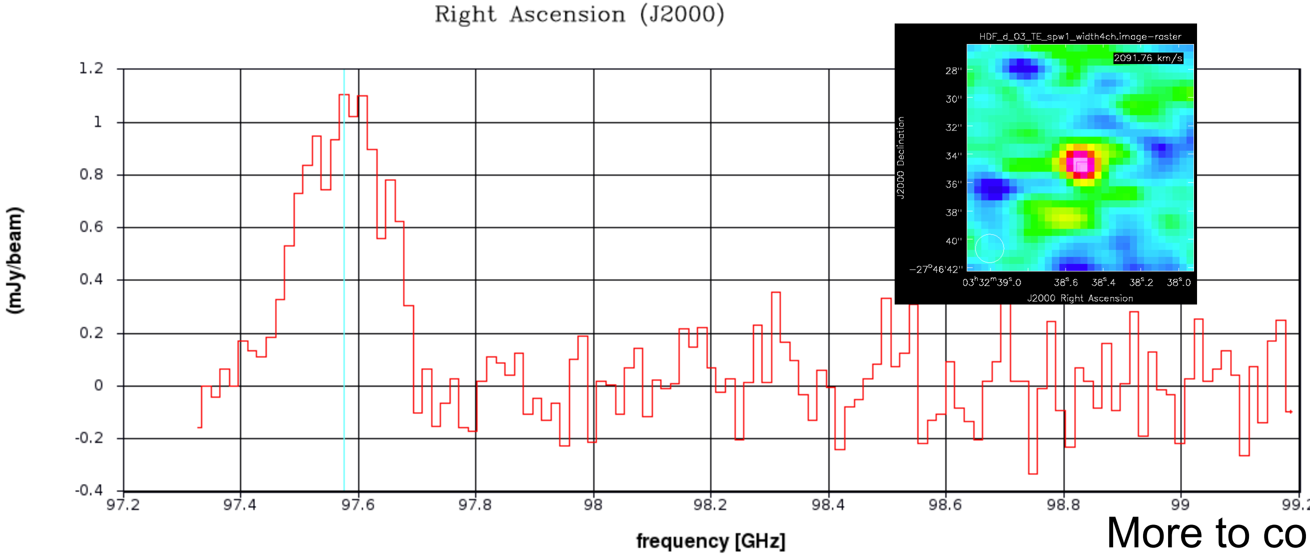
Because CO observations are biased to pre-selected galaxies

- What drives the cosmic star formation history?

(Serendipitous) ALMA detections of CO emitting galaxies ➔ "gas-mass-limited survey"







Tamura et al. 2014
ApJ, 781, L39

A CO emitter
in Hubble Ultra Deep Field
2013.1.00146.S

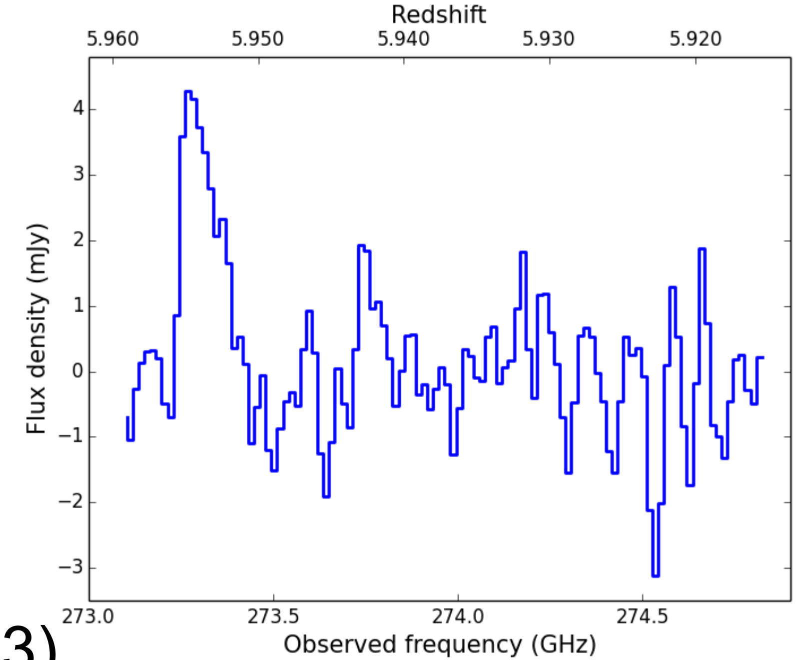
More to come.. (e.g., Yamaguchi et al.)

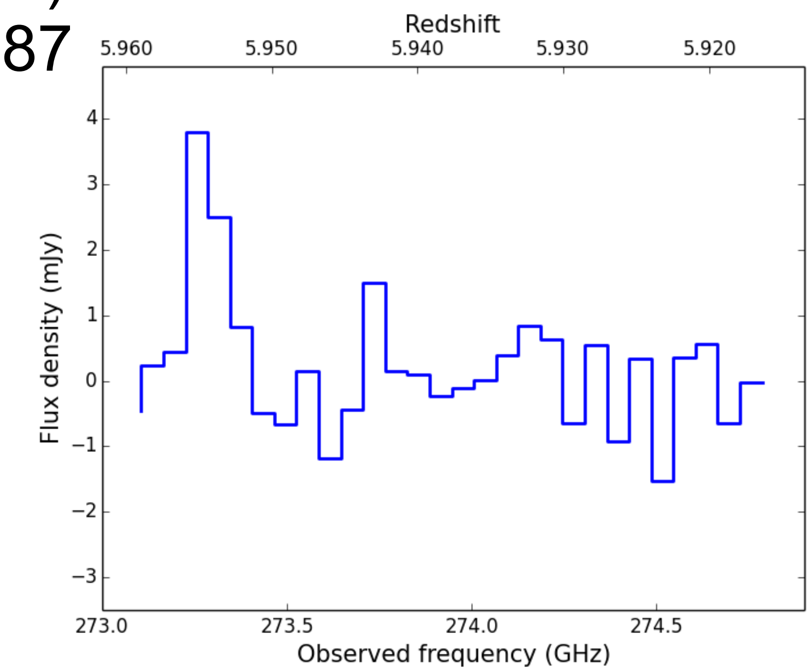
Blind detection of an emission line galaxy in SXDF-ALMA 2 arcmin^2?

