Chile-Japan Academic Forum 2018
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ALMA

ALMA deep surveys of blank fields and lensing clusters

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Collaborators

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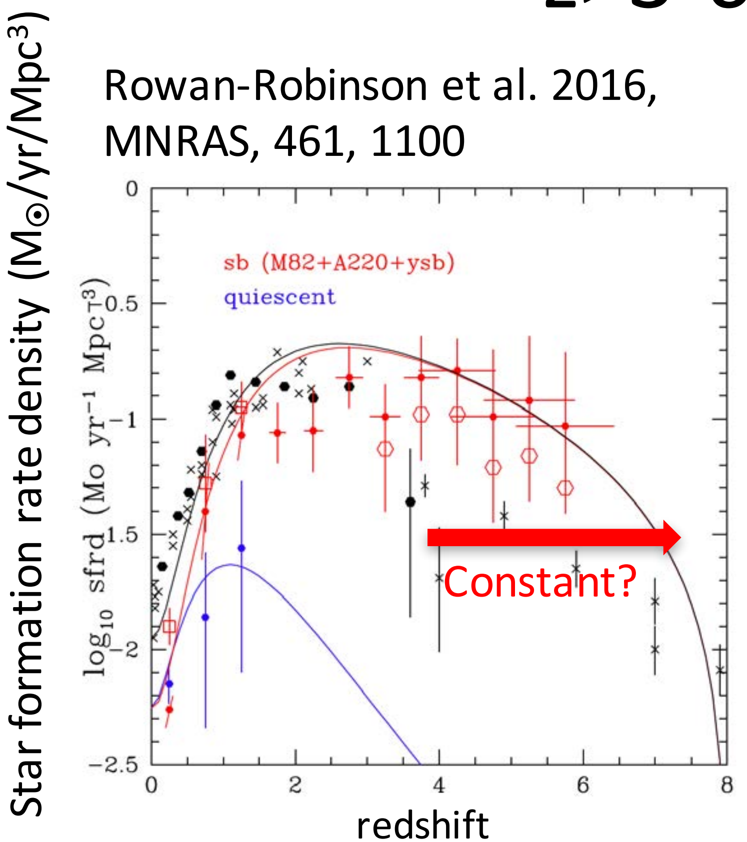
- Ivison, R., (ESO), Wilson, G., Yun, M. S. (UMASS), Hughes, D., Aretxaga, I. (INAOE), Wang, W.-H. (ASIAA), Dunlop, J. (ROE), **Ikarashi, S.**, **Caminha, G.**, **Caputi, K.** (U. Groningen), **Rieke, G.** (U. Arizona), **Ueda, Y.**, Ohta, K., (Kyoto U.), Inoue, A. (Osaka Sangyo U.), Nyland, K., Jagannathan, P. (NRAO), ALMA SXDF / SSA22 / GOODS-S team
- Thank the JAO and ARCs for their efforts on ALMA operation

Outline

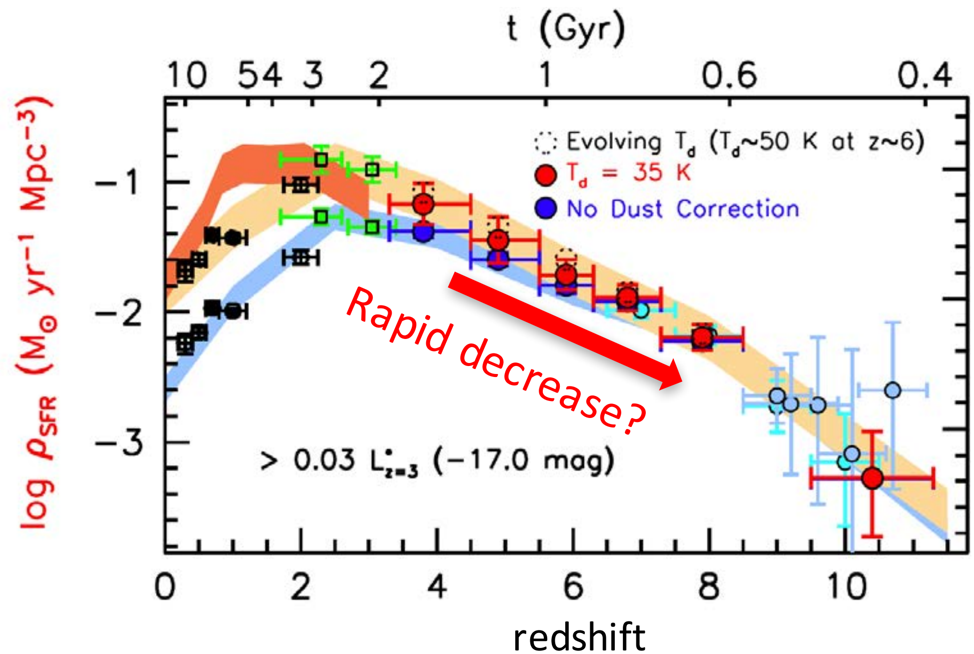
- Introduction
  - Why do we care about the dust-obscured part of galaxy formation history?
  - Roles of ALMA
- Quest for dusty galaxies using ALMA
  - Lessons from recent ALMA surveys on SXDF-UDS-CANDELS & HUDF/GOODS-S
  - How to follow-up dusty (H-band-dropouts) sources? Ultra-wideband spectrograph on LMT

Dust-enshrouded star-formation activities in z>3-6 and beyond ..?

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

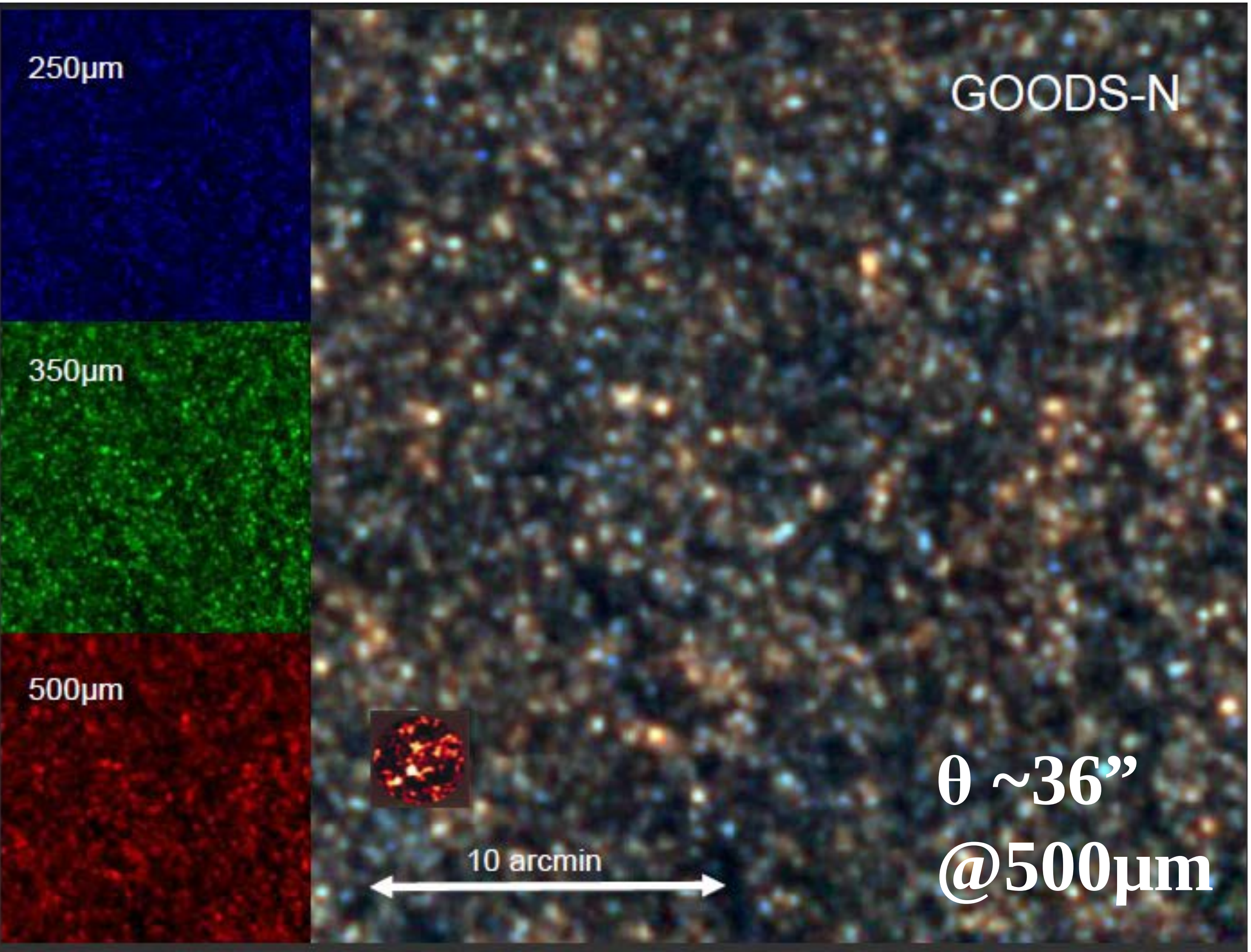


Bouwens et al. 2016, ApJ, 833, id. 72



- 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

Only ALMA can break the confusion limit of existing mm/submm deep surveys



Herschel Space Observatory + SPIRE

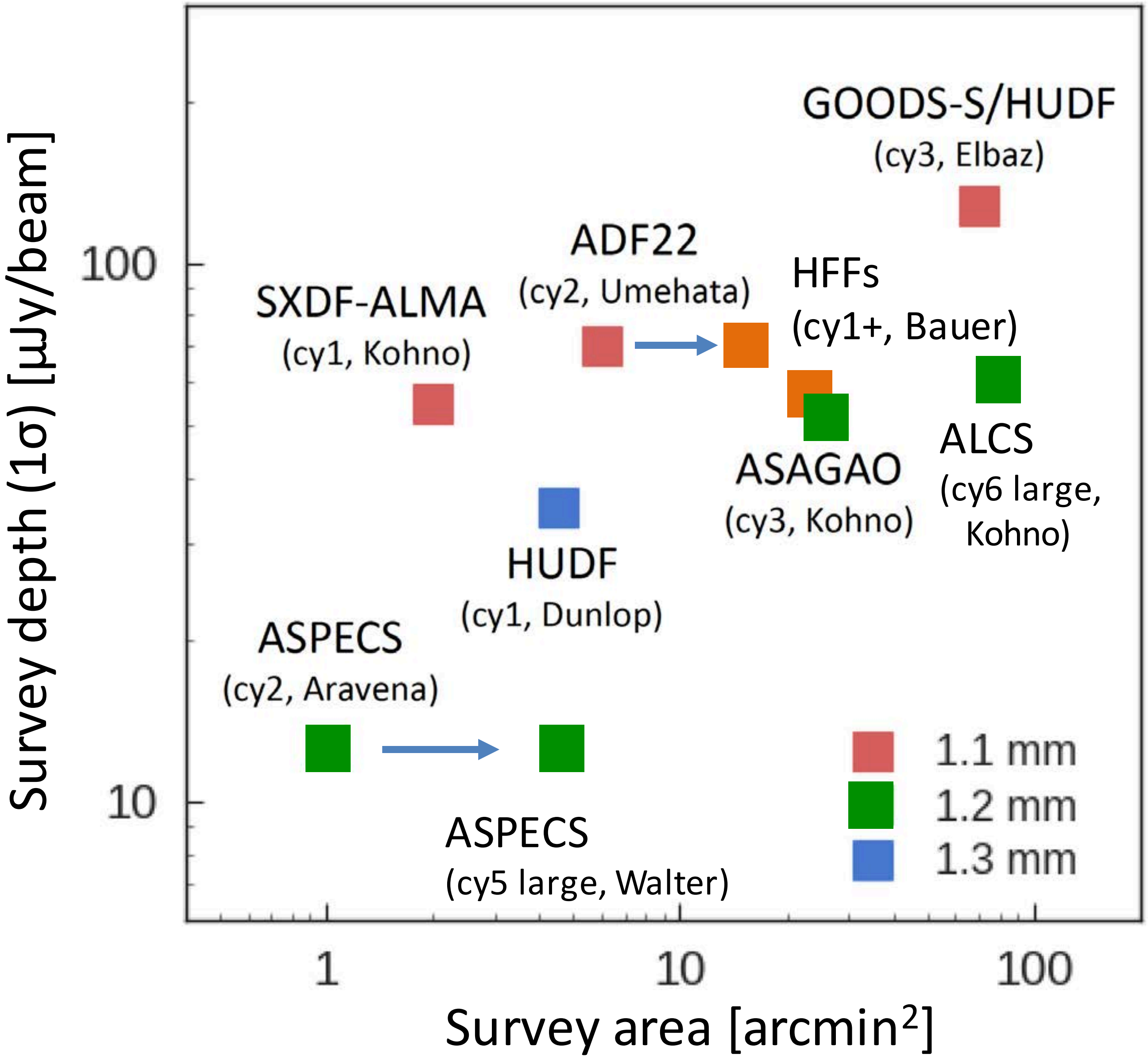
D = 3.5m

Science Goals of ALMA deep surveys: uncovering and characterizing "sub-mJy" galaxy population

