Guillermo Haro 2018 Workshop: September 3-14, 2018, Tonantzintla, Puebla "Synergy between the GTC and GTM/LMT"

# New science capabilities with DESHIMA/MOSAIC on LMT 50m

Kotaro KOHNO（IoA/Univ. of Tokyo)
On behalf of DESHIMA/MOSAIC collaboration

# DESHIMA/MOSAIC collaboration

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# The team & roles

## Software development + observational studies

名古屋大学

Yoichi Tamura
Responsible for data analysis
Methodology development
And implementation

大阪大学
OSAKA UNIVERSITY

Ken Nagamine
Theoretical studies
of high-z dust
production

東京大学
THE UNIVERSITY OF TOKYO

Kotaro Kohno (PI of JSPS grant)
+ Tatsuya Takekoshi

国立天文台
NAOJ
National Astronomical
Observatory of Japan

Tai Oshima
Takashi Noguchi

## Hardware development

TU Delft

Cosmology with
Nanotechnology,
Group leader

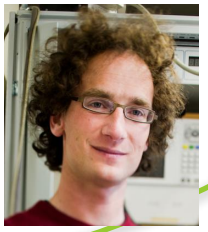
Akira Endo
(PI of DESHIMA)



SRON
Netherlands Institute for Space Research

Saitama University
埼玉大学

Masato Naruse



Jochem Baselmans
(PI of MOSAIC)

## Operation on LMT

Ryohei Kawabe

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UMassAmherst
The Commonwealth's Flagship Campus

David Hughes, LMT Director

# A proposal to LMT

Jochem Baselmans' talk

- We proposal to install the on-chip imaging-spectrograph DESHIMA/MOSAIC on LMT 50m.
- Instantaneous frequency coverage: 185 – 365 GHz (covering 180 GHz width in one shot!)
- With a coarse resolution R = f/df ~500 (dv ~600 km/s)
- 5 x 5 = 25 spatial pixels

  mainly for high-z but recall SPIRE-FTS!
- The proposed target year of installation: 2020
- **Suited for follow-up of AzTEC & Toltec (and other bright submm) sources**

  Note: beam steering will be in the 2nd generation MOSAIC
- Even without beam steering functions, 25-beam DESHIMA/MOSAIC on LMT is >10 times more efficient than ALMA in blind search for mm line emitting galaxies.
- This project has already been fully funded by Dutch & Japanese grants (ERC and JSPS grants, > 1 M Euro each)

# New science capabilities with MOSAIC on LMT 50m

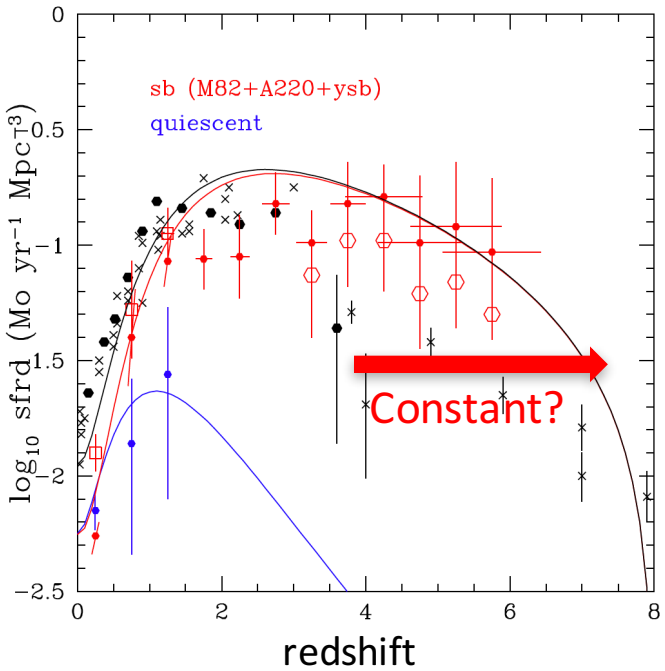
1. Dust-enshrouded star formation in the early universe
   - a large [CII] spectroscopic survey (z = 4.2 – 8.7) of mm/submm-selected galaxies drawn from AzTEC, Toltech and other surveys (Herschel, Plank, JCMT, ACT, ..)
2. Cosmic evolution of molecular gas density
   - a search for dual or multiple CO line emitters (z=0-1) by exploiting imaging capability
   - CO-SLED characterization for hidden AGNs (for z>1)
3. Plasma physics of clusters of galaxies via SZE
   - precise measurements of "the null frequency" ➔ relativistic correction to constrain Te + bulk motion of clusters via kinetic SZE

# 1. Probing the roles of dust-enshrouded star-formation in the early universe

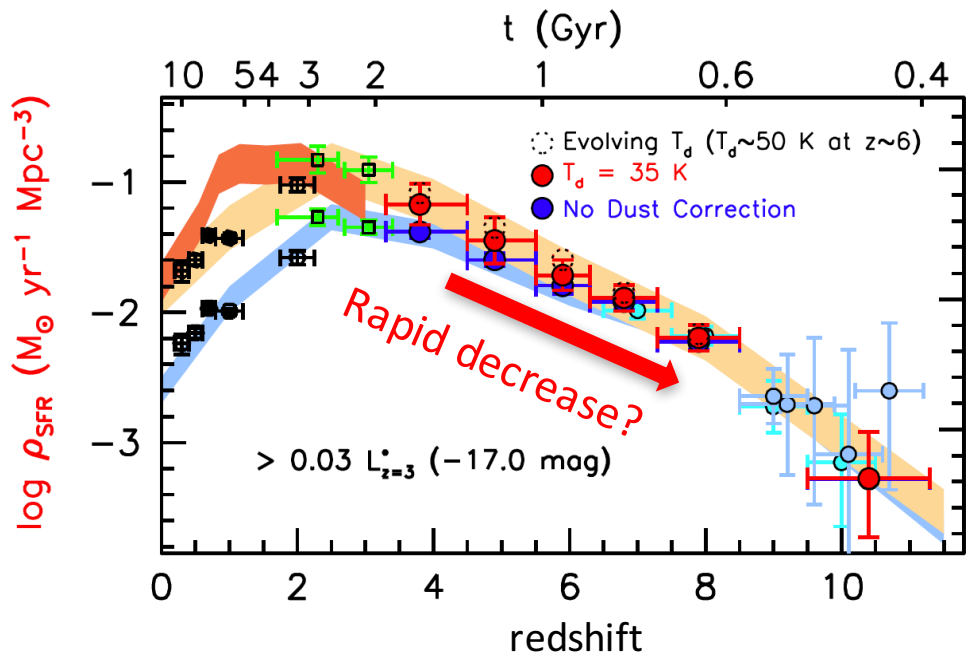
# Roles of dust-enshrouded star-formation activities in z>3-6 and beyond ..?

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

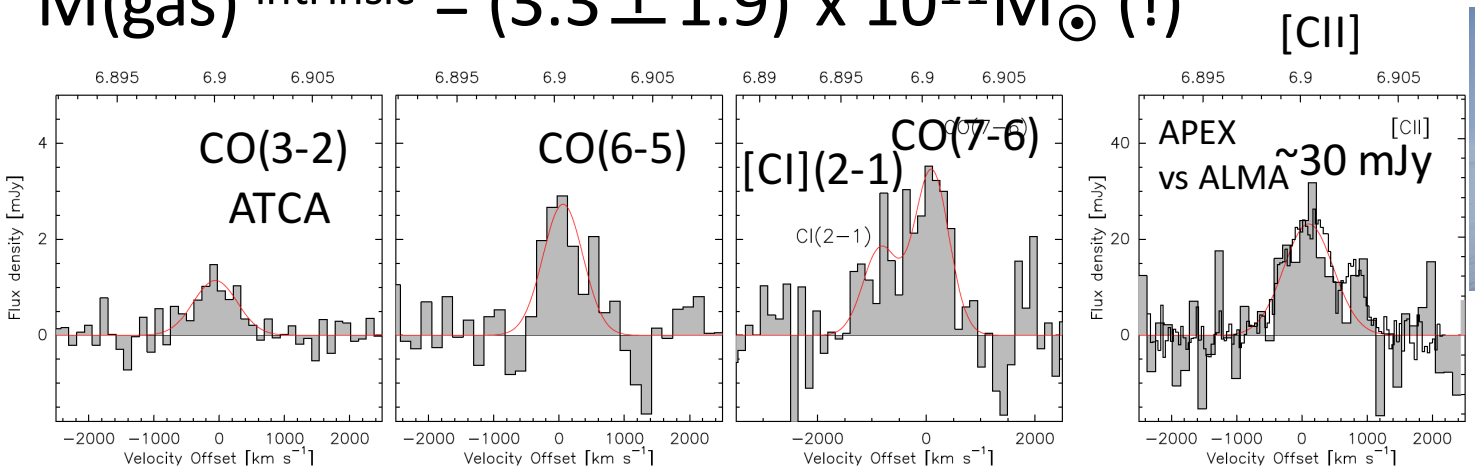


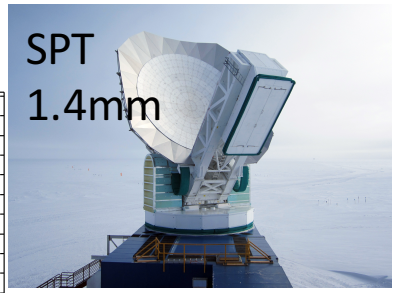

- Herschel wide area surveys of red submm sources ➔ significant amount of dust-obscured star formation up to z~6?
- An ALMA deep survey @HUDF(ASPECS): Dust-observed star-formation plays minor roles on the rest-frame-UV-selected galaxies

# The highest-redshift mm-selected dusty star-forming galaxy known to date @z∼7

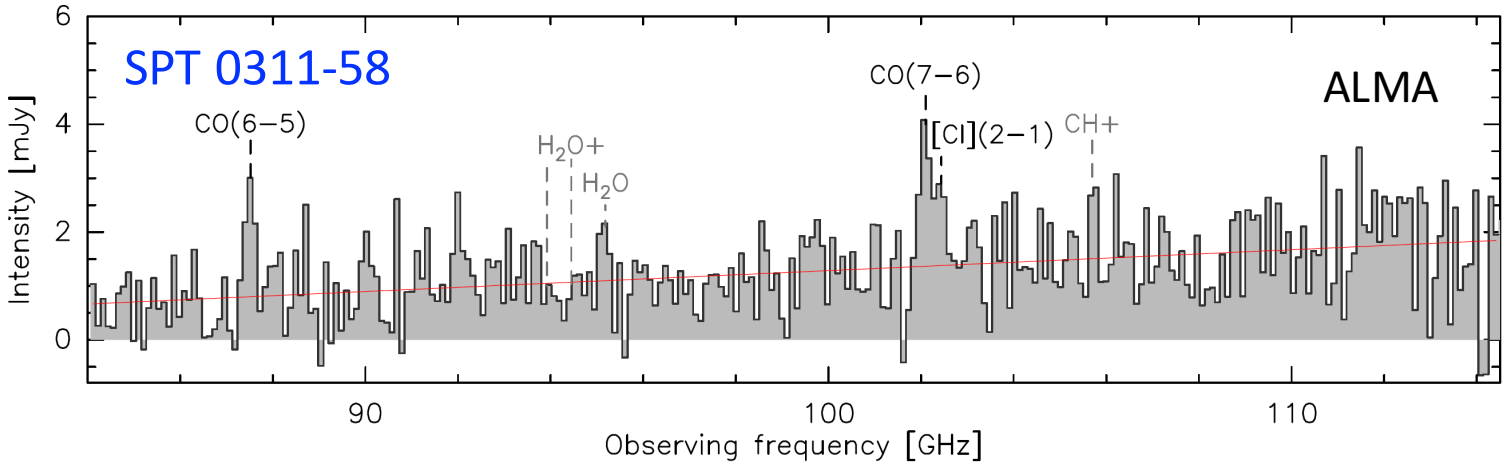
- located well into the EoR at a redshift of z = 6.900 ± 0.002
- M(dust) $^{intrinsic}$ = (3.0±0.4) x $10^9 M_\odot$
- M(gas) $^{intrinsic}$ = (3.3±1.9) x $10^{11} M_\odot$ (!)

$T_{dust}$ = 36 ± 7 K




Strandet et al. 2017, ApJ, 842, L15



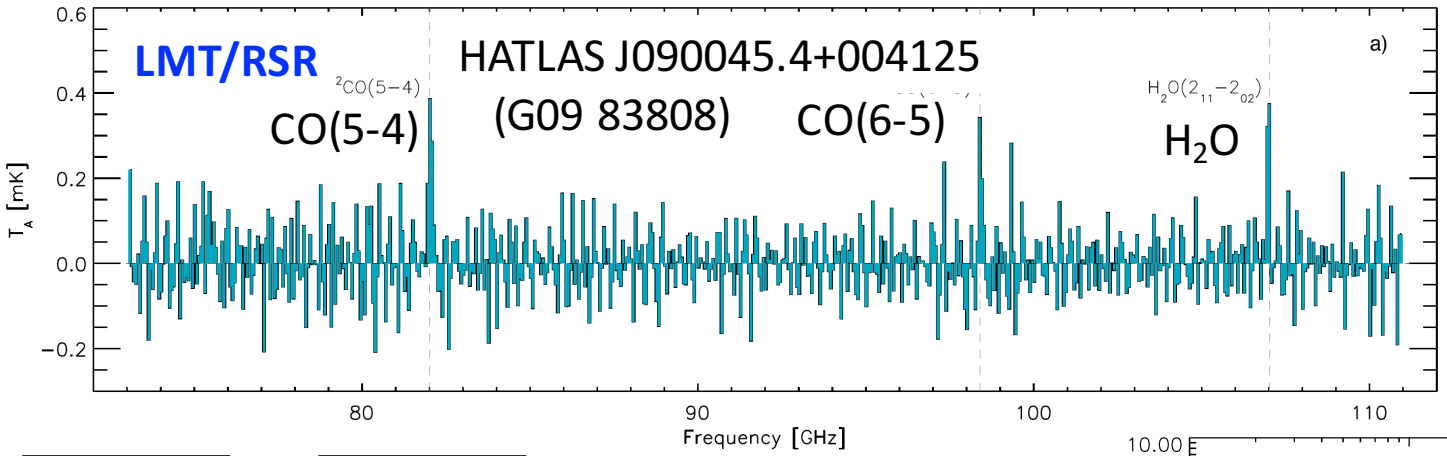

L(IR)·μ = (4.1±0.7) x $10^{13}$ $L_\odot$

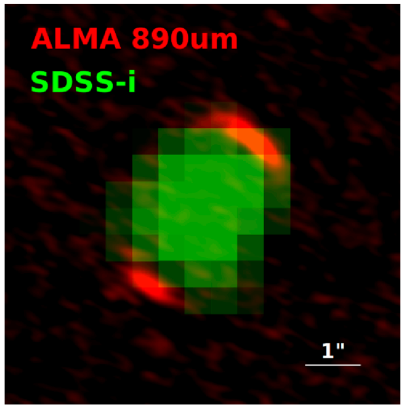
μ = 1.9

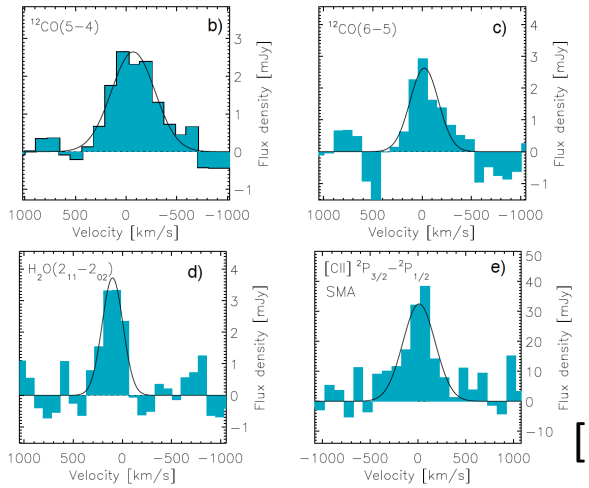
# And more z > 6 dusty extreme starbursts

