Obscured Star Formation in the Distant Universe Probed by Radio Observations

― ミリ波・サブミリ波ディープサーベイで見えてきた遠方銀河の性質 ―

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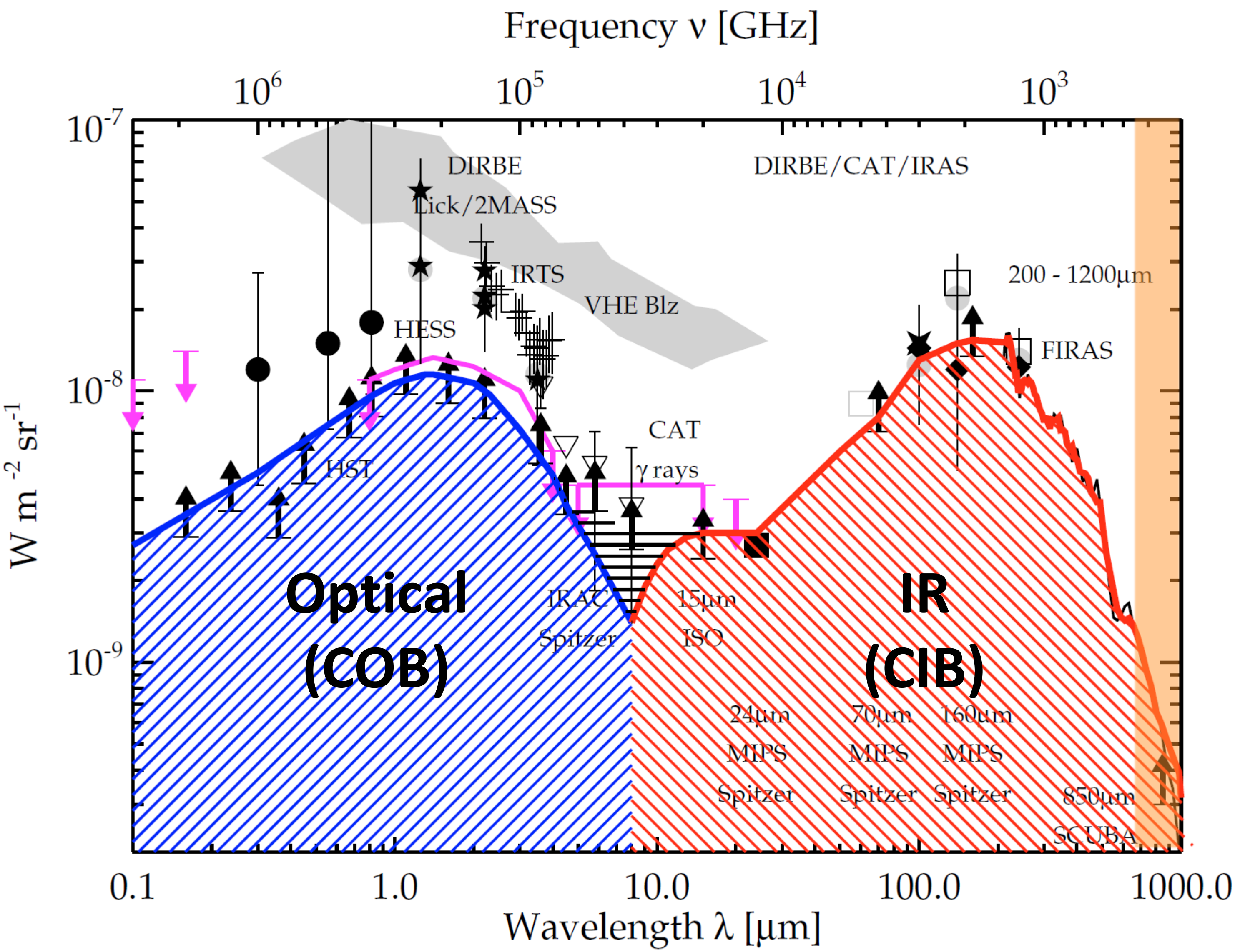
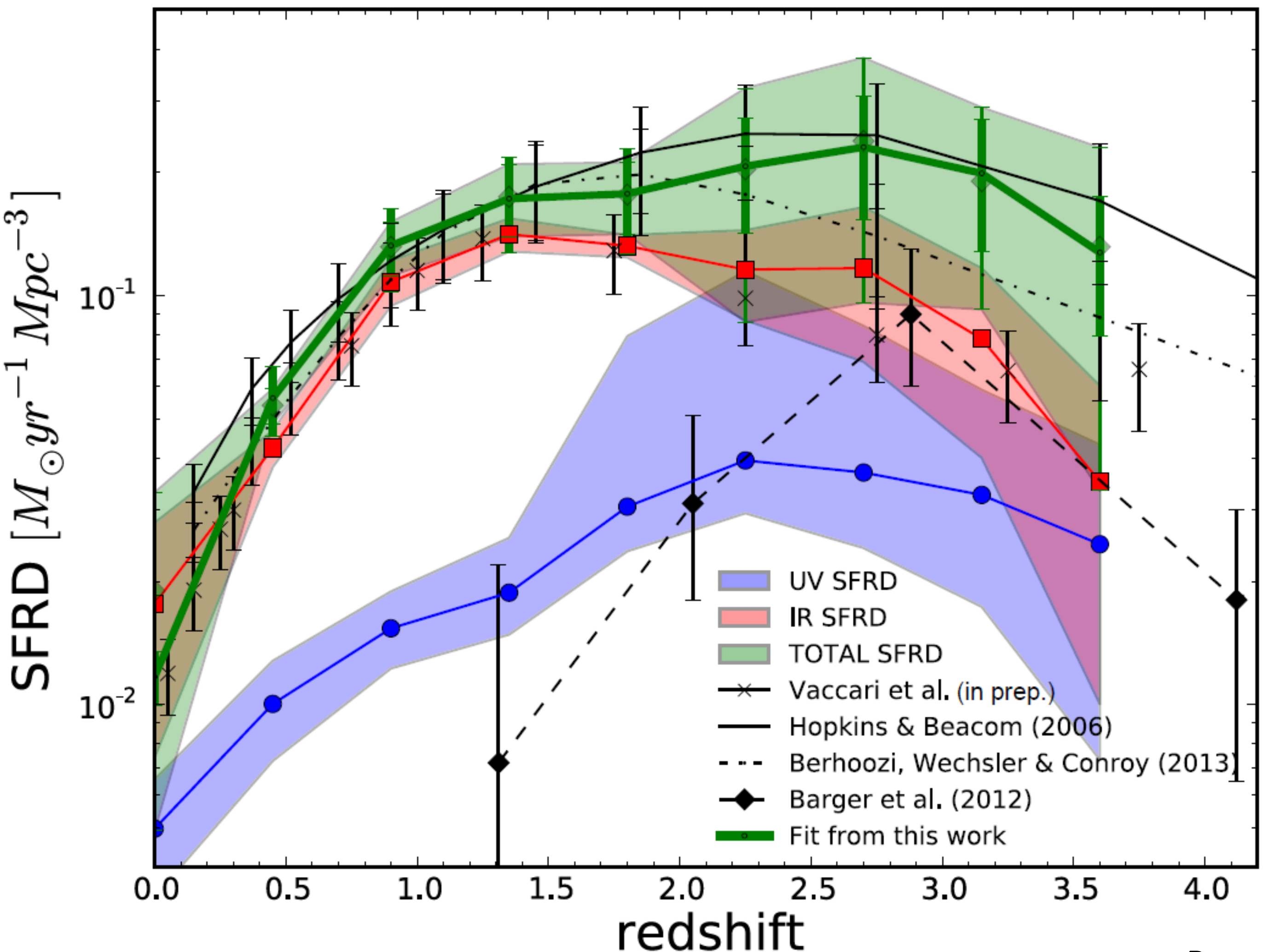
初代星・初代銀河研究会2017@呉 2018/02/10-12

Extragalactic Background Light (EBL)



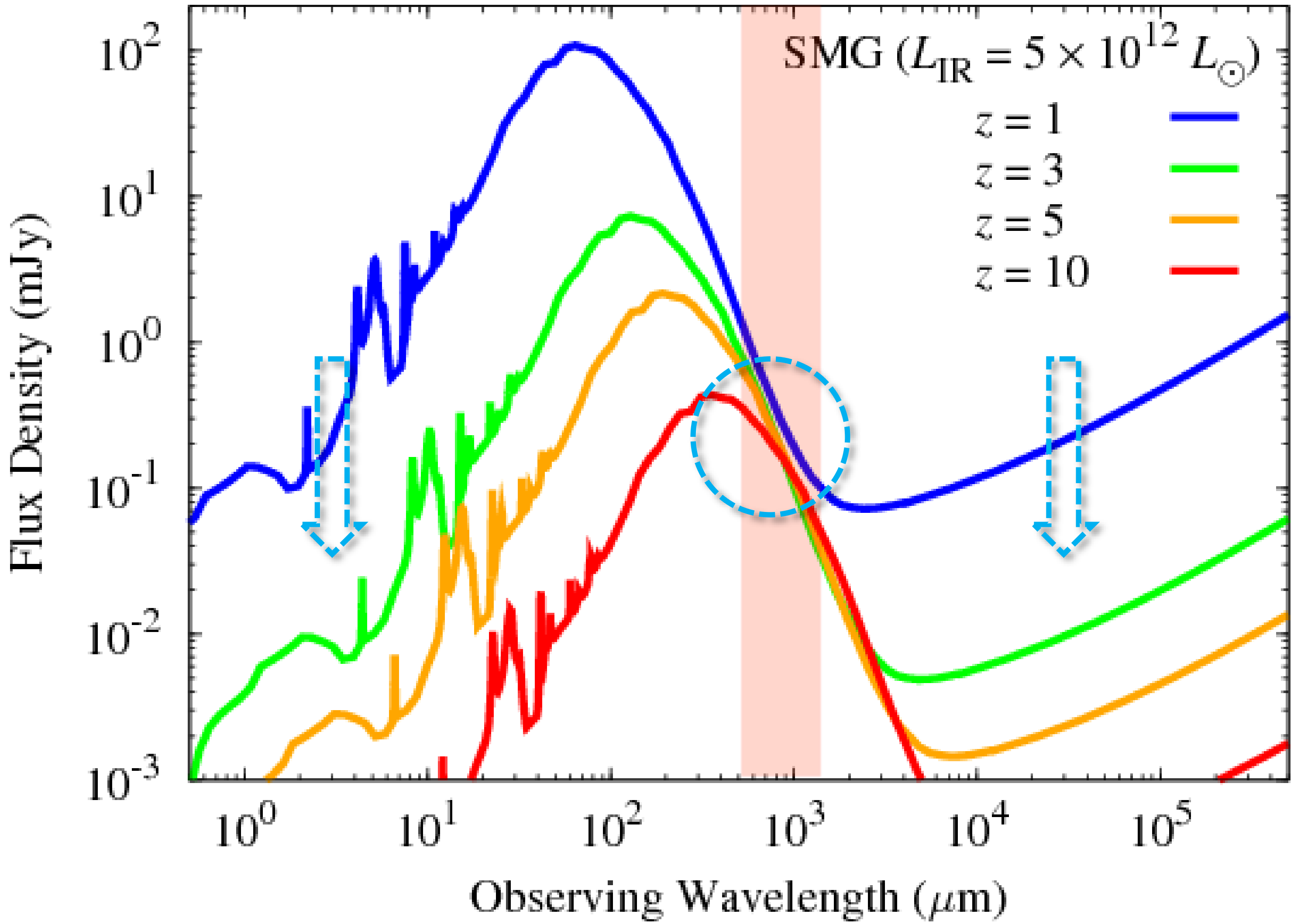
Dole+06

Obscured Star-formation Activity



Burgarella+13

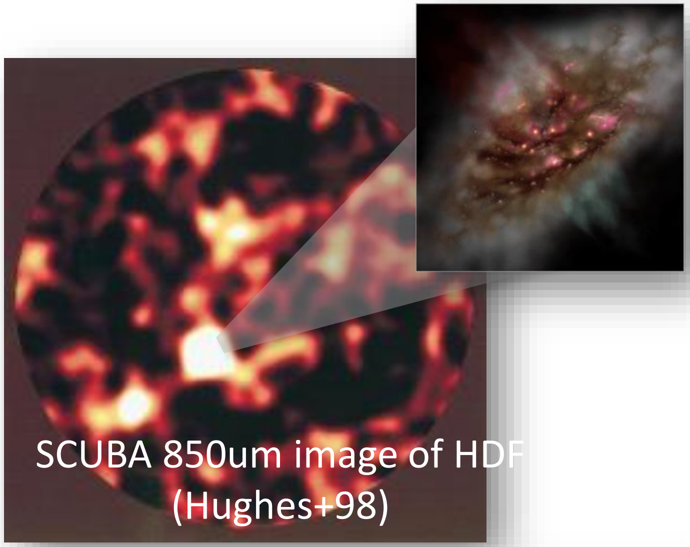
Submm/mm Observations

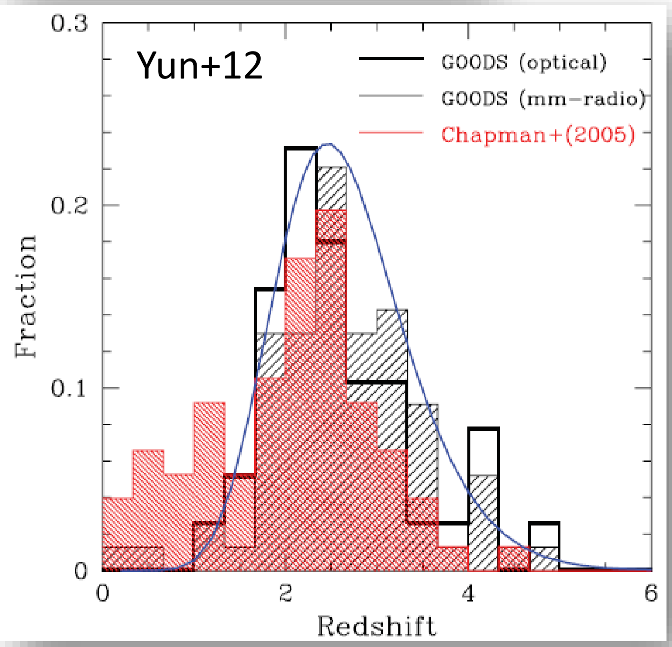


Submm/mm-bright Galaxies (SMGs)

- Deep surveys uncovered a new galaxy population
    - in the late-1990s; Smail+97, Hughes+98
  - Dust-enshrouded galaxies
  - Most of the energy is emitted at FIR-submm
  - L(FIR) > 10^12 Lsun
  - SFR > a few 100 Msun/yr
  - Redshift: z_{median} ~ 2-3
    - several SMGs are found to be at z > 4, 5

Progenitors of present-day massive ellipticals?