- Types of galaxies responsible for the sub-mJy population
- Redshift distribution of the sub-mJy population
- SMBH growth rates in the sub-mJy population
- mm-properties of various classes of star-forming galaxies via stacking analysis

- Constraining the evolution of the [CII] and CO luminosity functions

ALMA deep surveys @λ~1mm



← Alejandra's talk (yesterday)

ALCS:
33 clusters
88 $arcmin^2$
80 μJy (1σ)

ALMA Lensing Cluster Survey (cycle 6)

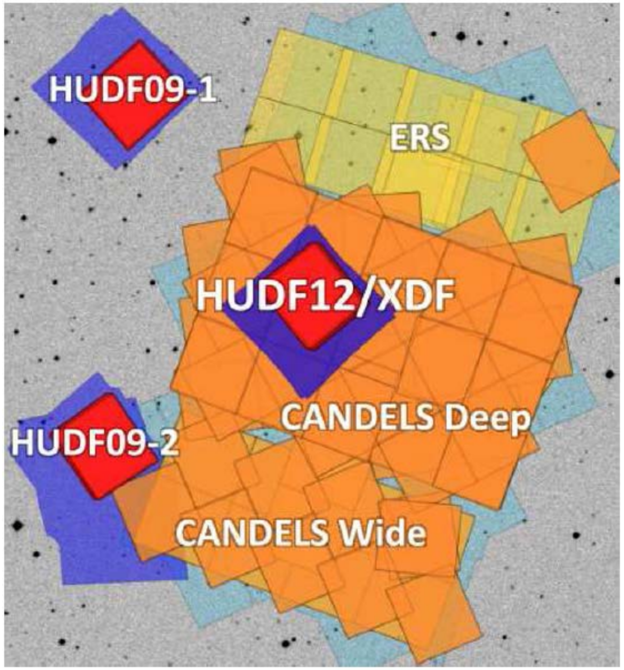
ALMA Lensing Cluster Survey	2018.1.00035.L

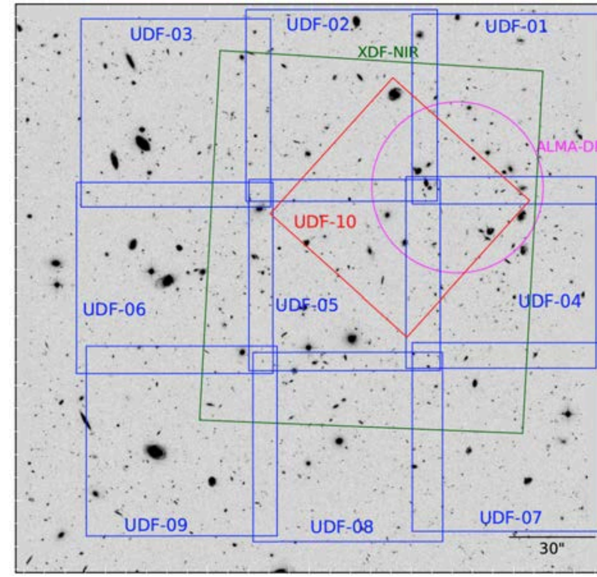
ABSTRACT

We propose an extensive survey of 33 clusters to a depth of 0.08 mJy (1.2 mm, 1 sigma). This will be accomplished with a 15-GHz-wide spectral scan, to enlarge the survey volume of line emitting galaxies. The sample comes from the best-studied clusters blessed with HST treasury programs, i.e., CLASH, HFF, and RELICS. We will map the high-magnification regions of these clusters with a total coverage of 88 arcmin^2.

The proposed survey is the logical next step after ongoing ALMA-HFF and cluster programs, based on successful ALMA detections of faint continuum sources and line emitter candidates in lensing clusters. In conjunction with the rich ACS/WFC3/IRAC data, we will determine the nature of faint submm galaxies and line emitters. Through the redshift distribution, SFR, stellar and ISM masses of sources that only ALMA can locate and study, we will probe the origin of the extragalactic background light, measure the [CII] luminosity functions near the Epoch of Reionization, and constrain the evolution of the molecular gas mass density up to the peak epoch of cosmic star formation. We will also discover rare highly lensed objects for future follow-up with ALMA.

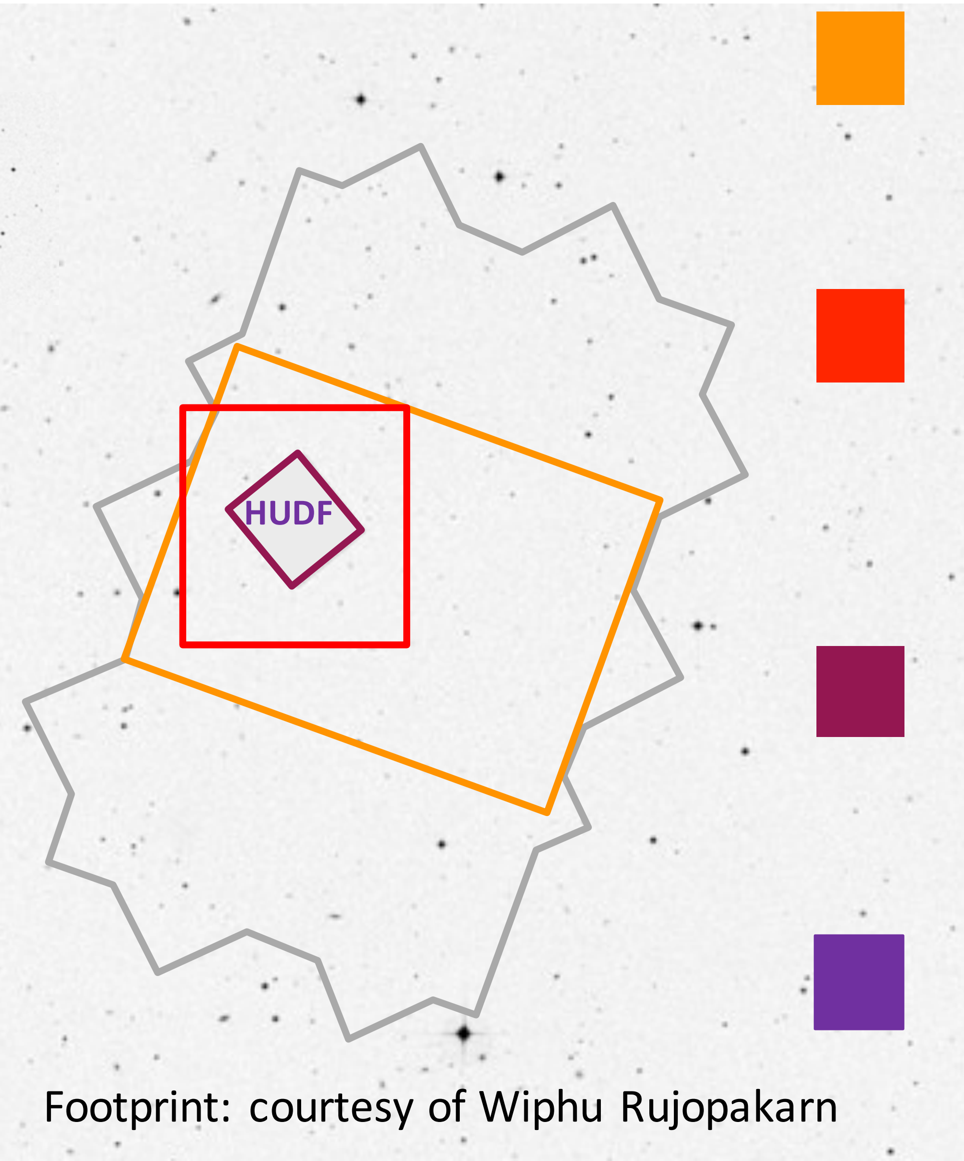
PI NAME:	Kotaro Kohno			**SCIENCE CATEGORY:**	Cosmology and the High Redshift Universe
ESTIMATED 12M TIME:	**95.5 h**	**ESTIMATED ACA TIME:**	**0.0 h**	**ESTIMATED NON-STANDARD MODE TIME (12-M):**	**0.0 h**
CO-PI NAME(S): (Large & VLBI Proposals only)	Franz Bauer; Marc Postman; Keiichi Umetsu; Jean-Paul Kneib; Masamune Oguri; Eiichi Egami; Johan Richard; Masami Ouchi; Dan Coe				
CO-INVESTIGATOR NAME(S):	Leopoldo Infante; Richard Ellis; Seiji Fujimoto; Yoichi Tamura; Bunyo Hatsukade; Andrew Baker; Adi Zitrin; John Wu; Kirsten Knudsen; Ivan Oteo; Akio Inoue; Yoshiaki Taniguchi; Tohru Nagao; Frederic Boone; Min Yun; Grant Wilson; David Hughes; Karina Caputi; Alexandra Pope; Itziar Aretxaga; Tim Rawle; Alain Omont; Pablo Pérez-González; Miroslava Dessauges-Zavadsky; Tomoka Tosaki; Daniel Schaerer; Kazuhiro Shimasaku; Yoshihiro Ueda; Ryohei Kawabe; Naoki Yoshida; Daisuke Iono; Yuichi Matsuda; Naomasa Nakai; Hideki Umehata; Tai Oshima; Tetsu Kitayama; Takuma Izumi; Akio Taniguchi; Minju Lee; Yuki Yamaguchi; Tsuyoshi Ishida; Haruka Kusakabe; Nicole Czakon; Soh Ikarashi; Kouichiro Nakanishi; Wiphu Rujopakarn; Kentaro Motohara; Wei-Hao Wang; Daniel Espada; Shun Ishii; Ian Smail; Rob Ivison; James Simpson; Hiroyuki Hirashita; Shotaro Kikuchihara; Tao Wang; Yuri Nishimura; Neil Nagar; Yui Yamashita; Chien-Feng Lee; Nicolas Laporte; Jean-Baptiste Jolly; Natsuki Hayatsu; Jorge González López; Yiping Ao; Yuki Yoshimura; Shinsuke Uno; Brett Salmon; Larry Bradley; Pascal Oesch; Yoshinobu Fudamoto				