- Peak flux = 3.8 ± 0.70 mJy (5.4σ)
- S(line) = 0.53 ± 0.079 Jy km/s (6.7σ)
- ➔ L[CII] = 5.1 × 10^8 $L_\odot$
  - (if this is [CII]; faintness of F160W/Ks/IRAC/(and radio) is consistent with z~6 ??)
- Velocity width ~ 100 km/s (FWHM) or 155 km/s (FWZI)

or CO(4-3) @z=0.687

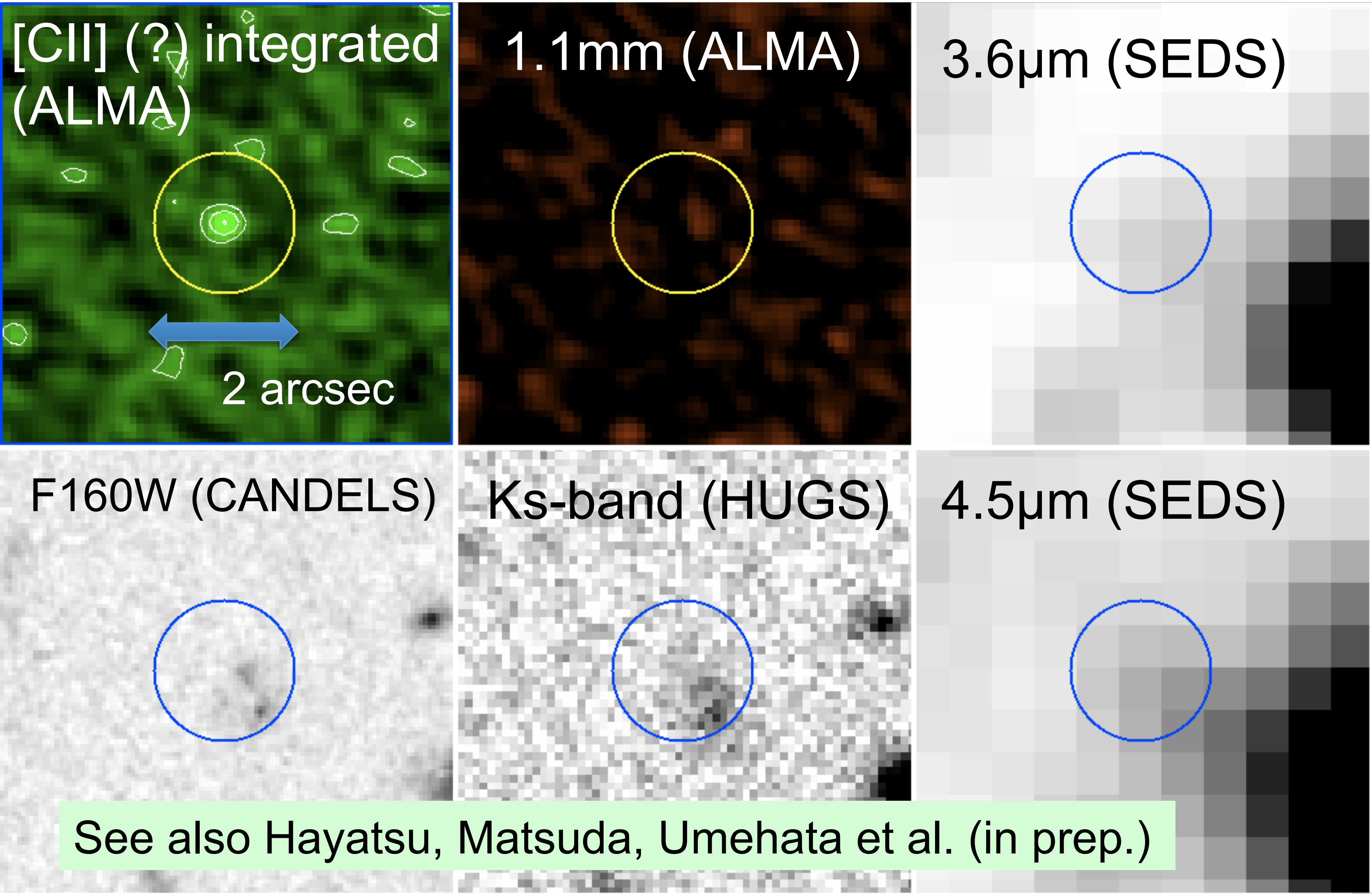
Yamaguchi, Kohno, Tamura, et al. in prep.





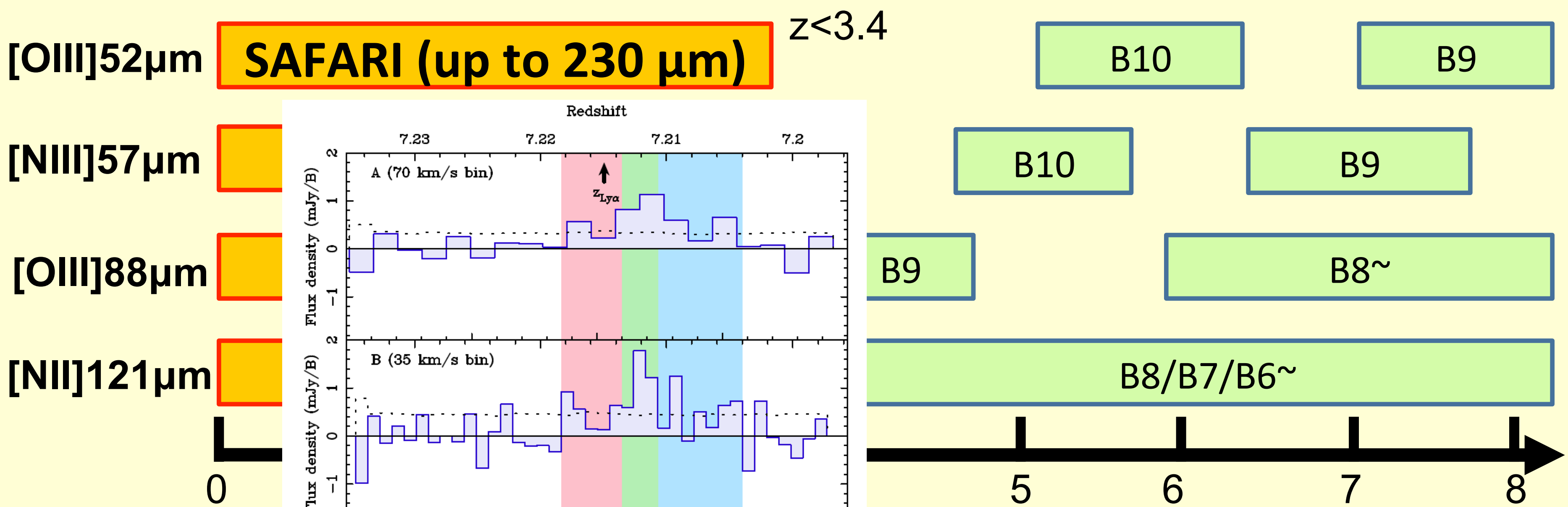
A candidate [CII] emitter @z=5.955??