- $z_{co} = 6.0269 \pm 0.0006$, $\mu(890\mu m) = 9.3 \pm 1.0$
- $L(IR)^{intrinsic} = (3.0 \pm 0.4) \times 10^{12}\ L_\odot$
- $M(dust)^{intrinsic} = (1.9 \pm 0.4) \times 10^{8}\ M_\odot$
- $M(gas)^{intrinsic} = (1.6 \pm 0.6) \times 10^{10}\ M_\odot$

Zavala, J. A., et al. 2018
Nature Astronomy,
Vol. 2, p. 56-62

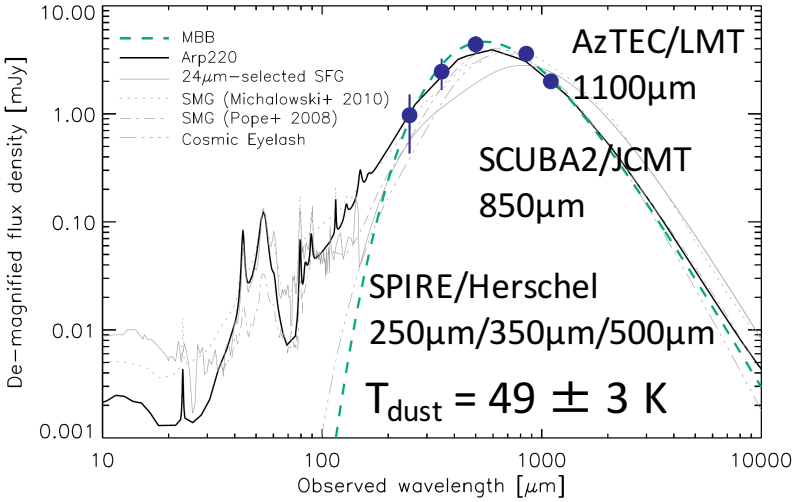



Selected from SPIRE on Herschel, as a "red SPIRE source" or "500µm riser"

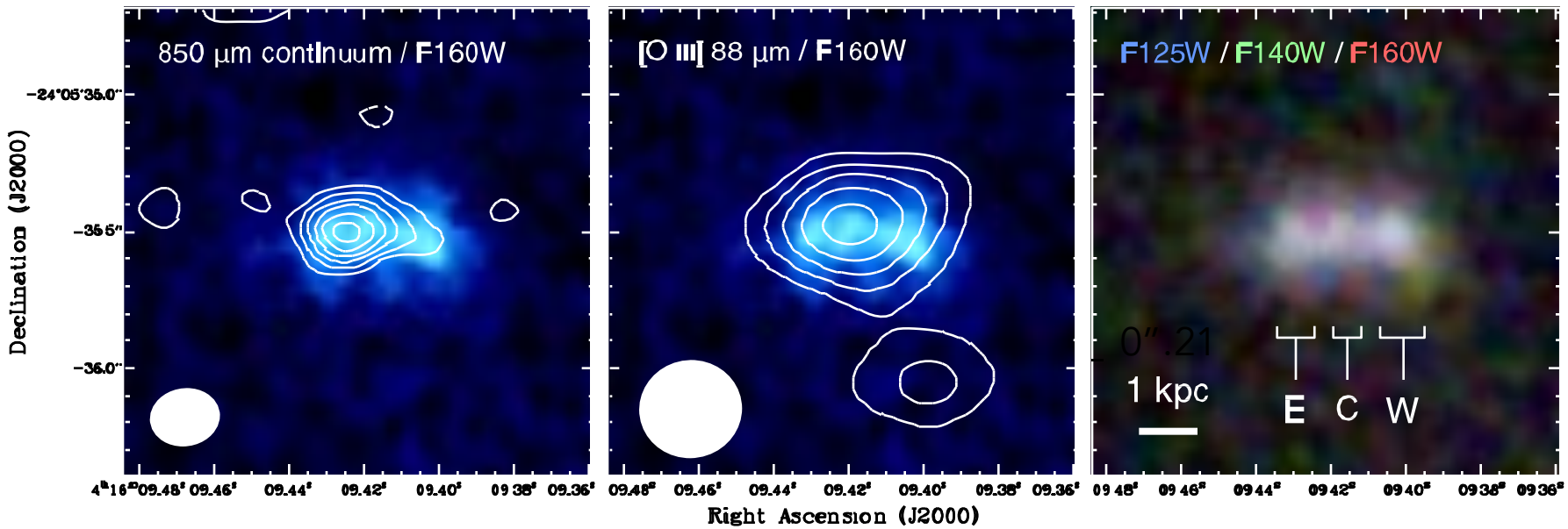
[CII] ~40 mJy (using SMA)



# more [OIII] 88μm clear detections using ALMA

## Tamura+2018: Rich in dust/metal at z = 8.3

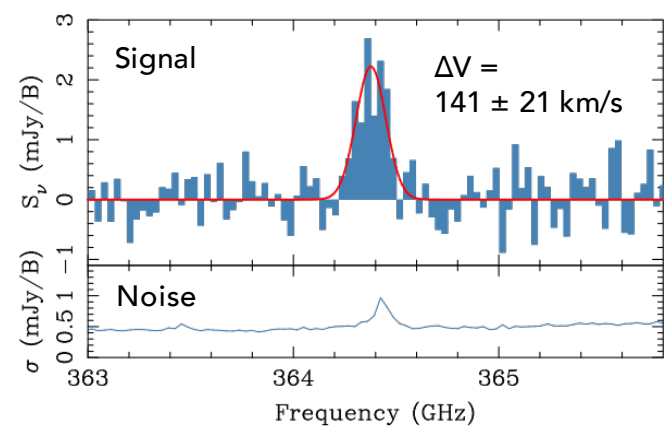
MACS J0416.1-2403, “MACS0416_Y1”



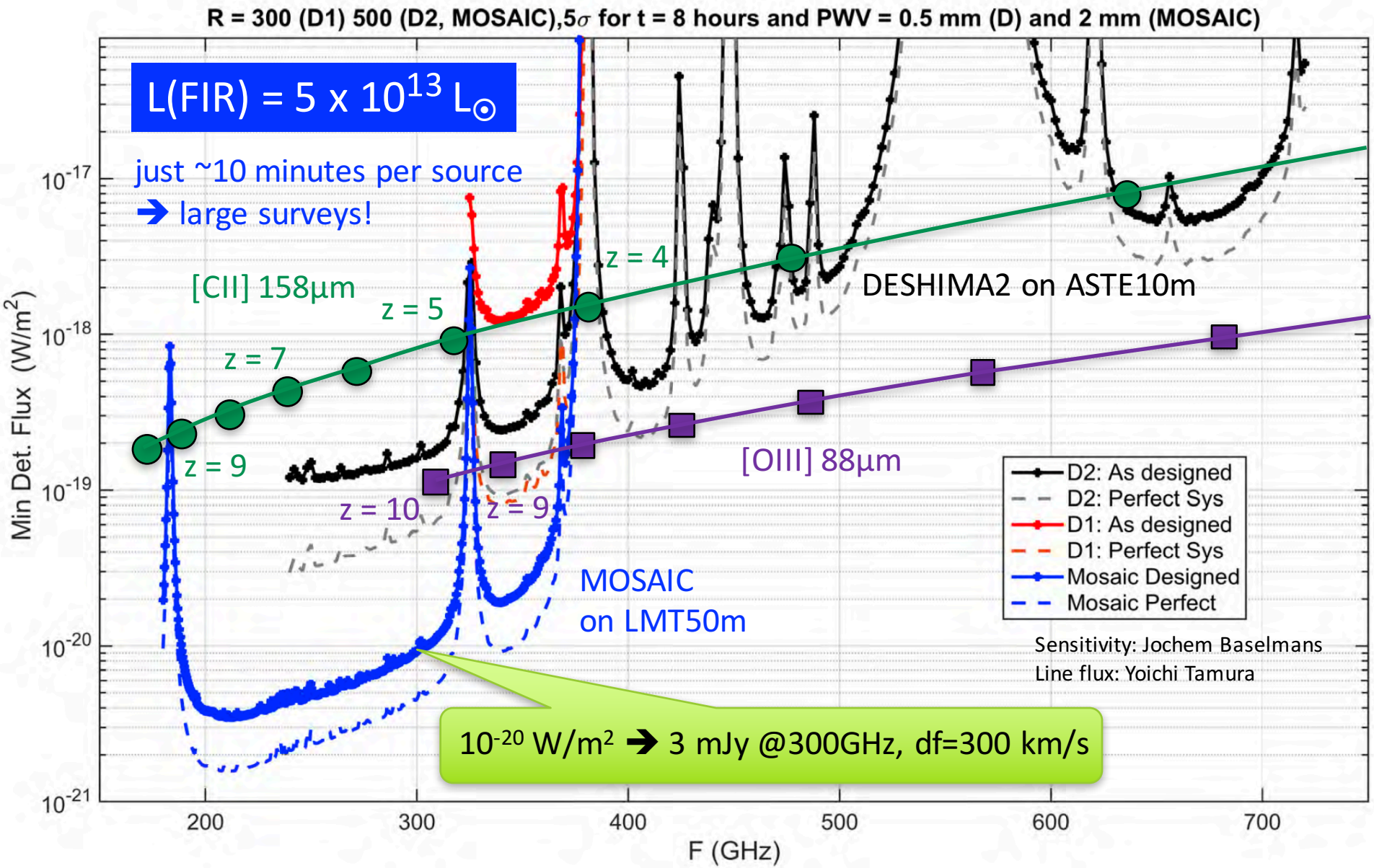

Tamura, Y., et al. (2018) submitted to ApJ

- Massive dust reservoir (L_IR = 2 × $10^{11}$ $L_\odot$)
  - Blue UV continuum (**β**_UV ~ –2, Av ≦ 0.4)
- Dust coexists rest-UV and [OIII] on ~kpc scale.

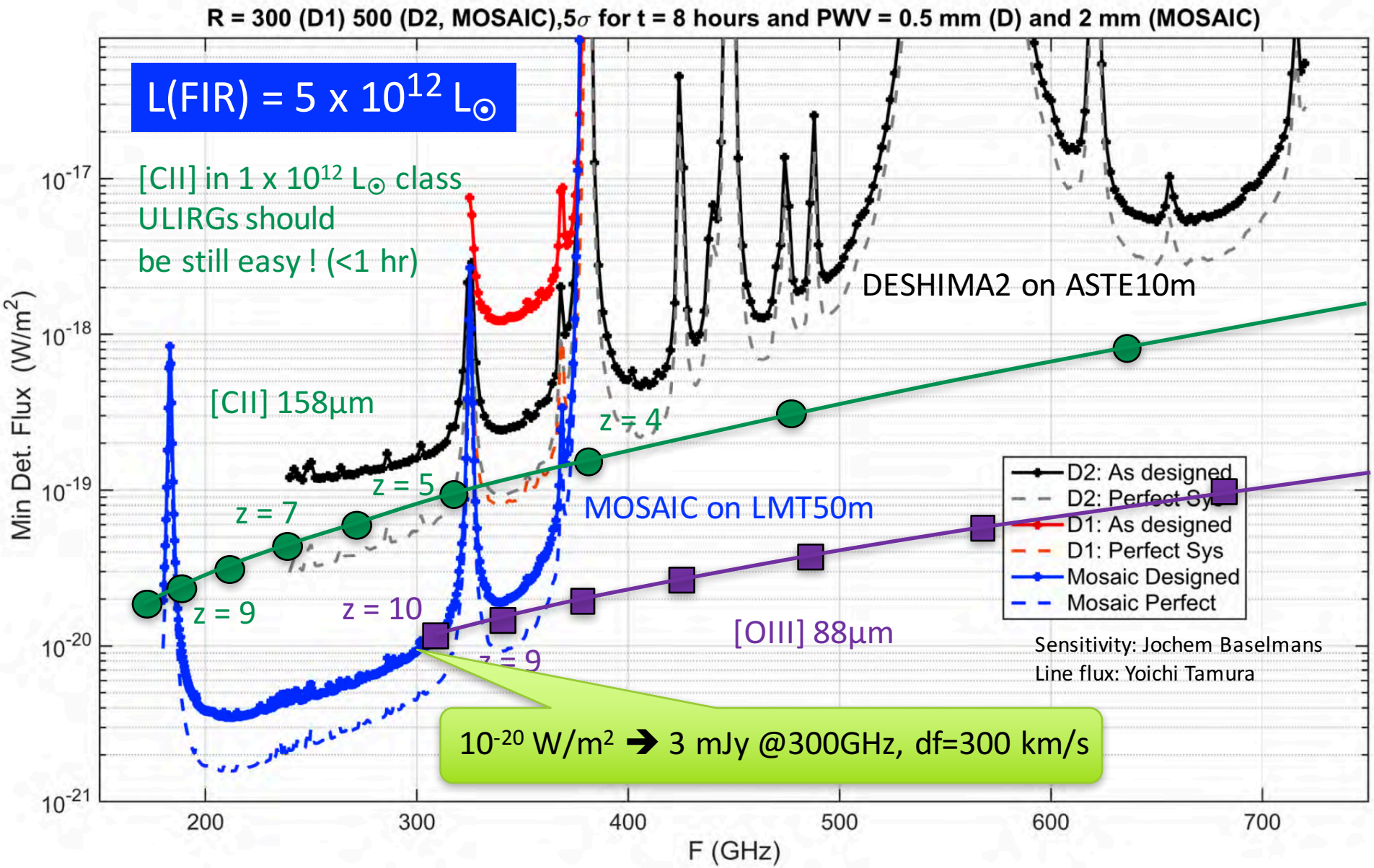
➔ Why !?