ALMA deep surveys in HUDF/GOODS-S

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

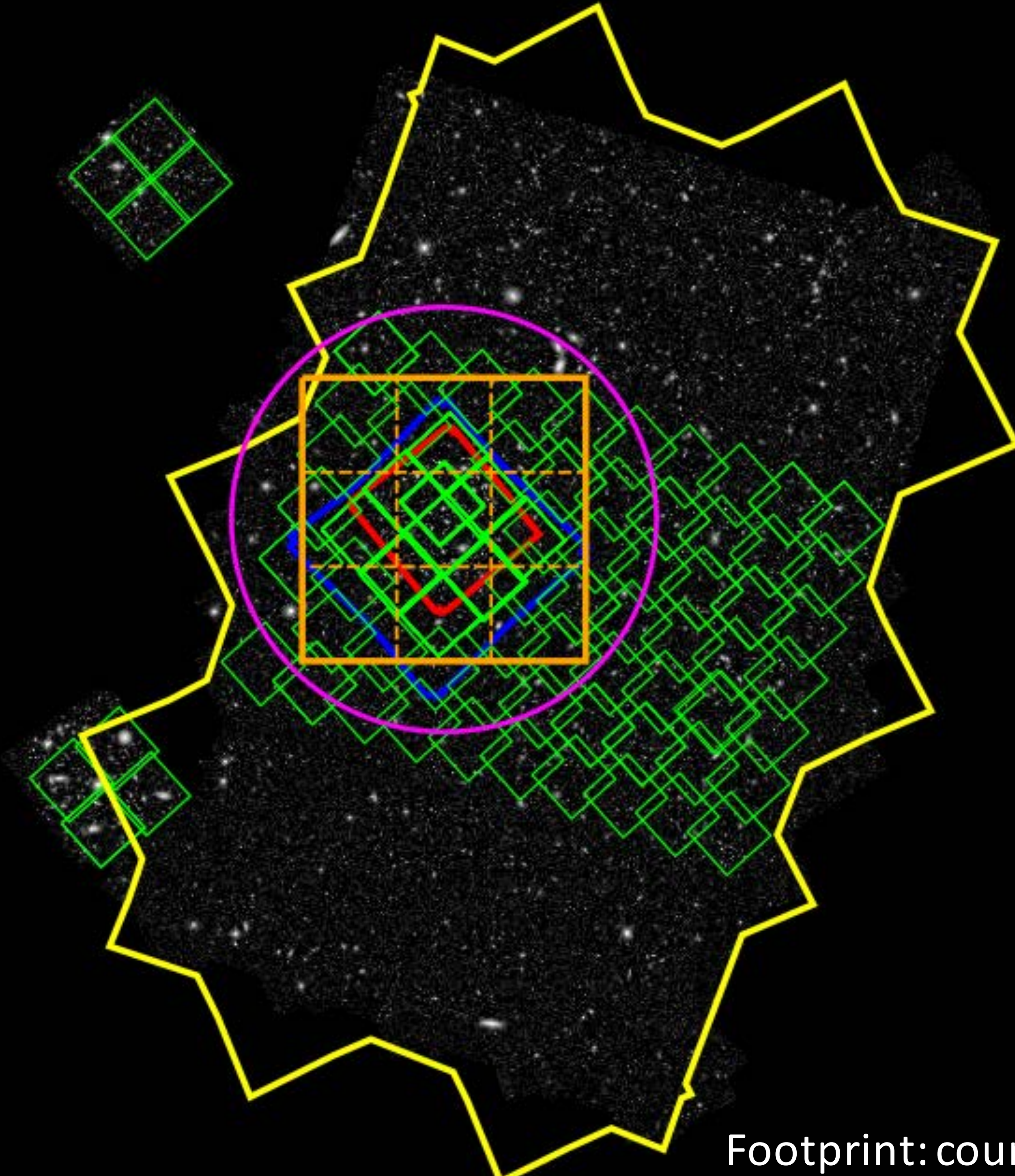
26 arcmin^2, 2 tuning (262 GHz + 253 GHz)
1σ = 60 μJy/beam

HUDF ALMA – PI: J. Dunlop

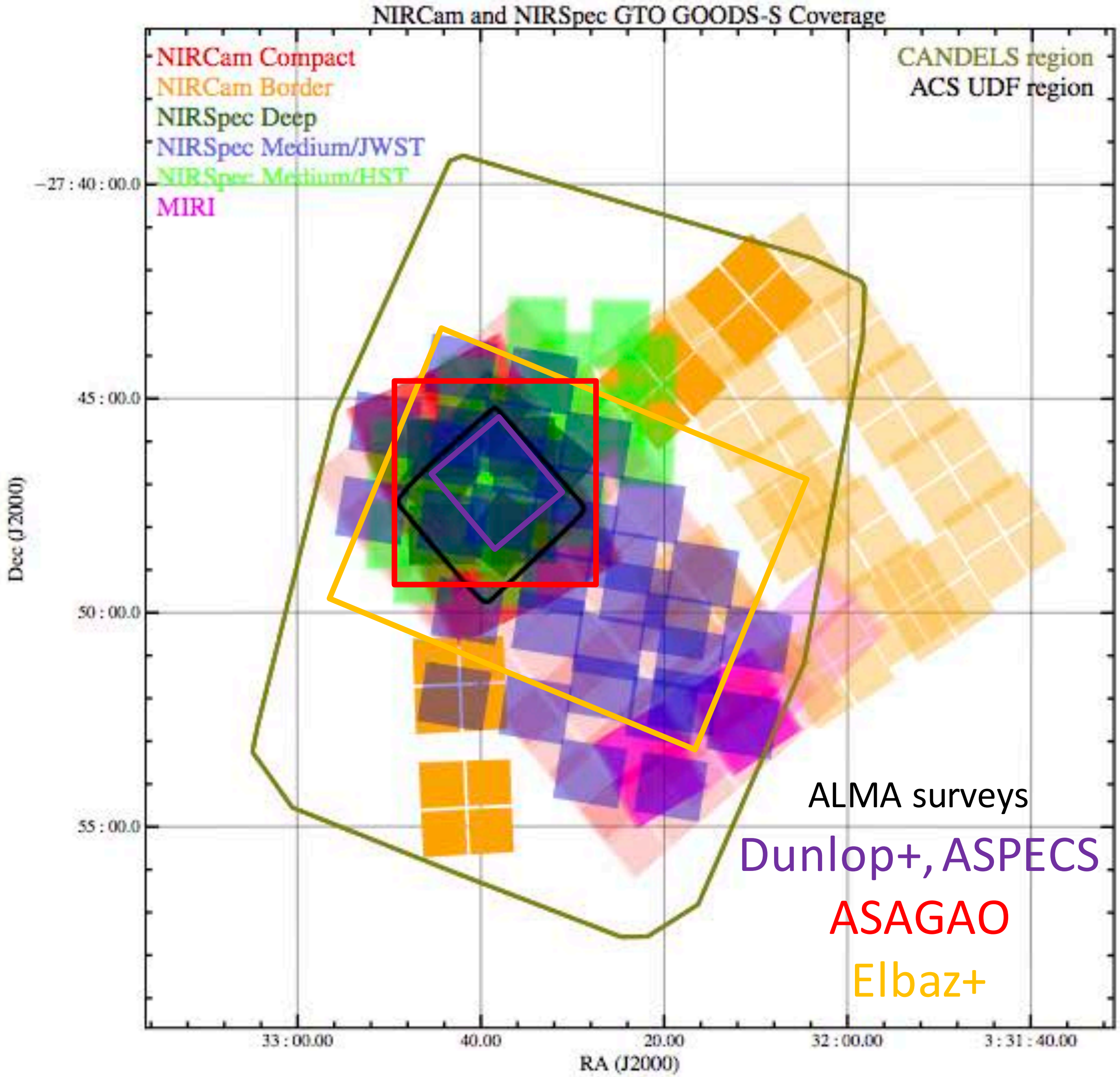
4.5 arcmin^2, 1 tuning (220 GHz)
1σ = 29 μJy/beam