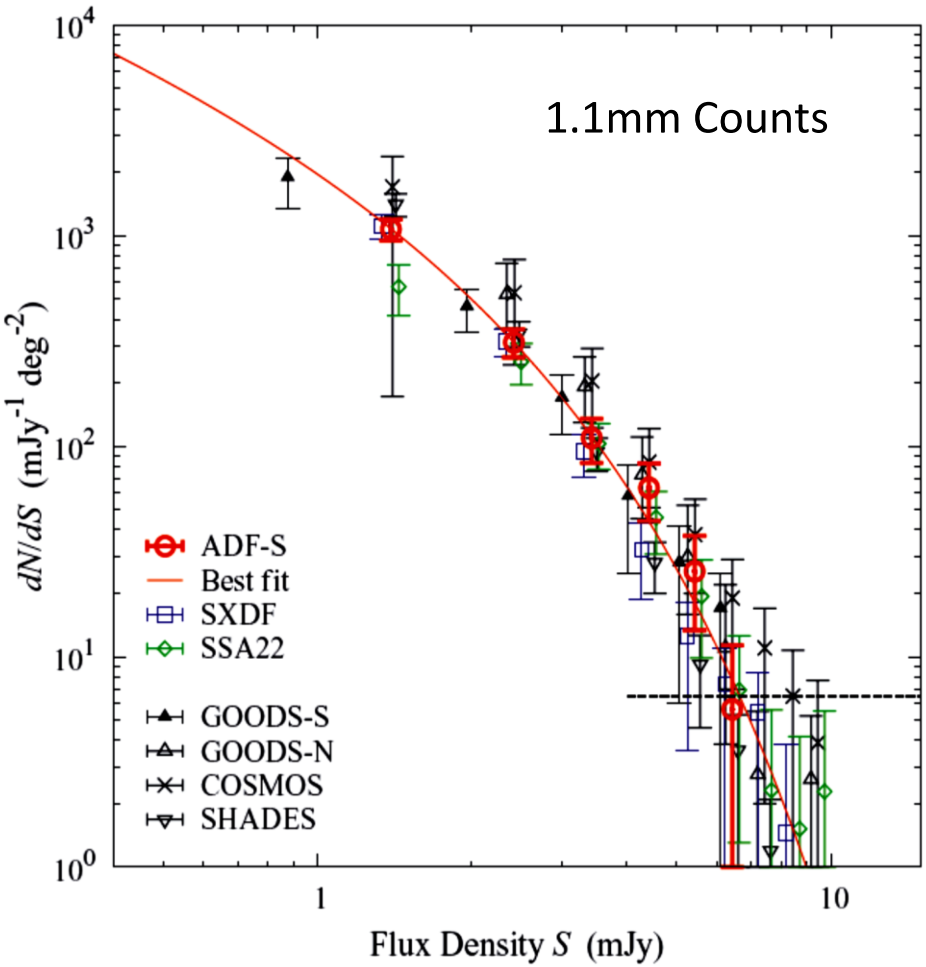




Contribution to EBL

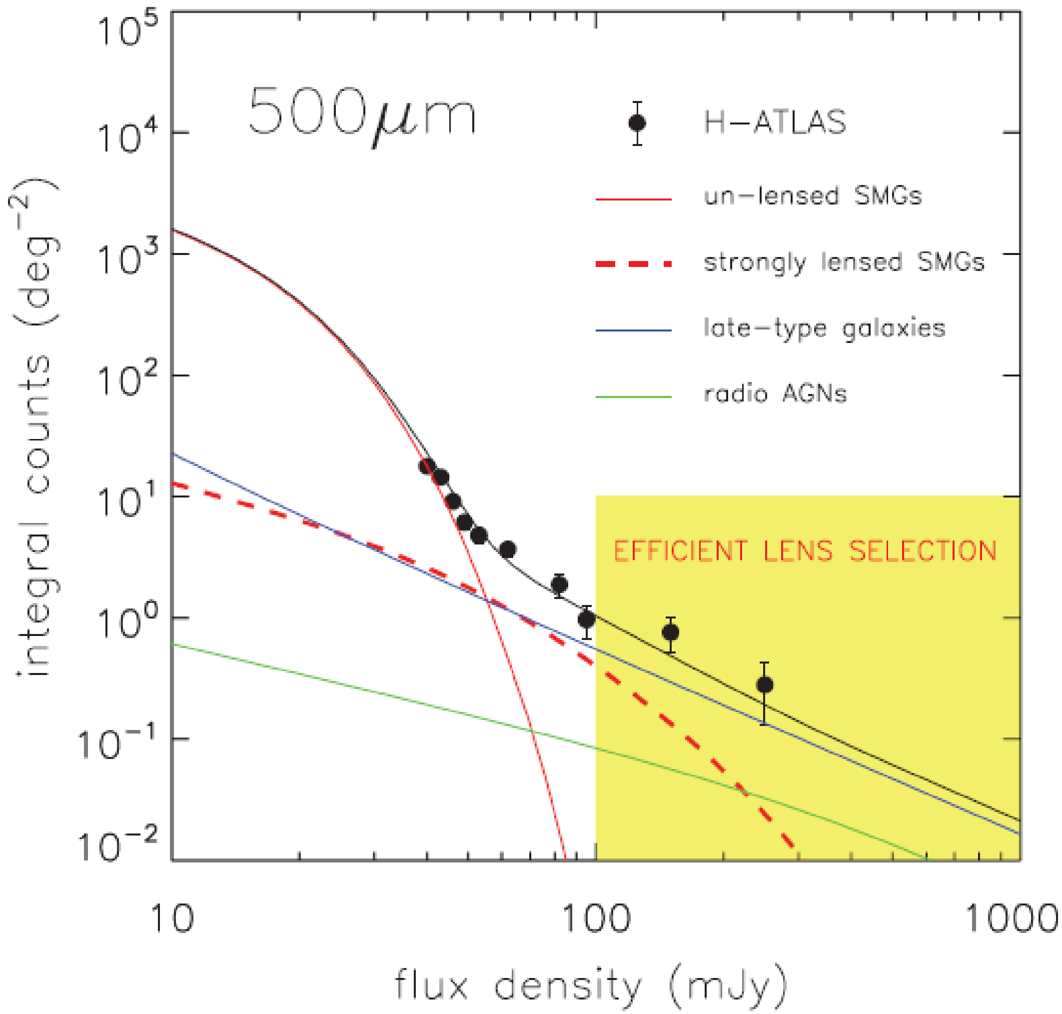
- Contribution of SMGs (S_{1mm} > 1 mJy) ~ 10%-20%

➔ EBL is dominated by fainter, normal star-forming galaxies

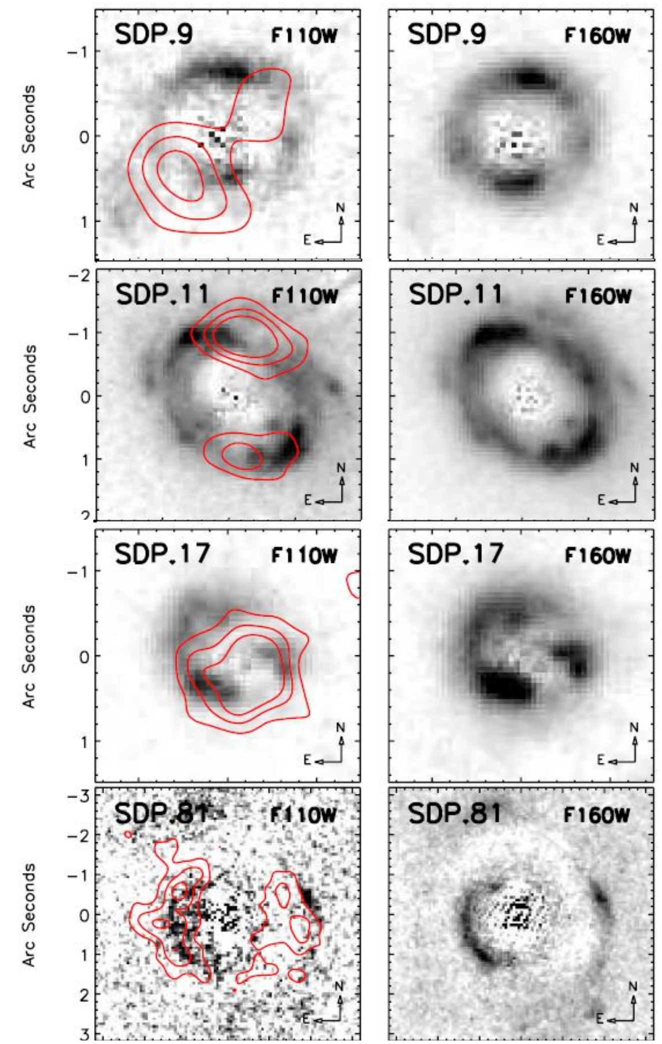


Hatsukade+11, Scott+12

Lensed SMGs



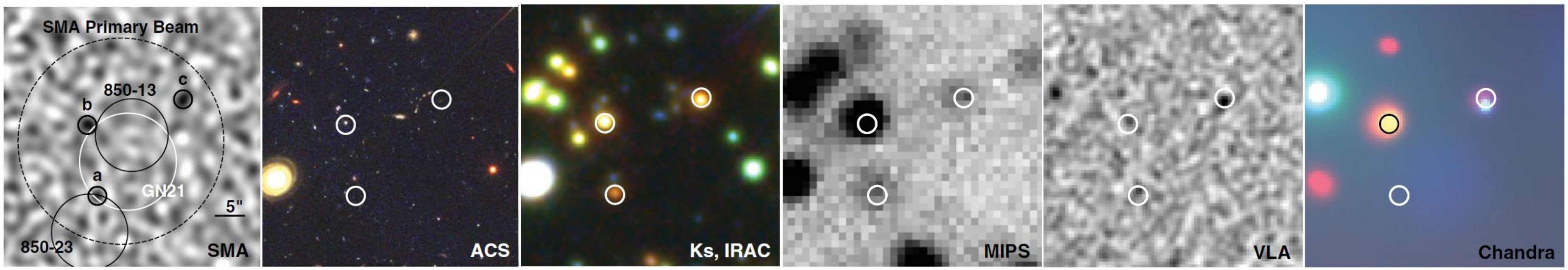
Negrello+10



Negrello+14

Issues in Single Dish Surveys

- Coarse angular resolution (~15”-30”)
  - confusion limit
  - source blending
  - misidentifications of counterparts



multiple counterpart candidates within a beam

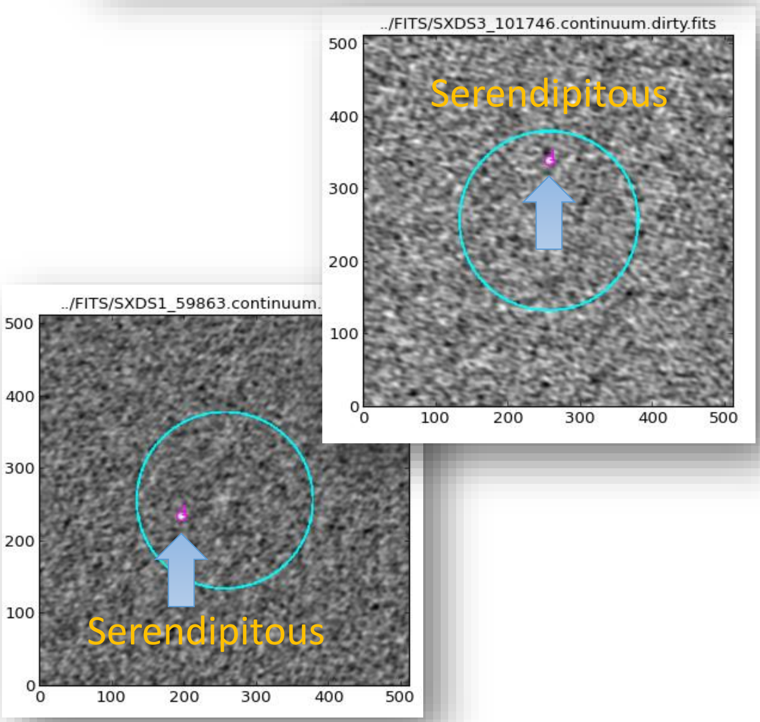
Wang+11

ALMA Reveals Faint Submm Sources

- ALMA (2011~)
  - high sensitivity
  - high angular resolution
  - ➔ no confusion limit

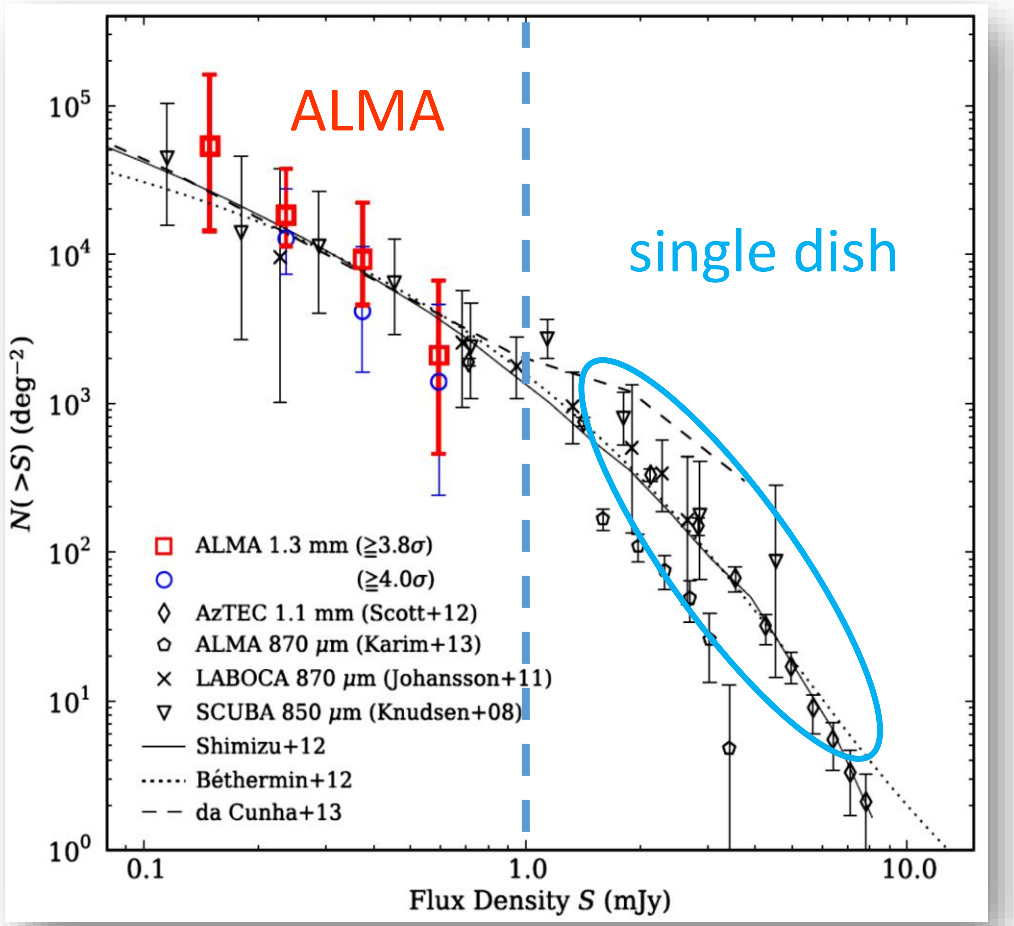
- >10x fainter sources compared to single-dish surveys even with a short obs time (<10 min)
  - serendipitous detection of faint sources (<1 mJy)

connecting between SMGs and normal SF galaxies



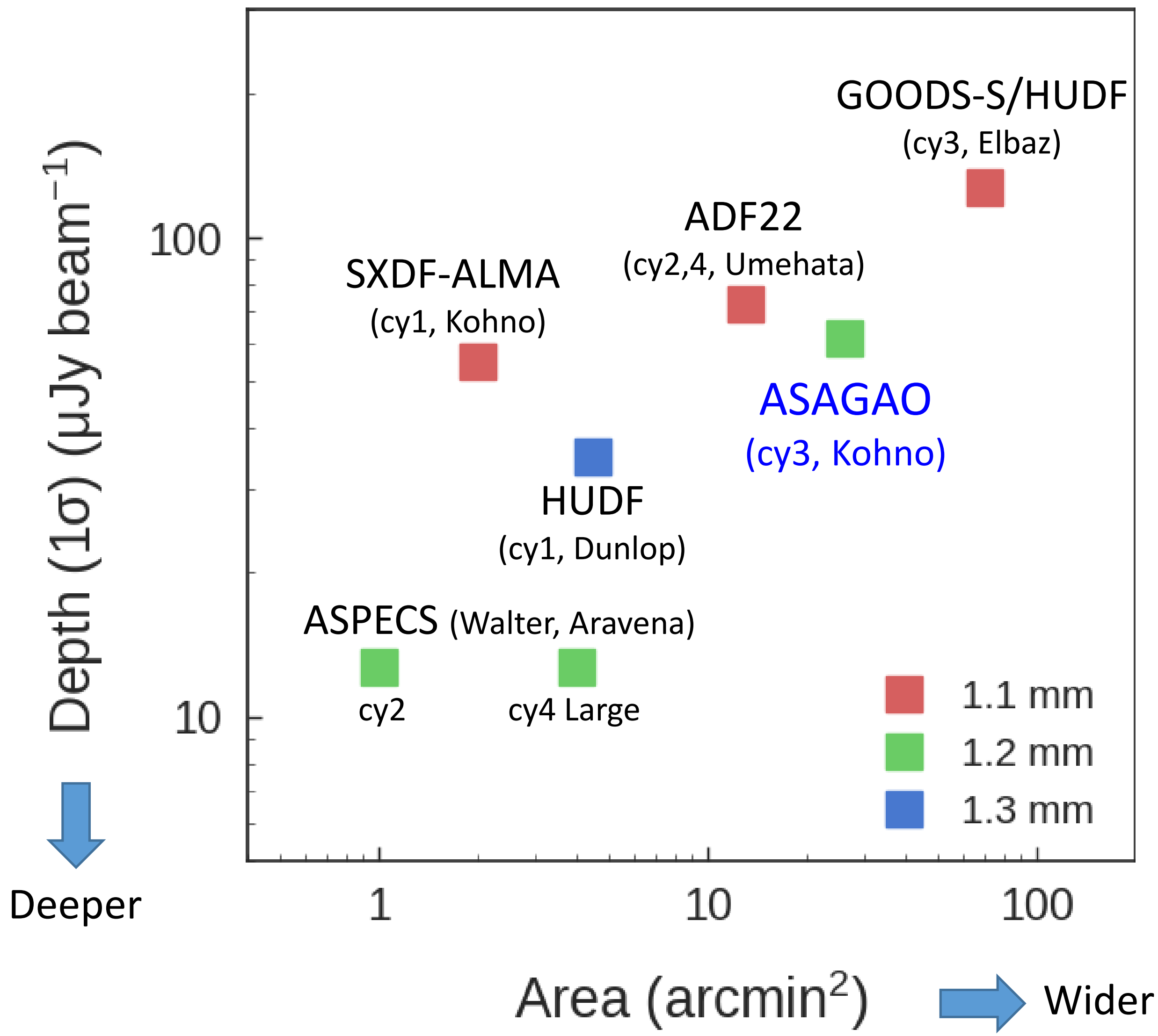
Faint End of Number Counts

- >50% of the EBL has been resolved in ALMA studies
  - Based on the ensemble of serendipitous sources
    - Hatsukade+13, Ono+14, Carniani+15, Fujimoto+16, Oteo+16