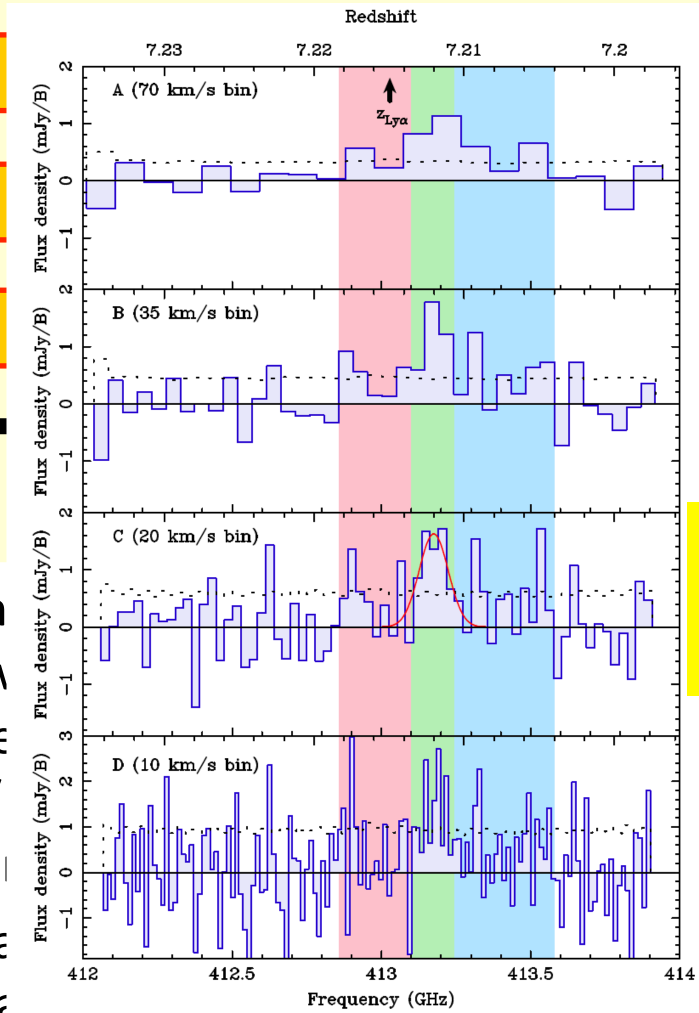
⚠ or CO(4-3) @z=0.687, an extremely gas rich galaxy (fgas = 0.69 – 0.97) !?



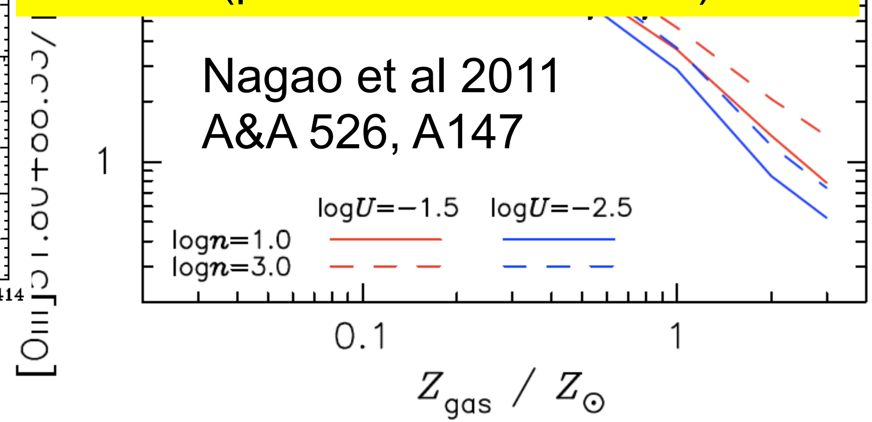
See also Hayatsu, Matsuda, Umehata et al. (in prep.)

Fine structure lines using ALMA





ALMA detection of [OIII]88μm@z=7.2
Inoue, A., Tamura, Y., KK et al. 2016
Science (press release TODAY)



- Combination … band 10 allo… proposed me… ([OIII]52μm/ … [OIII]88μm li…
- It also gives a … method to ga… and beyond.

Replies to questions

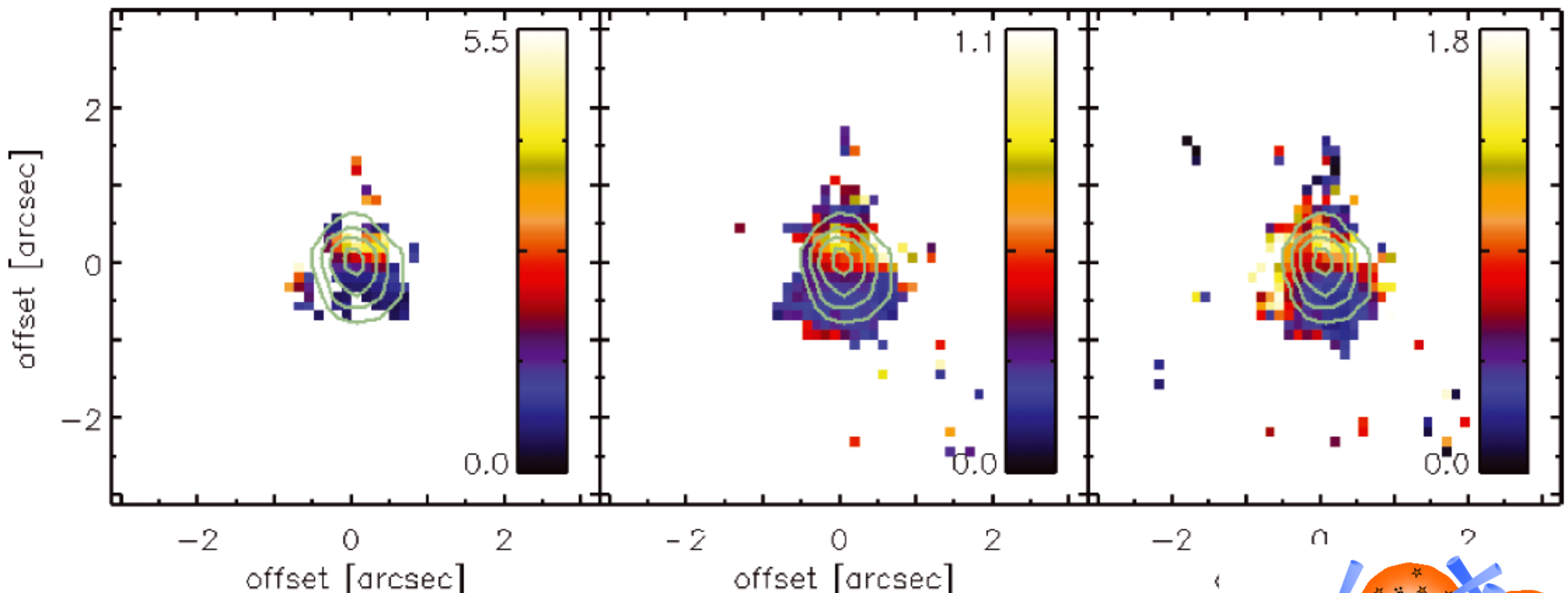
- Q1: What do you think is the "KEY" science/observations for ULTIMATE in your research field?
- → one of key science cases which shall be jointly developed by Subaru and ALMA is: physical characterization of newly uncovered ALMA populations, including
- (1) "faint submm galaxies", which dominate the infrared extragalactic background light, and
- (2) (sub)mm line emitting galaxies, which will be keys for cosmic molecular gas density evolution (if they are CO) and for obscured SFR history (if they are [CII] or [OIII]).
- Deep K-band and medium band imaging will be crucial to appropriately characterize their stellar component.