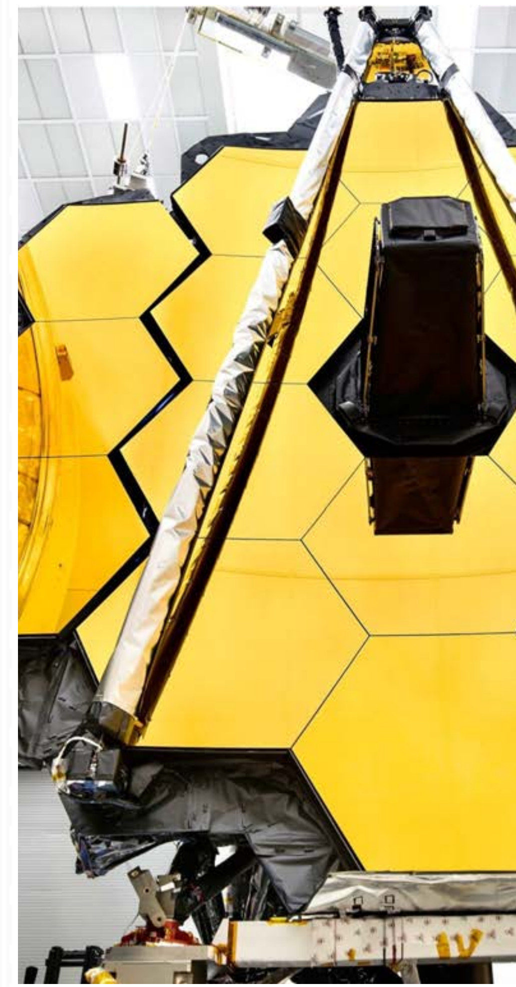
HUDF ASPECS – PI: F. Walter

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



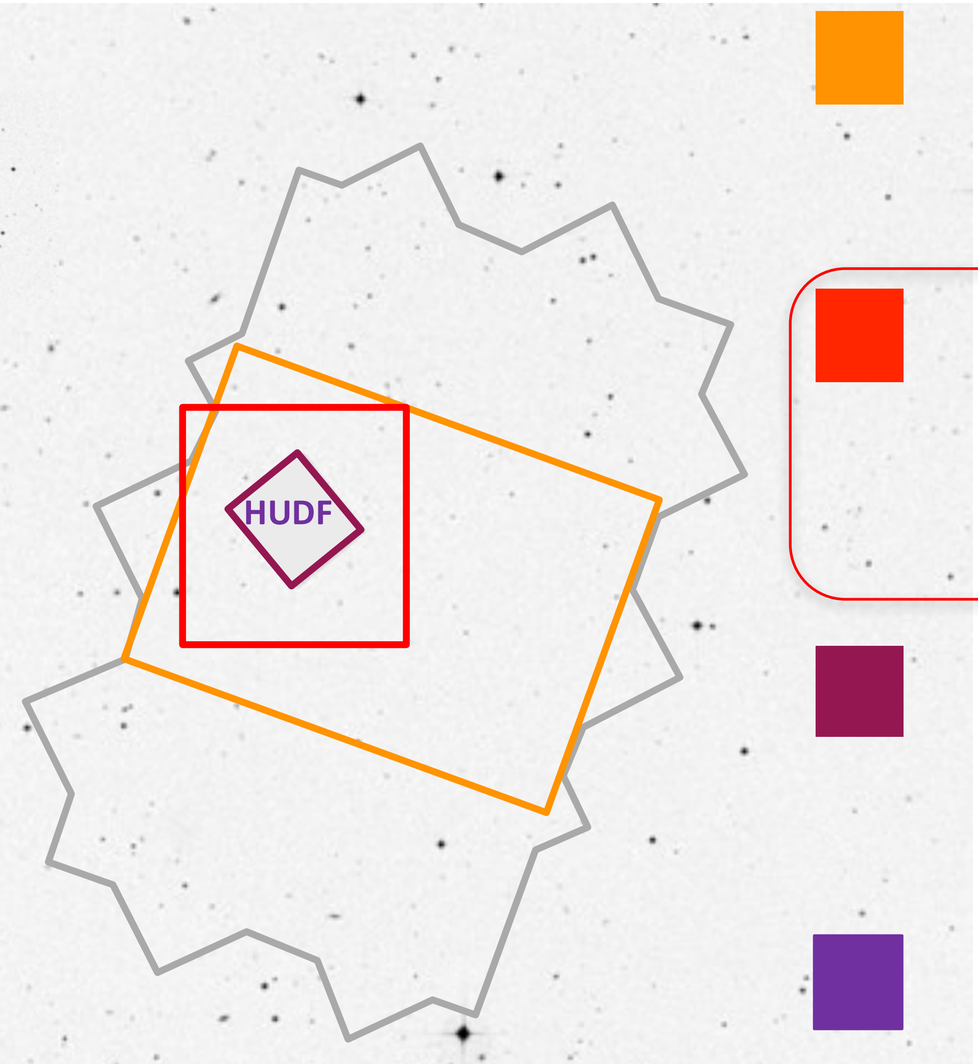
Footprint: courtesy of Wiphu Rujopakarn





https://jwst-docs.stsci.edu/display/JSP/JWST+GTO+Observation+Specifications

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



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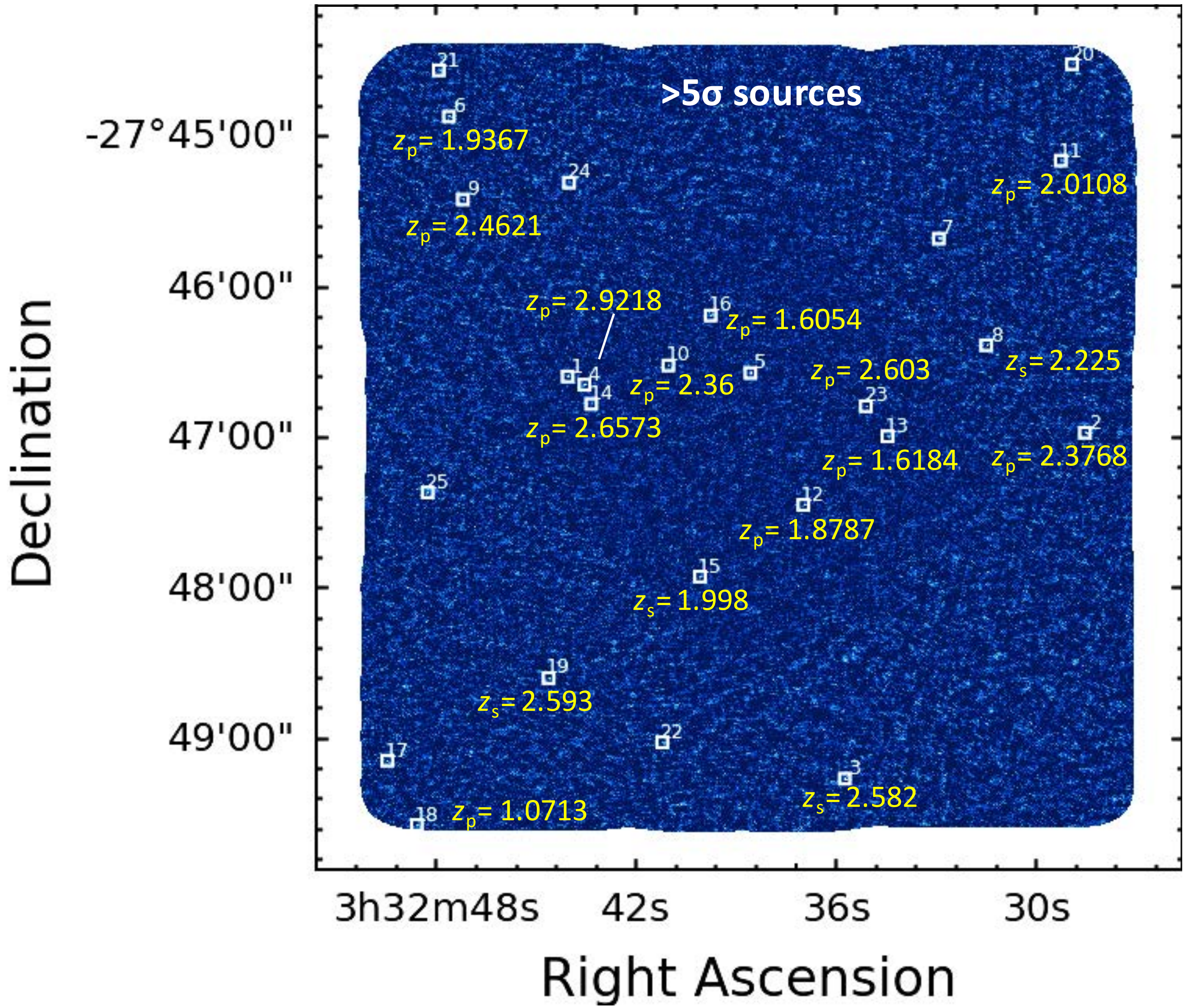
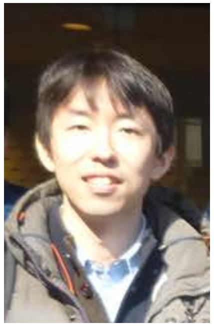
ALMA twenty-Six Arcmin^2 survey of Goods-south At One-millimetre (ASAGAO)

ASAGAO = Morning glory

Ueda, Hatsukade, KK, et al., 2018, ApJ, 853, id. 24 (X-ray AGN properties)
Fujimoto S., Ouchi, M., KK, et al., ApJ, 861, id. 7 (submm source sizes)
Hatsukade, KK, et al., 2018, PASJ, in press. (source catalogue and number counts)
Yamaguchi, KK, Hatsukade, Wang, T., Rujopakarn, et al., submitted to ApJ (multi-wavelengths IDs)
… more to come! e.g., Joint analysis with rest-frame optical line emitters (Kodama+)

ASAGAO+Dunlop+Elbaz (250kλ taper) (ASAGAO area)

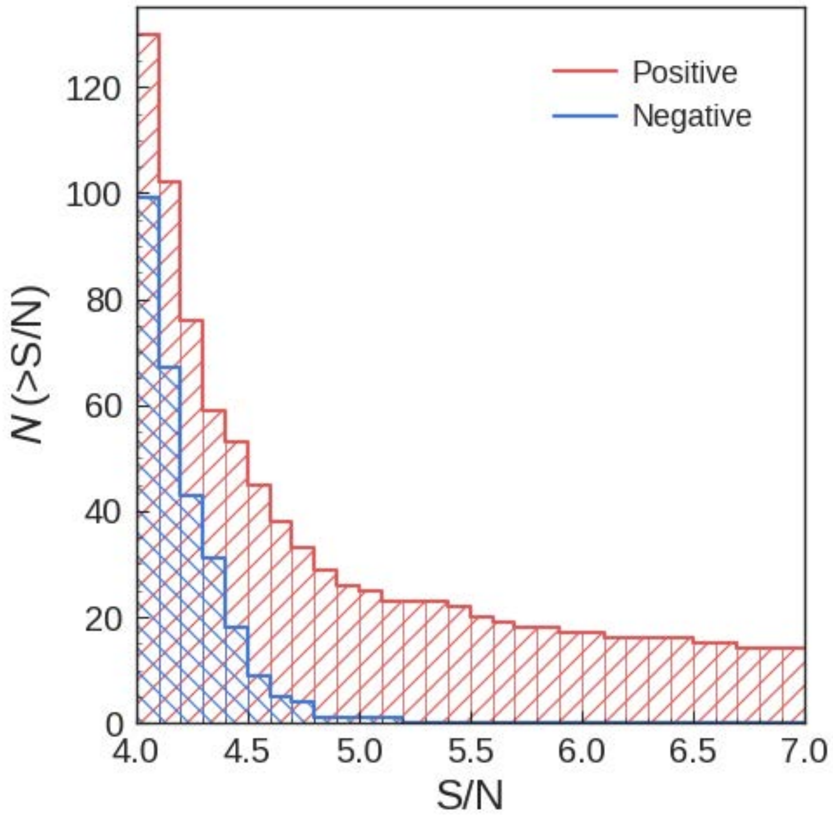




Hatsukade, B., et al., 2018 PASJ, in press.

ASAGAO+Dunlop+Elbaz (250kλ taper) (ASAGAO area)

- Positive detection
  - 25 (S/N ≥ 5.0)
  - 45 (S/N ≥ 4.5)
- Negative detection
  - 1 (S/N ≥ 5.0)
  - 9 (S/N ≥ 4.5)

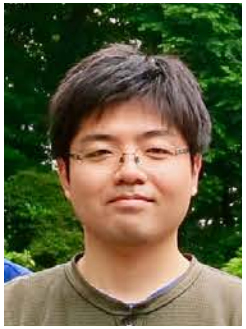


- ≥5σ continuum sources

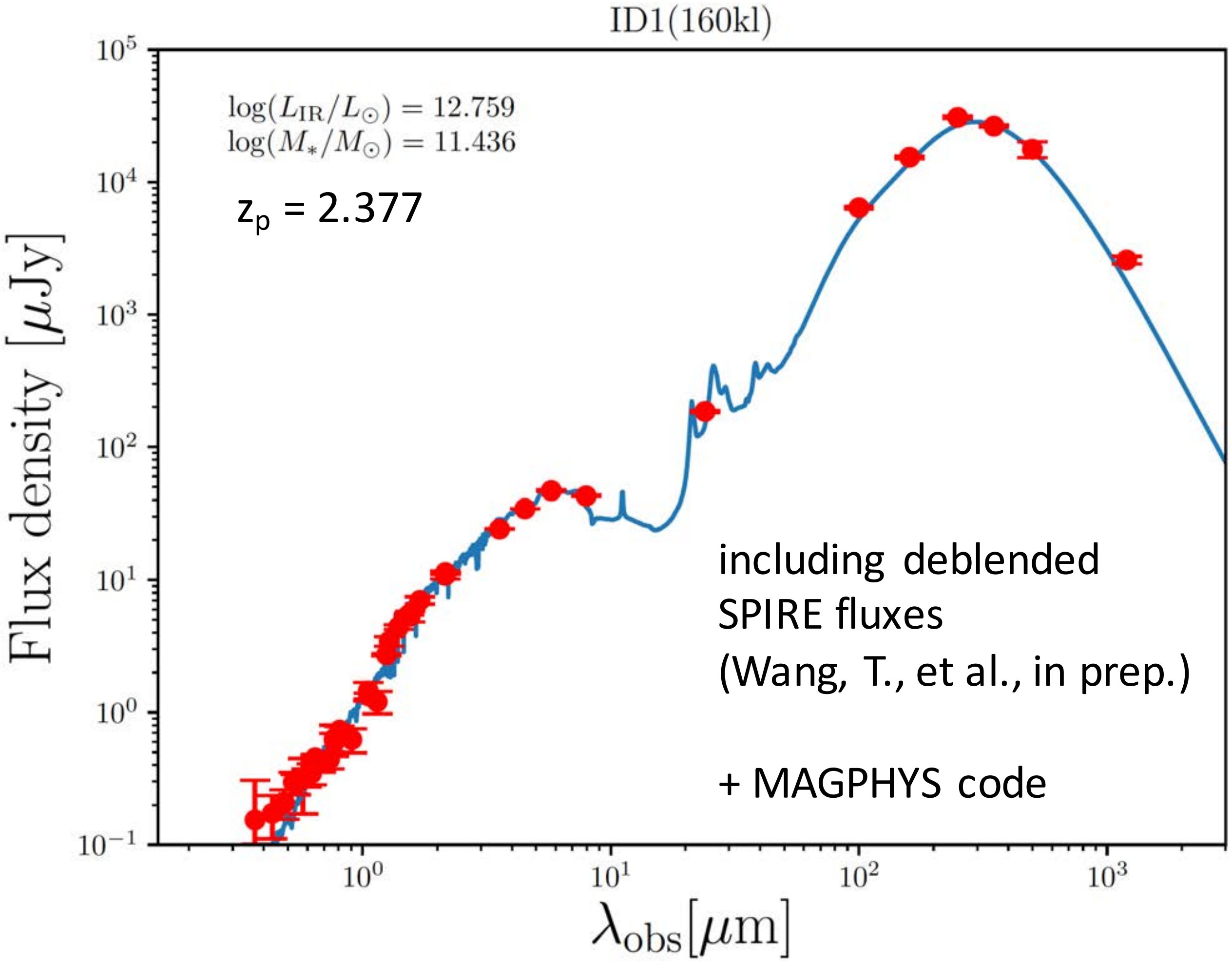
ASAGAO	SXDS	ASPECS	HUDF
25	5	5	5

Hatsukade, B., et al., 2018
PASJ, in press.