# Detectability of fine structure lines



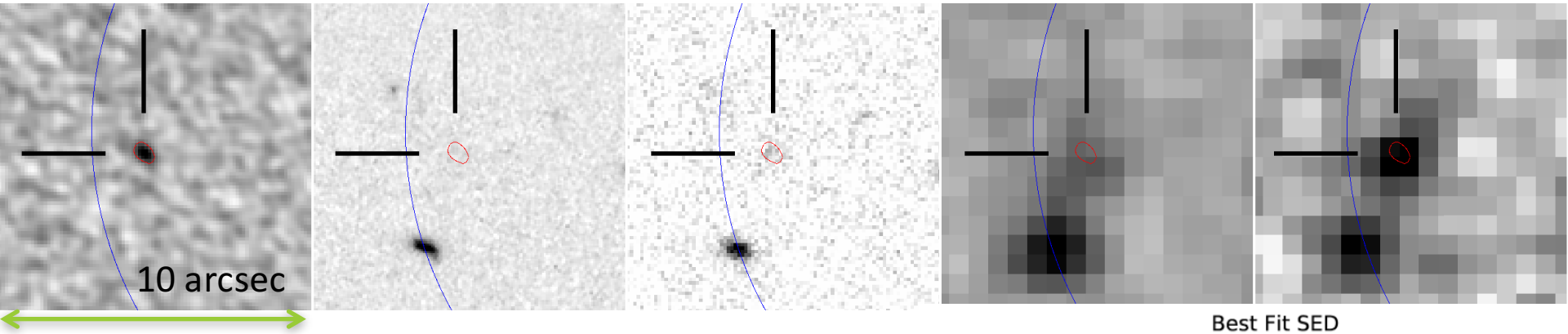
# Detectability of fine structure lines



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

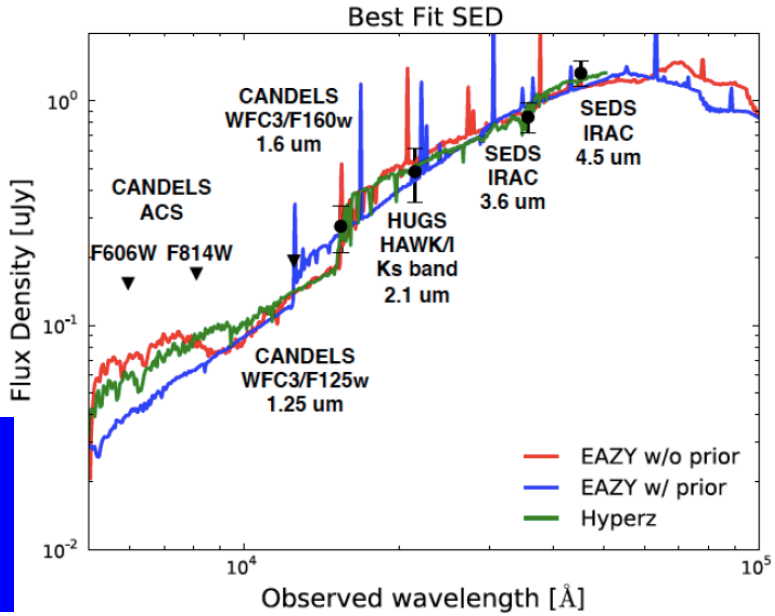
Kohno et al. 2016
Yamaguchi et al. 2016

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



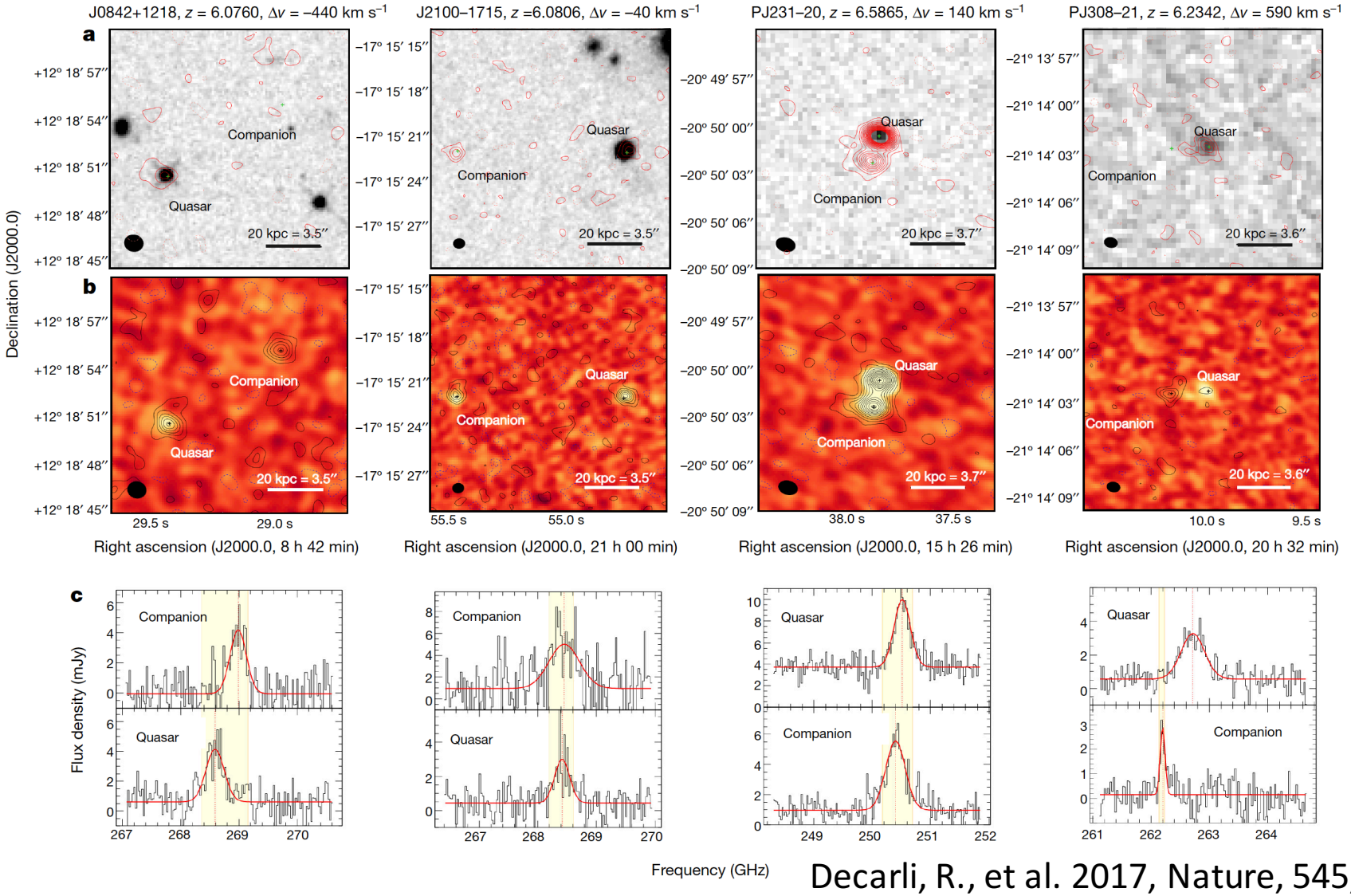

$z_{photo} = 3.1^{+3.9}_{-1.8}$ (Hyperz), $2.4^{+2.5}_{-2.0}$ (EAZY)

- 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??



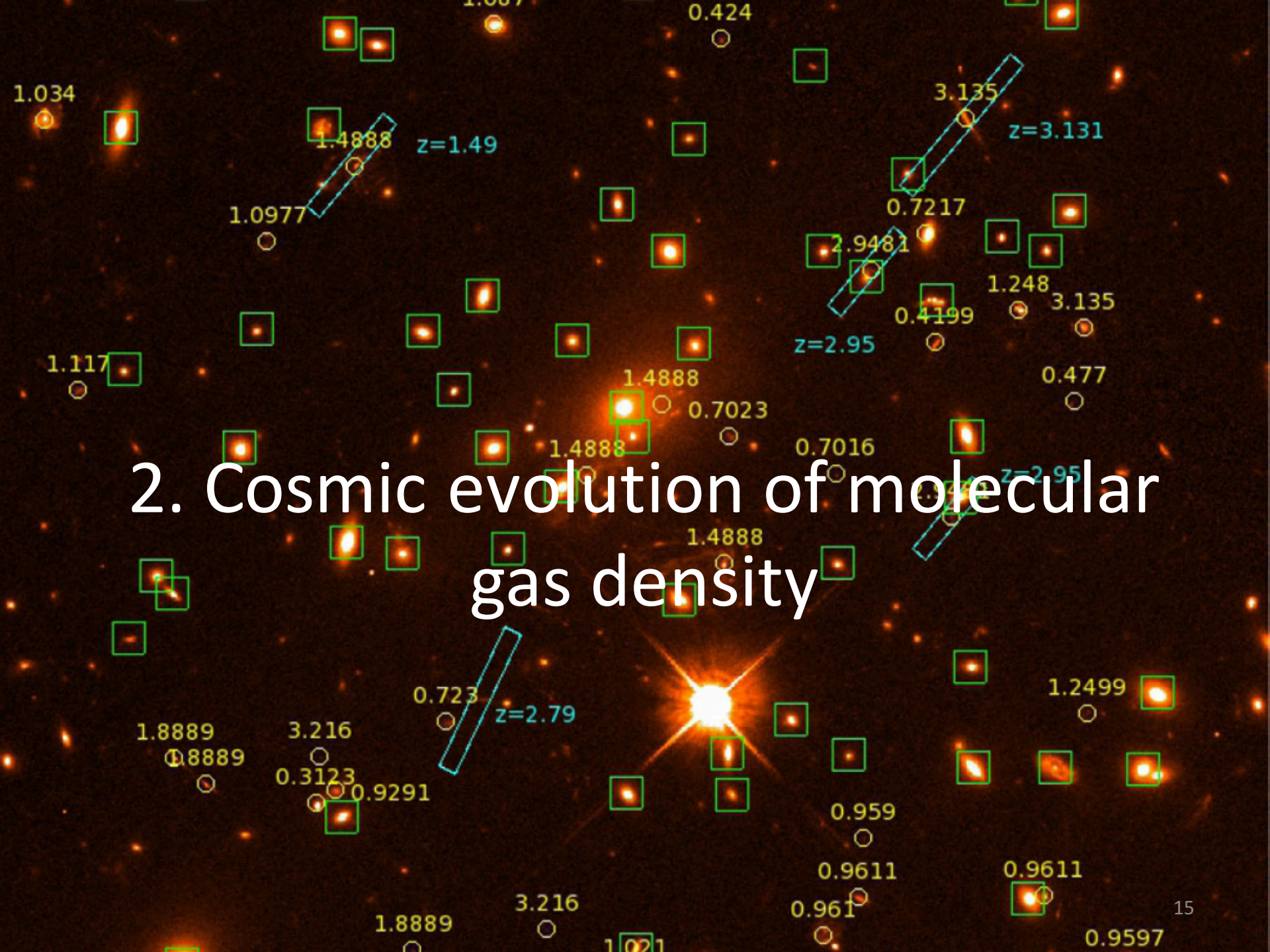

additional contributions to the SF history from faint submm galaxies, not fully overlapped with UV/optical-selected galaxies (e.g., Chen et al. 2014, ApJ, 789, 12)

# Search for excess of [CII] emitting galaxies around high-z (z~6) quasars with 5x5 pixels




Decarli, R., et al. 2017, Nature, 545, 457

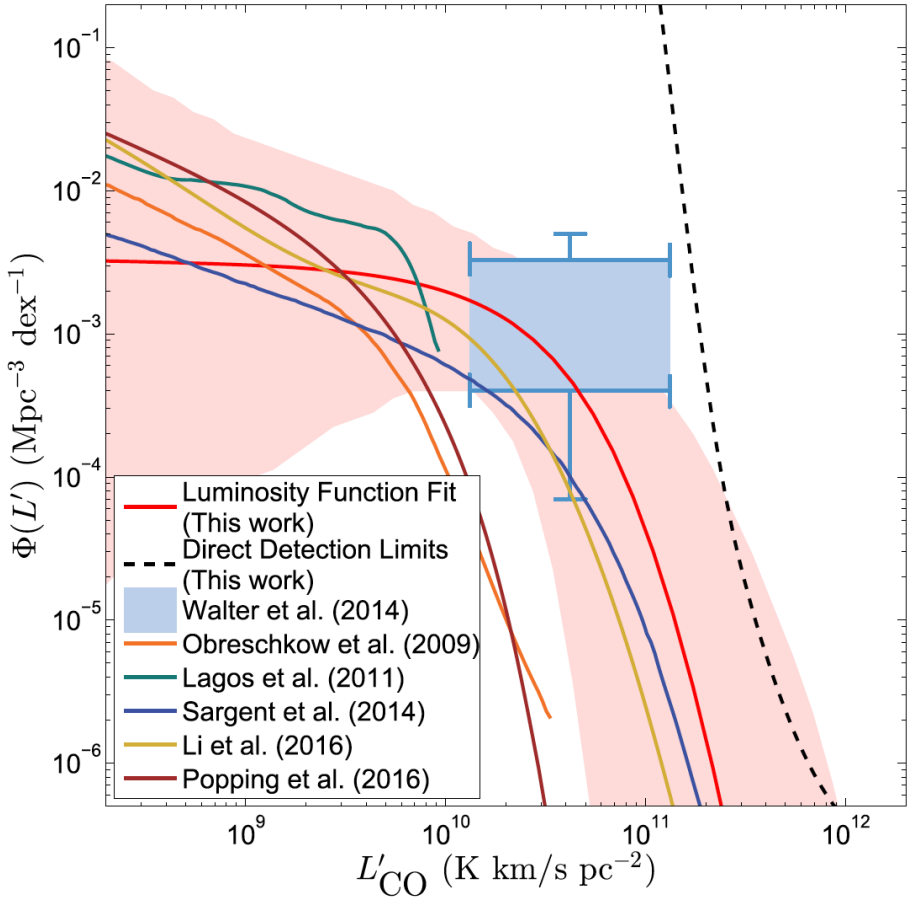
# 2. Cosmic evolution of molecular gas density