ALMA Deep Surveys

ALMA Deep Surveys

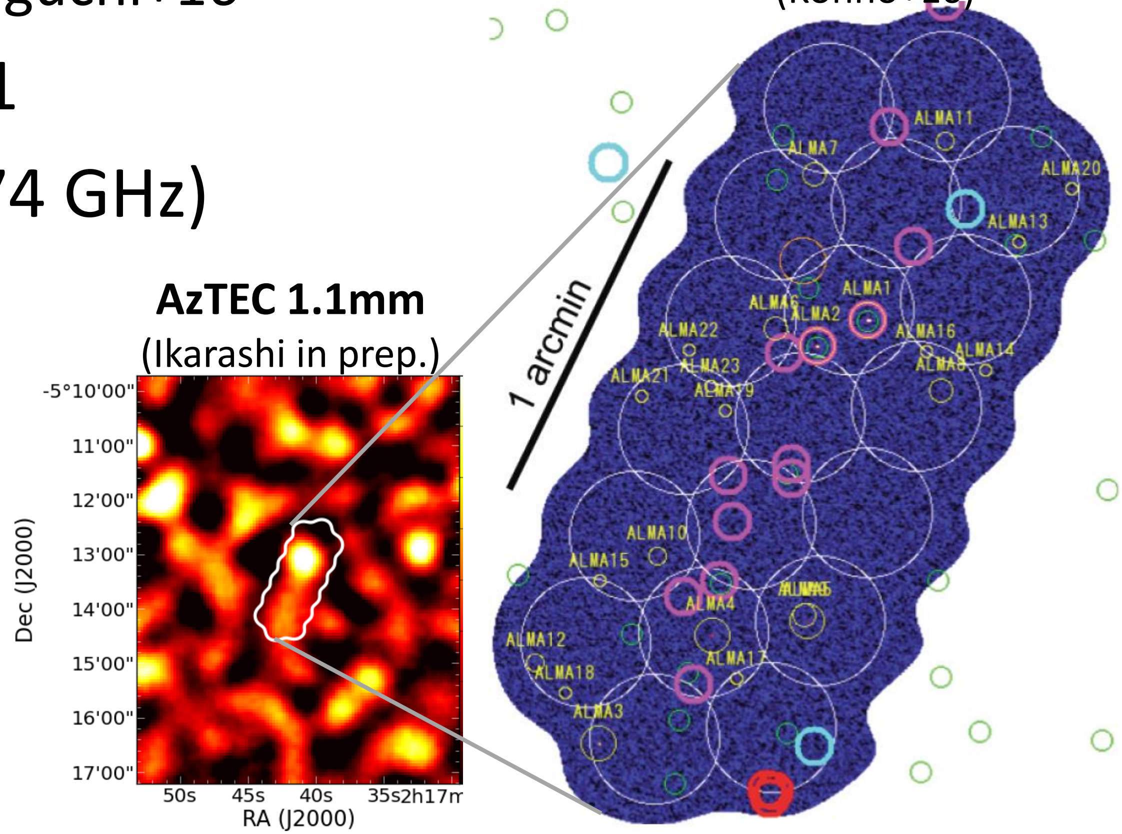


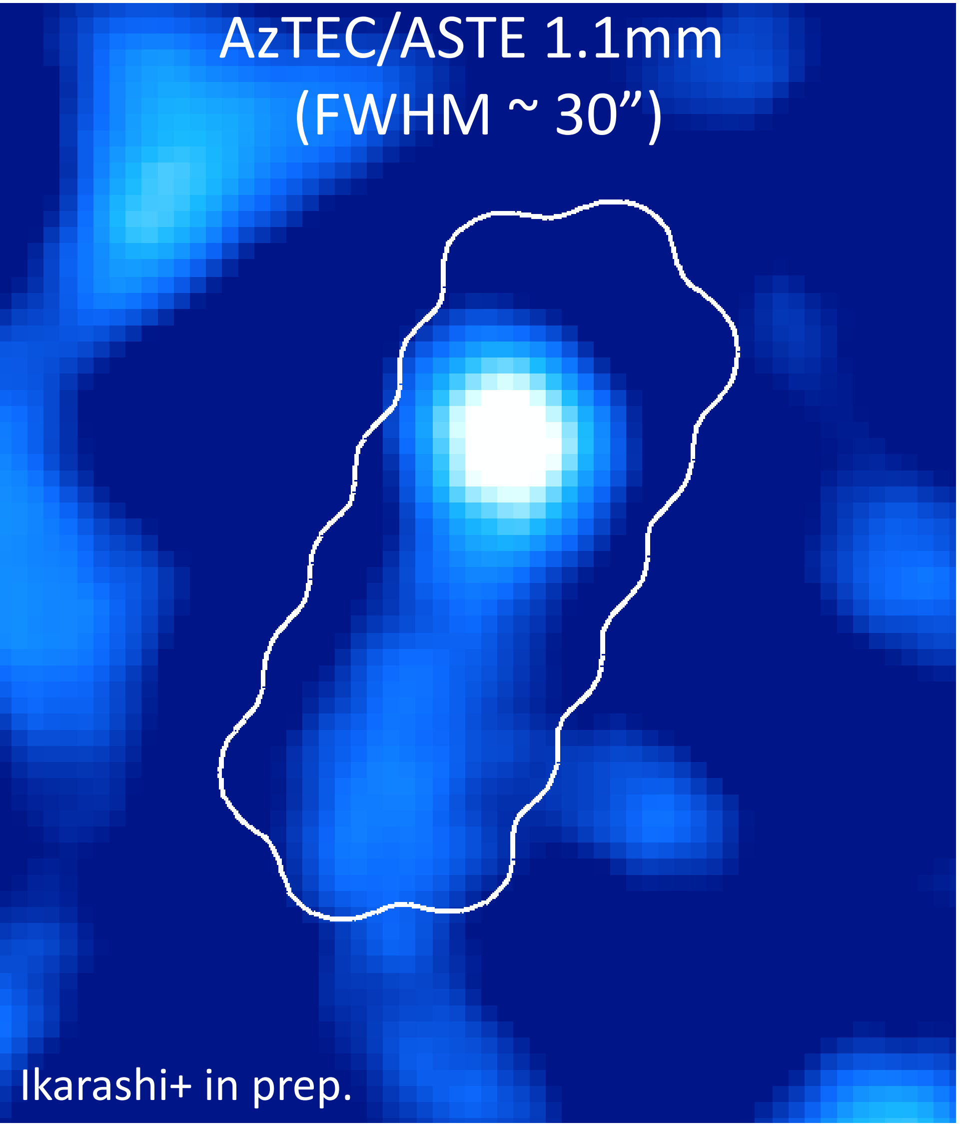
SXDF-ALMA

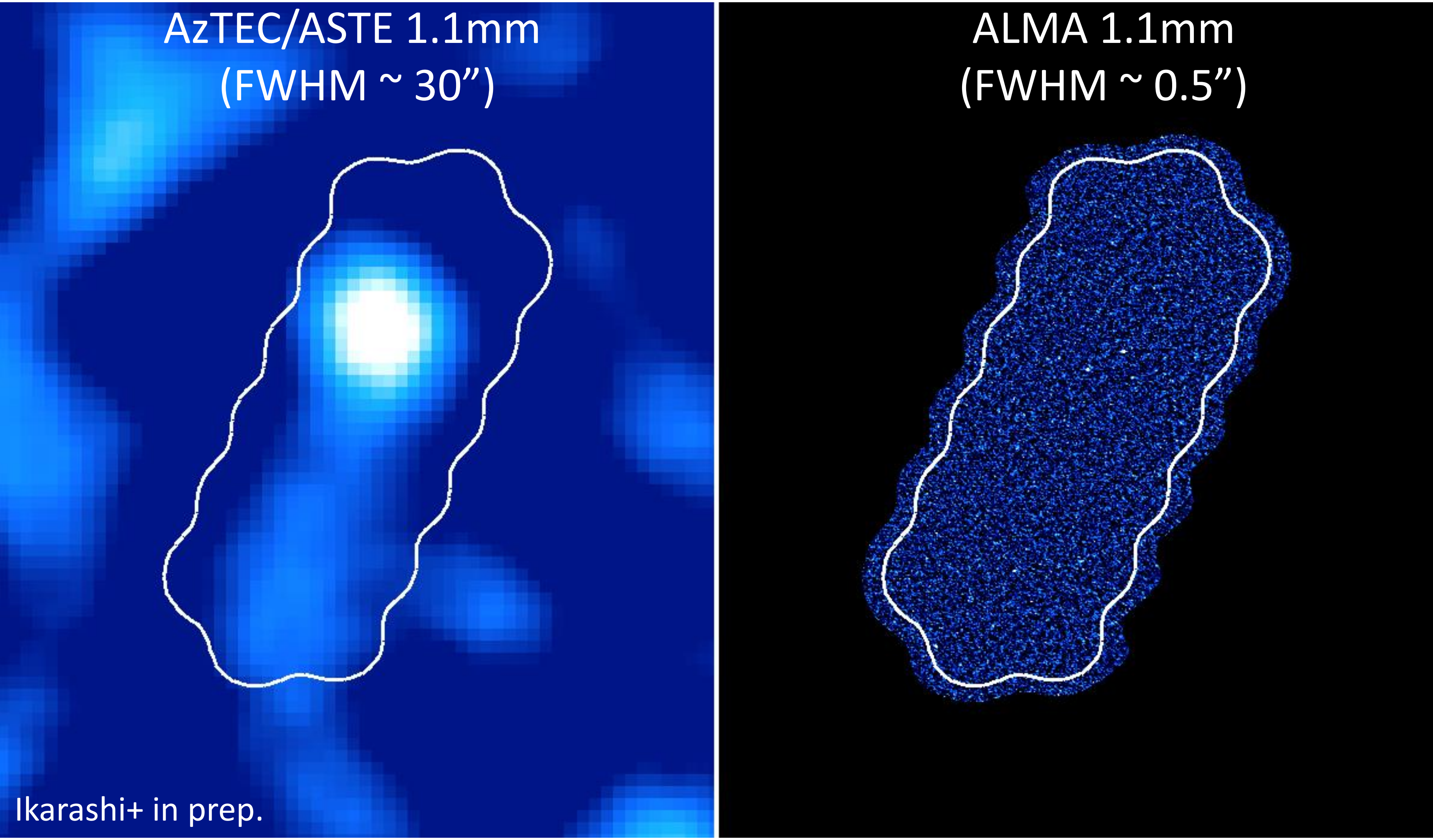
- A contiguous 105” x 50” (~2.5 arcmin^2) window in SXDF-UDS-CANDELS field
  - Kohno+16, Tadaki+15, Hatsukade+16, Wei-Hao+16, Yamaguchi+16
- PI: K. Kohno, cycle 1
- Band 6 (1.1 mm, 274 GHz)
- 19-point mosaic
- T_{obs} = 3.6 hours
- θ = 0.53” x 0.41”
- σ = 55 uJy/beam

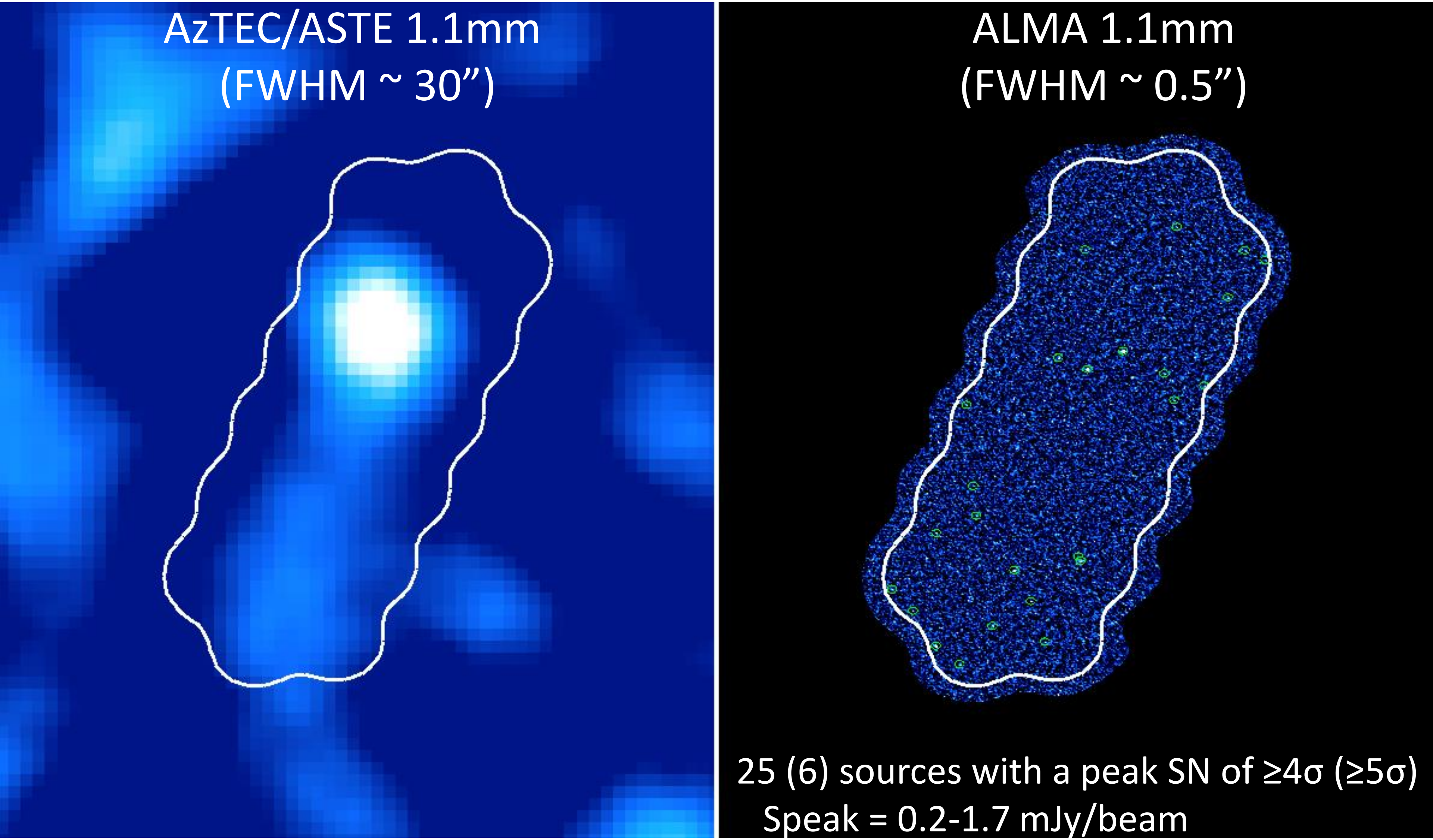
AzTEC 1.1mm
(Ikarashi in prep.)

ALMA 1.1mm map
(Kohno+16)




AzTEC/ASTE 1.1mm
(FWHM ~ 30”)
Ikarashi+ in prep.

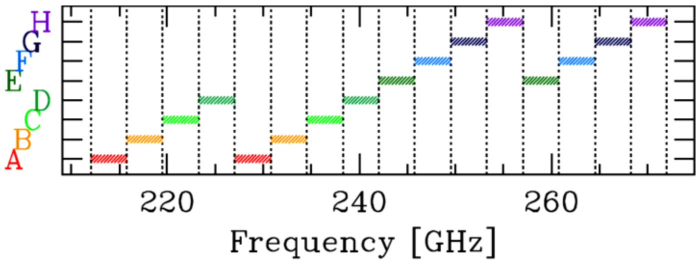

AzTEC/ASTE 1.1mm
(FWHM ~ 30")
Ikarashi+ in prep.
ALMA 1.1mm
(FWHM ~ 0.5")

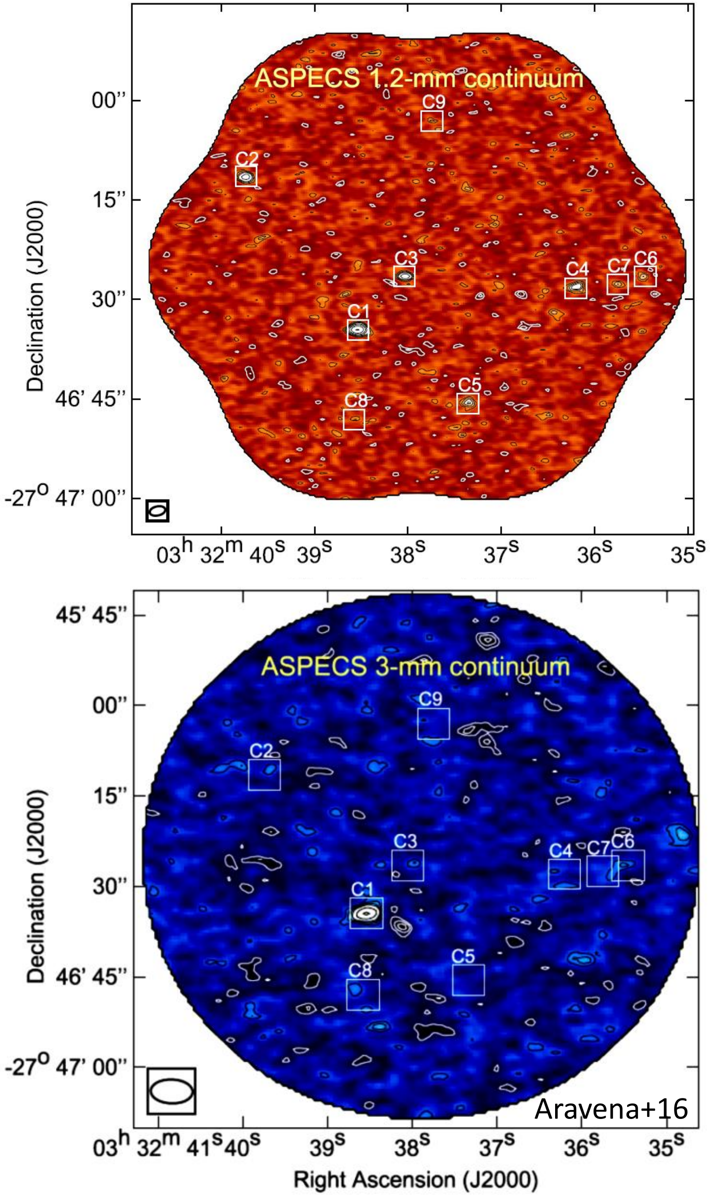

AzTEC/ASTE 1.1mm
(FWHM ~ 30")
ALMA 1.1mm
(FWHM ~ 0.5")
25 (6) sources with a peak SN of ≥4σ (≥5σ)
Speak = 0.2-1.7 mJy/beam