SED analysis of ASAGAO sources

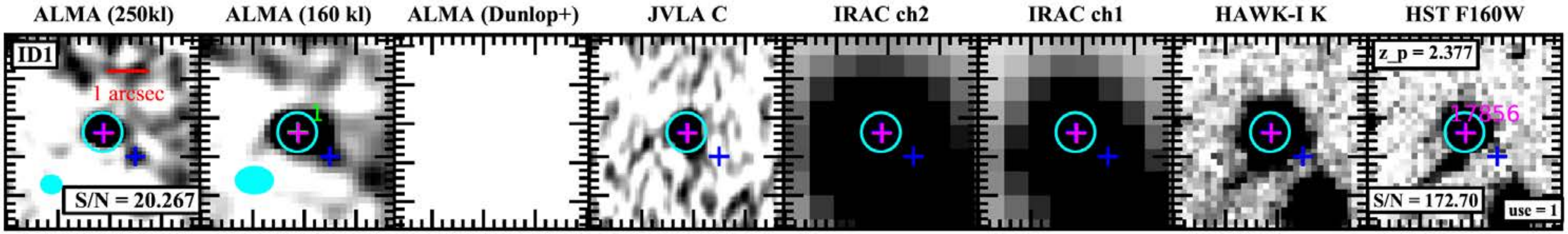


Yamaguchi, Y., KK, et al., submitted to ApJ



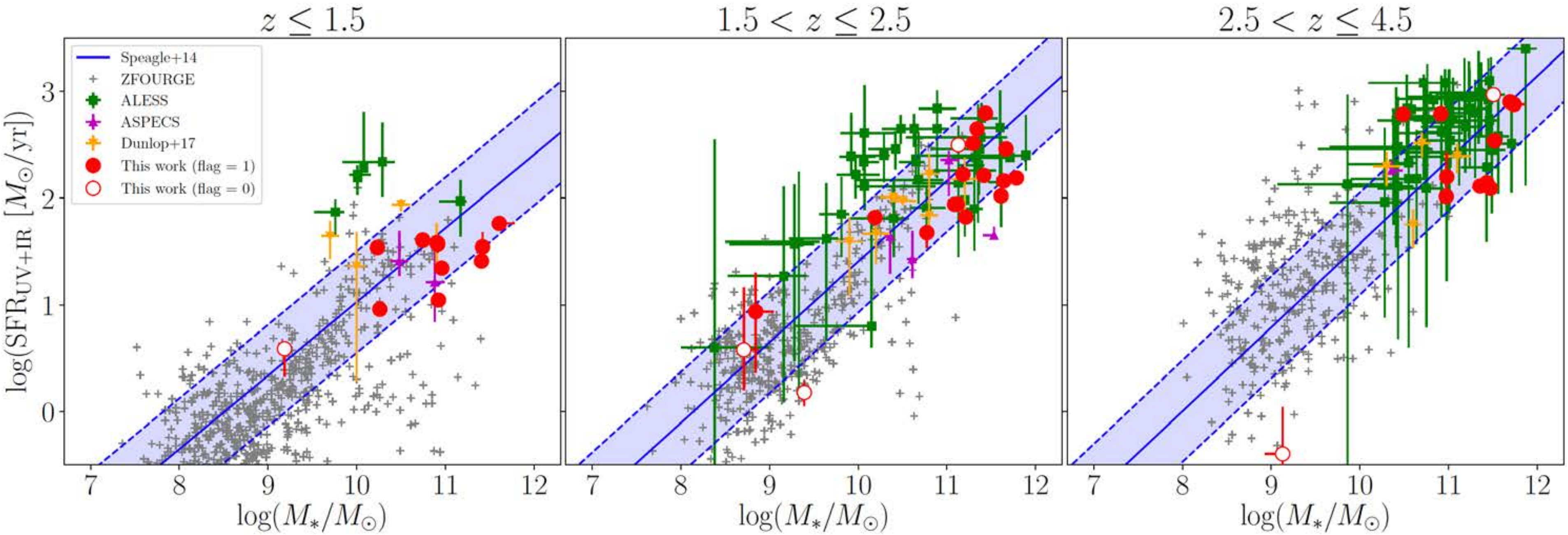
including deblended SPIRE fluxes (Wang, T., et al., in prep.)

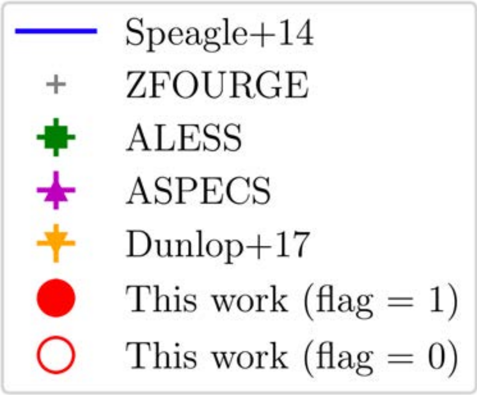
+ MAGPHYS code



ASAGAO sources are mostly on the main sequence at z = 1 - 4

with K-band counterpart

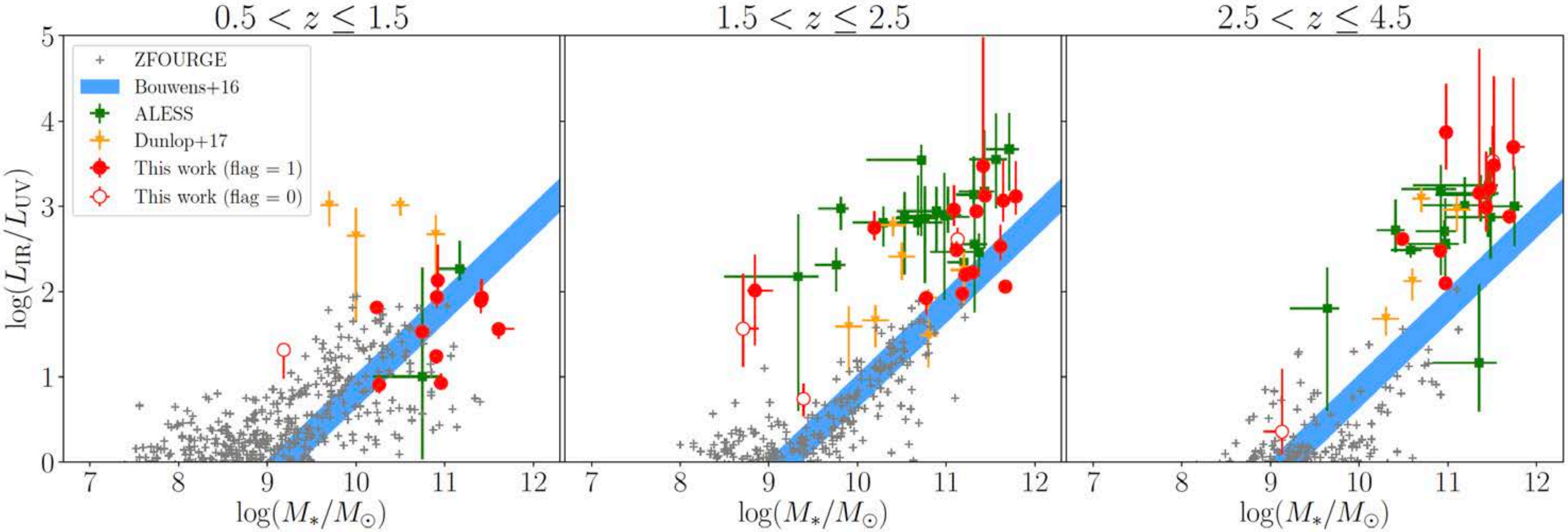




Stellar mass vs SFR

Yamaguchi, Y., KK, et al., submitted to ApJ

IRX = L_{IR}/L_{UV} vs stellar mass

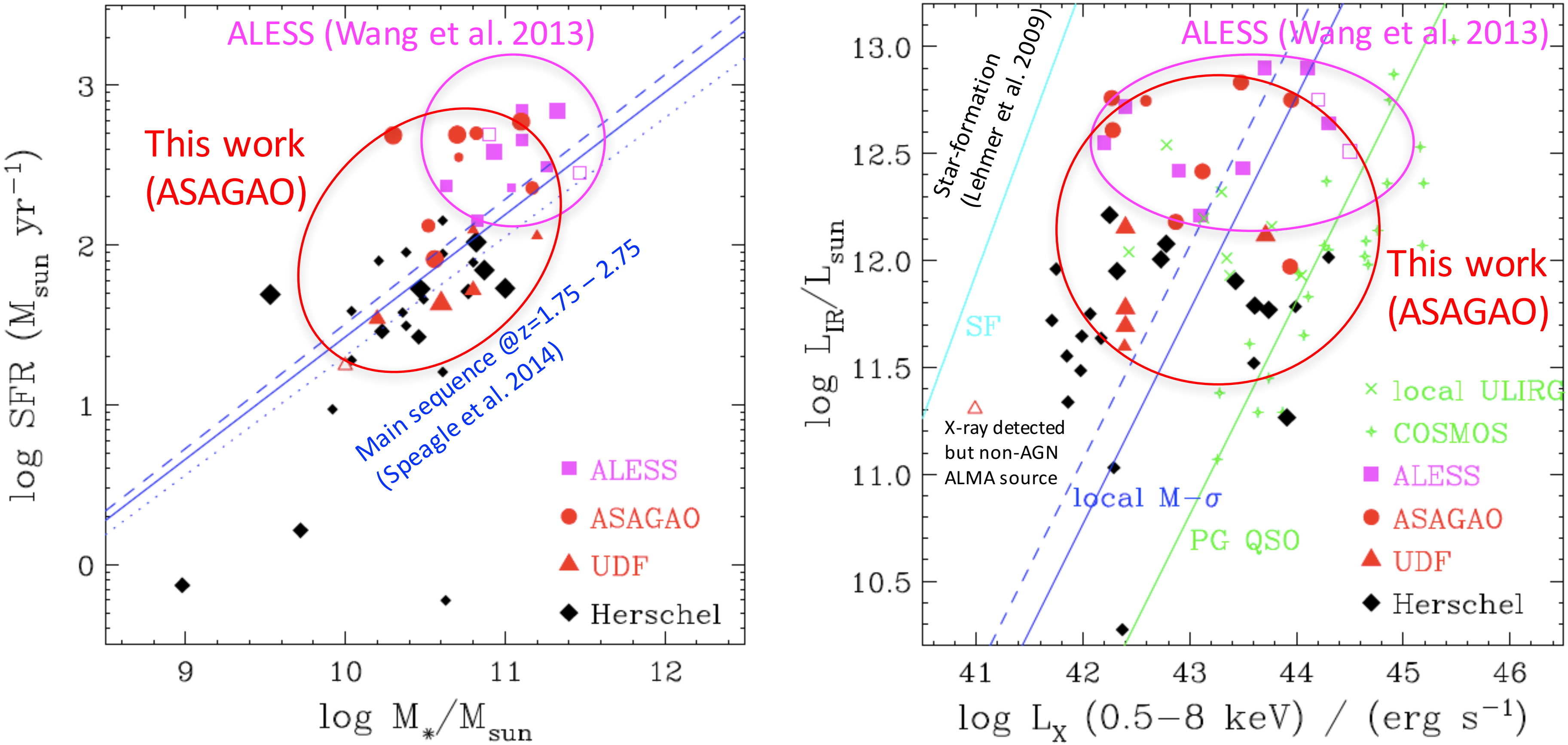


Yamaguchi, Y., KK, et al., submitted to ApJ

- ALMA detected sources show systematic offsets from IRX-$M_\star$ relation of UV-selected sources obtained by Bouwens+16 (especially z > 1.5)