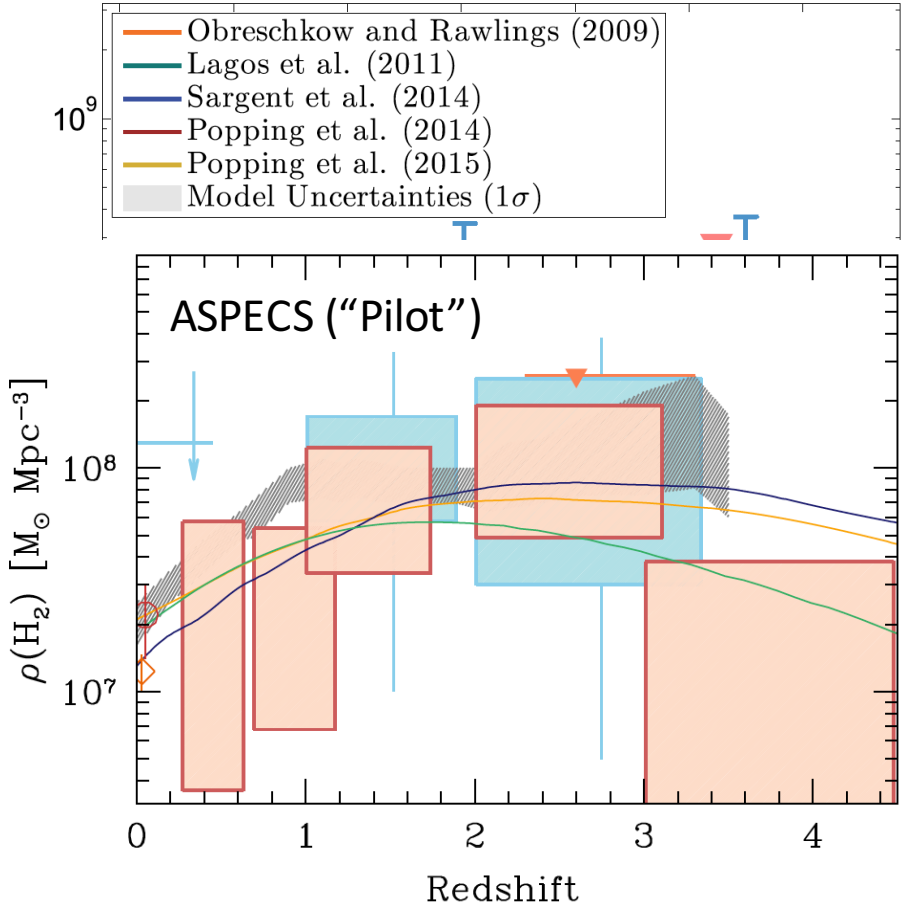
# What is the physical cause for the cosmic SFRD evolution? ➔ constraints on CO LF and $H_2$ mass density evolution

The Sunyaev-Zeldvich 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

# Blind search for mm/submm line emitting galaxies

- Recent ALMA observations serendipitously uncover mm line emitting galaxies
- These give us number counts of CO-emitting galaxies at z = 0 – 3 ➔ cosmic evolution of molecular gas density at z = 0 – 3
- It will also serendipitously uncover high-z (z>6) [CII]-emitting galaxies ➔ cosmic evolution of star formation rate density at z = 6 and beyond

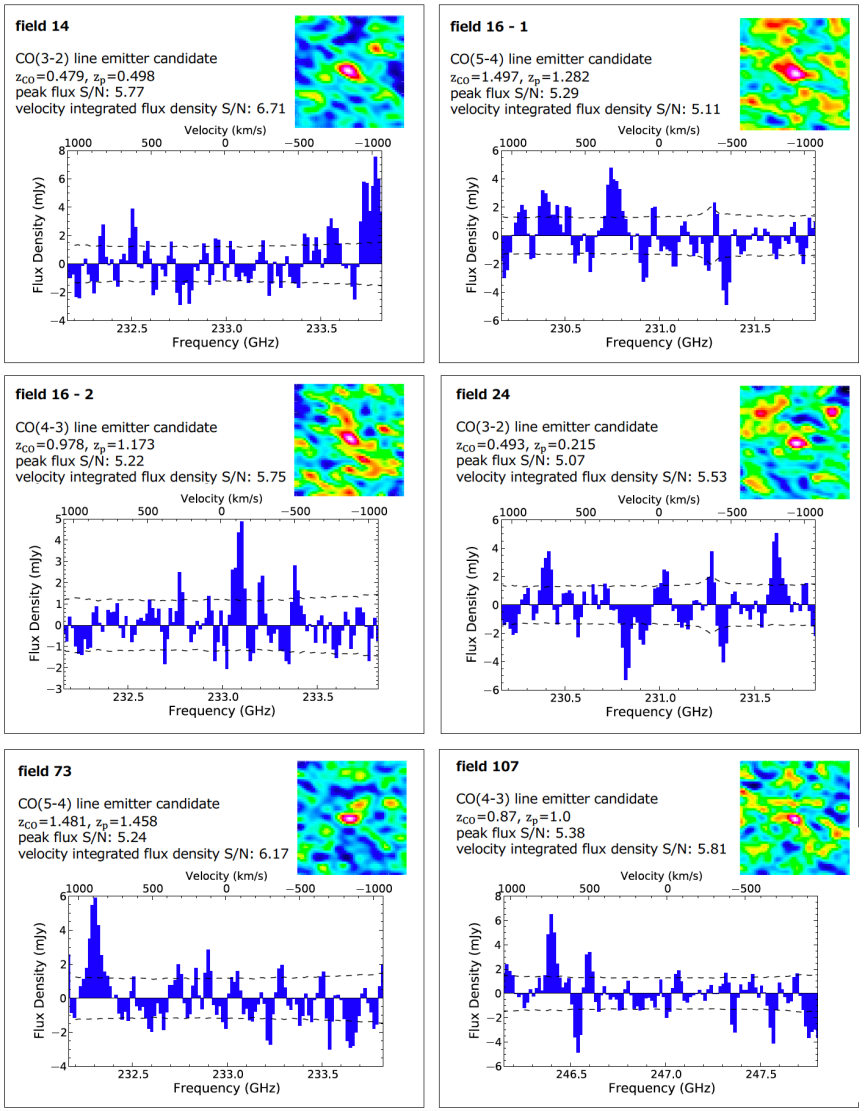
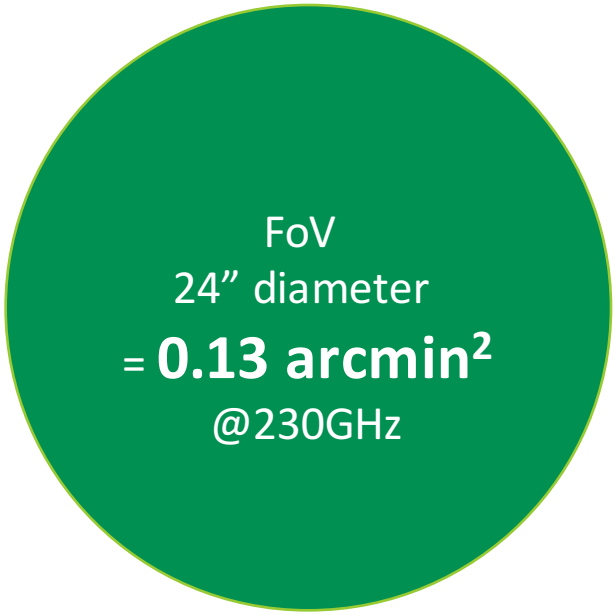


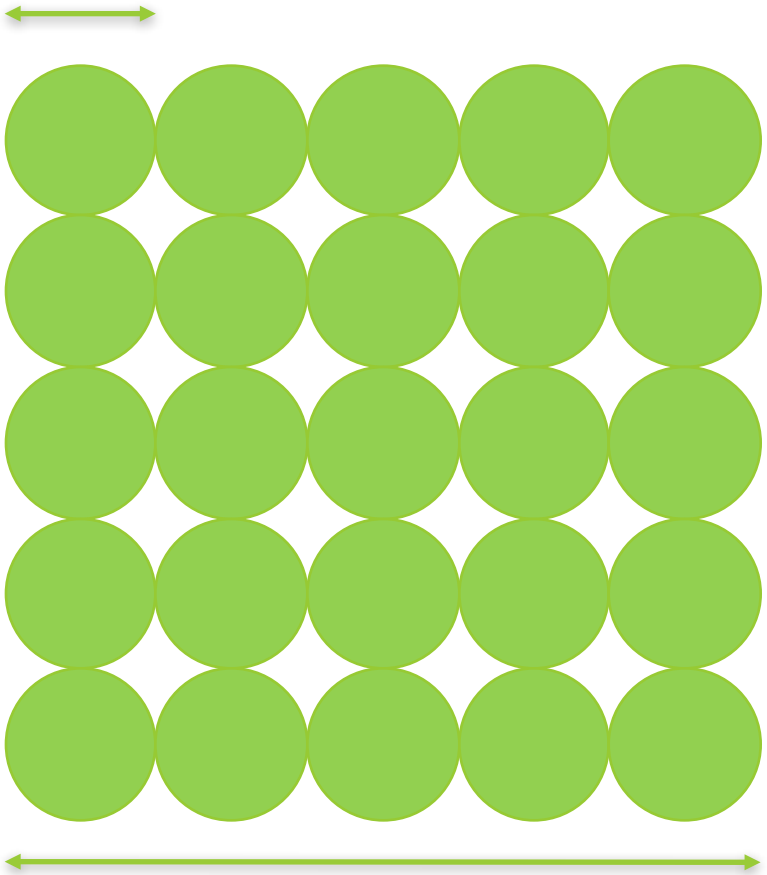

Figure: Spectra and images of CO-line emitting galaxies serendipitously uncovered by ALMA 230 GHz observations. Six unambiguous detections in 16 arcmin$^2$ area in total (Yamashita, Kohno, et al., in prep.)

# An imaging spectrograph on LMT versus ALMA

ALMA Band-6




LMT beam @230GHz ➔ 6” (HPBW)

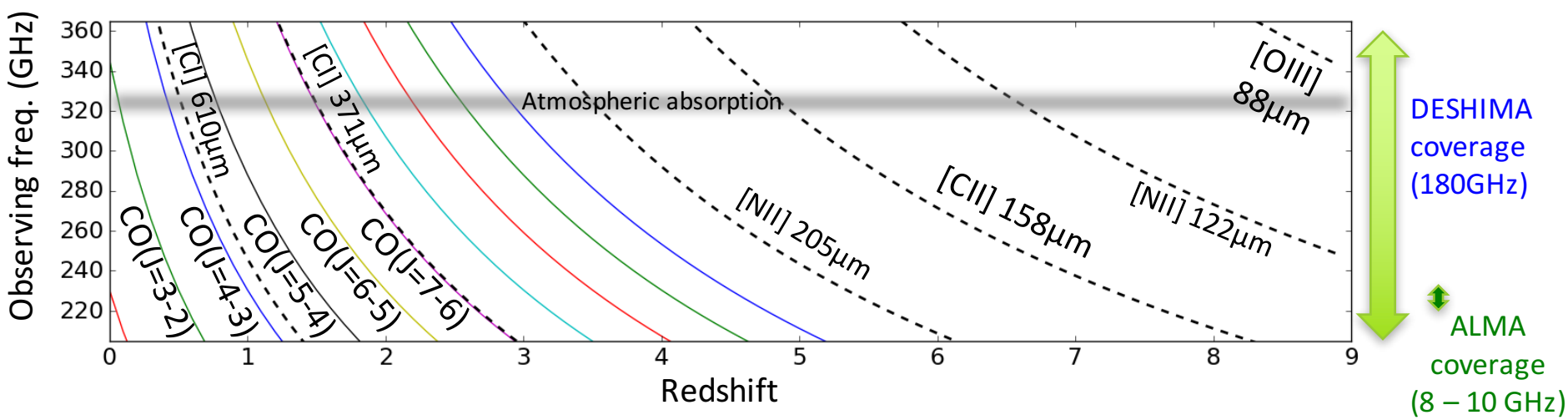


30” x 30” ➔ **0.25 arcmin²** @230GHz

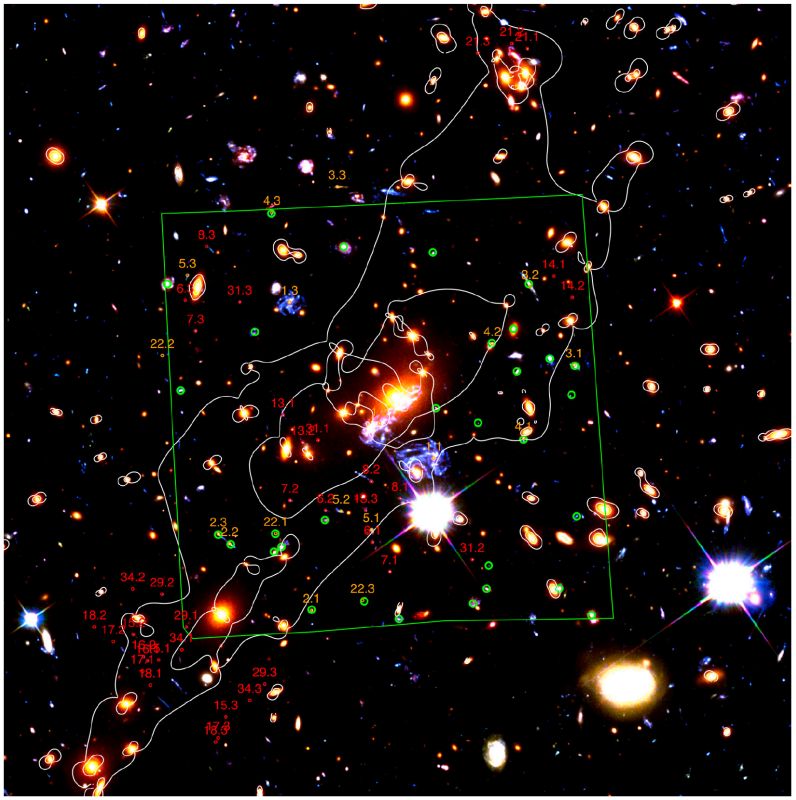
Note: MOSAIC beam configuration on sky is TBD (see Jochem Baselmans’ talk for options)