Replies to questions

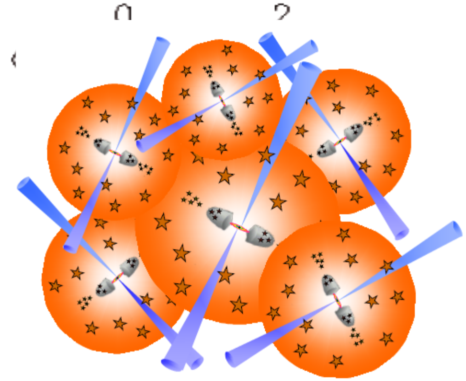
- Q2: Which instrument (WFC/MOS/IFU) do you think is 1st priority for ULTIMATE?
- ➔ I agree with WFC is 1st priority, although the IFU option also looks attractive (especially if it would cover up to K-band for [OIII]/Hβ IFU study up to z~3, although I know it is currently out of scope).
  - Possible target fields (just example):
    - 4C23.56 @z=2.5 ([OIII] @1.75μm, Hβ @1.70μm)
    - SSA22 @z=3.09 ([OIII] @2.05μm, Hβ @1.52μm)
  - Similar galaxies in the blank field for comparison
    - Hα emitters in SXDF @z=2.2, 2.5; Tadaki et al.
  - Identify AGN(s) and its/their roles (feedback) via [OIII] velocity field and [OIII]/Hβ line ratios

Spatially resolved [OIII]/Hβ line ratio map

- SINFONI/VLT, 3 hours (on-source)
- Consistent with (single) AGN



Can we find galaxies with signature
for multiple, off-center AGNs ???



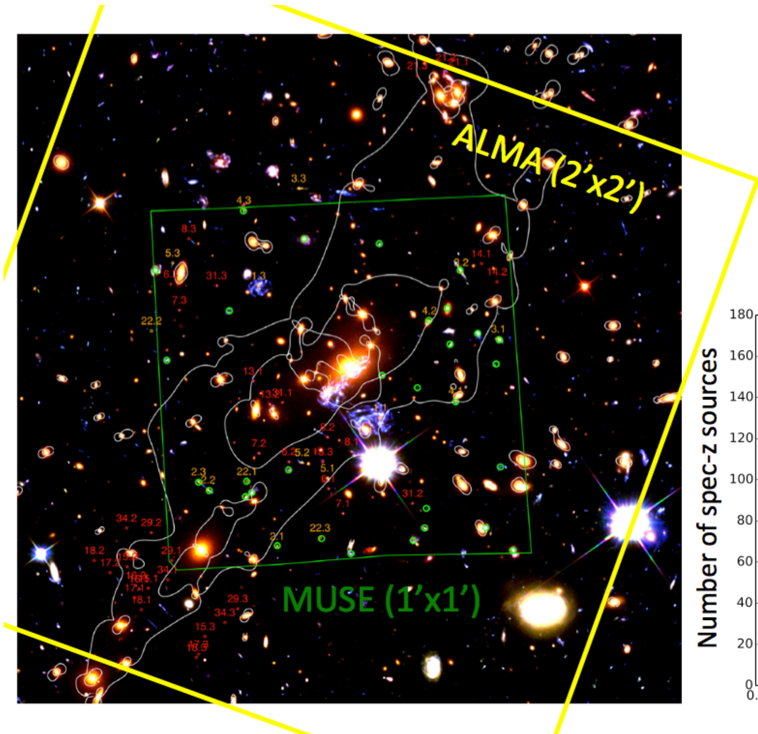
Nesvadba et al. 2011, MNRAS, 415, 2359

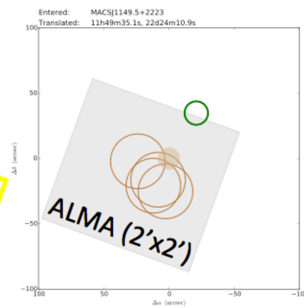
Replies to questions

- Q3: Our current plan is to (1) build GLAO first, and then to (2) build new NIR instrument(s). This means that we will start our ULTIMATE science with GLAO+MOIRCS at the first stage. Do you have good science cases to be done with GLAO+MOIRCS during the period of ~2020–2023?
- ➔ is it possible to use GLAO+MOIRCS to make NB emitter survey on lensing clusters including Hubble Frontier Fields clusters, CLASH, RELICS, and so on? We are now proposing an ALMA large program "ALMA Lensing Cluster Survey" (ALCS), to unveil faint submm population down to $S_{1.2mm,\,intrinsic}$~10μJy by exploiting lensing (and HST treasury BB images). If we can identify lensed Hα and/or [OIII] emitters, we can extend the study of bulge formation processes toward low stellar mass galaxies, although it must be too risky..

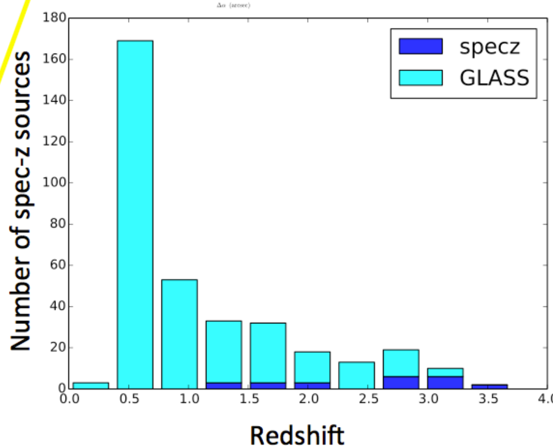
Proposed ALMA observations of MACS J1149.6+2223