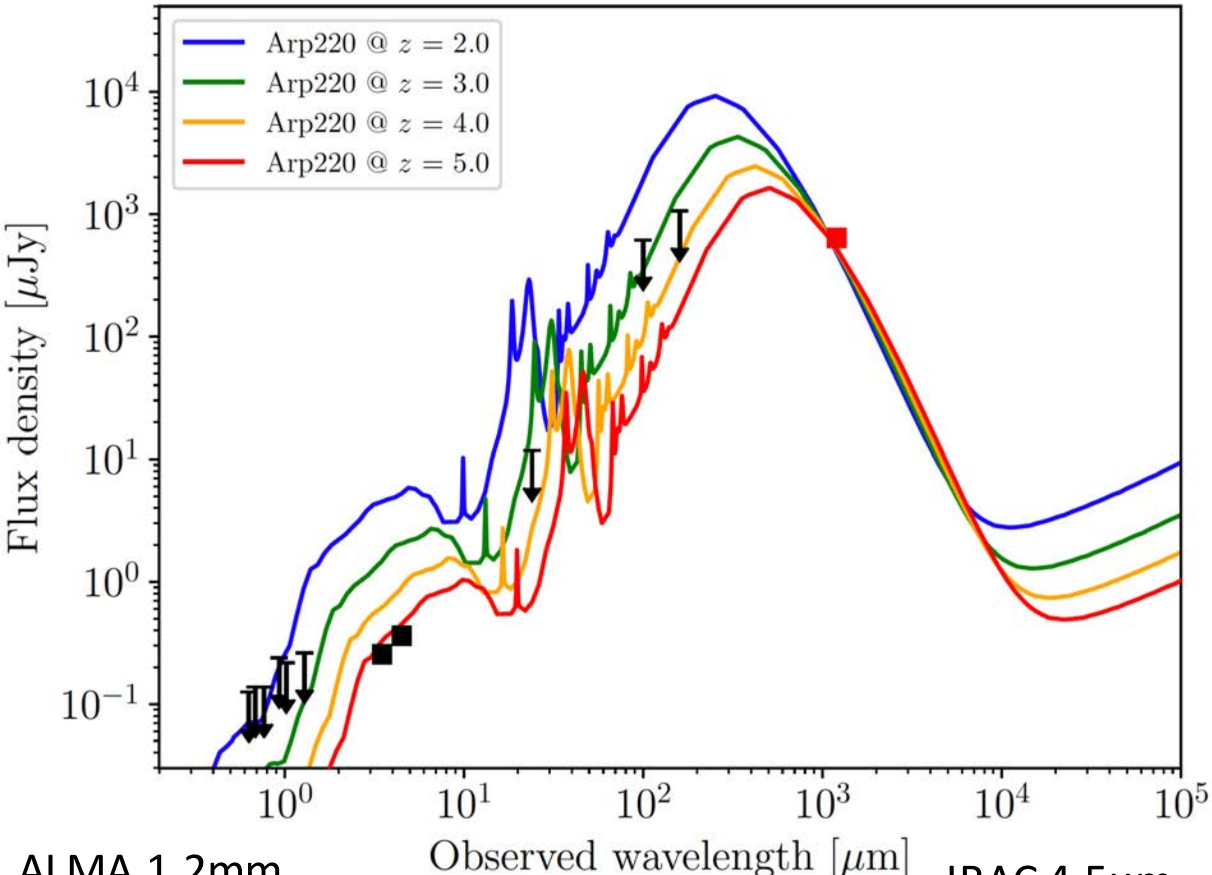
X-ray AGNs in ASAGAO (+ UDF) sources at z = 1.5 - 3

Ueda, Y., Hatsukade, B., KK, et al., 2018, ApJ, 853, id. 24



- Elevated AGN fraction at z = 1.5 – 3 ULIRG-class ALMA (ASAGAO) sources, up to 90^{+8}_{-19}% (!) 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?

A heavily obscured and/or high-redshift dusty starburst galaxy, which is invisible in WFC3, HAWK-I, and shorter wavebands?

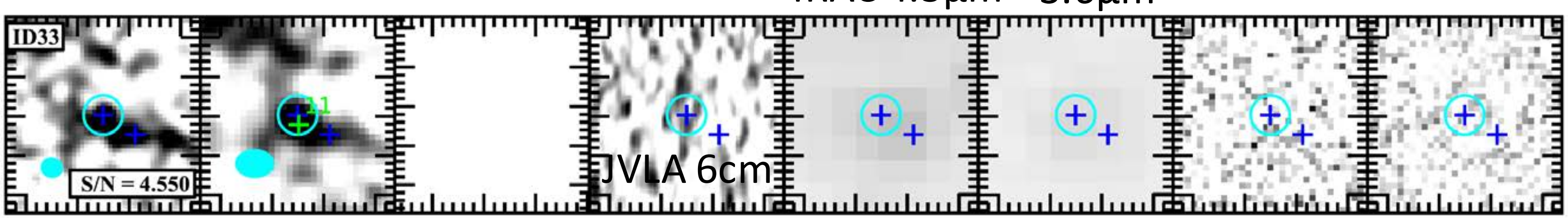


- Only an IRAC counterpart is visible !
- "K-Band dropout"

5 such sources in ASAGAO field to be followed up (ALMA cy6) by Bunyo Hatsukade

Yamaguchi, Y., KK, et al., submitted to ApJ

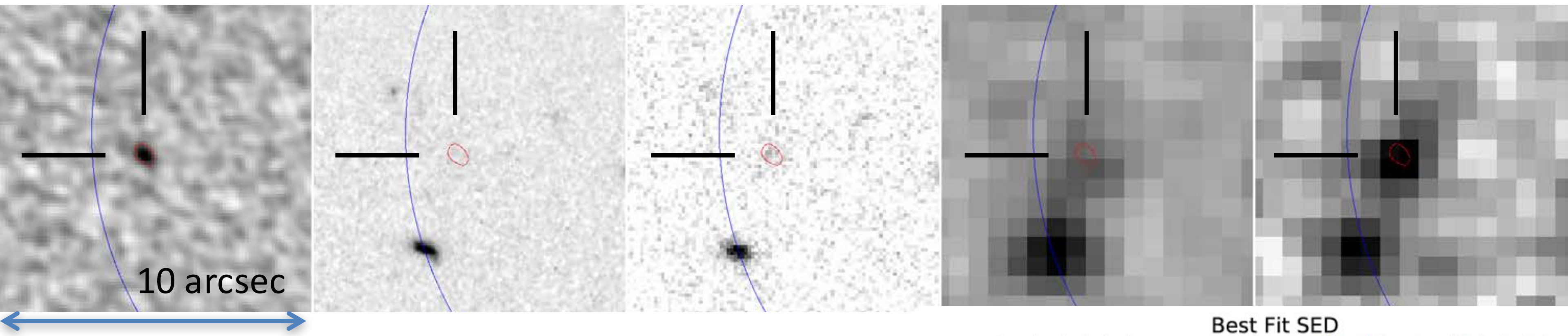
ALMA 1.2mm IRAC 4.5μm 3.6μm HAWK-I Ks-band WFC3 F160W



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

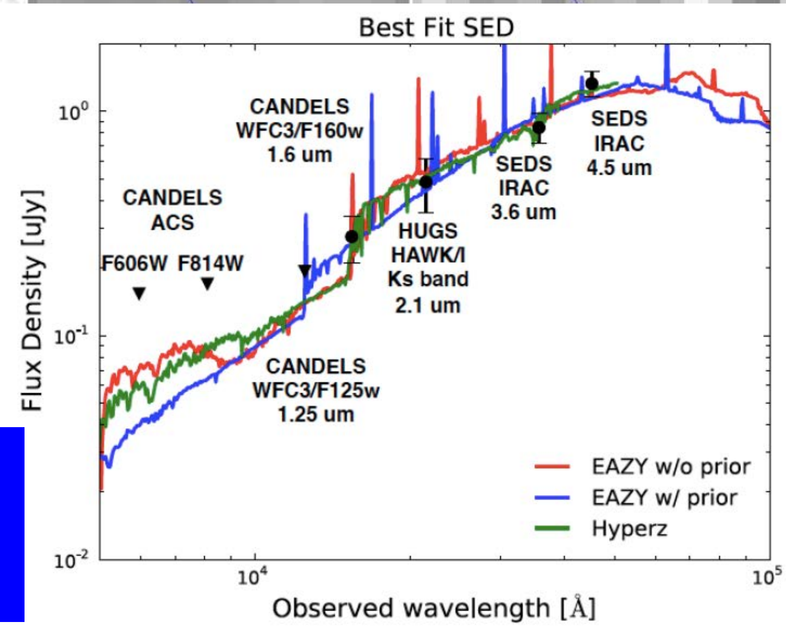
Kohno et al. 2016, IAUS, 319, 92 (arXiv:1601.00195)
Yamaguchi, Tamura, et al., 2016, PASJ, 68, 82

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)

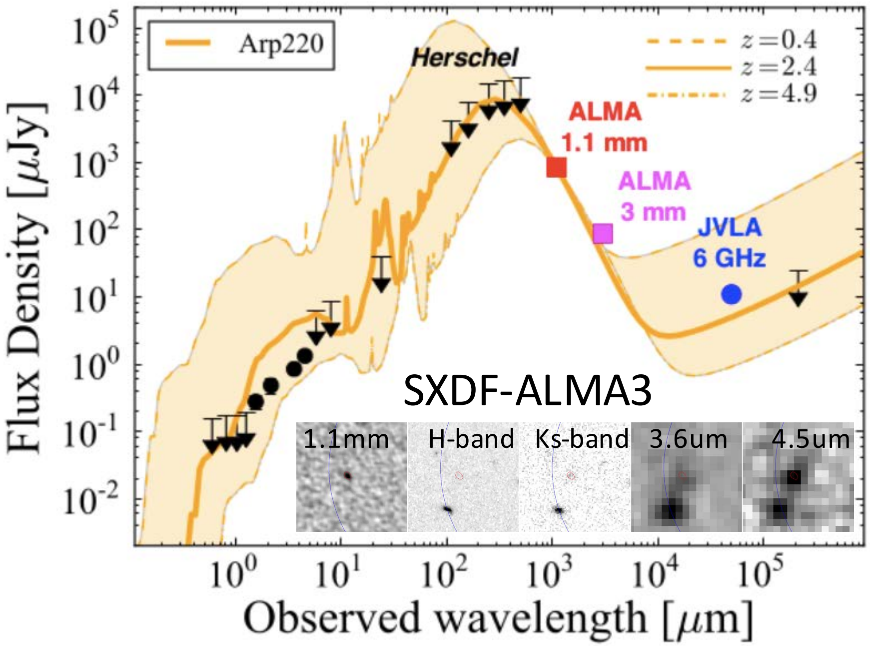
- One L(IR) = $(1^{+1}_{-0.7}) \times 10^{12} L_\odot$ galaxy in the survey volume (2 arcmin^2, z = 0.9 – 3.6)
- ➔ SFRD = (0.1 – 1) $\times 10^{-2}$ $M_\odot$/yr/Mpc^3
- ➔ 1 – 10% contribution to the IR SFRD??



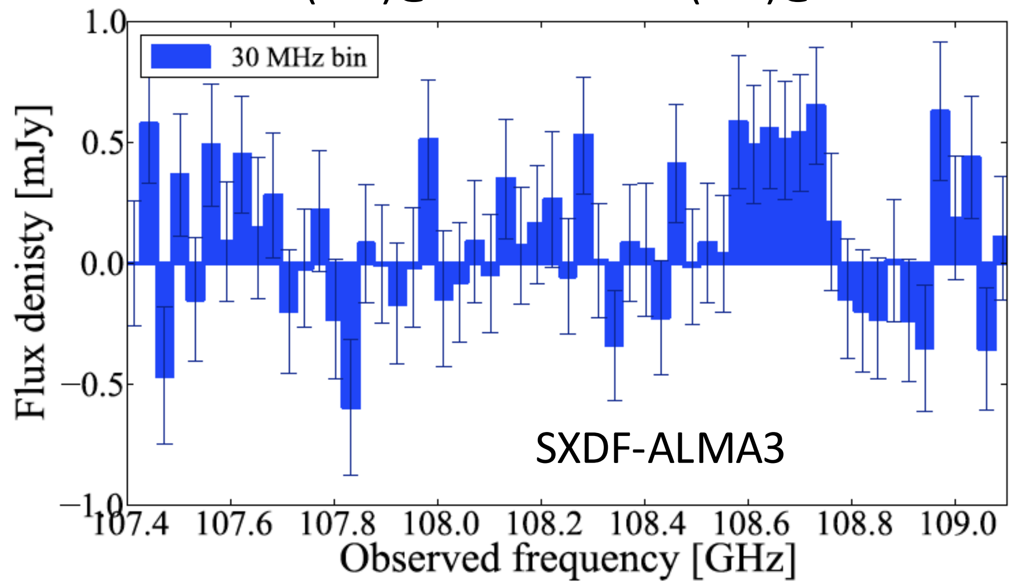
additional contributions to the SF history from faint submm galaxies, not fully overlapped with UV/optical-selected galaxies (e.g., Chen et al. 2014, ApJ, 789, 12)

H-dropout dusty high-z galaxies: Interesting, but not easy to follow up..