# An imaging spectrograph on LMT versus ALMA

- It covers from 185GHz to 365GHz (df = 180GHz ; >18 times wider than ALMA) with a moderate resolution (R=f/df～500)
- 25 spatial pixels, covering ~0.25 arcmin$^2$ (~2 times wider FoV than ALMA)
- ➔ It results in (collecting area) 0.4 x (FoV) 2 x (bandwidth) 18 = 14 times more efficient than ALMA (equivalent to D = 70 m) when it resides on LMT 50m

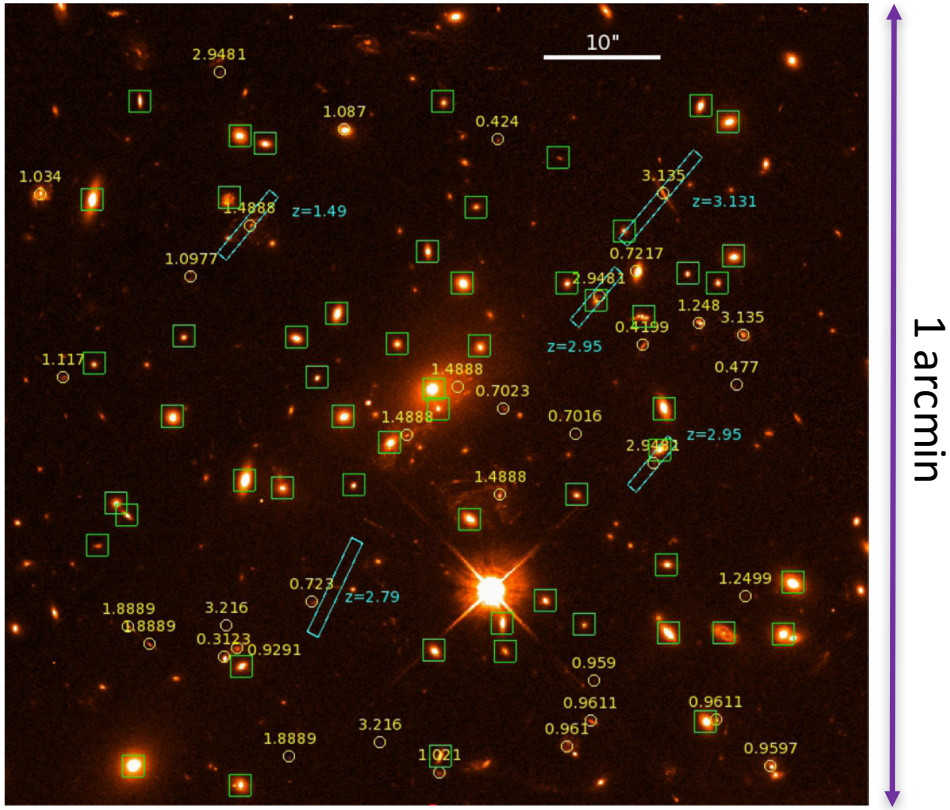


# One of (many) promising targets: MACS J1149+2223 @z=0.544



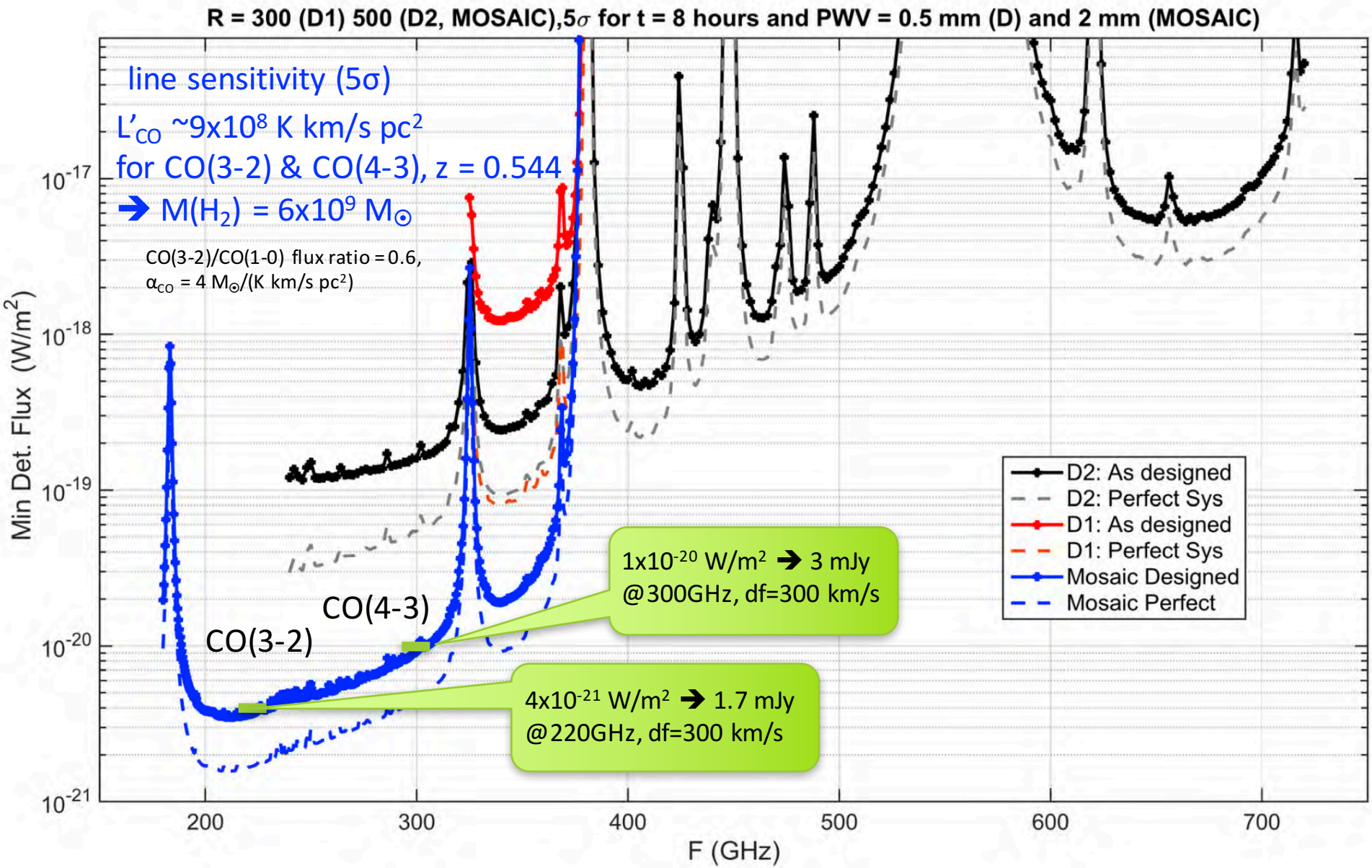
Jauzac et al. 2016, MNRAS, 457, 2029

MUSE/VLT spectroscopy ➔ 57 galaxies at z = 0.51 - 0.57 in the central 1'x1' region of the cluster