ASPECS

- Spectral scan at band 3 & 6
  - PI: F. Walter, E. Aravena, cy2 & 4 large
    - Walter+16, Aravena+16a,b, Bouwens+16, Carilli+16, Decarli+16a,b
  - 1.2 mm & 3 mm
  - ~1 arcmin^2
  - 1σ = 12.7 uJy (1.2mm), 3.8 uJy (3mm)

- Source detection
  - 9 sources (>3.5σ) at 1.2 mm
    - 16 sources (> 3.0σ)
  - 1 source at 3 mm
  - S(1.2mm) = 46-553 uJy

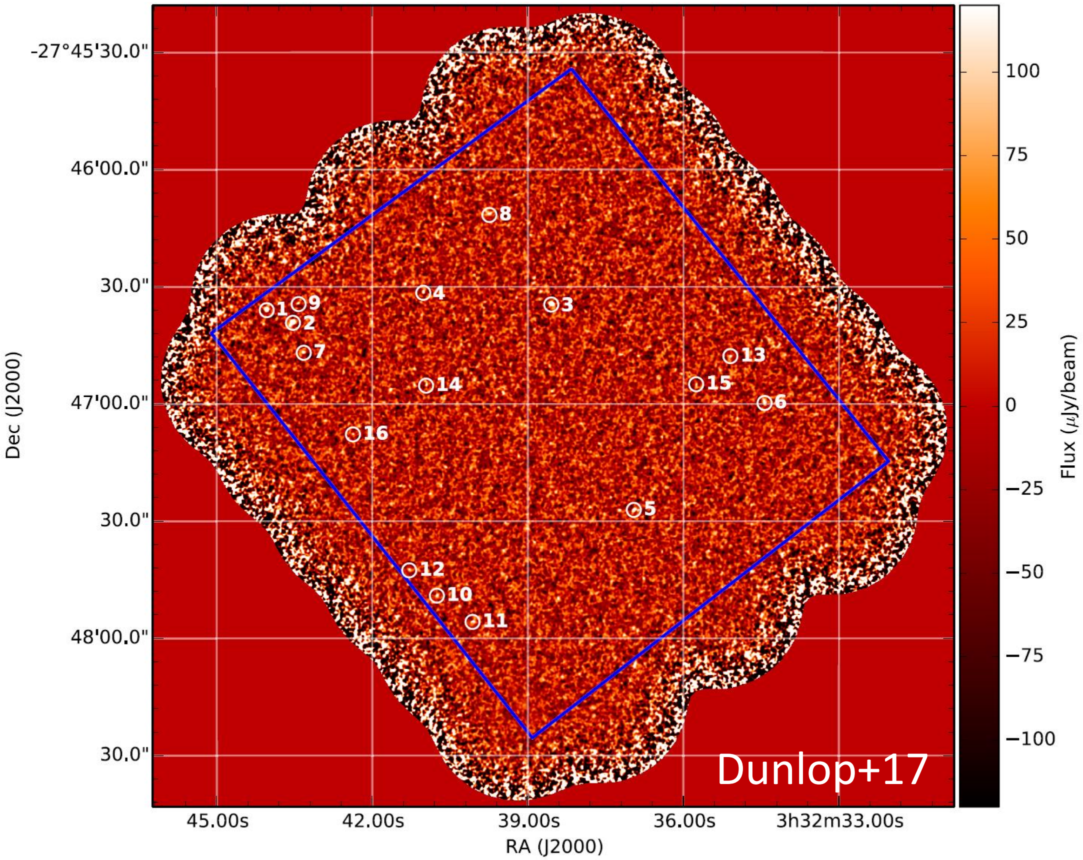




HUDF/GOODS-S

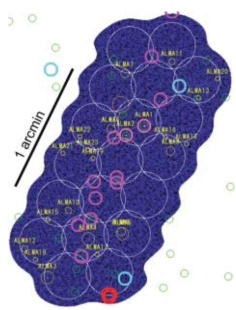
- HUDF (PI: J. Dunlop, cy1)
    - Dunlop+17, Rujopakarn+16
  - 1.3 mm
  - ~4.5 arcmin^2
  - 1σ = 35 uJy/beam

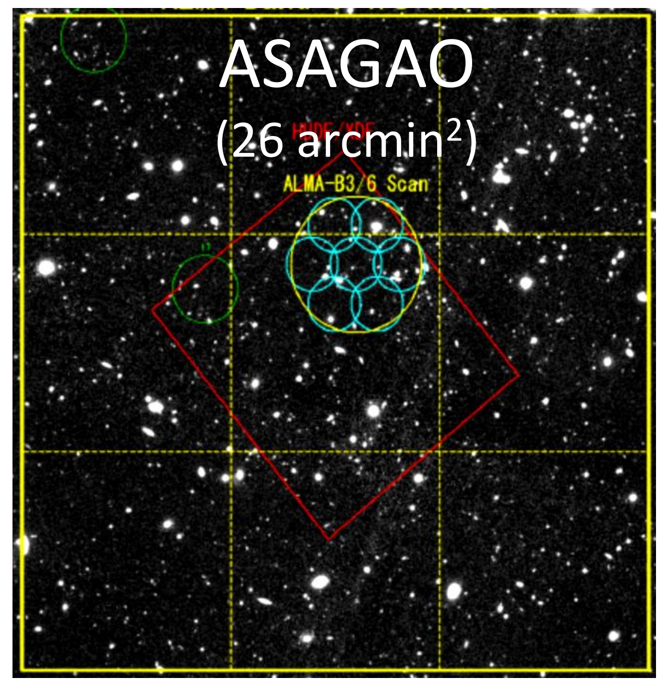
- Source detection
  - 47 candidate sources
    - >3.5σ, >120 uJy
    - 29 negative sources
  - 16 “robust” sources
    - >3.5σ, >120 uJy, optical counterparts



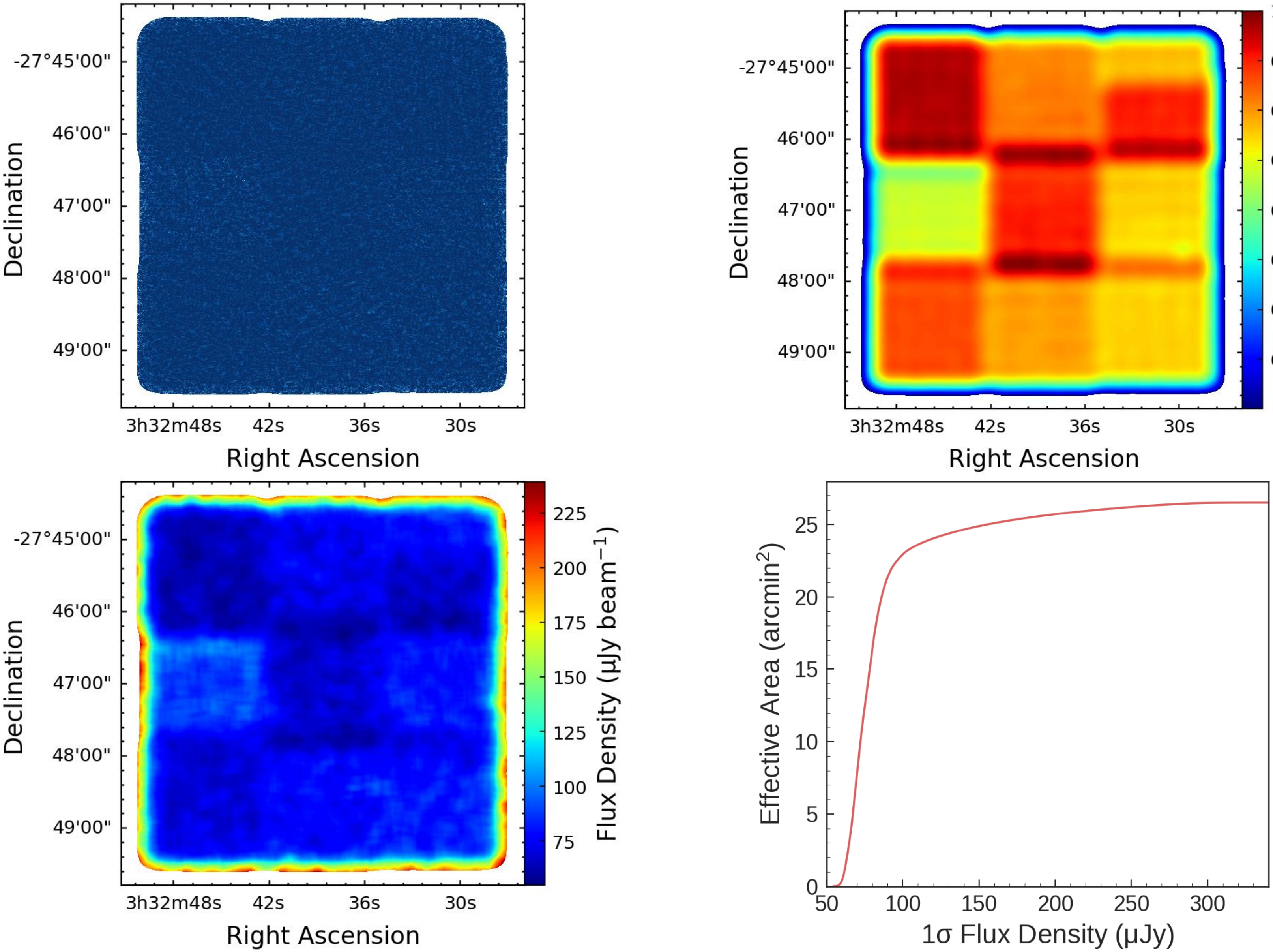
ALMA twenty-Six Arcmin^2 survey of GOODS-South At One-millimeter (ASAGAO)

SXDS
(2 arcmin^2)

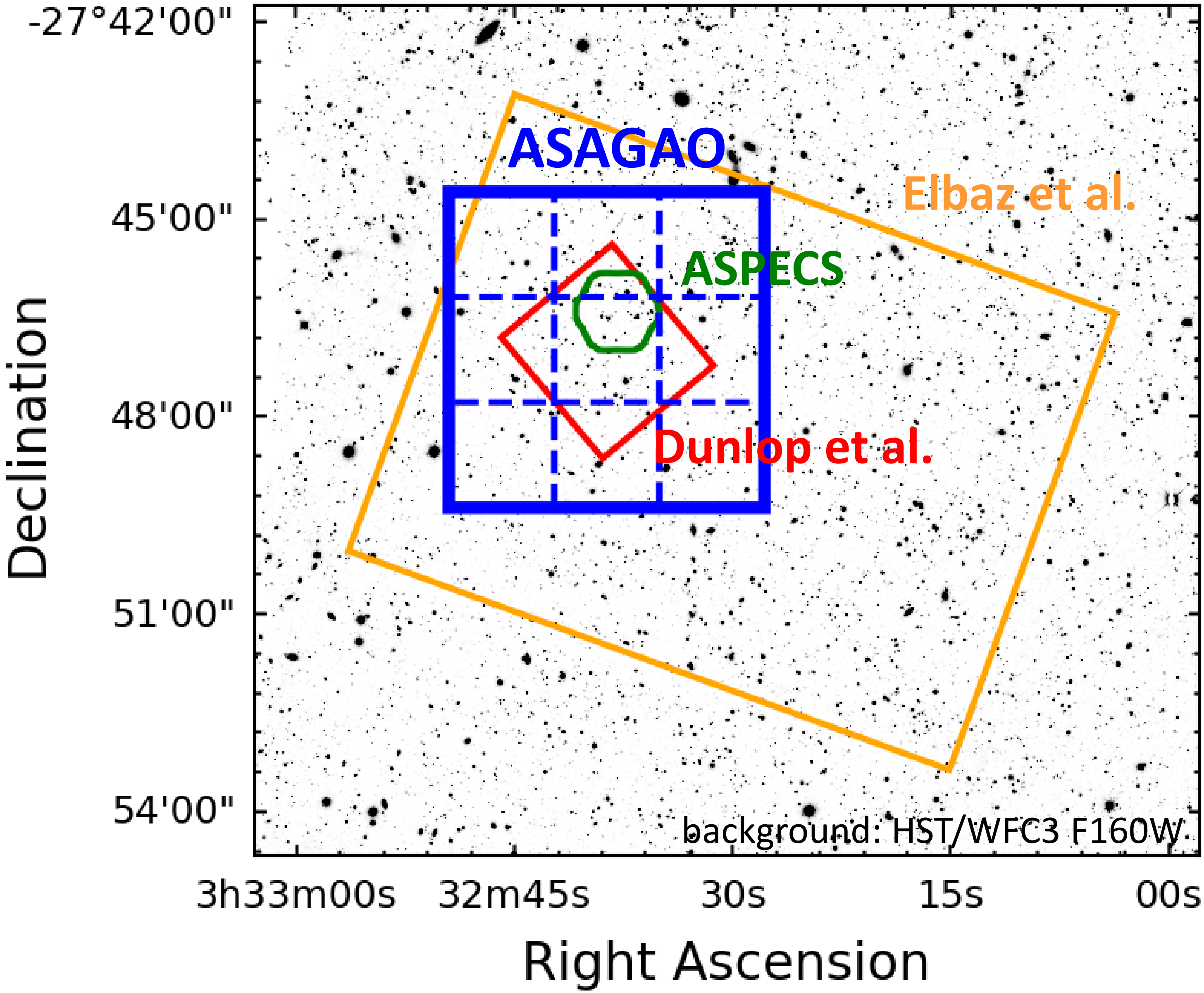




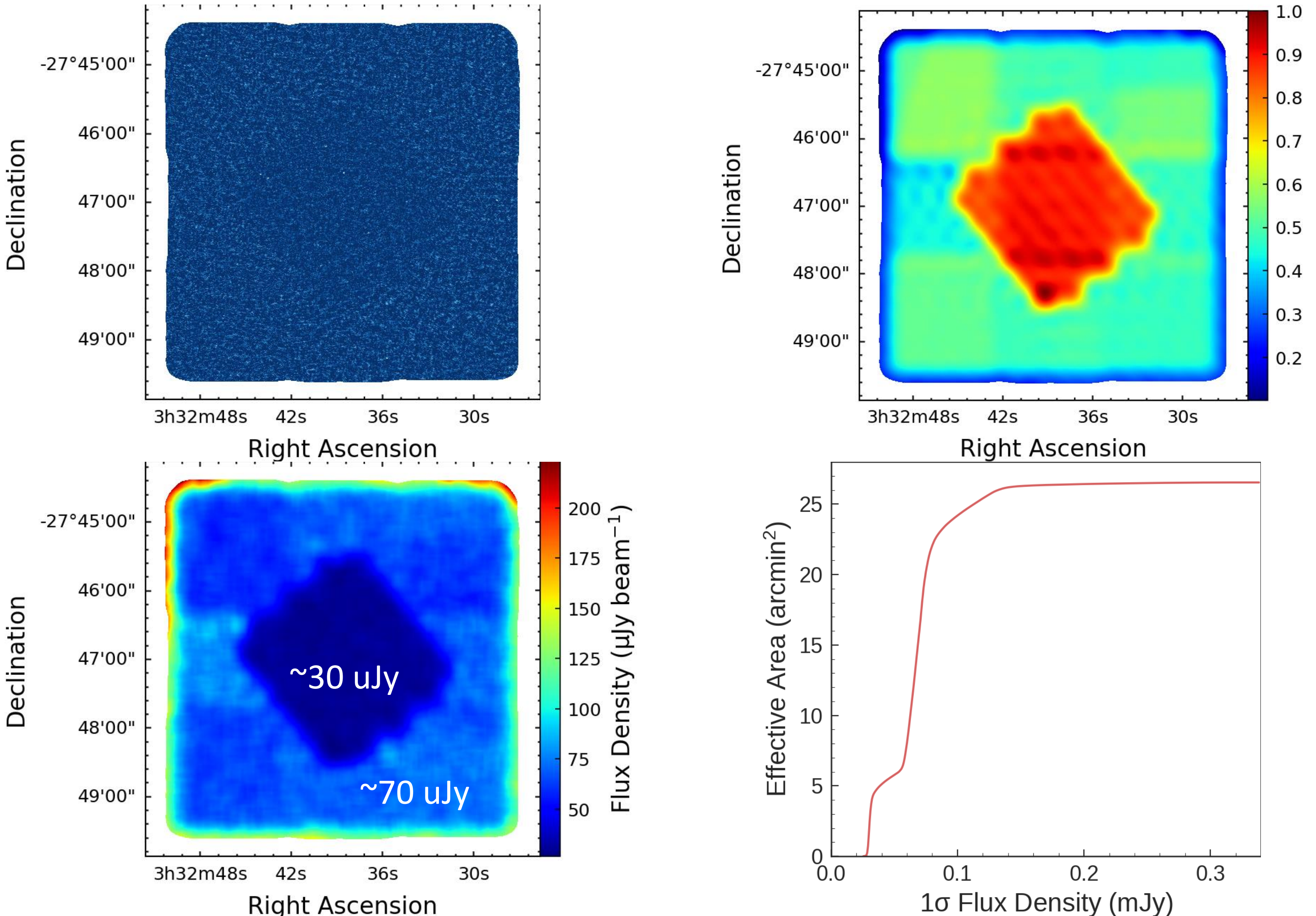
ASAGAO (250 kλ taper)