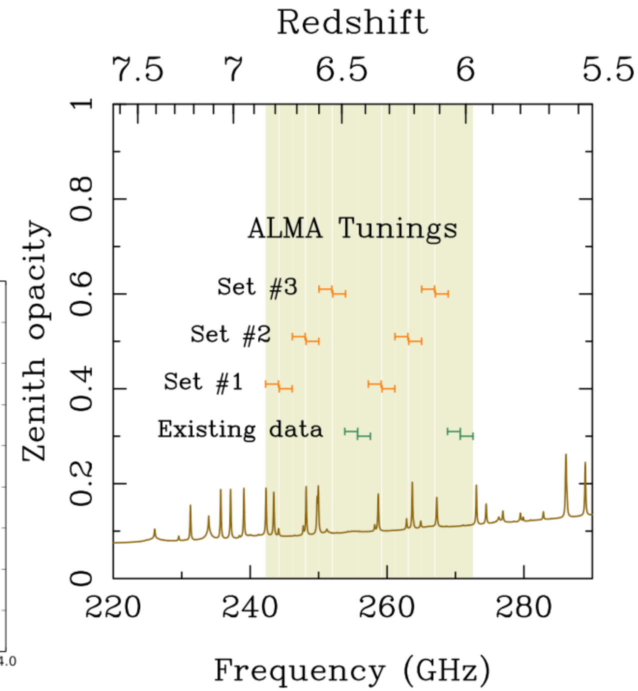
(Kohno et al.)





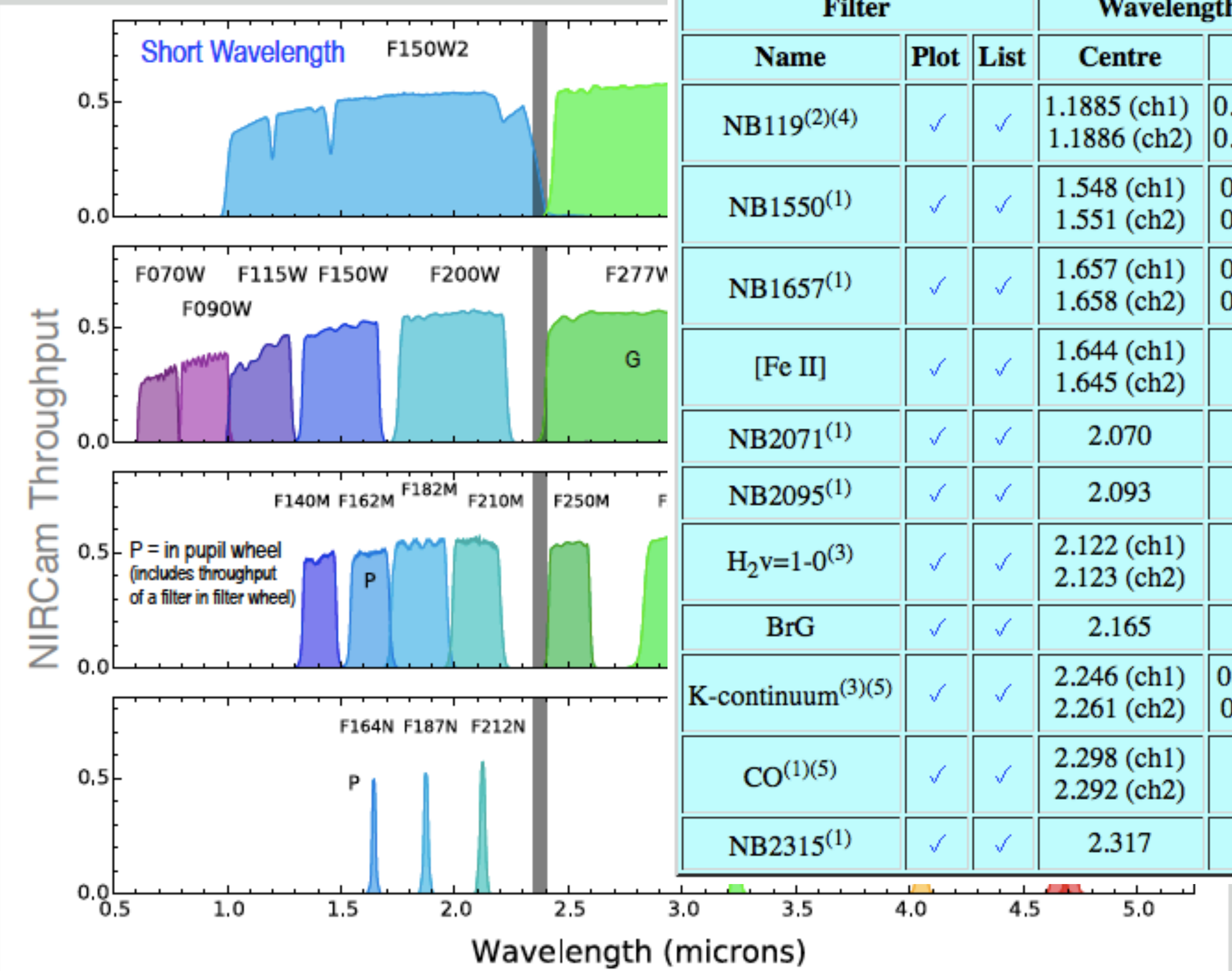
Existing ALMA observations 2013.1.00999.S





- Adding 3 tunings to an existing ALMA observation will give a contiguous redshift coverage z = 5.9 – 6.8 for [CII] emitting galaxy survey
- Possible cases using GLAO-MOIRCS or ULTIMATE: serendipitous search for background line emitting sources; too risky, maybe..