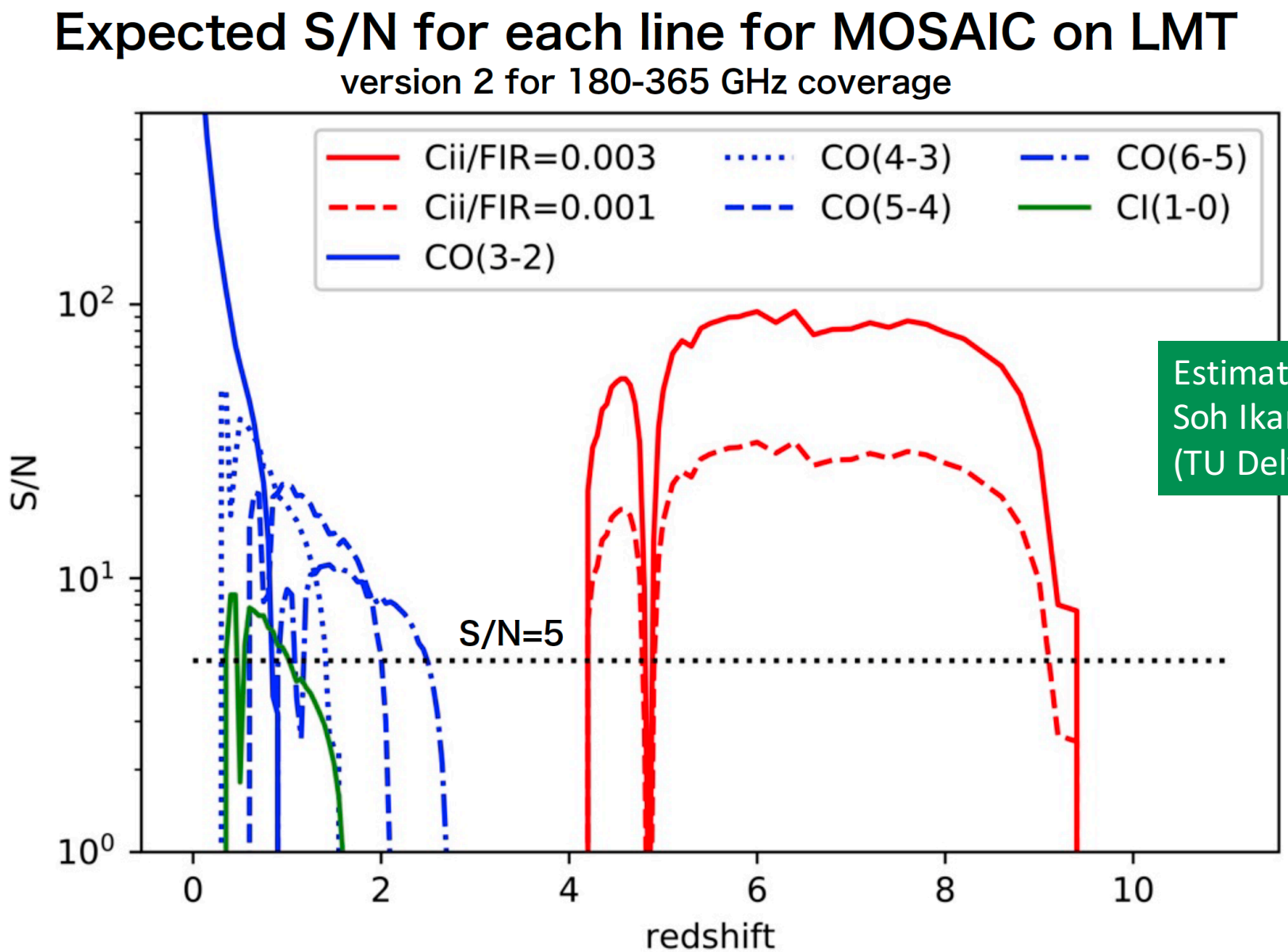



@z = 0.51 – 0.57
CO(3-2) @222-229 GHz
CO(4-3) @296-305 GHz

# Detectability of CO lines

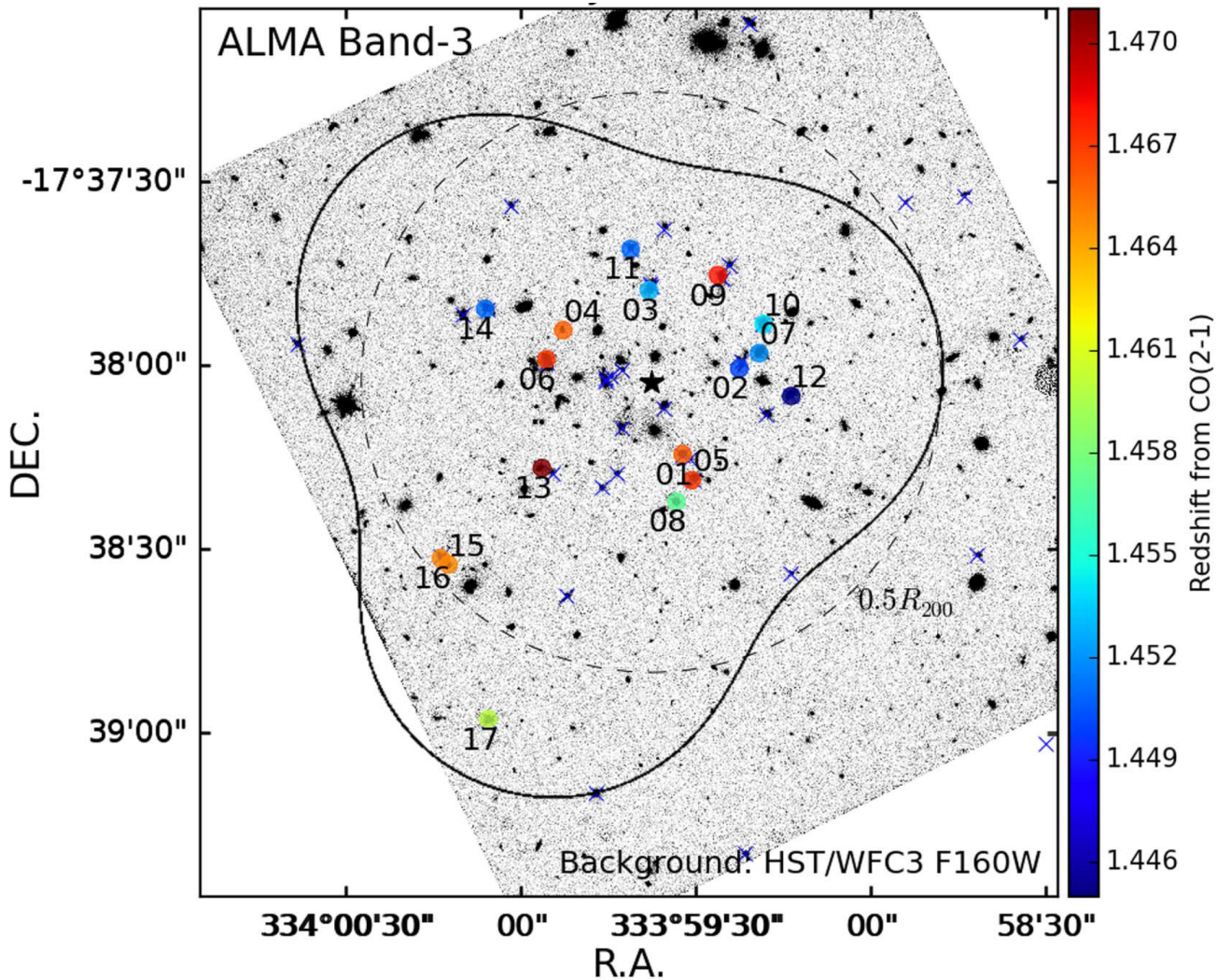


# CO lines at z=0.5 to 2.5 are also promising



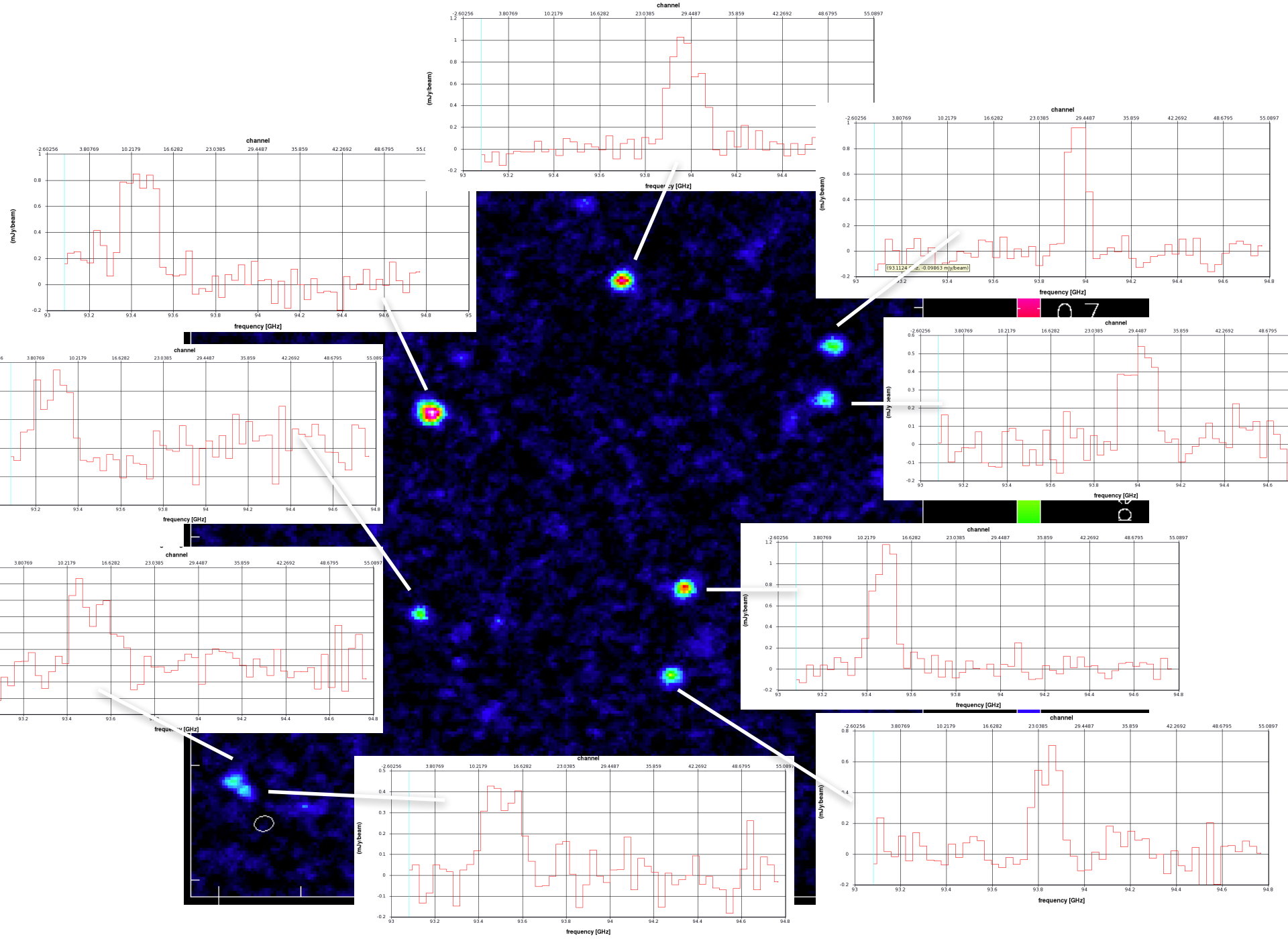

Estimated by Soh Ikarashi (TU Delft)

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

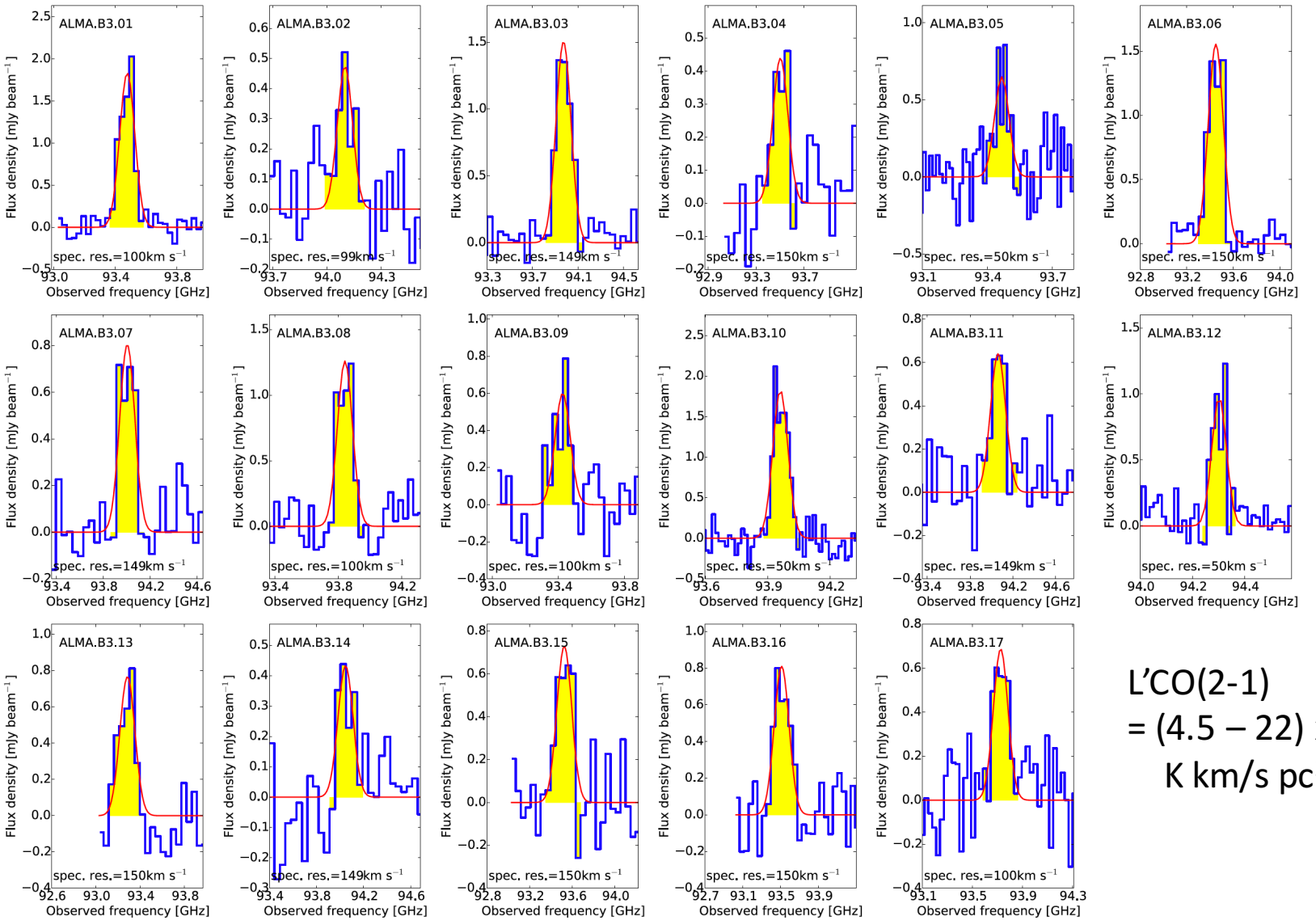



- 3 point mosaic
- 2.33 arcmin$^2$
- f(obs) = 93.03 – 94.86 GHz ➔ z = 1.430 – 1.478
- 1.04 hr on-source per pointing
- 1σ = 0.17 mJy/beam for dv = 50 km/s
- Clumpfind
- Cross-matched with optical data with 1" search radius

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


channel
(mJy/beam)
frequency [GHz]
(93.1124 GHz, -0.09863 mJy/beam)

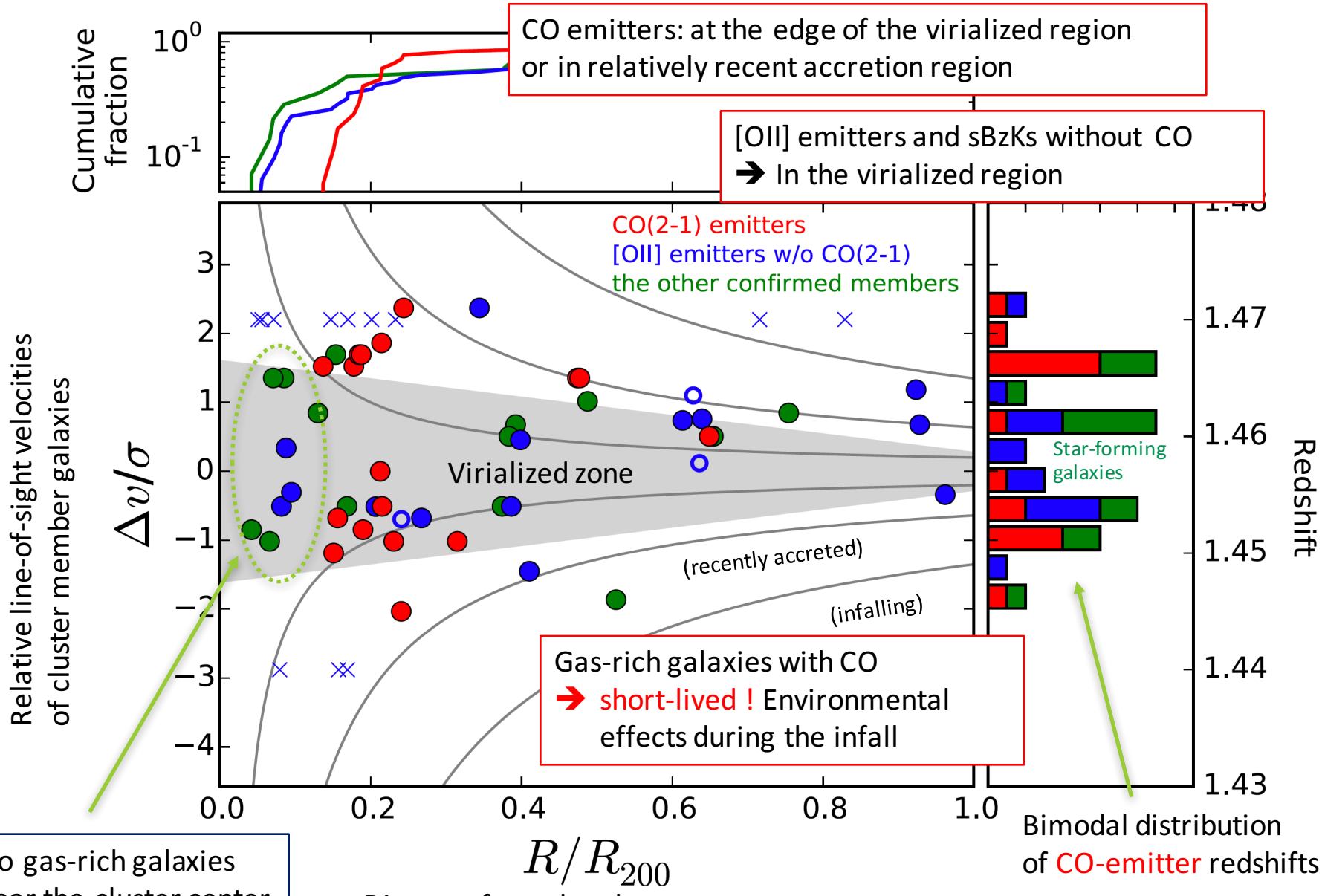
# 17 CO(2-1) emitters identified




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

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

# Phase-space diagram in XCS2215




Hayashi, M., et al., 2017, ApJ, 841, L21

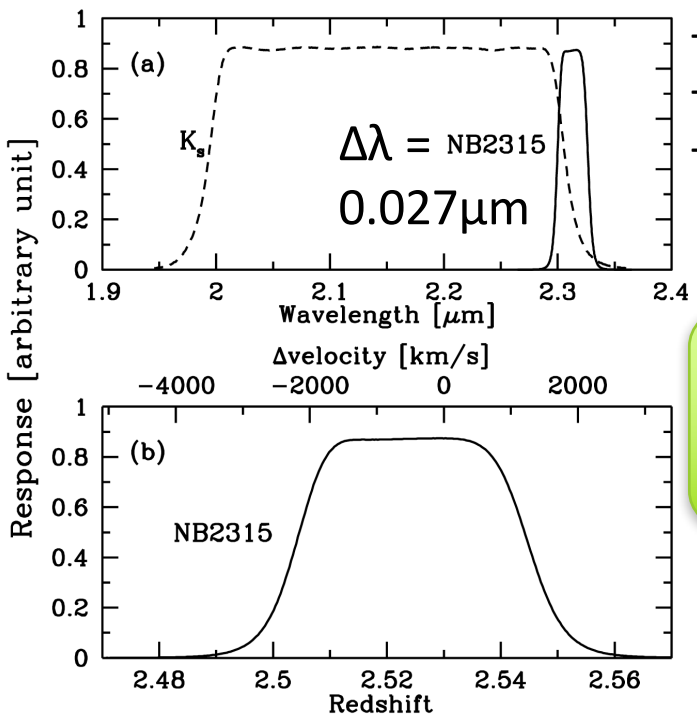
# Hα emitting galaxies in USS1558 proto-cluster at z=2.53

CO(6-5)@196GHz, CO(7-6)@229GHz, CO(8-7)@261GHz, CO(9-8)@294GHz, CO(10-9)@326GHz, CO(11-10)@359GHz

in one shot!