ALMA Surveys in GOODS-S

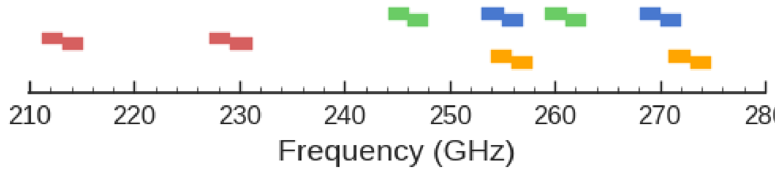


ASAGAO+Dunlop+Elbaz Combined



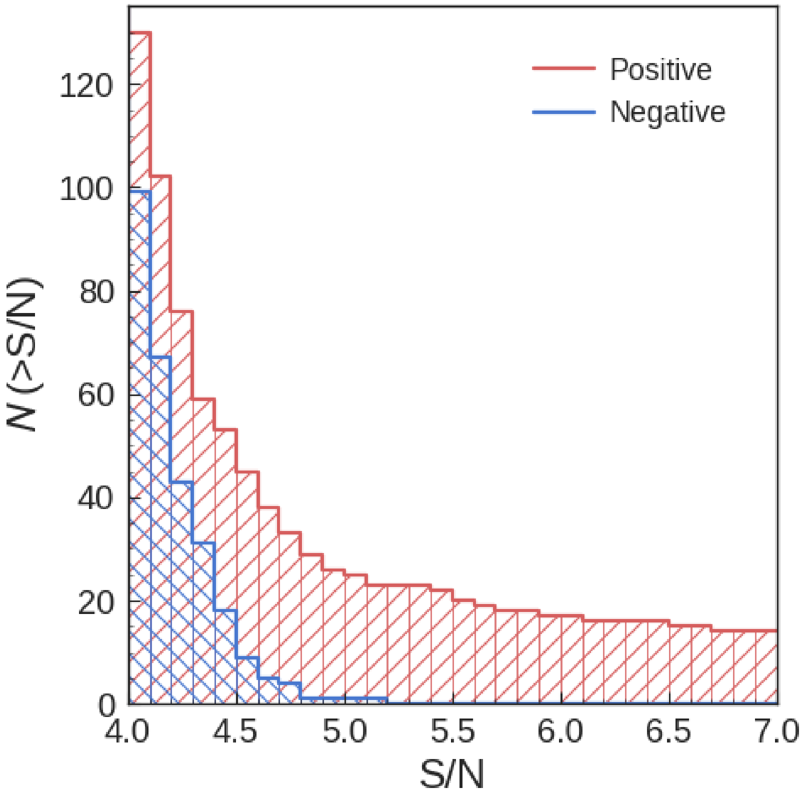
ASAGAO+Dunlop+Elbaz Combined

- Combined Map
  - 250 kλ taper
  - beam size: 0.59” x 0.53”
  - representative freq.: 243.047 GHz (1.23 mm)
  - total continuum coverage: 28 GHz



BH et a. (in prep.)

- Source Detection
  - 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 sources

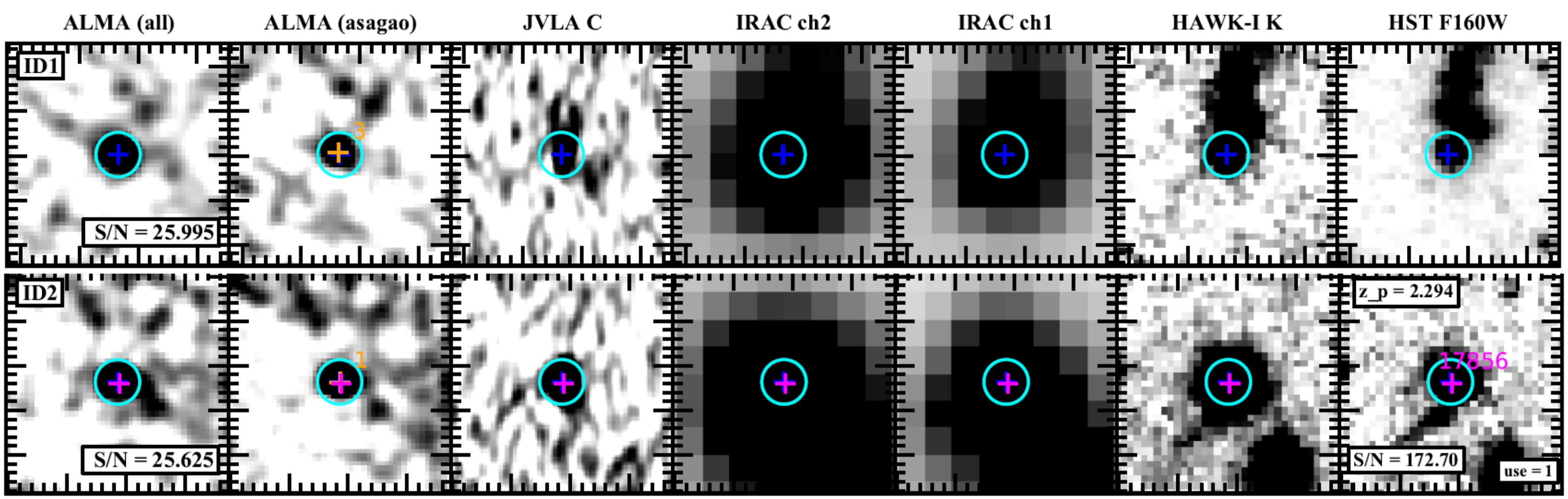
ASAGAO	SXDS	ASPECS	HUDF
25	5	5	5

Counterpart ID

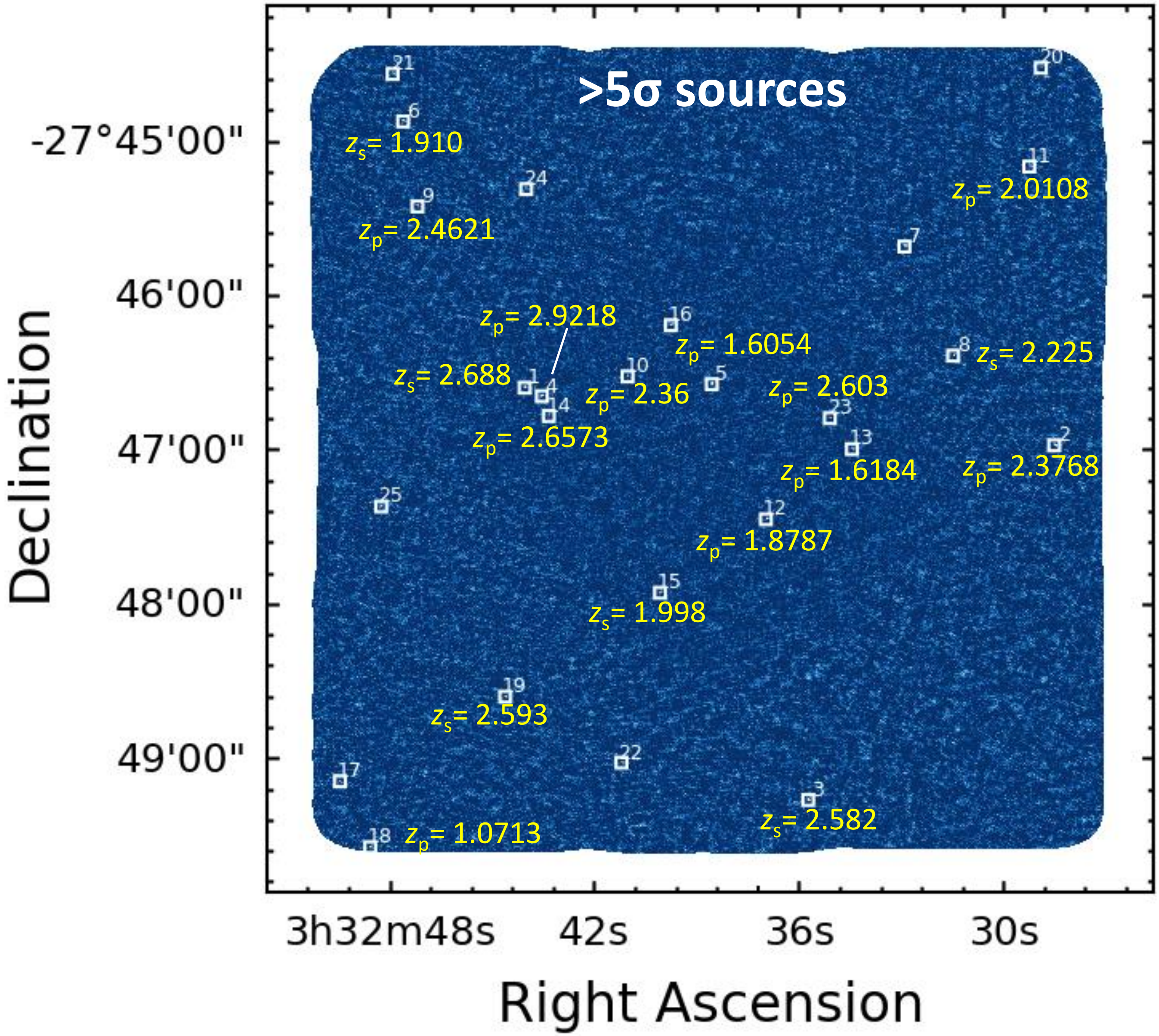
- ZFORGE
  - FourStar galaxy evolution survey (Straatman+16)
  - Ks = 26.0 mag (80% completeness), 26.3 mag (50%) (5σ)

- Cross match between ASAGA and ZFORGE

  ➔ 66 ASAGAO sources (3.5σ) with ZFORGE counterparts
    - 85%, 55%, and 12 % of ASAGAO sources with 5σ, 4.5σ, and 3.5σ

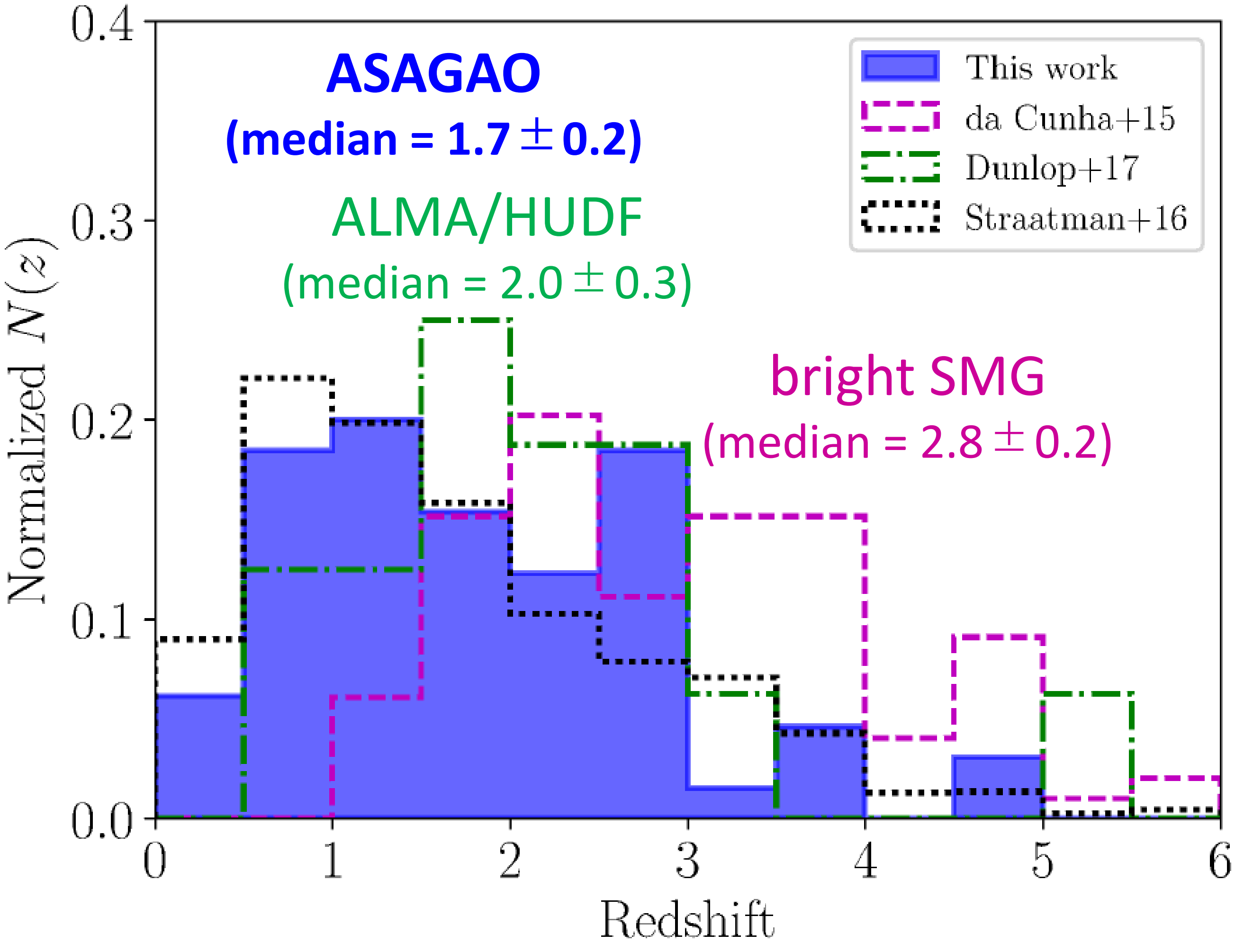


Redshift from Existing Catalog



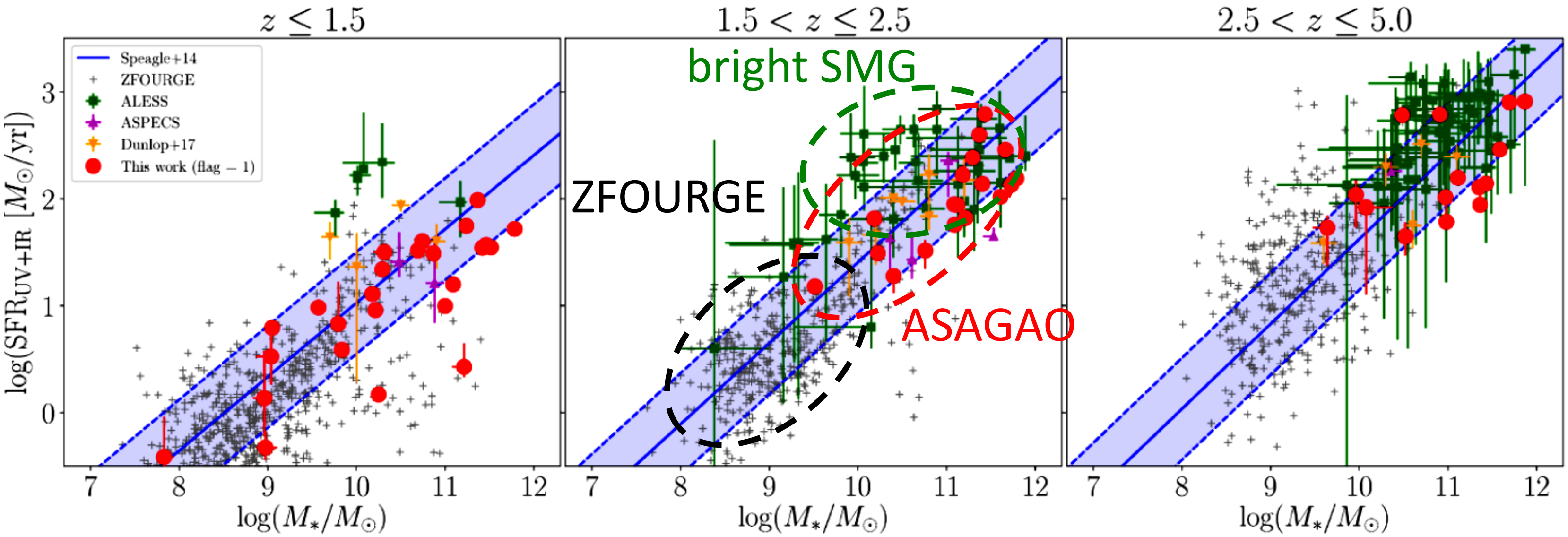
Redshift Distribution

Yamaguchi, Kohno, BH, et al. (in prep.)