- Nothing can do in the optical/near-infrared??
- We can do ALMA spectral scans (targeting CO lines), though it is fairly expensive; [CII], [OIII] .. ??
- JWST and SPICA for mid-infrared spectroscopy using PAH features?
  - 3.3μm for JWST, 6.2μm, 7.7μm, etc. for SPICA



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

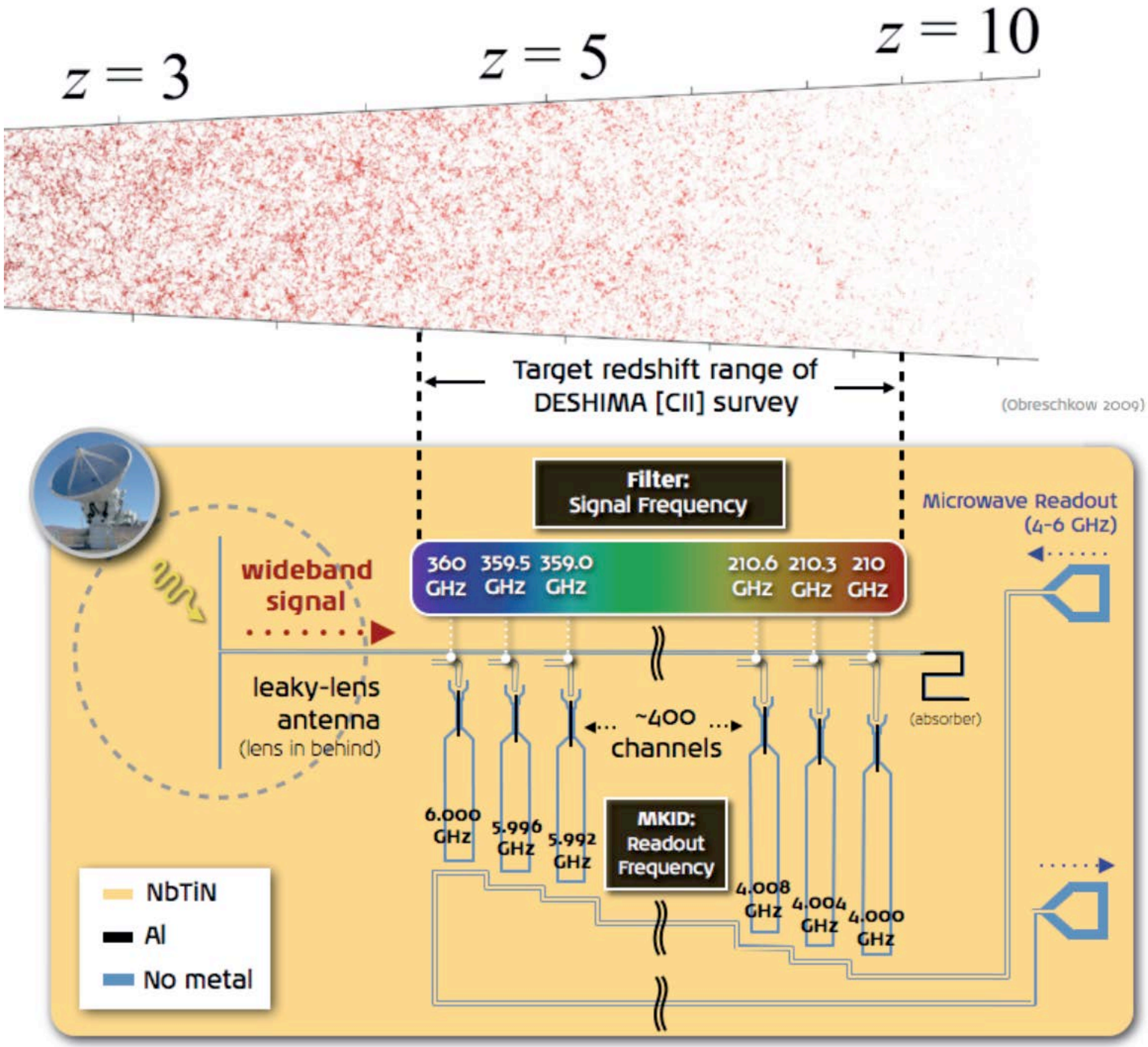


Yamaguchi, KK, et al., in prep.

Ultra-wideband Spectrograph on LMT 50m

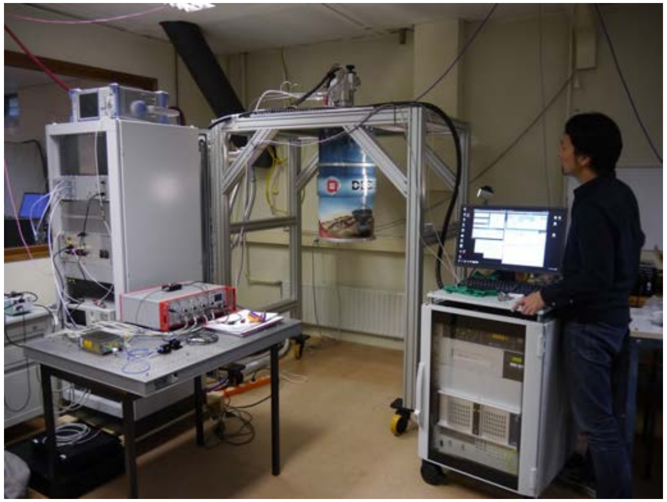
- Led by Netherlands (TU. Delft & SRON) and Japan (Nagoya Univ., NAOJ, Saitama U., & U. Tokyo) + LMT (INAOE+UMASS)
- Instantaneous frequency coverage: 185 – 365 GHz (covering 180 GHz width in one shot! ➔ [CII] z = 4.2 – 8.7)
- With a coarse resolution R = f/df ~500 (dv ~600 km/s)
- 5 x 5 = 25 spatial pixels
- The proposed target year of installation: 2020
- **Suited for follow-up of AzTEC, MUSCAT, & Toltec (and other bright submm) sources**
- 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

On-chip superconducting spectrograph DESHIMA (does already exist!)



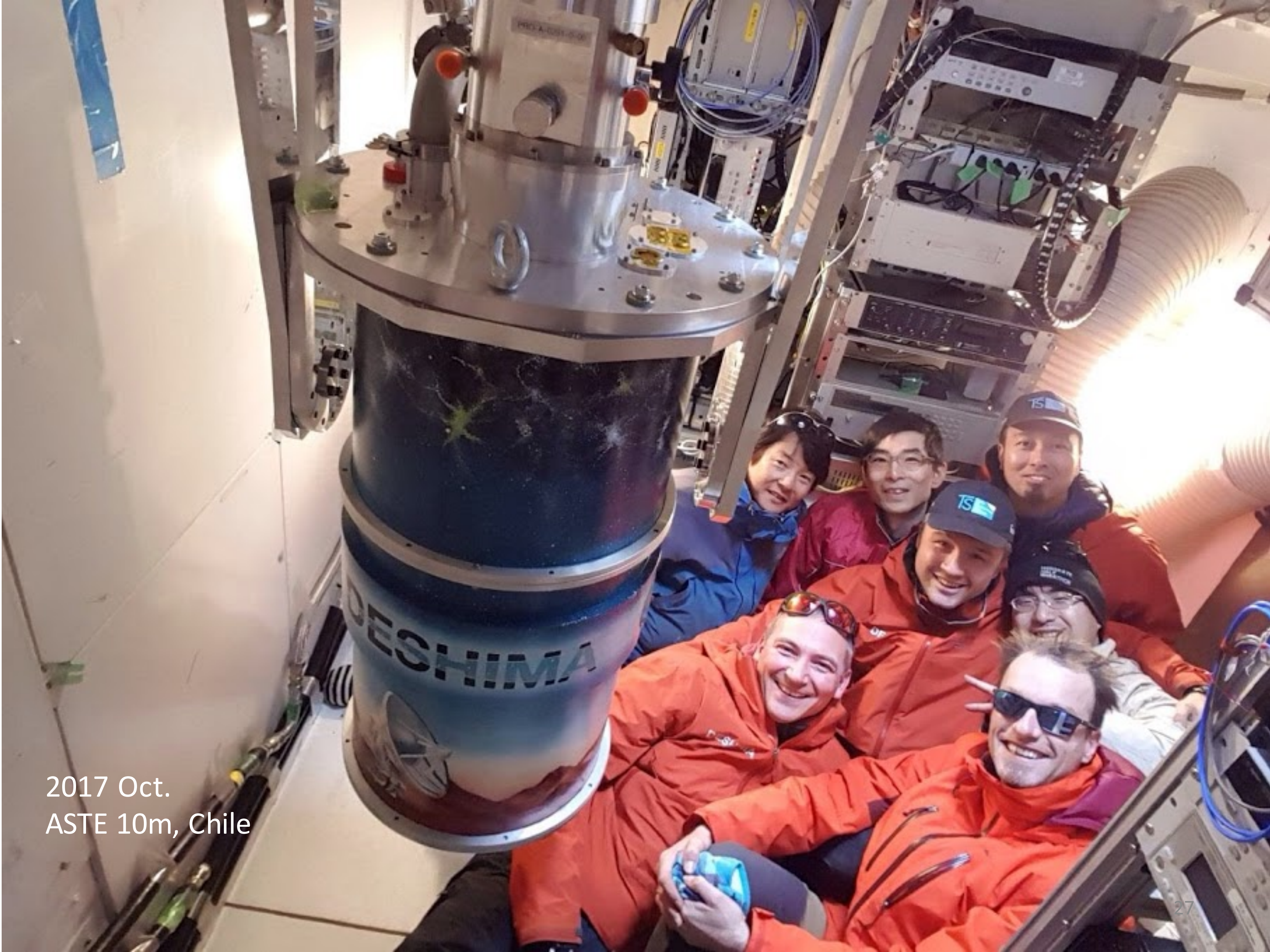
Endo et al. 2012, JLTP, 167, 341

Evaluation @TU Delft



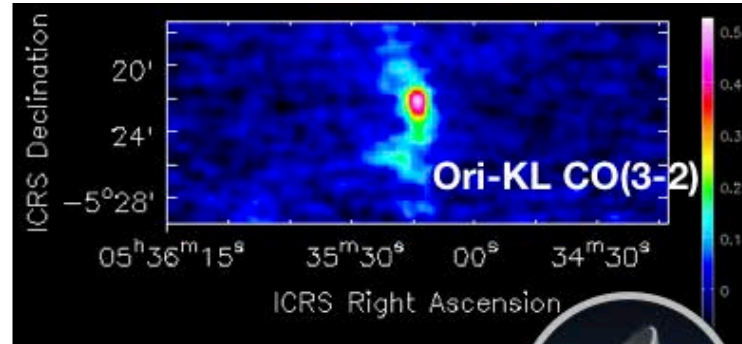
Small !! ➔ large format multi-beam


2017 Oct.
ASTE 10m, Chile
FMA
TRES PUNTOS DE APOYO
CAPACITY:320 kg

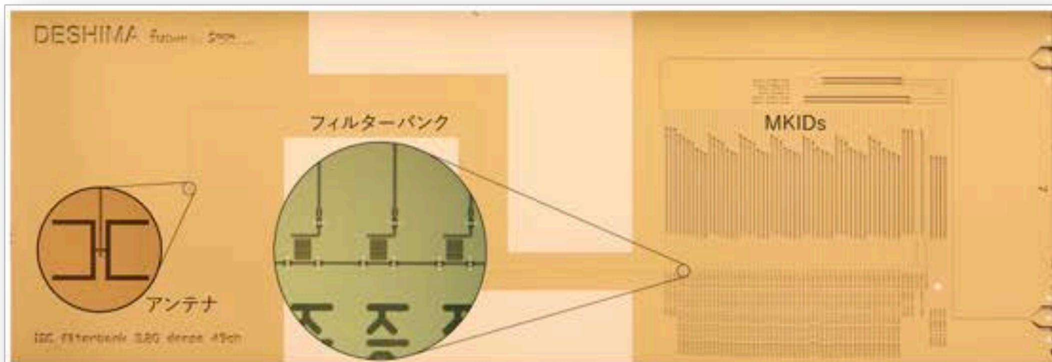


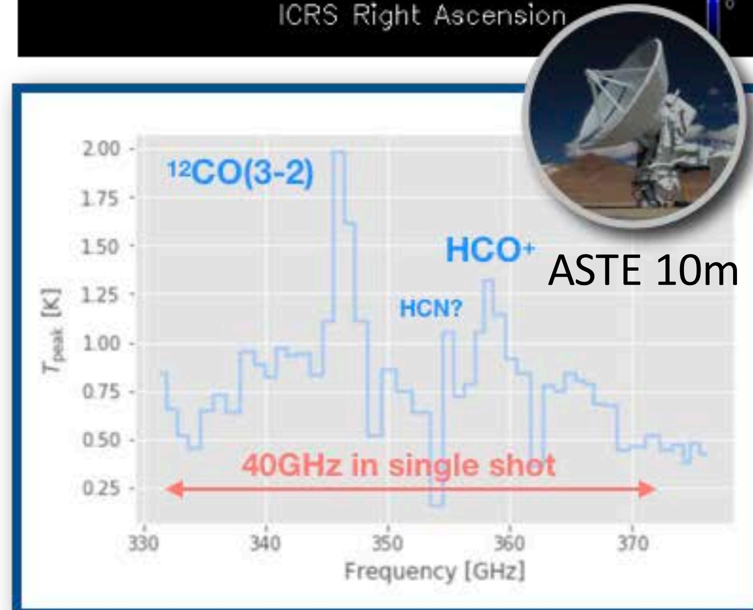
2017 Oct.
ASTE 10m, Chile

The first proof of concept: on-chip super-conducting filter-bank array DESHIMA on ASTE 10m