➔ once some are detected useful to address AGNs

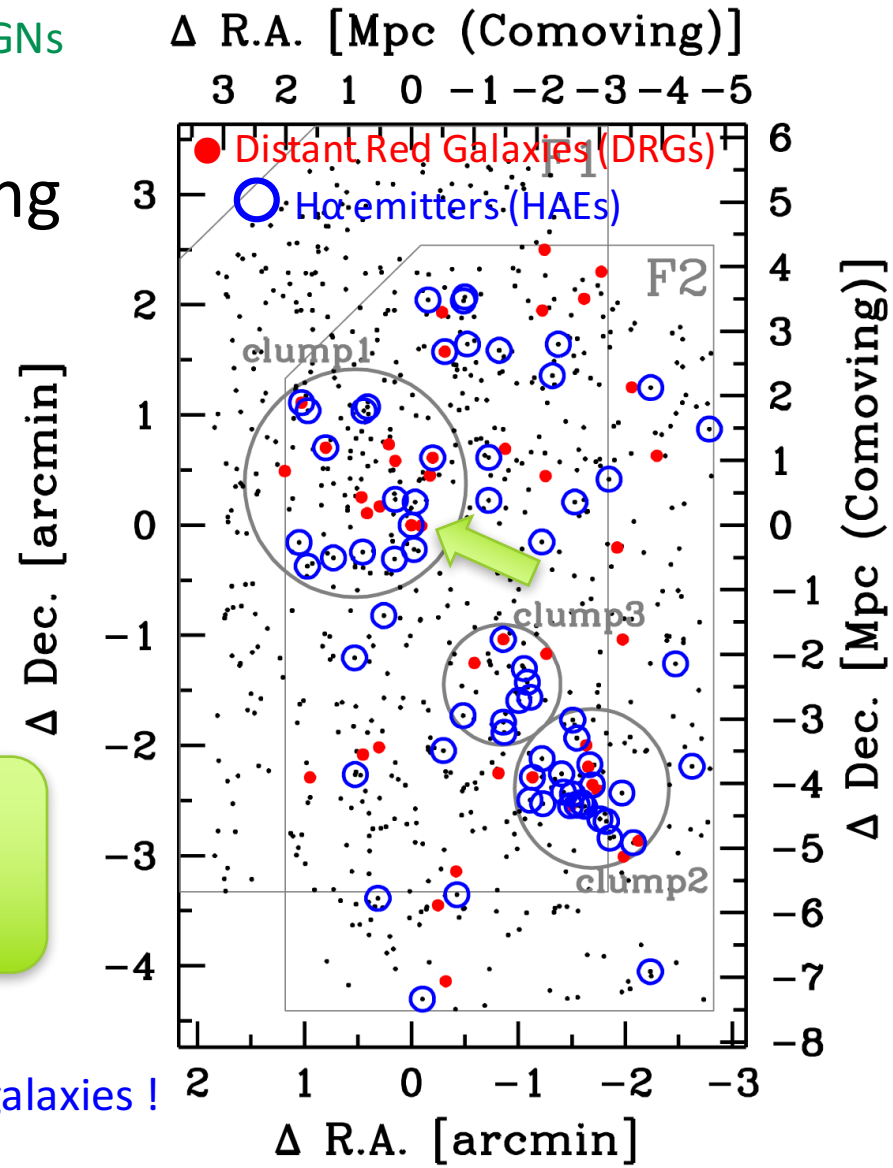
- Significant over-density of Hα emitting galaxies at z=2.53 using NB filter + MOIRCS camera on SUBARU telescope




- 3.4 hours (NB)
- 68 Hα emitters
- Limiting SFR: 8.6 $M_\odot$/yr

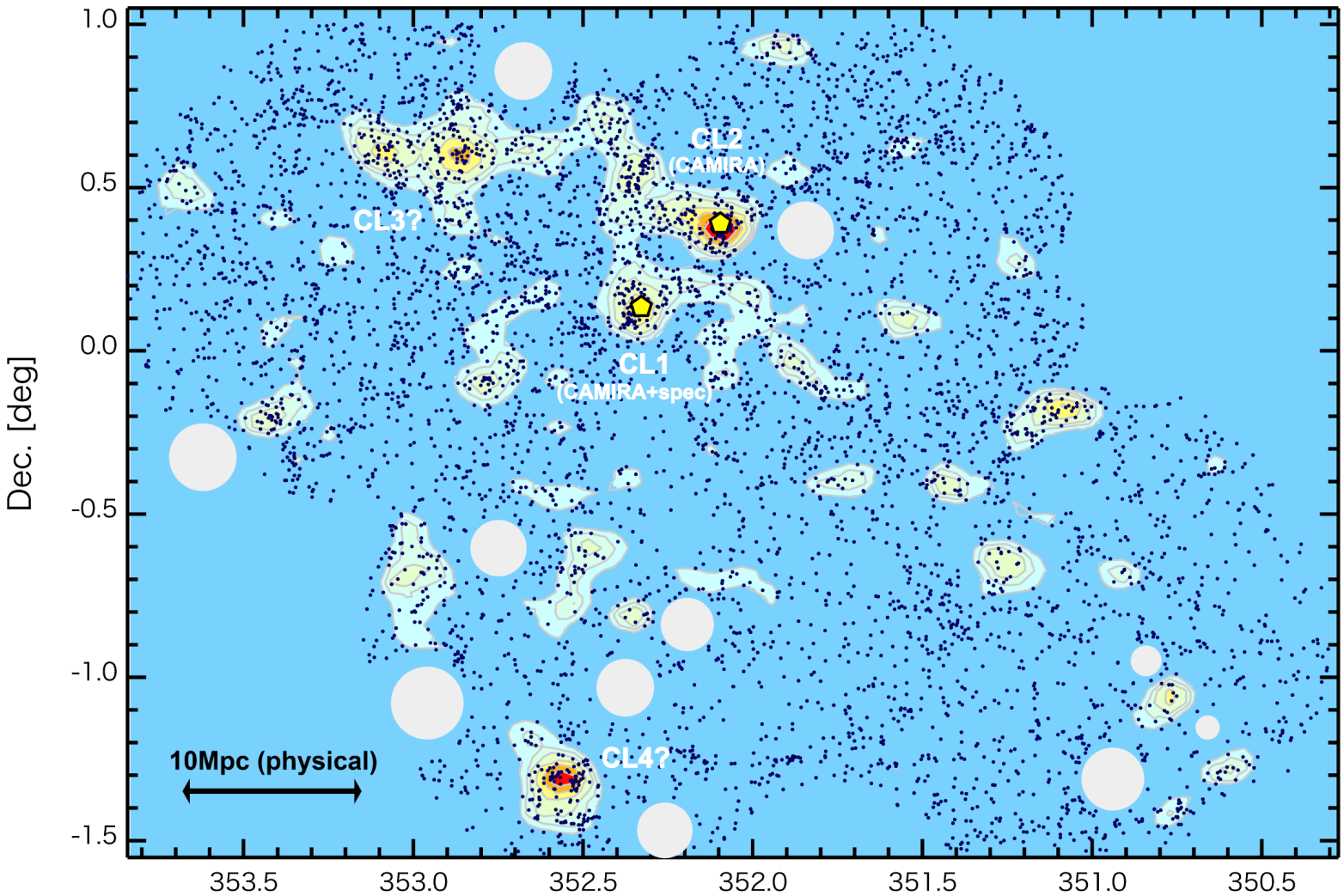
Hayashi et al. 2012, ApJ, 757, 15

Offset clumps of Hα emitting galaxies !

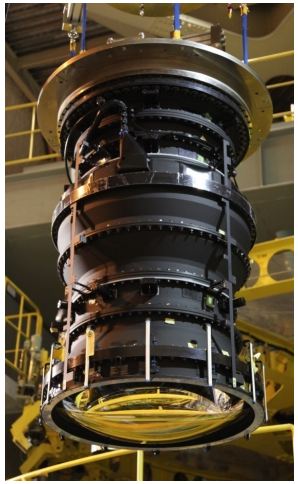


# Synergy with optical surveys: Subaru HSC surveys on-going

Spatial distribution of Hα emitters at z = 0.4 obtained by HSC+NB921

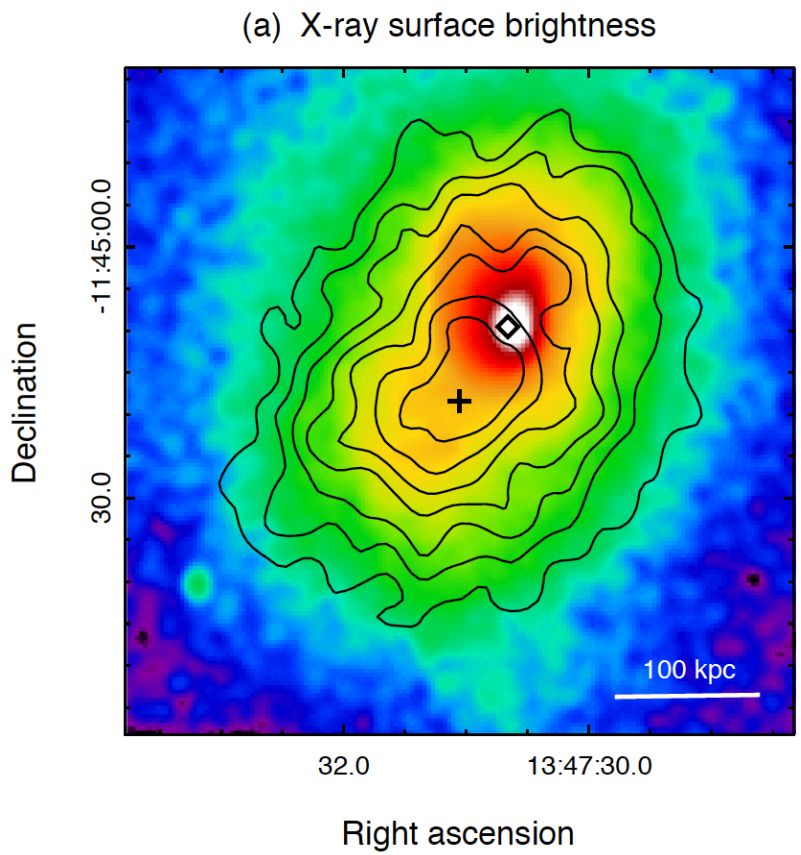



1 deg



HSC
1.5 deg FoV!

Koyama, Y., et al. 2018, PASJ, 70, S21



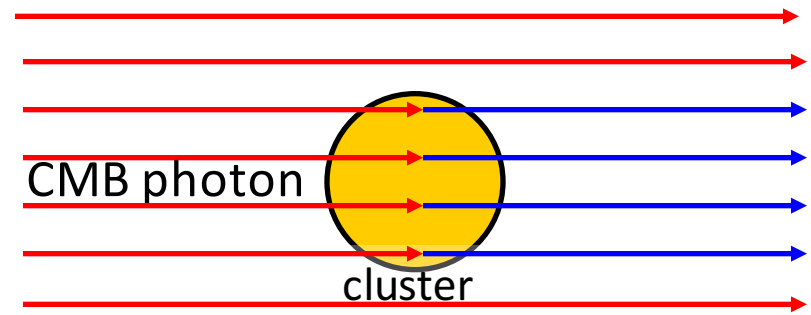

ALMA SZE vs Chandra
RXJ1347-1145

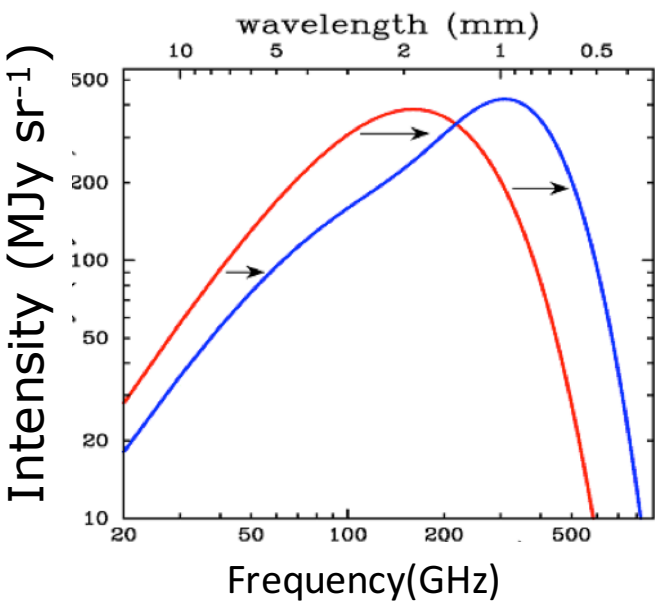
Kitayama, RK, KK, et al. 2016, PASJ, 68, 88

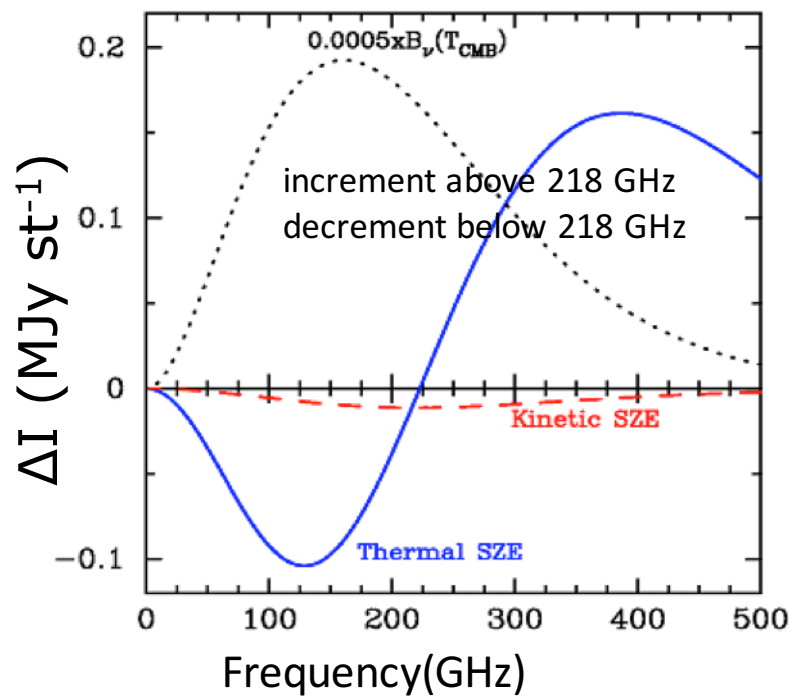
# 3. Physical properties of plasma in clusters of galaxies

# Sunyaev - Zel'dovich Effect

Cosmic microwave background (CMB) photons passing through a massive cluster have a ~1% probability of interacting with an energetic inter-cluster medium (ICM) electron ➔ The resulting inverse Compton scattering preferentially boosts the energy of the CMB photon by roughly $k_B T_e / m_e c^2$ ➔ causing a small (<1 mK) distortion in the CMB spectrum.