M*, SFR

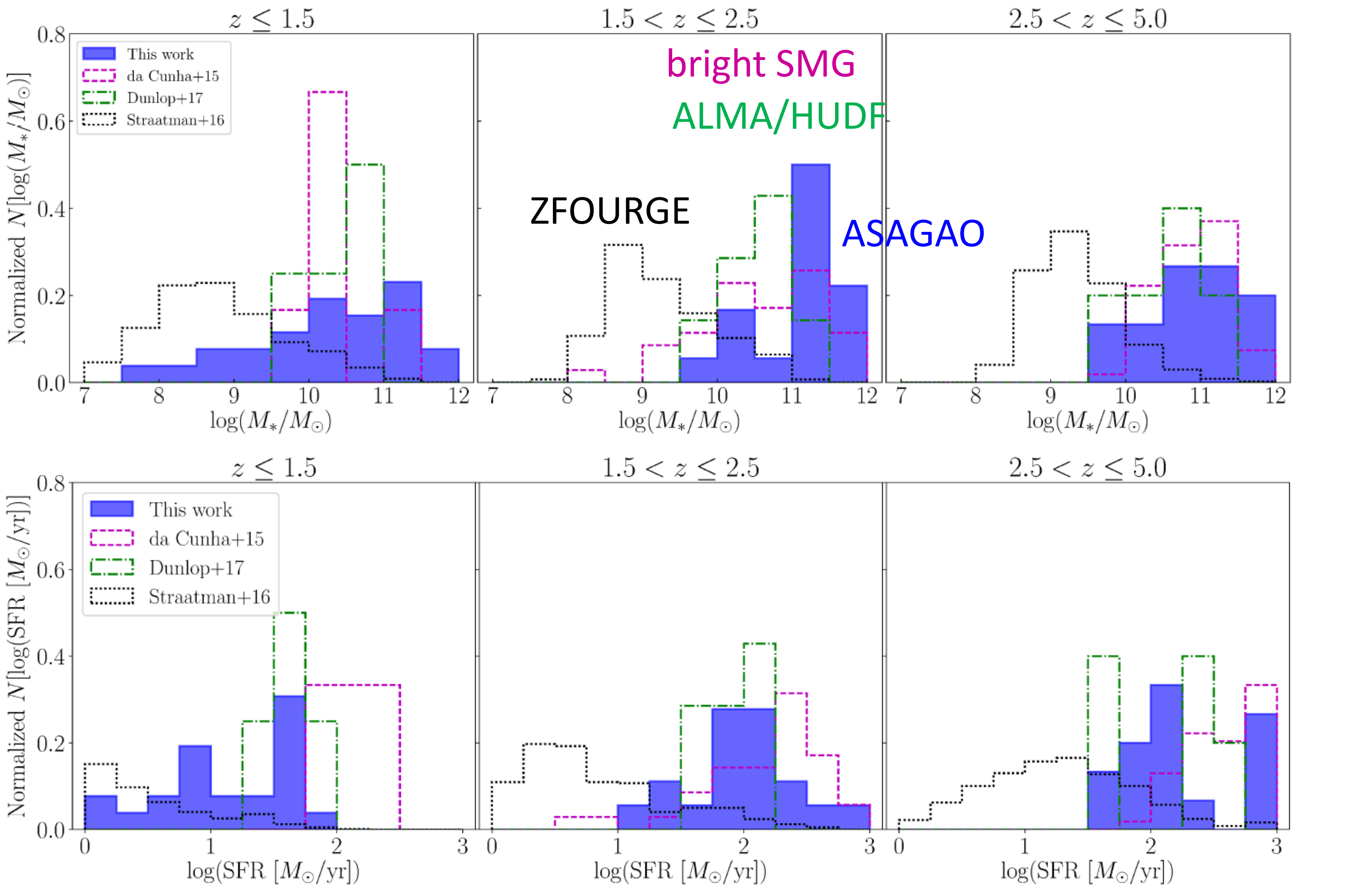
ASAGAO sources: massive end of main sequence



Yamaguchi, Kohno, BH, et al. (in prep.)

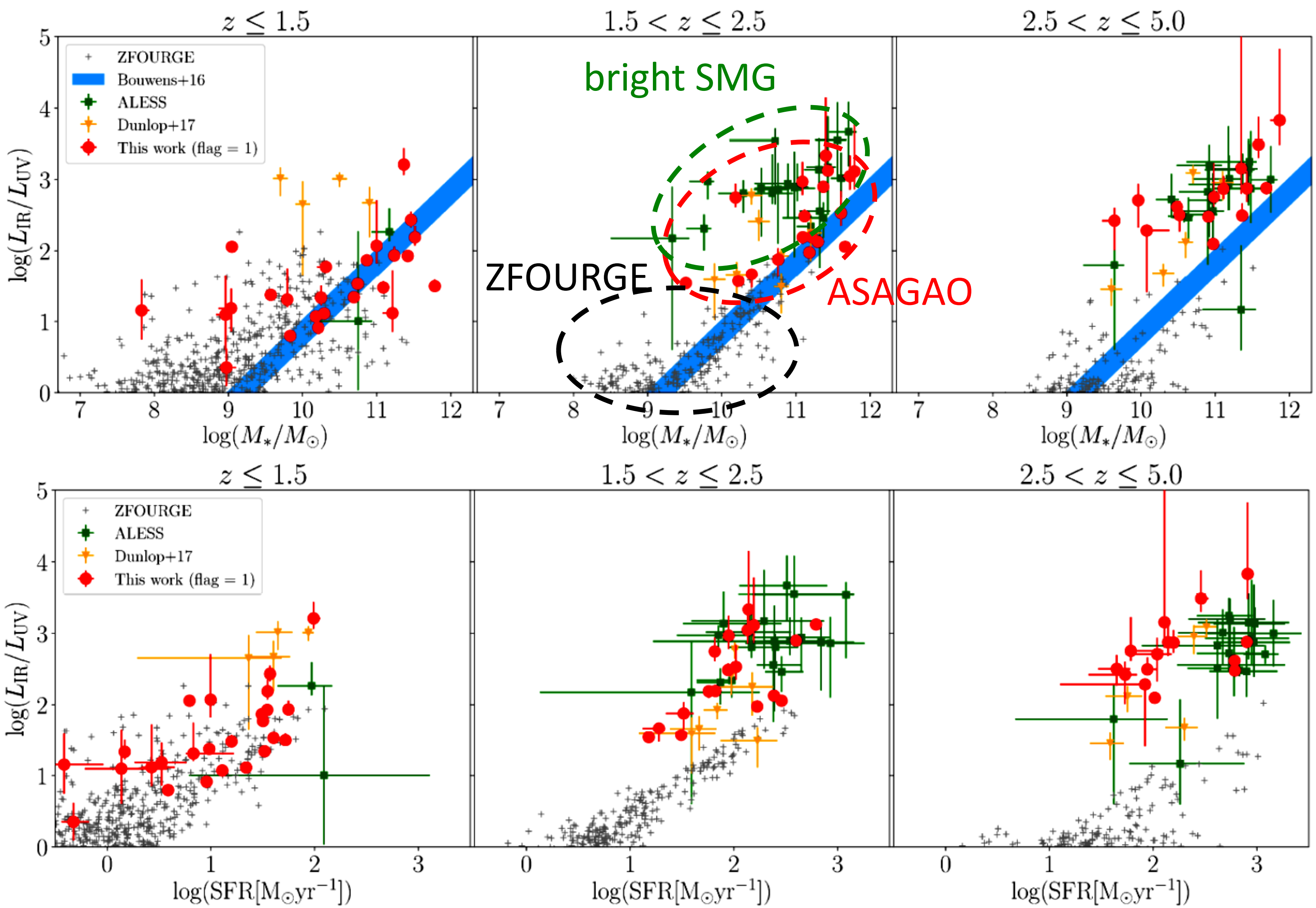
M*, SFR

Yamaguchi, Kohno, BH, et al. (in prep.)



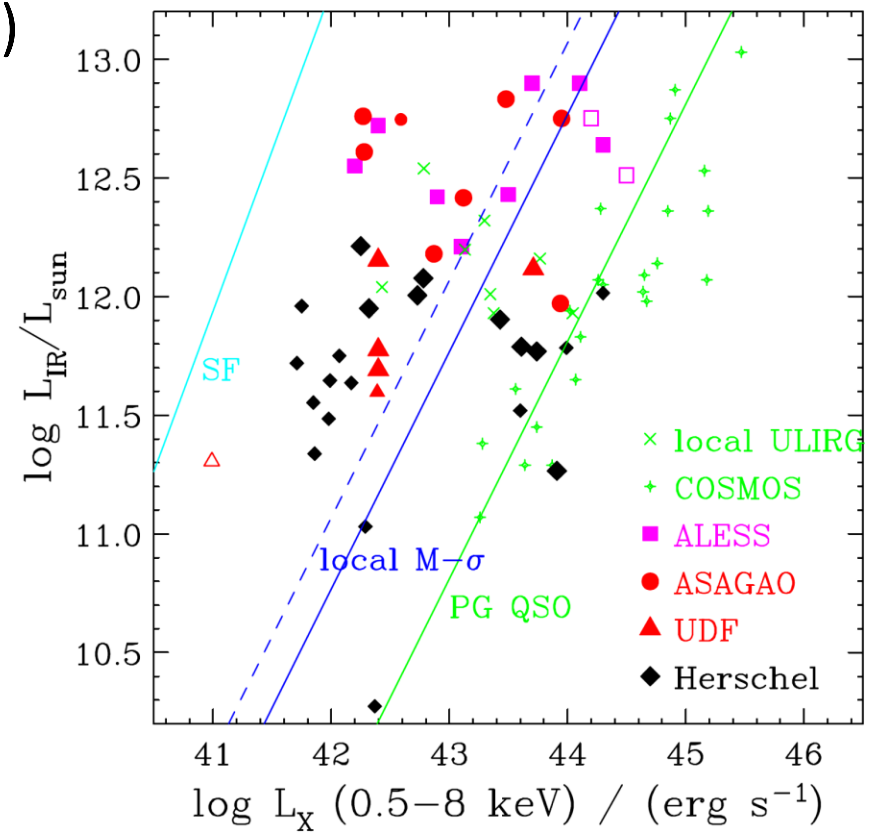
ALMA-detected/undetected: IRX

Yamaguchi, Kohno, BH, et al. (in prep.)



X-ray AGNs at z = 1.5-3

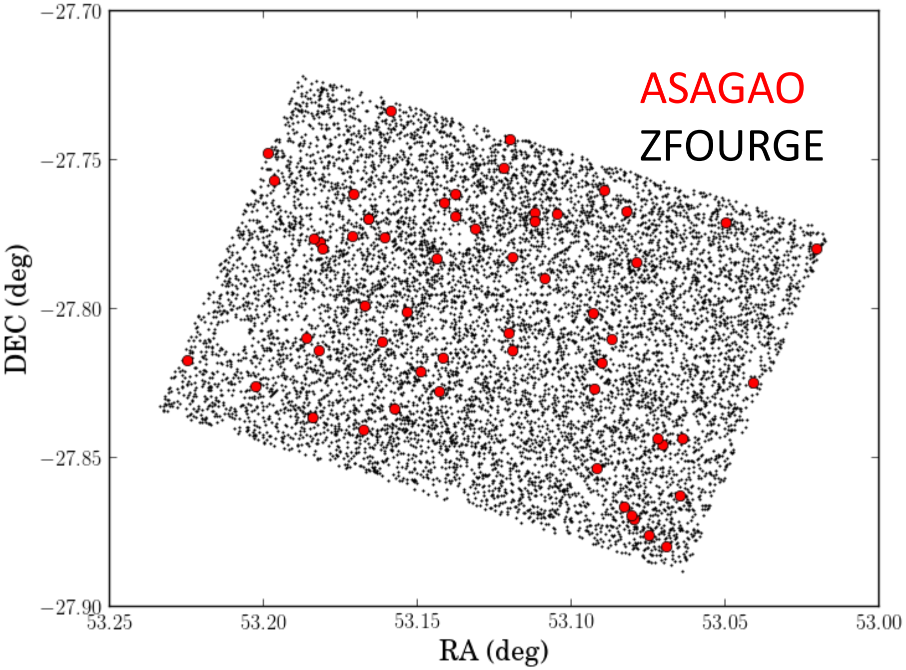
- Cross-match with Chandra 7-Ms catalog
    - flux limit: 5×10^{-17} erg/cm^2/s (0.5-7 keV)
  - 8 ASAGAO sources (out of 10)
  - 6 UDF sources (out of 13)
- High AGN fraction
  - 90% for ULIRGs
  - 57% for LIRGs
- Lx-LIR ratio is smaller than "simultaneous evolution"
  - Star formation occurs first, AGN-dominant phase follows later?



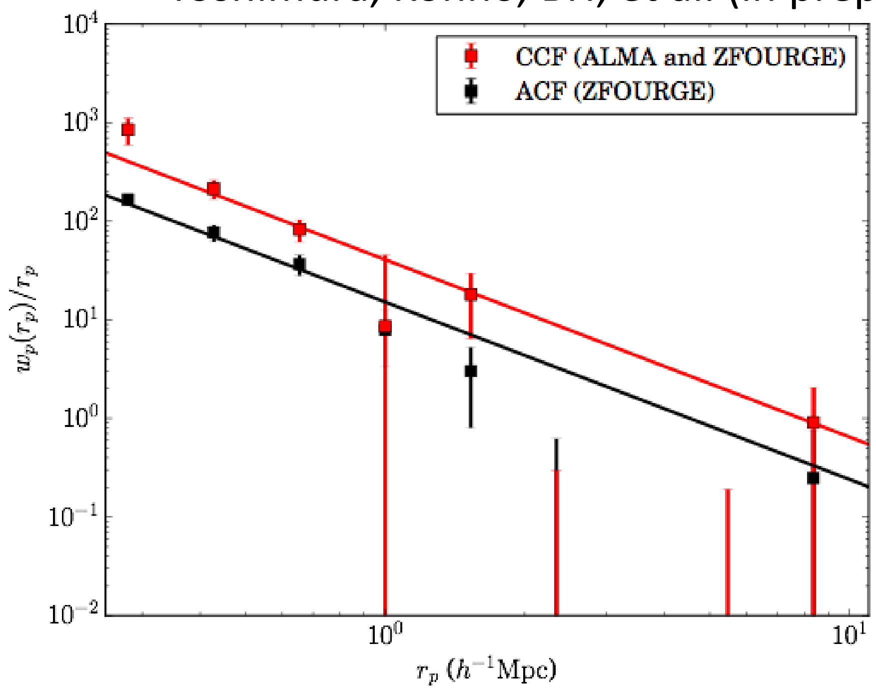
Ueda, BH, et al. 2018

Clustering

- Cross-correlation between ASAGAO & ZFOURGE sources
  - 35 ASAGAO sources, ~4800 ZFOURGE sources
- Projected correlation by using z probability distribution
- First detection of significant signals
  - for fainter submm sources (<3 mJy)
  - without source blending



Yoshimura, Kohno, BH, et al. (in prep.)



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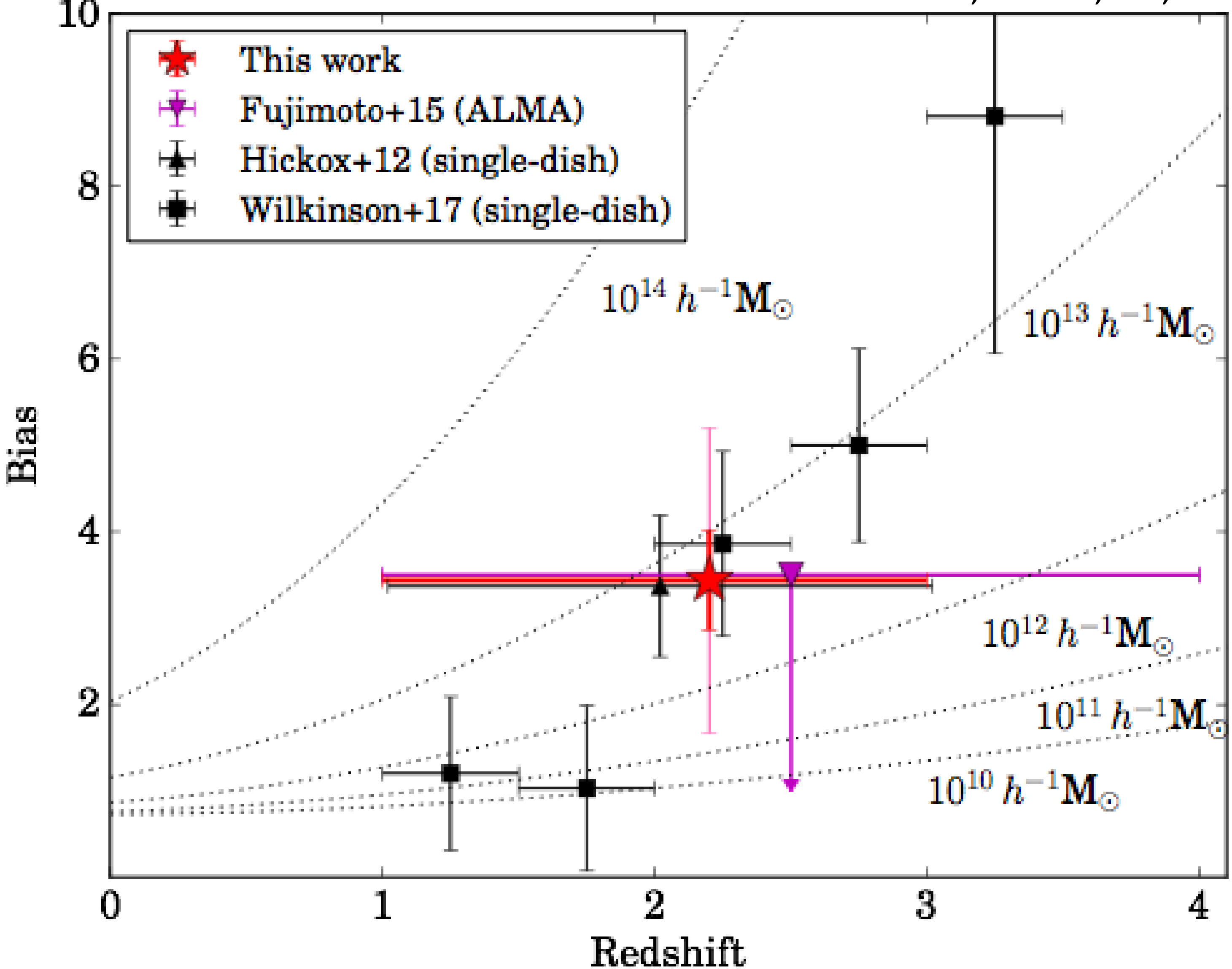
Yoshimura, Kohno, BH, et al. (in prep.)