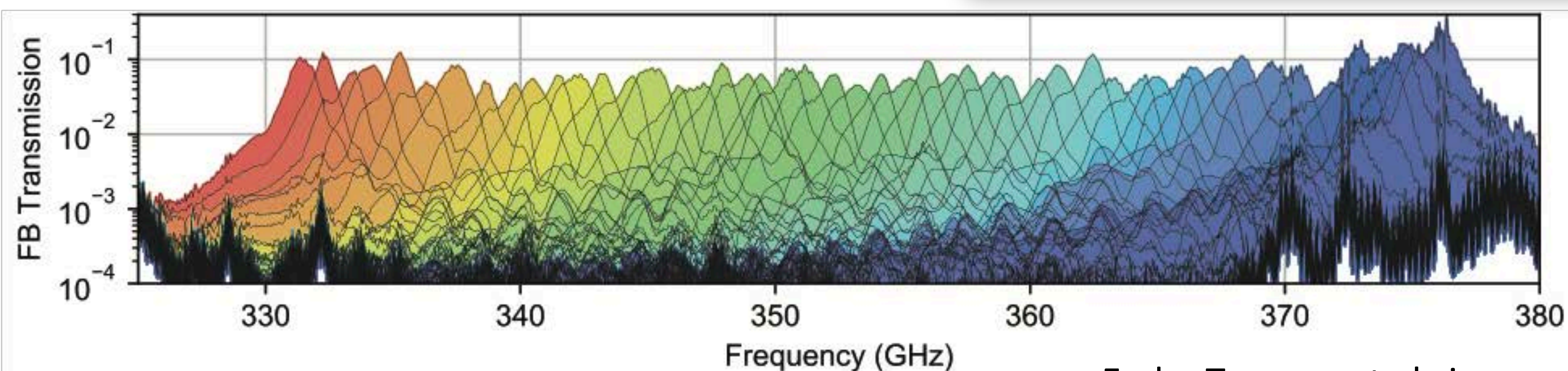


November 2017, Atacama, Chile



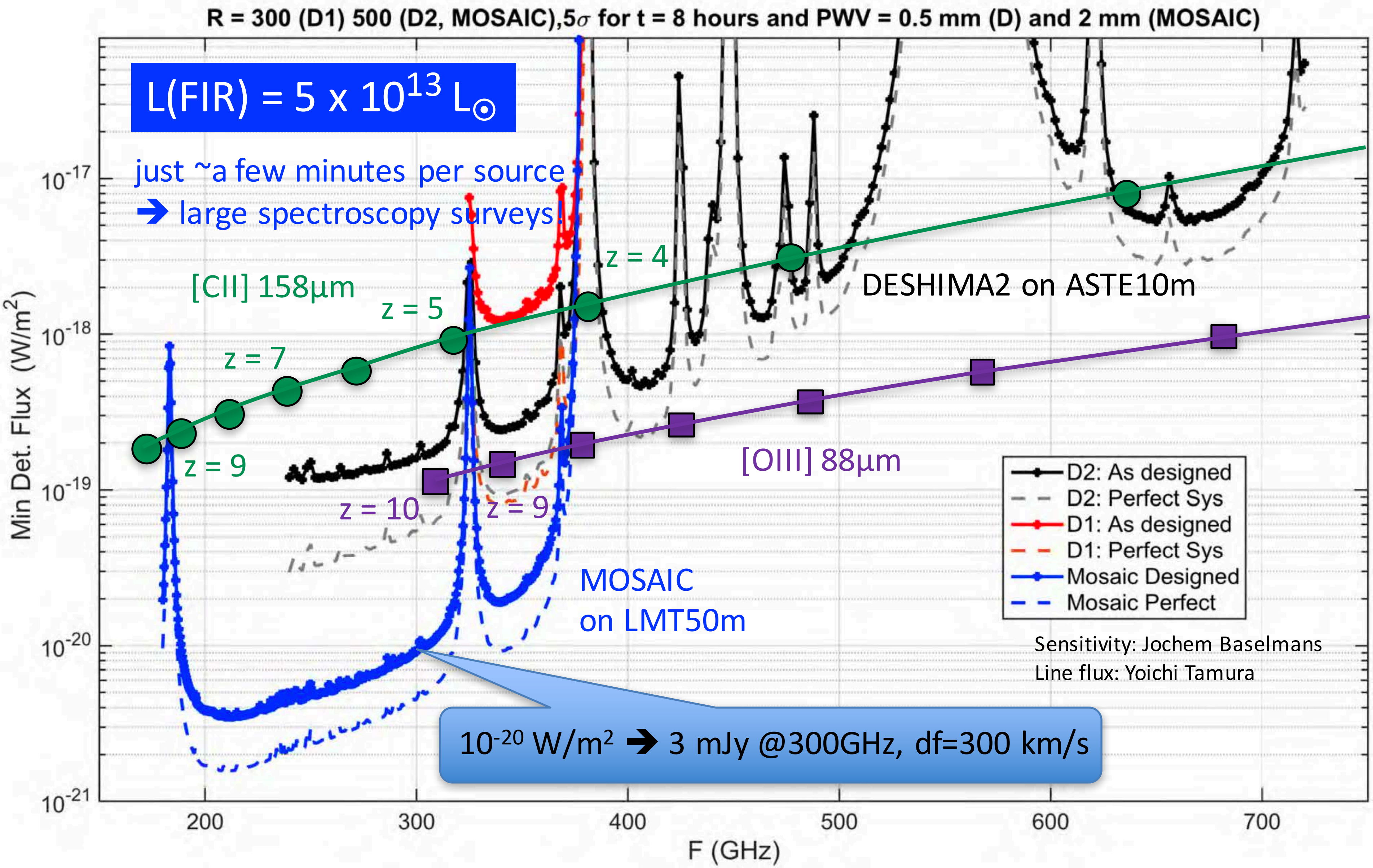


ASTE 10m



Endo, Tamura, et al., in prep.

Detectability of fine structure lines



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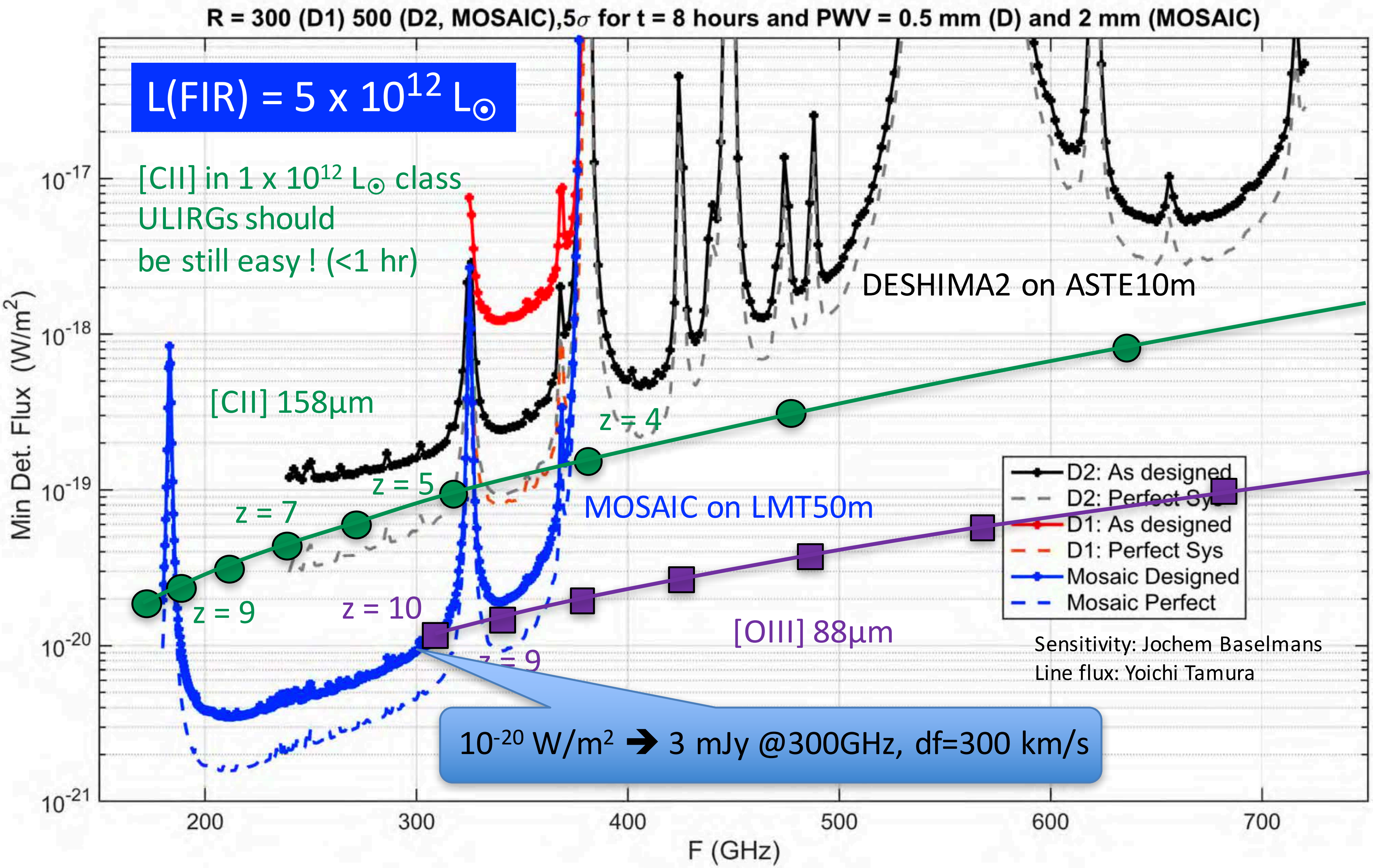

Summary

- Roles of dusty star-formation are still not yet understood especially for z>3 Universe
- ALMA deep surveys in GOODS-S/HUDF
  - ASAGAO: 26 $arcmin^2$ survey with a depth of 60 μJy
  - Capturing obscured (high IRX) star-forming activities on typical star-forming galaxies ("main-sequence galaxies") at each epoch
  - Co-growth of super massive black holes among these dusty star-forming main-sequence galaxies
  - ALMA starts to capture very dusty high-z population, which is invisible in the existing rest-UV/optical deep surveys
- ALMA Lensing Cluster Survey (cycle 6, large program)
- How to spectroscopically follow-up such dusty galaxies
  - Synergy with JWST and SPICA
  - crucial to study the early dust production
  - Ultra-wideband imaging spectrograph DESHIMA/MOSAIC on LMT 50m ➔ large spectroscopic surveys of dusty galaxies