NIRCam Instrument Throughput

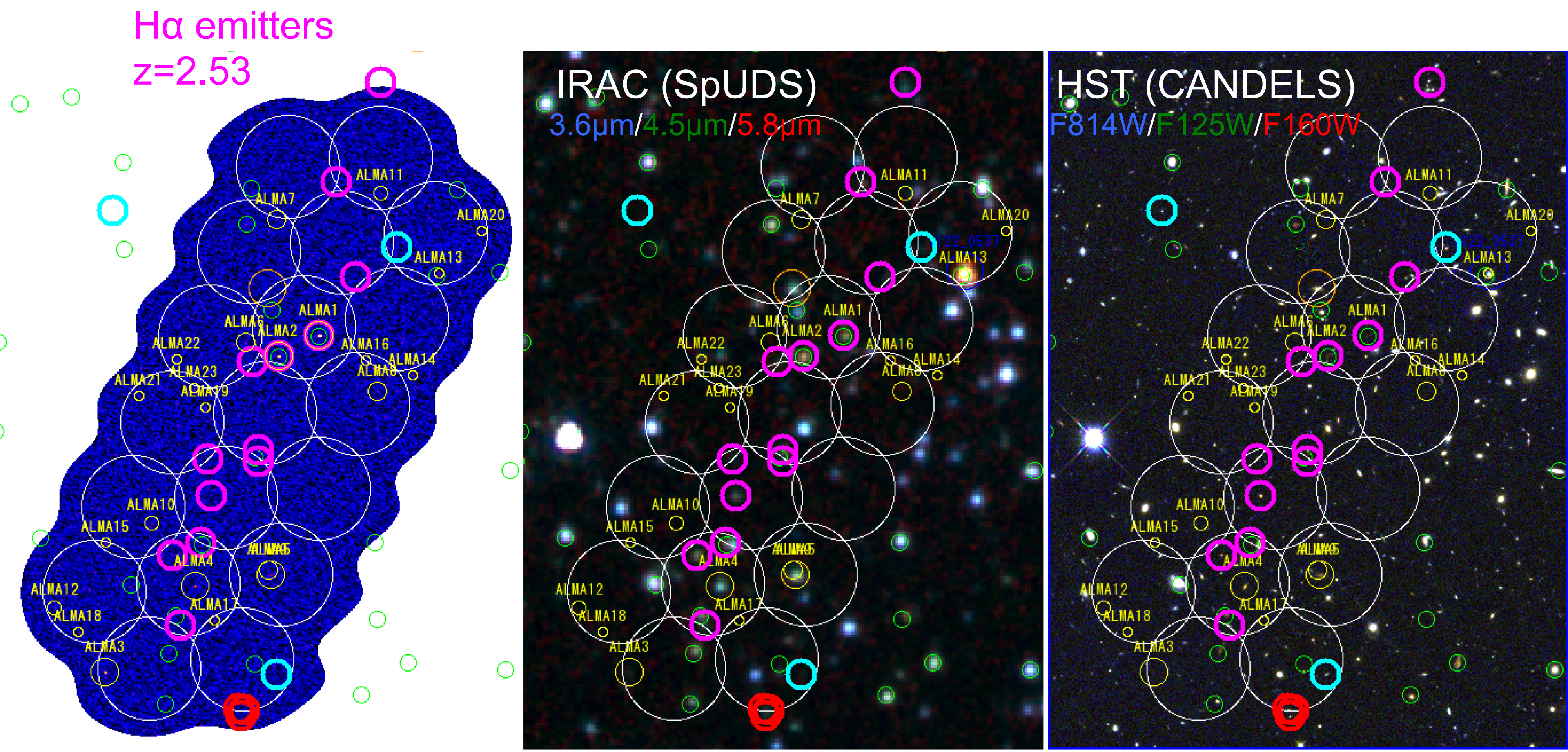


Filter			Wavelength [um]	
Name	Plot	List	Centre	Width
NB119[2][4]	✓	✓	1.1885 (ch1) 1.1886 (ch2)	0.0141 (ch1) 0.0135 (ch2)
NB1550[1]	✓	✓	1.548 (ch1) 1.551 (ch2)	0.018 (ch1) 0.019 (ch2)
NB1657[1]	✓	✓	1.657 (ch1) 1.658 (ch2)	0.020 (ch1) 0.019 (ch2)
[Fe II]	✓	✓	1.644 (ch1) 1.645 (ch2)	0.027
NB2071[1]	✓	✓	2.070	0.027
NB2095[1]	✓	✓	2.093	0.026
H_2v=1-0[3]	✓	✓	2.122 (ch1) 2.123 (ch2)	0.021
BrG	✓	✓	2.165	0.025
K-continuum[3][5]	✓	✓	2.246 (ch1) 2.261 (ch2)	0.062 (ch1) 0.060 (ch2)
CO[1][5]	✓	✓	2.298 (ch1) 2.292 (ch2)	0.023
NB2315[1]	✓	✓	2.317	0.026

Replies to questions

- Q4: Which survey design sounds best for you?
- ➔ survey plan #1 (combination of NB, MB, and BB) sounds optimal for my motivations
- Emission line galaxies via NB survey can be unique too
  - Identifying proto-clusters
  - SFR-limited sample of star-forming galaxies
  - These are good target for ALMA follow up