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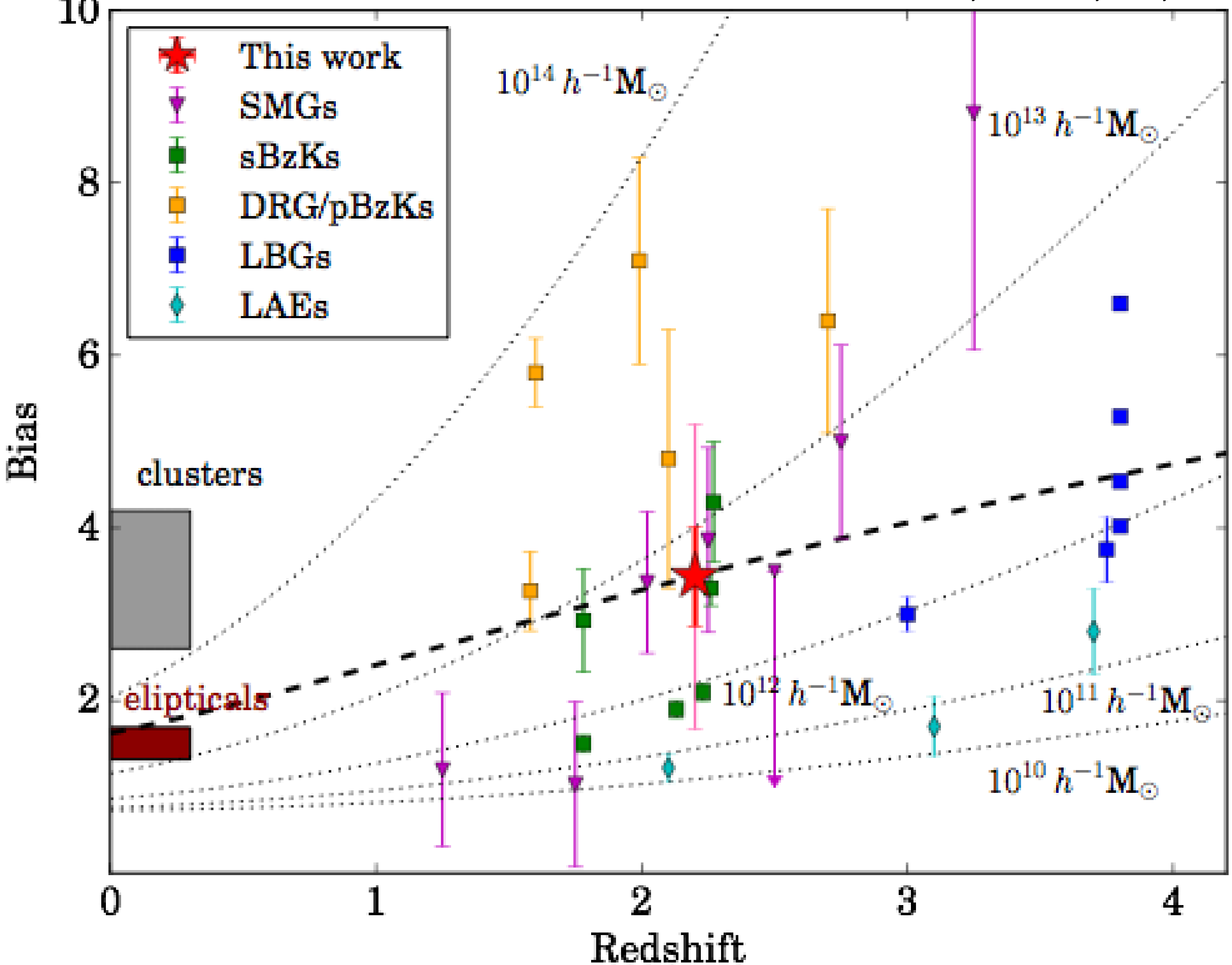
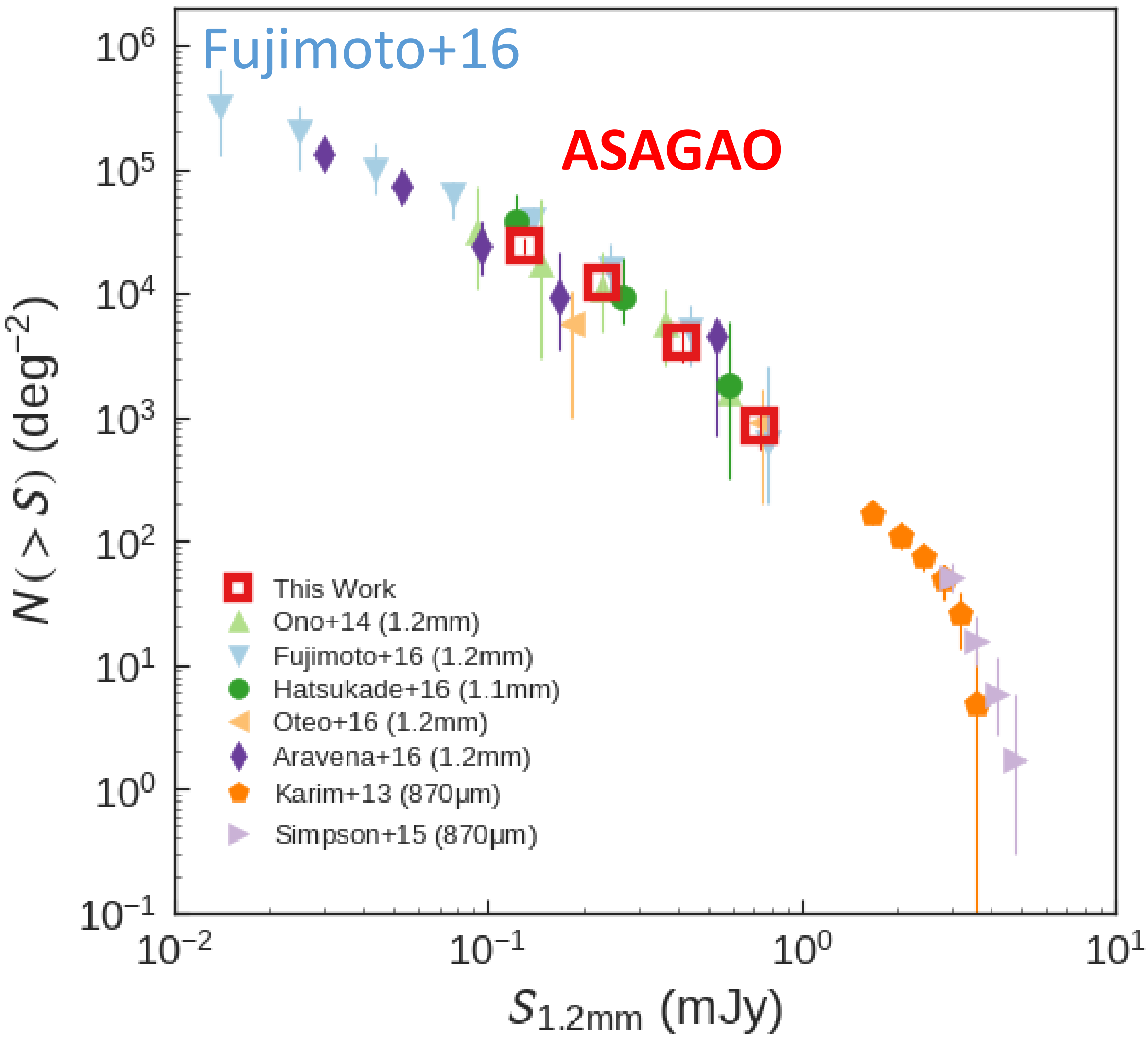
Yoshimura, Kohno, BH, et al. (in prep.)



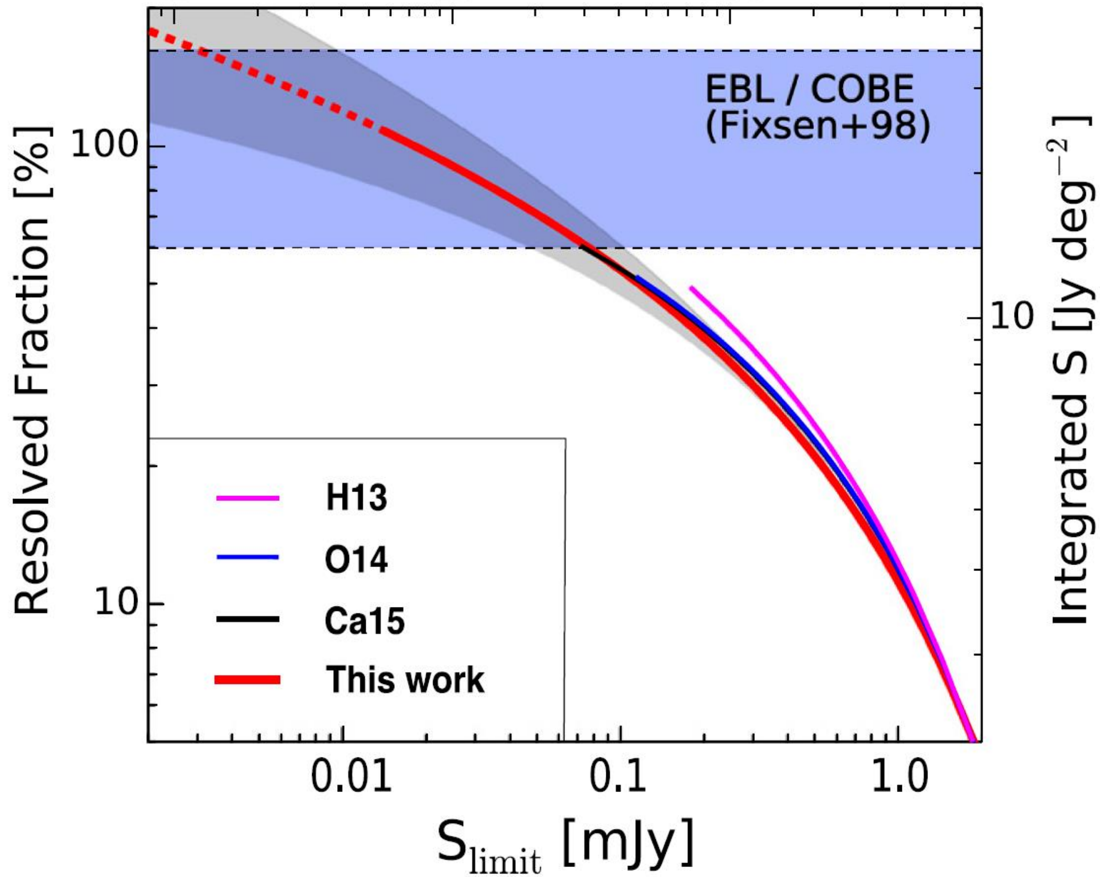
Number Counts



BH et al. (in prep.)

Contribution to EBL

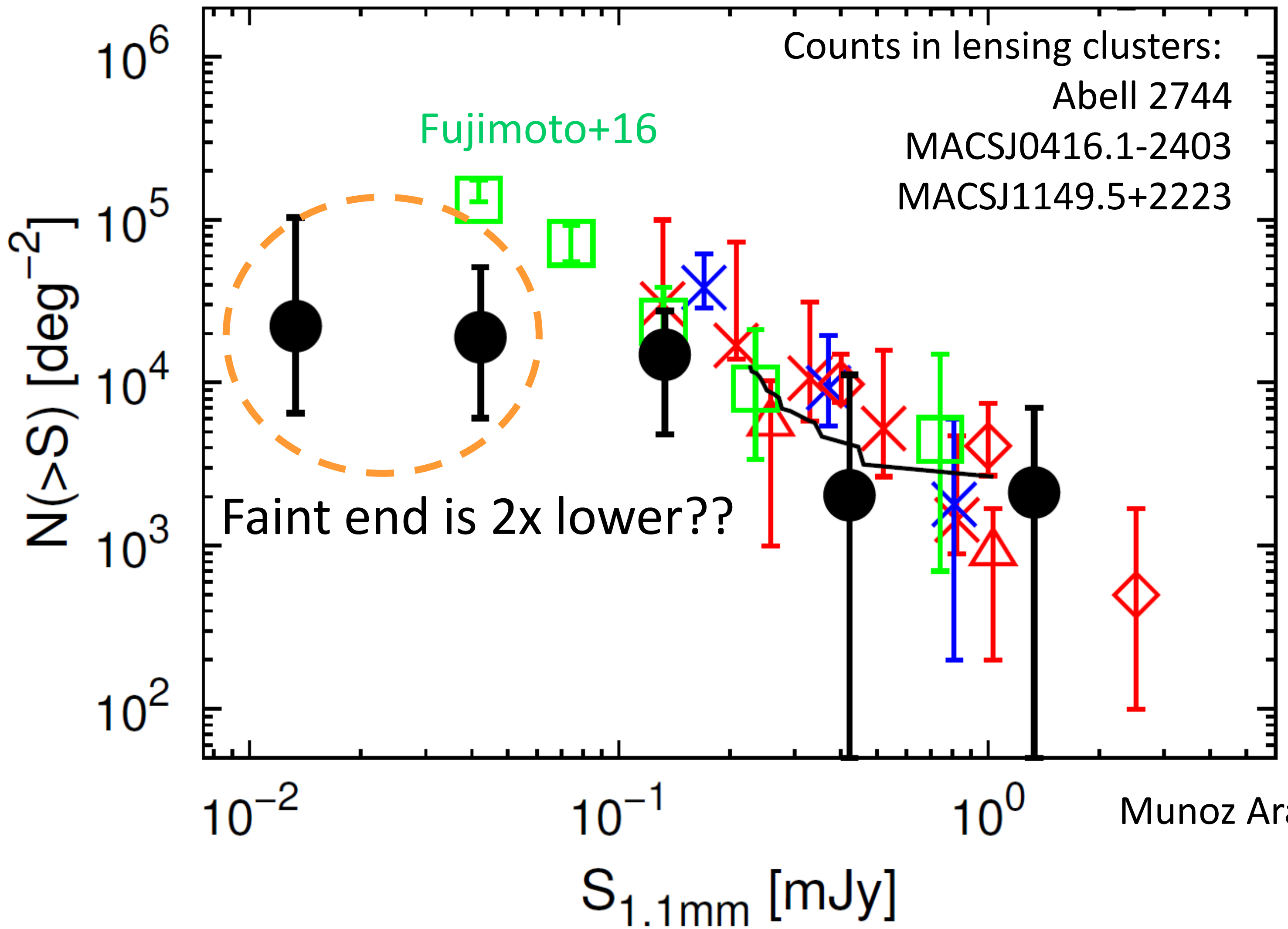
Resolved Fraction	Flux Limit (mJy)	Ref.
~50%	0.1	Hatsukade+16; Ono+14
~80%	0.037	Aravena+16
100%	0.02 (including lensed sources)	Fujimoto+16