Birkinshaw 1999, Physics Reports, 310, 97-195
Carlstrom et al. 2002, ARAA, 40, 643
Kitayama, T., Prog. Theor. Exp. Phys. 2014, 06B111

# Sunyaev - Zel'dovich Effect

・complementary to X-ray observations

SZE $\Delta I_{SZ} \propto \int n_e T_e dl$ ← sensitive to $T_e$

X-ray $S_X \propto \int n_e^2 T_e^{1/2} dl$ ← sensitive to $n_e$

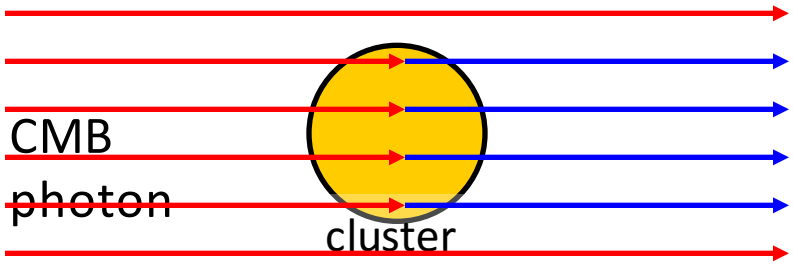
・observable even for high-z clusters

because the surface brightness of SZE is independent of z

$\Delta I_{SZ} \propto I_{CMB} \propto (1+z)^4$ $I_{\mathrm{CMB}}$ : CMB intensity entering the cluster

energy density $\propto (1+z)^3$
wavelength $\propto (1+z)$

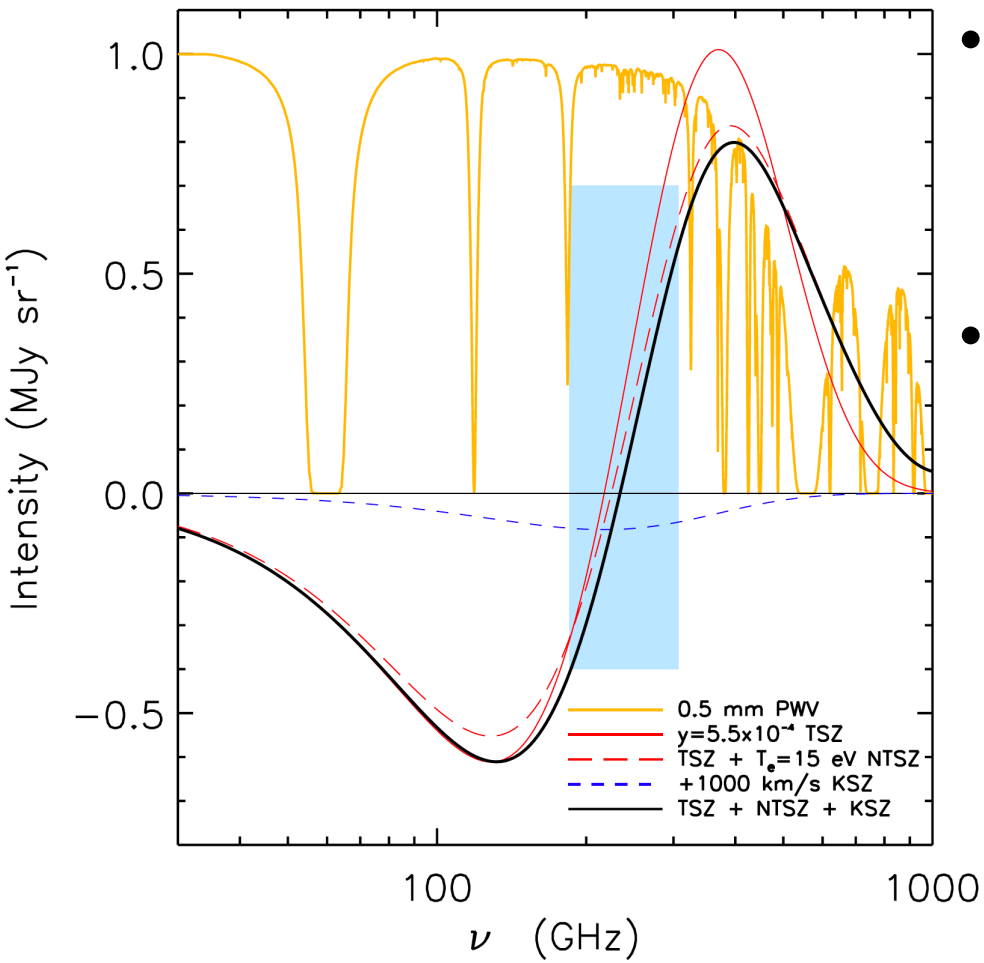
Increment of energy due to inverse-Compton Scattering $\propto$ the energy of incoming photons




Cosmic diming of the surface brightness

$$\propto \frac{S}{\theta^2} \propto \frac{(D_L)^{-2}}{(D_A)^{-2}} = \frac{\left((1+z)^2 \cdot D_A\right)^{-2}}{(D_A)^{-2}} = (1+z)^{-4}$$

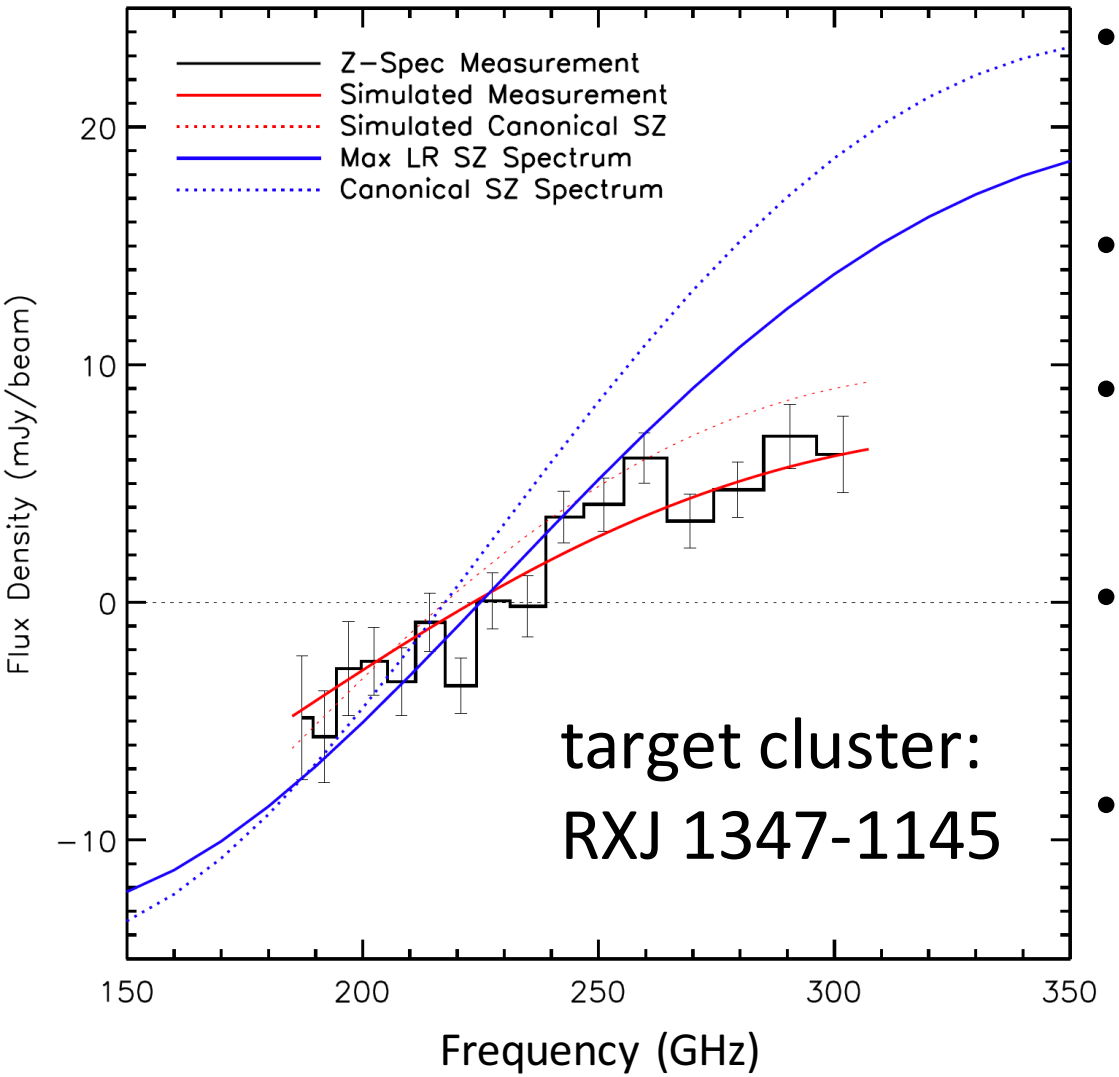
# clusters of galaxies: SZE using MOSAIC on LMT




- The Sunyaev-Zel'dovich effect (SZE) spectrum crosses through a null near $\nu_0$ = 217 GHz
- In a cluster of galaxies, $\nu_0$ can be shifted from the canonical thermal SZE value due to the properties of the inter-cluster medium (plasma).
  - relativistic correction
  - kinetic SZE (bulk motion of a cluster)

Zemcov et al. 2012, ApJ, 749, 114

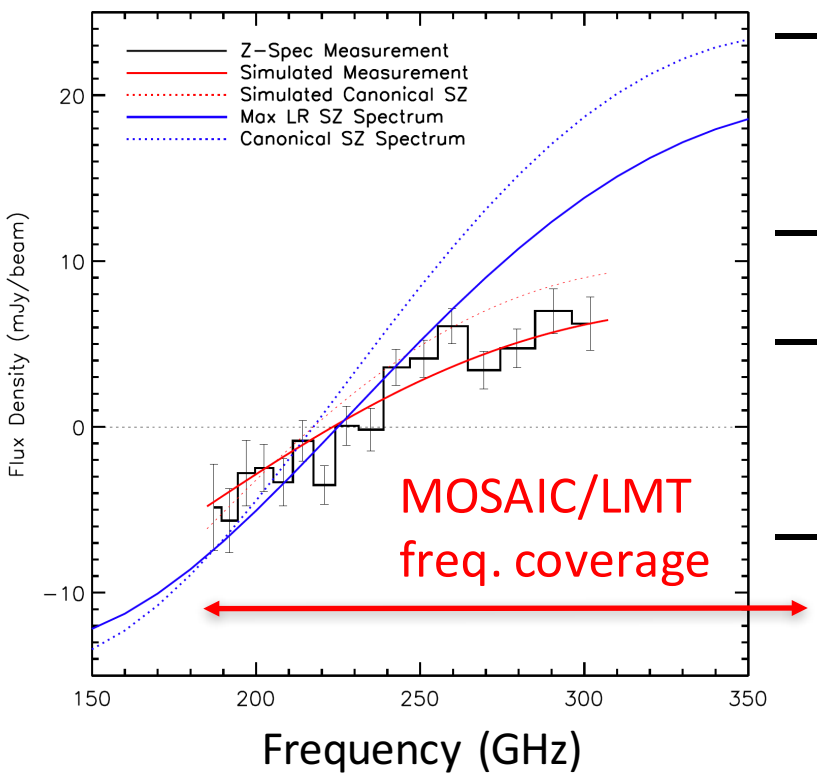
# Z-Spec/CSO 10m measurements




- Z-Spec: 185 GHz – 305 GHz, R=300 (dv~1000 km/s), single pixel
- $\nu_0$ = 225.8 ±2.5 (stat.)±1.2 (sys.) GHz
- ➔ 3σ level difference from the canonical null frequency
- if it solely due to relativistic corrections ➔ kTe = 17.1 ± 5.3 keV
- if the bulk motion exists: $v_{pec}$ = +450 ± 810 km/s

Zemcov et al. 2012, ApJ, 749, 114

# MOSAIC on LMT: a big leap in SZE science




- MOSAIC on LMT 50m
  vs. Z-Spec on CSO 10m
  - spectral coverage: 1.5x wider (approaching to the peak t-SZE)
  - spatial resolution: 5x sharper
  - spatial coverage: 5x5 imaging (⇔ single point)
  - sensitivity: ~$(50/10)^2$ times better

# Summary: new science capabilities with MOSAIC on LMT 50m

1. dust-enshrouded star formation in the early universe
   - a large [CII] spectroscopic survey (z = 4.2 – 8.7) of mm/submm-selected galaxies drawn from AzTEC, MUSCAT, Toltech + other surveys (Herschel, Plank, JCMT, ACT, ..)
2. cosmic evolution of molecular gas density
   - a search for dual or multiple CO line emitters (z=0-1) by exploiting imaging capability synergies with optical MOS/IFU like MEGARA/GTC
   - CO-SLED characterization for hidden AGNs (for z>1)
3. plasma physics of clusters of galaxies via SZE
   - precise measurements of "the null frequency" ➔ relativistic shift to constrain Te + bulk motion via k-SZE

And more possibilities for Galactic and local galaxies (recall SPIRE-FTS)