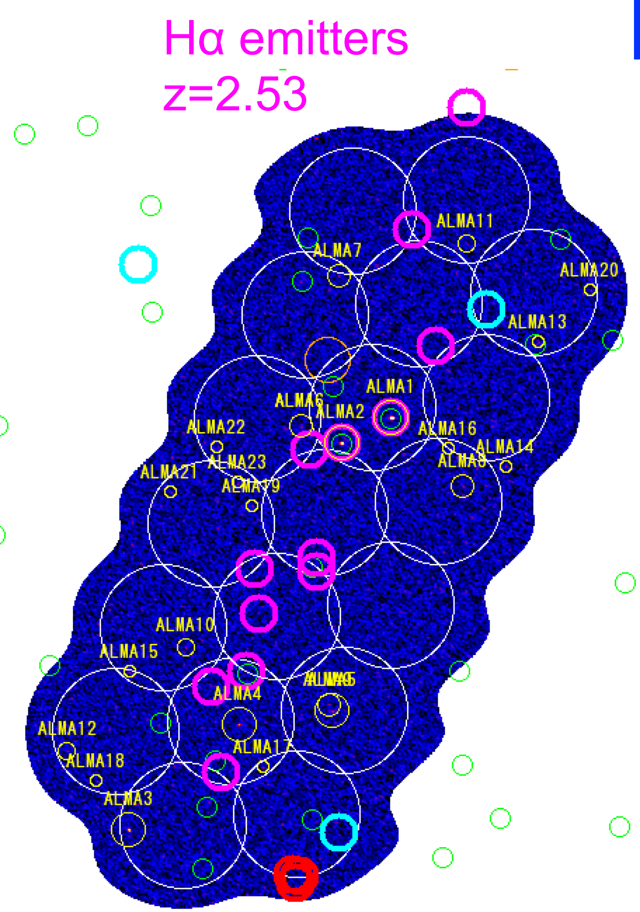
ALMA 1.1mm vs IRAC, ACS/WFC3



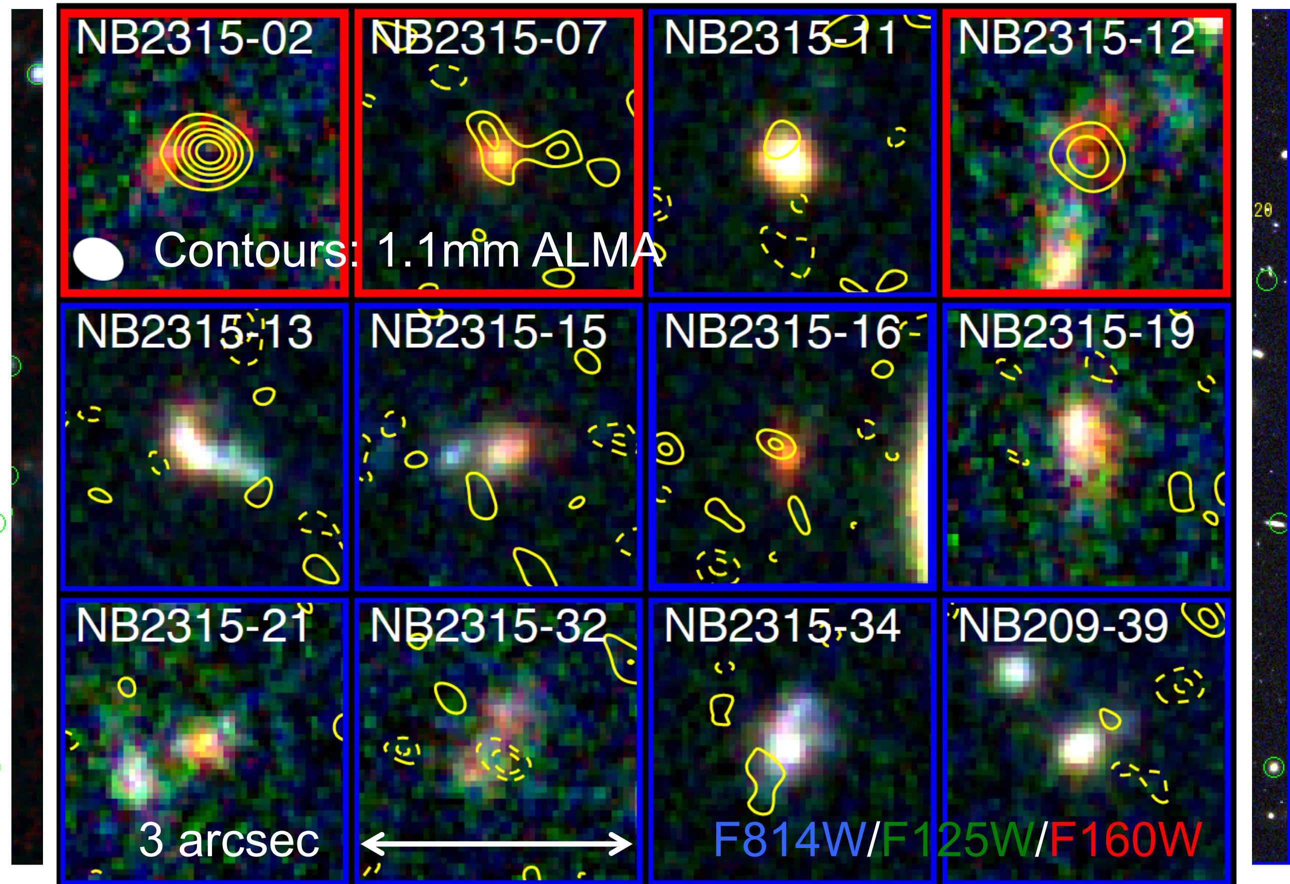
Tadaki et al.
2015, ApJ, 811, L3

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

ALMA 1.1mm vs IRAC, ACS/WFC3



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



2 Hα emitters: clearly detected in ALMA
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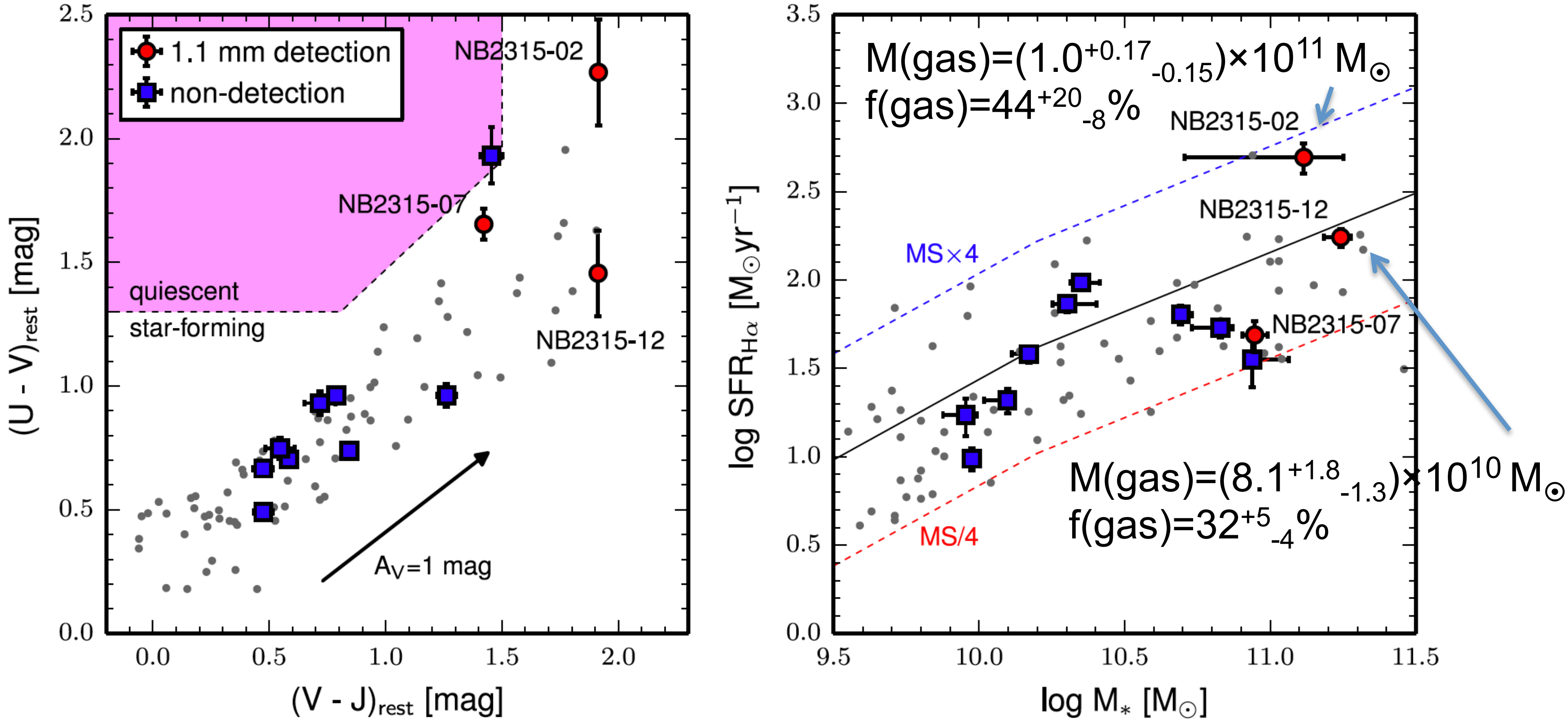
Tadaki et al. 2015, ApJ, 811, L3