Fujimoto+16

Contribution to EBL

Contribution is only 32% down to 0.013 mJy

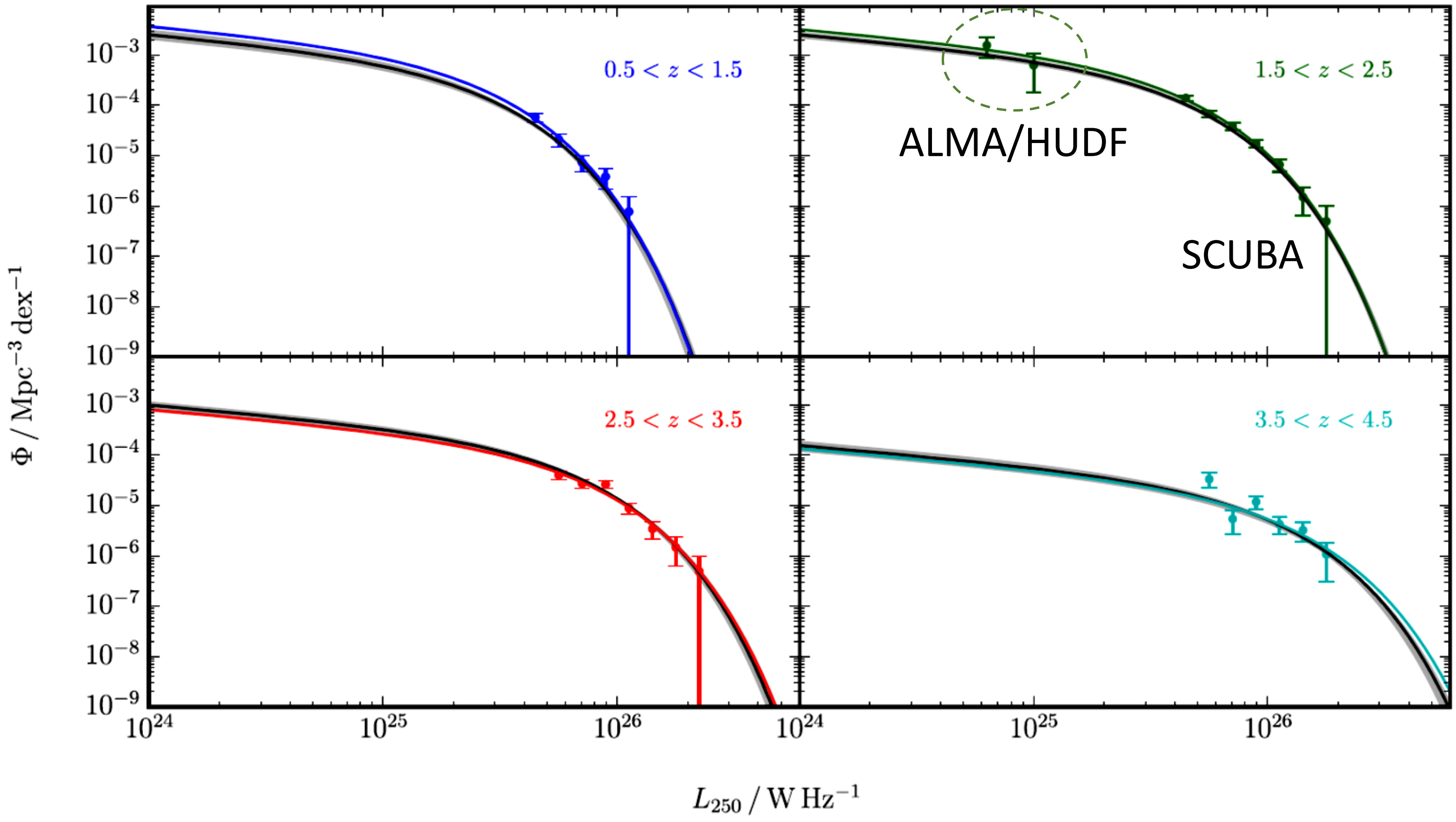


Munoz Arancibia+17

Luminosity Function

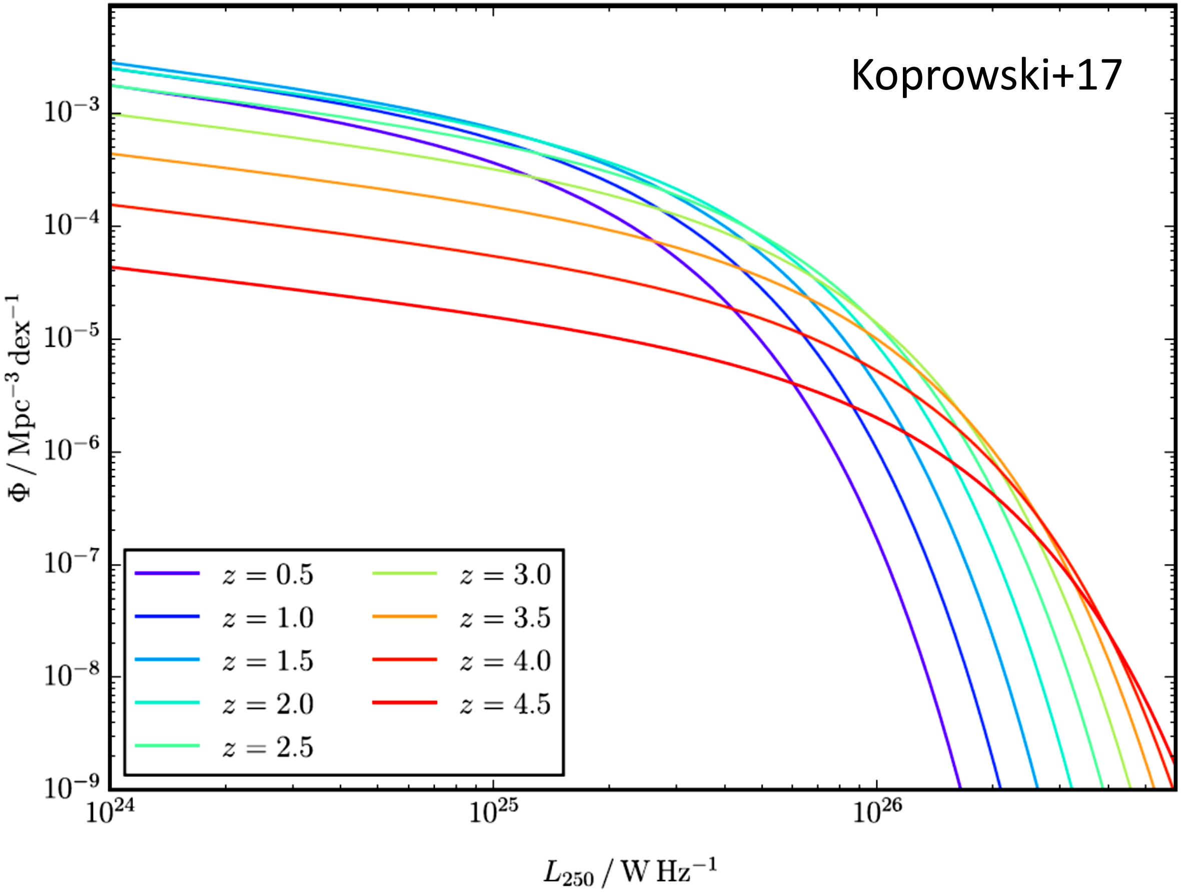
- ALMA probes faint end of L(IR) LF

Koprowski+17



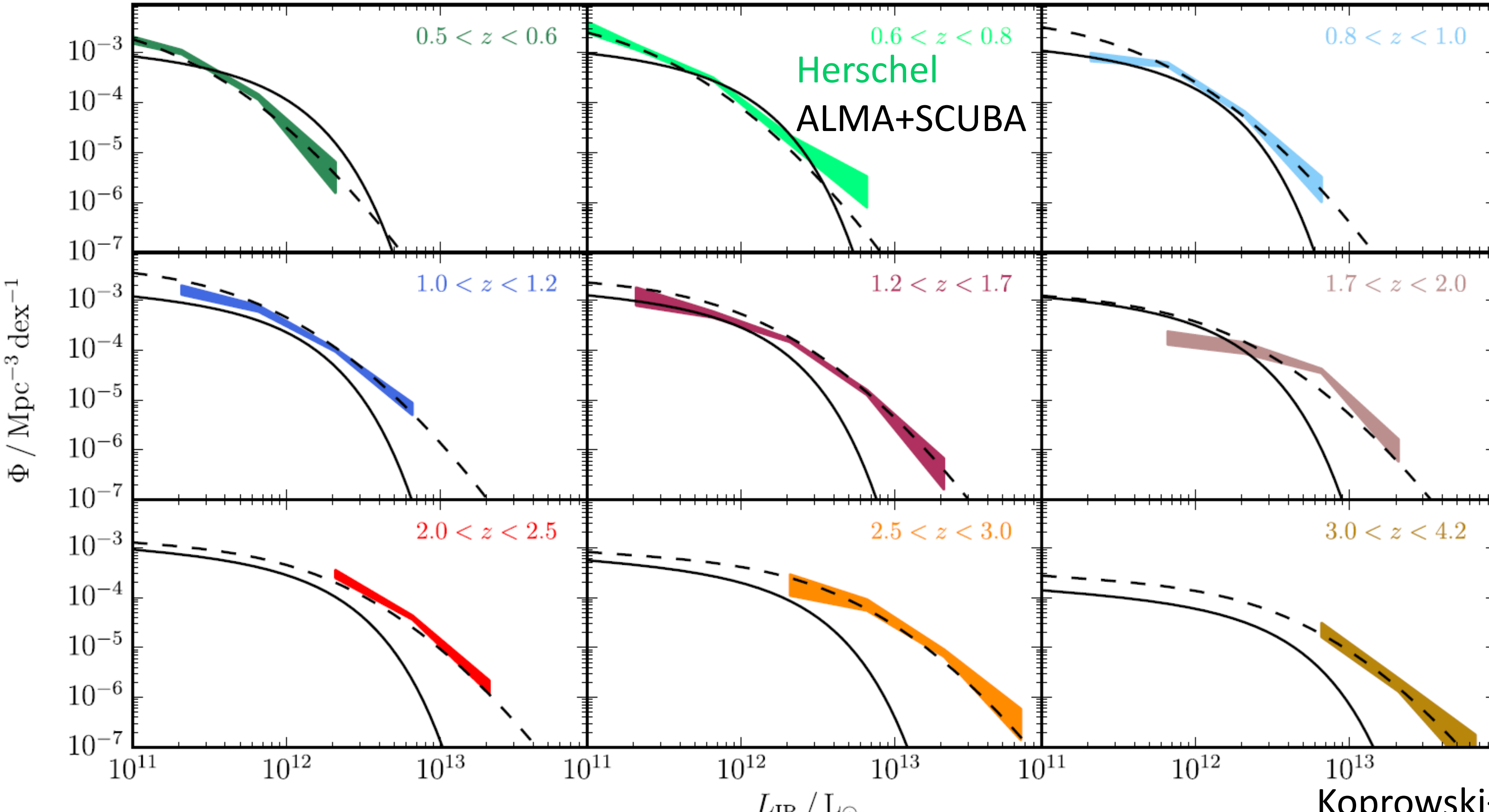
Luminosity Function

- redshift evolution
    - positive luminosity evolution
    - negative density evolution



Comparison with Herschel LF

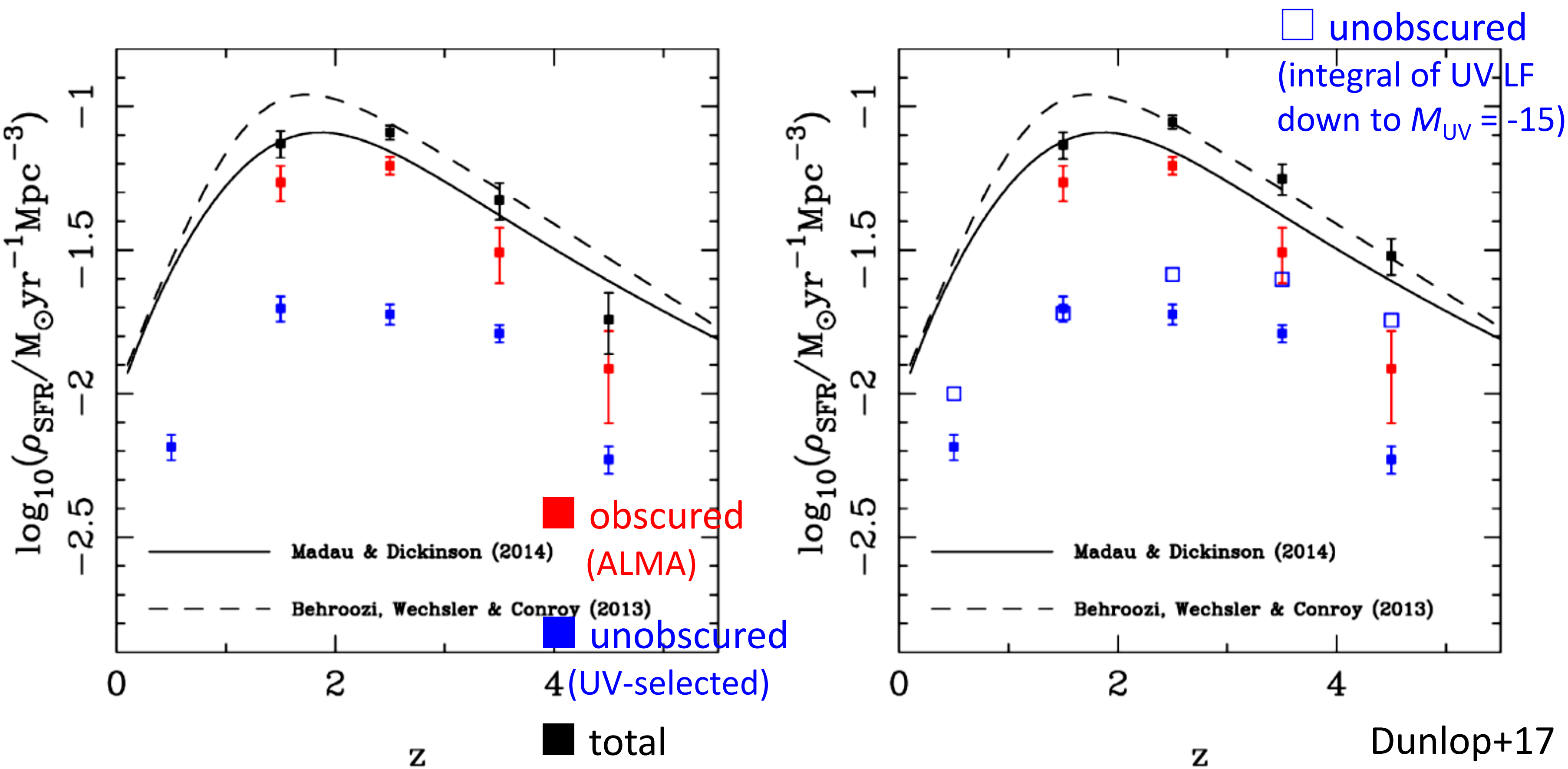
- Herschel LF overestimate faint and bright end?
  - source blending, miss ID of counterparts, AGN contamination?



Koprowski+17

Contribution to SFRD

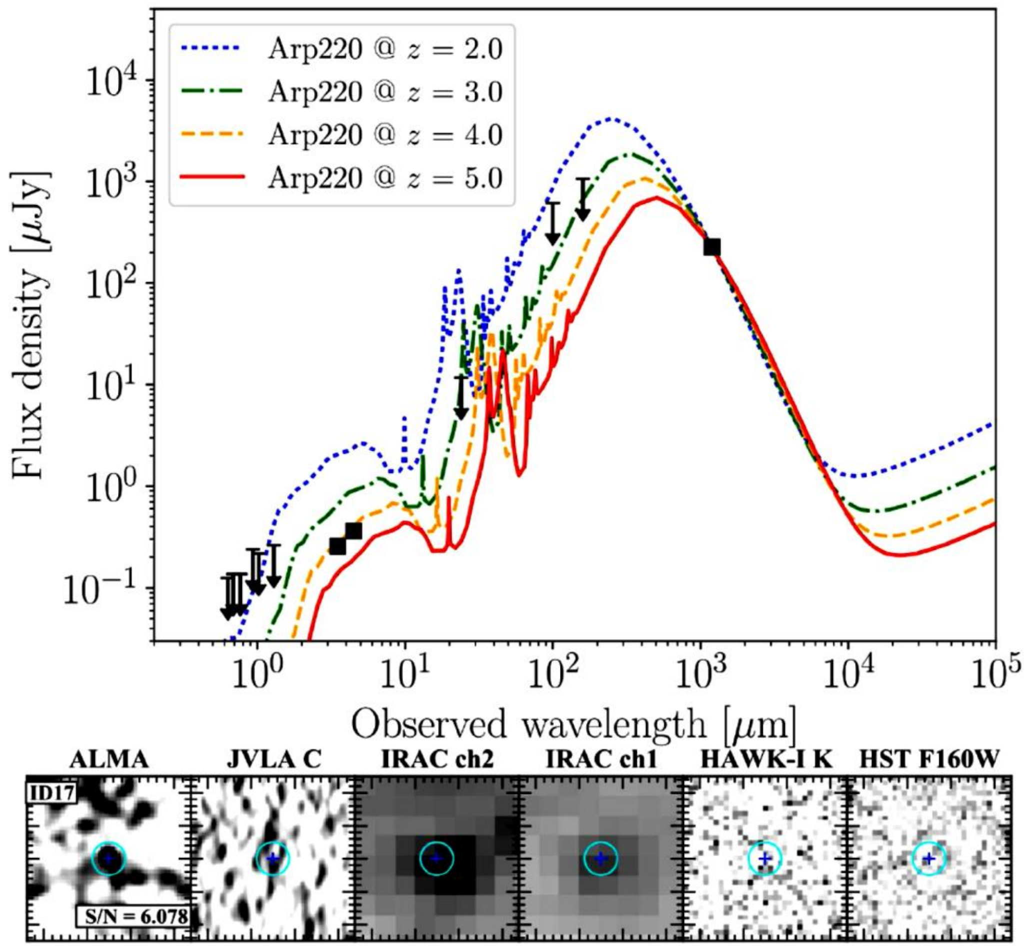
- Fall-off in obscured SF at higher-z
- Dominated by unobscured UV component at z > 4?



Dunlop+17

Optically-faint High-z Sources?

- ASAGAO sources without optical counterparts: “*K dropouts*”
  - 15% for 5σ sources
  - 45% for 4.5σ sources
- Spurious?
- High-z dusty galaxies?



Yamaguchi, Kohno, BH, et al. (in prep.)

Summary

- ALMA deep surveys
  - several surveys ongoing
  - 1σ ~ 10-100 mJy/beam, area ~ a few – 100 arcmin2
- Faint submm sources detected in ALMA deep surveys
  - z ~ 2, M* ~ 10^{11} Msun, SFR ~ 100 Msun/yr
  - massive end of main sequence
  - higher L_{IR}/L_{UV}
- Contribution to EBL
  - ~50%-100%, but the faintest end (<0.1 mJy) is still unclear
- Contribution to SFRD
  - ALMA sources are dominant population at z ~ 2-3
  - dominated by unobscured UV component at z > 4?
  - but the contribution of "*K* dropouts" is yet unknown