Hα emitters with/without 1.1mm emission

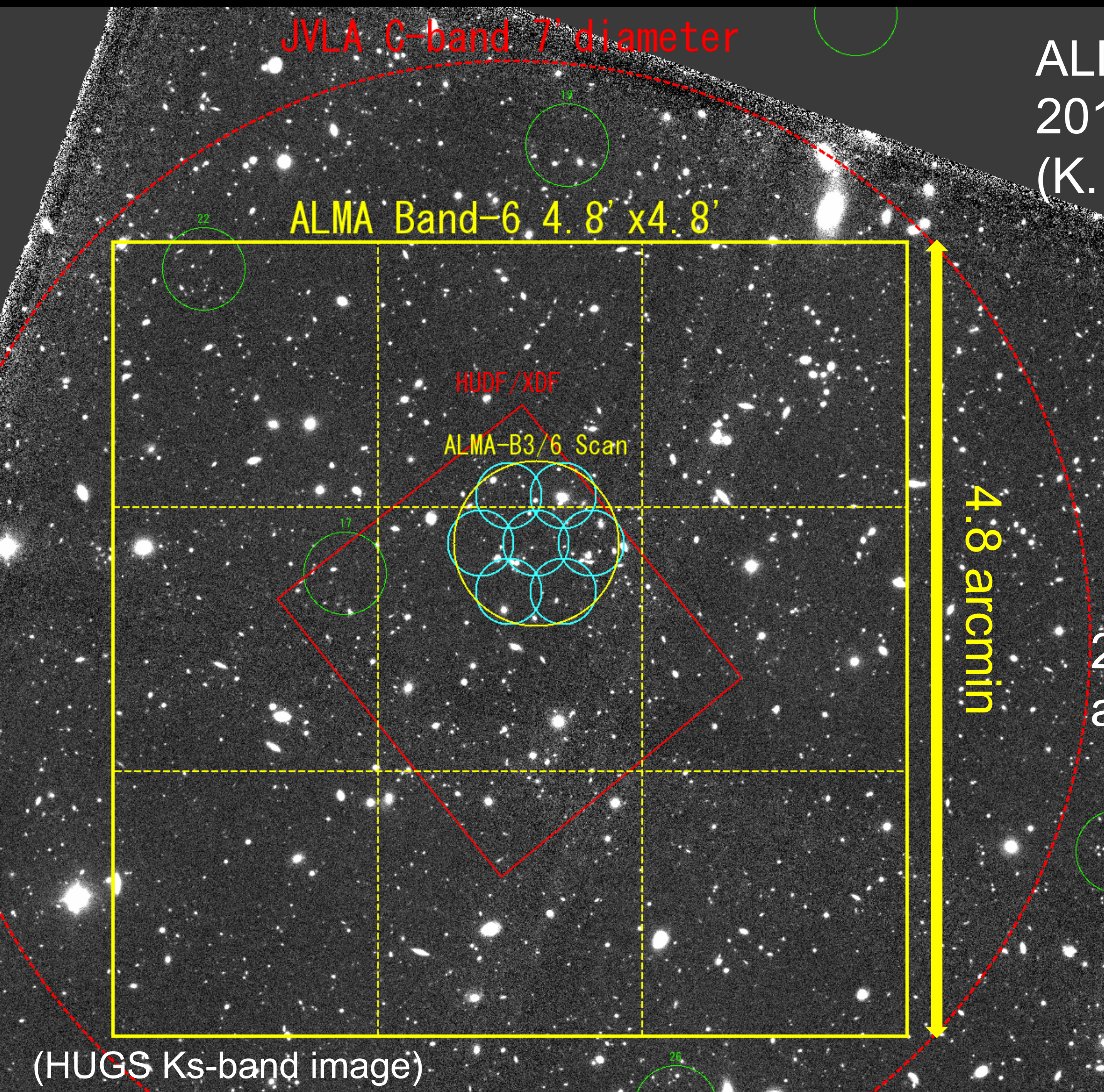


- Hα emitters with 1.1mm emission
  - red in the rest-frame optical, massive
- Hα emitters without 1.1mm S(1.1mm) < 290 μJy (2σ upper limit).
  - blue, main-sequence galaxies

Tadaki et al. 2015, ApJ, 811, L3

Replies to questions

- Q4: Which survey design sounds best for you?
- (cont.)
- Perhaps survey field selection can be discussed if we think about the expected large facilities in mid-late 2020s
  - Synergy with **SPICA**: will conduct up to ~10 deg^2 scale low-R MIR spectroscopic imaging survey, which will have good synergy with the proposed ULTIMATE surveys. Equator fields are not suited for deep observations using SPICA (lack of visibilities) ➔ GOODS-S! NEP shall be best for Subaru & SPICA, but it lacks accesses to ALMA and SKA.
  - Synergy with **JWST**: again, some observing time shall be invested on GOODS-S because it will be one of the prime fields for JWST too. Observing some lensing clusters in HST treasury programs, such as MACSJ1149.6+2223 in HFFs (although it is much smaller than the wide FoV of WFC-ULTIMATE; perhaps GLAO+MOIRCS is enough?); adding AO-assisted ultra-deep, multiple NB observations can be unique contributions..?



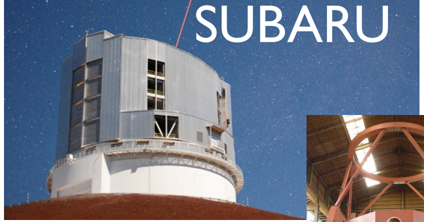
ALMA cy3 program
2015.1.00098.S
(K. Kohno et al.)

23 arcmin^2
60 μJy (1σ)
⇔ 38 arcmin^2
ultra-deep JVLA
(0.3 μJy, 1σ)

2 tunings (1.1mm and 1.2mm) for [CII] emitters
(z = 6.0 – 6.7)

44.4 hours
(~9% of all cy3 EA-ALMA time)

Summary



1) Wide area surveys with Subaru ➔ ALMA follow up of (relatively) rare but important sources

- HSC (+TAO/SWIMS) wide surveys of z >5-7 (z>7.2) quasars ➔ ALMA: M(BH)/M(Bulge), growth of spheroidal, feedback, dust enrichment/metallicity, etc.
- Lyα emitters, Hα/[OIII] emitters, etc. ➔ dust + CO/[CII] follow up ➔ SFR-Mstar relation vs gas fraction

2) ALMA deep surveys in ULTIMATE deep fields

- richness of narrow/medium/broad bands by ULTIMATE is essential to study the nature of ALMA sources
- Deep emitter surveys on GOODS-S (Kodama et al.): rich synergies with on-going ALMA deep surveys